Urbanization and food systems

vorgelegt von

Dipl.-Kfm., M.Sc.

Christopher Bren d'Amour

geb. in Bonn

von der Fakultät VI – Planen Bauen Umwelt
der Technischen Universität Berlin
zu Erlangung des akademischen Grades

Doktor der Naturwissenschaften

- Dr. rer. nat. –

genehmigte Dissertation

Promotionsausschuss:

Vorsitzende: Prof. Dr. Eva Paton
Gutachter: Prof. Dr. Felix Creutzig
Gutachter: Prof. Dr. Ottmar Edenhofer
Gutachter: Prof. Dr. Jan Minx
Gutachter: PD Dr. Daniel Müller

Tag der wissenschaftlichen Aussprache: 14.03.2018

Berlin 2018

Abstract

Food systems are shaped by global change. Climate change adversely affects yields and already strained resources necessary for food production. Economic and demographic development influence consumer preferences and create unprecedented demands, transforming the entire food value chain. Understanding how global change drivers are influencing food systems is essential in finding solutions for sustainably providing food for nine billion people.

Urbanization is one of these defining drivers of food system transitions. Yet, its effects have not been sufficiently explored. This dissertation contributes to a better understanding of the role of urbanization by investigating the implications of two dimensions of urbanization on two dimensions of the food system: the spatial dimension and urban living on the one hand, and the food production and food consumption activities on the other hand. Specifically, it addresses two overarching research questions in two separate parts: (i) How is urban area expansion affecting food production activities? (ii) How is urbanization and associated urban living affecting food consumption patterns?

The first part of this dissertation addresses the first question and analyzes the implications of the spatial dimension of urbanization on food production activities. Chapter 2 sets the stage with a comprehensive assessment of the extent and density of multiple drivers and impacts of land use change. It reveals significant co-occurrences of expanding human activities and pervasive pressure on biodiversity. Further, it highlights the need for a more detailed understanding of competing land use dynamics driven by human activities. Chapter 3 examines the implications of urban areas expansion on croplands at the global level. It shows that while global cropland losses are marginal, they are very relevant in some of the rapidly urbanizing regions of Africa and Asia. It also finds that the croplands surrounding urban areas are almost twice as productive as the remaining croplands. The implications at the local level are far-reaching, affecting livelihoods and ultimately food security. In this context, some countries are likely to lose their food self-sufficiency. Chapter 4 supplements the earlier findings and explores the risks associated with high import dependencies on key staple crops for developing countries. It investigates how high dependency on food imports could potentially affect the calorie supply in developing countries.

The second part of the dissertation investigates the second question and explores how urbanization and associated urban living is affecting food consumption patterns. Chapter 5 analyzes the empirical relationships between urban development and packaged food, processed food, and food away from home consumption at different spatial scales. The analysis reveals that the level of urban development affects the consumption of packaged foods at the country level. Further, it shows variations in processed food and food away from home consumption at different levels of urban development within India. While income is still the most important driver for changing food consumption, the findings also identify a significant urban effect on diets.

The concluding chapter 6 discusses the broader implications and significance of the findings of this dissertation. In particular, it is discussed how the findings affect food system outcomes, namely food security and livelihoods. Chapter 6 also highlights potential avenues for future research.

Zusammenfassung

Das Ernährungssystem wird fundamental von den Veränderungsprozessen des globalen Wandels beeinflusst. Der Klimawandel etwa hat negative Folgen für die weltweiten Ernteerträge und wirkt sich bereits jetzt auf dringend benötigte Ressourcen zur Nahrungsmittelproduktion aus. Die wirtschaftliche und demographische Entwicklung beeinflusst das Konsumverhalten der Menschen und sorgt für eine rasant steigende Nachfrage nach Lebensmitteln. Es ist essentiell zu verstehen, wie die Treiber der globalen Veränderung das Ernährungssystem beeinflussen, um Lösungen für eine nachhaltige Versorgung mit Lebensmitteln für neun Milliarden Menschen zu finden.

Einer der wichtigsten Treiber hinter dem globalen Wandel ist die Urbanisierung. Bisher sind deren Effekte auf Ernährungssysteme noch nicht hinreichend erforscht. Diese Dissertation leistet einen Beitrag zum besseren Verständnis der Rolle der Urbanisierung, indem sie die Auswirkungen von zwei Aspekten der Urbanisierung auf zwei Aspekte des Ernährungssystems untersucht: die räumliche Dimension und das urbane Leben auf der einen und die Nahrungsmittelproduktion und der Nahrungsmittelverbrauch auf der anderen Seite. Zwei umfassende Forschungsfragen werden in jeweils einem Teil der Dissertation bearbeitet. Die erste Frage lautet, wie die räumliche Expansion der urbanen Gebiete die Nahrungsmittelproduktion beeinflusst. Die zweite Frage ist, wie sich die Urbanisierung und das damit verbundene urbane Leben auf die Essgewohnheiten auswirken.

Der erste Teil der Dissertation befasst sich mit der ersten Frage. Mit einer umfangreichen räumlichen Analyse der Intensitäten verschiedener Landnutzungsdynamiken schafft Kapitel zwei die Voraussetzungen dafür. Es zeigt insbesondere Zusammenhänge zwischen dem sich ausdehnenden menschlichen Handeln und dem allgegenwärtigen Druck auf die Biodiversität. Des Weiteren unterstreicht es die Notwendigkeit eines besseren Verständnisses der konkurrierenden Landnutzungsdynamiken, die aus menschlichem Handeln resultieren. Kapitel drei untersucht die Auswirkungen der Expansion urbaner Gebiete auf Ackerflächen in einem globalen Zusammenhang. Es wird deutlich, dass die Verluste an Ackerflächen zwar global gesehen marginal sind. Gleichzeitig sind sie aber sehr produktiv und besonders relevant in Regionen mit schnell expandierenden urbanen Gebieten in Asien und Afrika. Die Auswirkungen sind auf lokaler Ebene weitreichend und betreffen die Lebensgrundlage und letztlich die Nahrungsmittelsicherheit. In diesem Zusammenhang ist es wahrscheinlich, dass einige Länder sich in Zukunft nicht mehr ausreichend selber mit Lebensmitteln versorgen können. Kapitel vier ergänzt die bisherigen Erkenntnisse und beleuchtet die Risiken von Importabhängigkeiten für Entwicklungsländer. Es wird geprüft, wie hohe Abhängigkeiten von Nahrungsmittelimporten im Falle von Angebotsschocks möglicherweise die Kalorienversorgung in diesen Ländern beeinflussen könnte.

Der zweite Teil der Dissertation untersucht die zweite Frage – wie sich die Urbanisierung und damit verbunden das urbane Leben auf die Gewohnheiten des Nahrungsmittelkonsums auswirken. Kapitel fünf analysiert die empirischen Zusammenhänge zwischen urbaner Entwicklung und verpackten Lebensmitteln, verarbeiteten Lebensmitteln und dem Konsum von Lebensmitteln außerhalb der eigenen vier Wände auf verschiedenen räumlichen Skalen. Die Analyse zeigt, dass das Level der urbanen Entwicklung den Konsum von verpackten Lebensmitteln auf dem Land beeinflusst. Außerdem wird deutlich, dass es auf verschiedenen Ebenen der urbanen Entwicklung in Indien Variationen des Konsums von verarbeiteten Lebensmitteln und des Konsums von Lebensmitteln außer Haus gibt. Während das Einkommen immer noch der wichtigste Treiber für veränderte Essgewohnheiten ist, zeigen die Ergebnisse auch einen signifikanten urbanen Einfluss auf die Ernährung.

Das abschließende Kapitel sechs diskutiert die breiteren Auswirkungen und die Signifikanz der vorliegenden Dissertation. Besonderes Augenmerk liegt dabei auf der Diskussion, wie die Ergebnisse die Literatur zu Nahrungsmittelsystemen unter dem Einfluss des globalen Wandels komplementiert. Kapitel sechs beleuchtet außerdem mögliche Wege für weitere Forschungsvorhaben.

Contents

Chapter 1

1. Introduction

Food systems are responsible for achieving food and nutrition security across the developing world in a sustainable way. By 2050, world food supply will need to increase by 60% compared to 2005 levels (Alexandratos and Bruinsma, 2012). The increasing demand from a rapidly growing population with changing preferences is only one aspect that makes providing enough food a major challenge. Climate change, for example, will have vast impacts on food production capabilities (Porter et al., 2014). Average yields will decrease with rising mean temperatures (Lobell et al., 2013; Lobell and Field, 2007); heat waves will lead to more variability in yields and hence output. These effects will not be distributed equally: emerging and developing regions will be more exposed to these developments (Lobell et al., 2008; Porter et al., 2014).

Providing enough calories to tackle undernutrition and hunger is only one part of the solution. Malnutrition in general is becoming an issue of great concern (Global Panel on Agriculture and Food Systems for Nutrition, 2017). While malnutrition is often associated with undernutrition, it mostly means poor nutrition (Ingram, 2017), or lack of proper and healthy nutrition. Food and nutrition security are inherently connected. Both are important components of the sustainable development agenda. Specifically, the Sustainable Development Goal (SDG) number 2 explicitly aims at eradicating hunger and all forms of malnutrition by 2030 (United Nations, 2015). It will require tremendous efforts and a more detailed understanding of how global change dynamics are affecting food systems.

The influence of urbanization is still not well understood (Seto and Ramankutty, 2016). Cities are predominant engines of wealth creation (Bettencourt et al., 2007; Grubler et al., 2012) and, more importantly, hotspots of consumption (Creutzig et al., 2015; Seto et al., 2014). The multiple dimensions of urbanization – including the share of people living in urban areas, the expansion of built environments, and the associated urban way of living – are driving environmental change (Grimm et al., 2008). In this context, urbanization is also fundamentally affecting food systems (FAO, 2011). Rapid urbanization is forecast to take place in developing regions of Sub-Saharan Africa and Asia (United Nations, 2014), regions that are prone to food and nutrition insecurity (FAO, IFAD and WFP, 2016). Understanding how urbanization influences food production activities and how urbanization and associated urban living is affecting food consumption patterns would allow for more informed and targeted policies.

The remainder of this chapter provides background information on the current status of research on transforming food systems, and details the structure of this dissertation. Part 1 describes the nature of i) food systems activities and ii) food systems outcomes. Part 2 establishes how urbanization is affecting food system activities, and discusses the need for a more detailed understanding of the implications of urban area expansion and urban food consumption patterns. Part 3 introduces the guiding research questions and outlines the structure of the dissertation.

1.1. Background: food systems, food security, and urbanization

This section provides a brief overview over concepts used in this dissertation and the status quo of research on food systems under global change. It uses a framework to describe the concepts of food systems and food security and the interactions with global change drivers, providing an overview over the literature and approaches to analyze food security.

1.1.1. Food system transitions

Food systems can be defined as "*the chain of activities connecting food production, processing, distribution, consumption, and waste management, as well as all the associated regulatory institutions and activities*" (Pothukuchi and Kaufman, 2000). All these activities are shaped by global change dynamics. Economic growth and rising incomes, for example, are changing consumer preferences towards a "*westernization of diets*" in the developing world, away from basic staples towards more processed foods and animal based products (Pingali, 2007). This has important implications for resource use (Erb et al., 2016; Kastner et al., 2012; Tilman and Clark, 2014) and public health (Popkin, 2001, 1994). In parallel, a rapid proliferation of modern food retail outlets is observed, transforming the retail sector of developing economies (Reardon et al., 2012, 2003). These transformations have far-reaching consequences beyond the immediate food systems activities, for example for social welfare in terms of income generation and employment, health, and ultimately food security. They are generally interlinked and occur as the overall structure of the food system of an economy modernizes (Reardon and Timmer, 2014).

To facilitate the understanding of food systems and the complex interactions with global change, Ericksen (2008) developed a food systems framework for environmental change research, which includes feedbacks and interactions with drivers, and considers multiple outcomes. Central to this framework is the notion that the primary outcome of any generic food system is food security. It further builds upon the idea that within complex systems, it is possible to identify key processes as well as determinants that affect the outcomes. Here, I use a slightly adjusted version of this Global Environmental Change and Food Systems framework (GECAFS, based on Ingram (2011), Figure 1) to describe the concept of food systems activities and outcomes, and the interactions with global change drivers.

In this framework, food systems activities are grouped into four components: *producing food*, *processing & packaging*, *distribution & retail*, and *consuming* (Figure 1). The *producing* activities include all activities involved in the production of raw food materials, and include inputs such as natural resources. Factors such as climate change determine these activities. *Processing & packaging* includes all activities that process the raw materials and add value in the economic sense. Determinants include, for example, trade organizations that set standards. *Distribution & retailing* includes all activities that move the products from one place to another, as well as getting the products to the consumer. Infrastructure is a key determinant in this context. *Consuming* includes everything from deciding what to eat to the preparing and consumption of meals. Advertising is an example of a determinant of consumption.

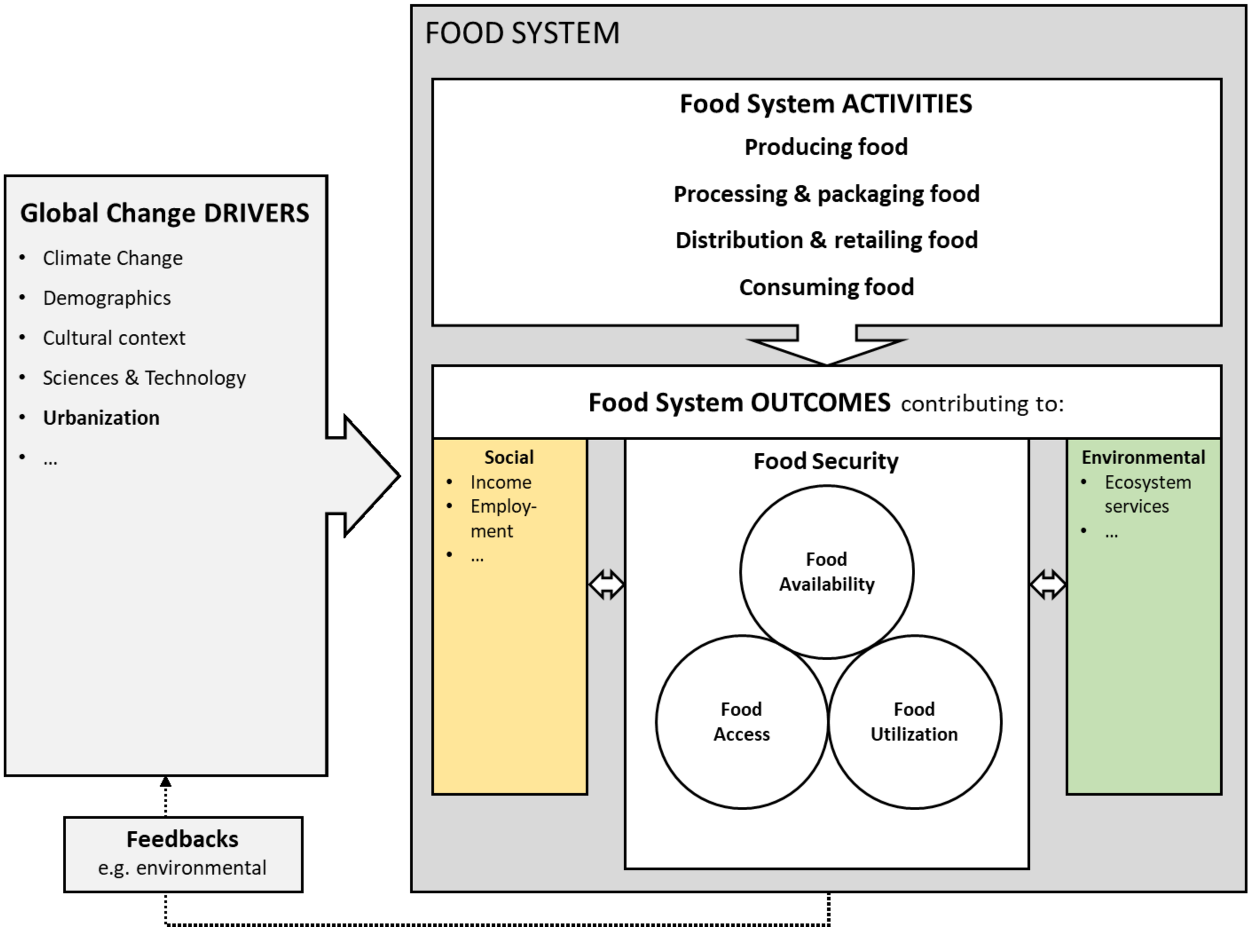

Figure 1 – Food system activities, outcomes, and drivers. Adjusted Global Environmental Change and Food Systems (GECAFS) framework, based on Ericksen (2008) and Ingram (2011).

These activities will have different outcomes, grouped into three components: *social*, *food security*, and *environmental* (Figure 1). *Social* outcomes relate to how these activities are affecting employment and income of people that work along the food value chain. *Food security* outcomes are the primary outcomes of food systems. They will be discussed in detail in the next section. *Environmental* outcomes include natural capital and ecosystem services that are impacted, for example by farming activities. It is important to note that *social* and *environmental* outcomes are both outcomes of food system activities, but also determinants of food security. For example, a higher income of a household as outcome of employment in food processing will also determine its food security by increasing the accessibility of food. At the same time, marginalization of small shop owners due to the super market revolution might have a negative outcome in terms of livelihoods, which will also affect the accessibility of food.

Global change dynamics drive these food systems activities and subsequently outcomes. The impacts of these drivers can be explored in isolation or interacting with other drivers and determinants. To reduce the complexity, they can also be further broken down. For example, researching the impacts of climate change on production activities could be done only considering the effects of increasing mean temperature on yields, without accounting for increasing climatic variability. A more holistic approach would also consider the CO_2-fertilizer-effect that arises with increasing CO_2-levels in the atmosphere and can have a positive effect on yields (Smith et al., 2014). Since agricultural activities contribute significantly to GHGemissions (Smith et al., 2014), largely due to the emission of methane via enteric fermentation, this would also constitute an environmental *feedback* from food system activities to the global change drivers.

This version of the framework regards both food system activities and outcomes as part of the 'overall' food system (grey box, Figure 1), a slight abstraction from the definition introduced earlier in this section that only includes the activities. Further, it groups different global change drivers that were put separately in the original framework (e.g. socio-economic drivers & global environmental change drivers) in one box under the heading *global change drivers*. Additionally, the potential feedbacks are grouped together. All of this is done to reduce the complexity for the purpose of this dissertation. The overall validity of the framework is unaffected.

1.1.2. Food systems and food security under global change

Food security is considered as the principal outcome of food systems (Ericksen, 2008). It is achieved when "*all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life*" (FAO, 1996). Generally, food security has three dimensions: availability, accessibility, and utilization. Following the GECAFS framework presented in Figure 1, availability refers to elements such as the production (how much is available through local production?), and exchange (how much is obtained via trade rather than local production?). Accessibility concerns the monetary affordability and allocation of food items (where and how can food be accessed by consumers?). Utilization contains nutritional value of the food as well as food safety concerns. By definition, nutrition security is hence a component of food security. Achieving food security requires a detailed understanding of all of these components.

A range of approaches for achieving food security exists, each focusing on different aspects (Burchi and De Muro, 2016). However, much of the debate about food security and corresponding research has been centered on aspects of food production (Burchi and De Muro, 2016; Ingram, 2017, 2011). The basic concept of increasing production to meet increasing demand, the '*productionist approach*', has been the reference approach for the international community. For much of the twentieth century, food security was seen as a matter of aggregate per capita food supply. This changed with the World Food Summit 1996 and the subsequent introduction of the commonly used definition of food security introduced earlier in this section. The notion of accessibility was put at the center stage, acknowledging that the inability to access food was and is to this day the main reason for food insecurity (Ingram, 2011). The emphasis changed from increasing production to increasing accessibility. The definition also encompassed the notions of availability in a broader sense (not just production but also exchange and distribution) and utilization.

Much of the research on food security under global change still centers on issues related to food production (Garnett, 2016). Central in this context is the limited availability of key resource inputs, most notably land, which is becoming increasingly scarce (Creutzig, 2017; Lambin and Meyfroidt, 2011; Smith et al., 2010), but also water (Jackson et al., 2007). Landmark papers such as Godfray et al (2010) on the challenge of feeding nine billion people or Foley et al (2011) on solutions for a cultivated planet, for example, focus on addressing the unprecedented demands on agriculture and natural resources. In an important contribution on potential leverage points to improve food security, West et al (2014) explicitly focus on how to provide enough calories to meet the additional demand. Other studies (Licker et al., 2010; Mueller et al., 2012; van Ittersum et al., 2013) focus on closing yield gaps, i.e. the gaps between actual yields and potentially attainable yields, which would promise additional potential in regions such as Sub-Saharan Africa (SSA). These contributions analyze how to produce enough food in light of a range of global change drivers. While some draw inferences regarding general food security, they mostly only address the availability dimension.

Climate change poses arguably the biggest challenge to the production side of food systems. Many studies are concerned with implications of climate change on food production activities, discussing how climate change is affecting yields and yield variability (Asseng et al., 2011; Lobell, 2011; Lobell and Field, 2007; Parry et al., 2004). According to the IPCC WGII report, the implications "*are expected to be widespread, complex, geographically and temporally variable*" (Porter et al., 2014). The effects will not be distributed equally, with the Southern hemisphere being more exposed to climate hazards than the Northern hemisphere (Lobell et al., 2008; Schlenker and Lobell, 2010). Since much of the population growth is forecast to come from the Southern regions (United Nations, 2012), this raises concerns about distributional effects. Countries might lose their food self-sufficiency. Due to the complex nature of food system activities and food system outcomes, however, the implications of climate change for food security are much less clear. The IPCC states that quantifying the effect of climate change on food security is "*an extremely difficult task*", concluding that "*there is […] limited direct evidence that unambiguously links climate change to impacts on food security*" (Porter et al., 2014).

Providing enough food has long been an important strategy to alleviate food security concerns, and still is today. However, as already indicated, it does not sufficiently capture the complexity of food security for a number of reasons. First, it does not address the multidimensionality of the issue. The availability dimension is over-emphasized. Successfully assessing food security will require considering all dimensions, as the example of trade highlights. In order to mitigate the distributional effects, trade will become increasingly important as countries have to resort to imports to feed their populations (Erb et al., 2016; Kastner et al., 2012). Imports will increase the domestic food availability in a country, but it will also increase the country's exposure to global food shocks, which is concerning in a "*global food system […] vulnerable to systemic disruptions*" (Puma et al., 2015). Supply shocks, for example due to severe droughts in exporting countries, would mostly be mediated by price effects. In such a scenario, assessing the implications for food security becomes a question of accessibility, specifically of "*how do international prices transmit to domestic prices and what does this mean for the most vulnerable parts of the population*?" (Kalkuhl, 2014; Kornher and Kalkuhl, 2013). Hence, any food security assessment for food import-dependent countries requires a detailed analysis of issues related to food accessibility.

Second, providing enough calories does not necessarily achieve food security per definition, even if accessibility is not an issue. Malnutrition is becoming a matter of grave concern (Global Panel on Agriculture and Food Systems for Nutrition, 2017; Ingram, 2017). More than two billion people consume excess calories, and, paradoxically, many of those do not get enough nutrients (Ng et al., 2014). This in turn has important implications for public health, raising concerns about obesity and other diet-related noncommunicable diseases (Garnett, 2016; Mendez and Popkin, 2004). To tackle these issues, nutrition and nutrition security have been put at the center stage. In 2016, the United Nations General Assembly proclaimed the '*Decade of Nutrition*' as part of the UN Sustainable Development Goals initiative (FAO, 2016). The same year, the Global Panel on Agriculture and Food Systems for Nutrition, comprised of international experts, many of which from relevant UN agencies, states that "*food systems need to be repositioned: from feeding people to nourishing people well*" (Global Panel on Agriculture and Food Systems for Nutrition, 2017). This is also reflected in the 2017 '*State of Food Security and Nutrition in the World*' report (FAO, IFAD, UNICEF, WFP and WHO, 2017), published by a consortium consisting of numerous UN agencies, including the Food and Agriculture Organization of the United Nations (FAO) and the World Health Organization (WHO). This report is specifically designed to monitor progress towards both ending hunger and all forms of malnutrition. To tackle the nutrition problem, Ingram (2017) proposes a food systems approach, which includes "*identifying problems at the consumer end of the supply chain, and working backwards to the producer from there*". He argues that this bottom up approach would allow for more targeted policy intervention. However, this would also require a more detailed understanding of what is driving consumer preferences.

1.2. Linkages between food systems and urbanization

Figure 1 shows how global change dynamics are driving transitions in food system activities and how that in turn is affecting food system outcomes. This dissertation is based on the hypothesis that urbanization is one of the defining global change drivers shaping food systems. This section describes potential linkages between urbanization and food systems, and highlights potential challenges.

Urbanization involves changes in multiple dimensions. First, a growing percentage of people is living in urban areas (United Nations, 2014): by 2050, 6.5 billion people will live in cities, equaling two thirds of the population. Second, there is a rapid expansion of urban areas (Seto et al., 2011). Urban areas are expected to triple from 2000 to 2030 (Seto et al., 2012), making it the fastest growing land use form. Third, there are changes in norms and ways of living that are unique to urban areas (Bettencourt and West, 2010). All of these have implications for food systems. The latter, for example, affect food consumption patterns towards more resource intensive diets (Popkin, 1999). As Seto and Ramankutty (2016) highlight, urbanization is affecting the activities of the food systems in a multitude of ways. Table 1 lists some examples of how urbanization is transforming food system activities.

Table 1 – Implications of urbanization on food system activities. This table provides a selection of potential implications and is non-exhaustive.

Global Change Driver	Producing food	Processing & packaging of food	Distributing & retailing of food	Consuming food
Urbanization	Competition for resources (land and water) (Bagan and Yamagata, 2014; Chen, 2007)	Transformation of agro-processing chain: marginalization of small scale actors (Reardon et al., 2014; Reardon and Timmer, 2014)	Proliferation of modern retail & fast-food restaurants (Reardon et al., 2012; Reardon and Berdegue, 2002)	Higher opportunity cost of cooking – more food away from home consumption (Gaiha et al., 2009; Ma et al., 2006)

Urbanization and associated urban area expansion convert valuable croplands, as confirmed by case studies around the world (Ahmad et al., 2016; Bagan and Yamagata, 2014; Chen, 2007). Given that 60% of the world's irrigated croplands lie in the vicinity of urban areas (Thebo et al., 2014), this is likely to continue to be a problem for many countries. In arid regions such as Egypt, the competition for resources is not only limited to land: urban areas and croplands also compete for scarce water resources. This competition for biophysical resources affects the food producing activities of countries. However, while there are case studies highlighting the importance of the issue, there are no global estimates of the magnitude of the effects.

The preference of urban consumers for processed foods and the different retail structure in cities have important implications for the processing and packaging of food. In Indian cities, for example, only 17% of the food consumed does not undergo any kind of processing (Morisset and Kumar, 2008). These dynamics are transforming the food value chains, providing ample non-farm employment along the way (Reardon, 2015).

Urbanization also has major implications for the distribution and retailing of food. Cities play an important role in the proliferation of supermarkets, other modern retail options, and fast food restaurants (Reardon et al., 2003; Reardon and Berdegue, 2002). Again, this is providing new service sector employment. However, it might have unintended consequences, such as the marginalization of smallholder agriculture, as supermarkets tend to source from larger, commercial farms.

The transformation of the retail sector is inherently linked with the urban food consumption patterns. Different employment structures and an increasing participation of women in the work force lead to higher opportunity costs of cooking at home. This in turn leads to more meals consumed away from home (Gaiha et al., 2009; Ma et al., 2006).

While the effects on food system activities are comparatively clear, the implications for food system outcomes are more complex to assess. Important questions arise. For example, will the people that are displaced as urban areas expand find access to urban labor markets? Will these households manage to be food secure? Displaced subsistence farmers might lose the ability to feed themselves, thus becoming net buyers of food. For these households, and the urban poor in general, food security is much more an issue of financial accessibility than availability (Cohen and Garrett, 2010). In this context, household's access to labor markets is essential.

Many of these questions on the linkages between urbanization and food systems remain to be explored (Seto and Ramankutty, 2016). Most studies that specifically analyze the implications of urbanization are case studies at the city or regional level, specifically on the spatial dimension of urbanization. Global estimates of the magnitude of these effects are lacking. Studies on, for example, changing food consumption patterns generally conflate urbanization and income effects (Seto and Ramankutty, 2016).

It was only relatively recently that the international community focused more explicitly on urbanization (FAO, 2011). However, its importance is increasingly acknowledged. The United States Agency for International Development (USAID), for example, held a strategic expert meeting on '*Cities and the future of agriculture and food security: a policy and programmatic roundtable*' in 2016 (Richards et al., 2016), essentially highlighting the need for a better understanding of urbanization in rapidly changing food systems, making it a priority for future research and funding. The 2017 Global Food Policy Report by the International Food Policy Research Institute (IFPRI, 2017) also focuses explicitly on the impacts of urbanization on food security and nutrition, recognizing the need for a better understanding of the role of urbanization in order to reshape food systems to benefit both urban and rural populations.

1.3 Thesis objectives and outline

This dissertation contributes to the understanding of how urbanization as global change driver is shaping food systems by investigating the implications of two dimensions of urbanization on two dimensions of the food system: the spatial dimension and urban living on the one hand, and the food production and food consumption activities on the other hand. In particular, this thesis contributes by addressing two main research questions:

- How is urban area expansion affecting food production activities?
- How is urbanization and associated urban living affecting food consumption patterns? What are the potential implications for broader food systems and public health?

This dissertation addresses the two research questions in four manuscripts, corresponding to journal publications. They are reproduced as chapters 2-5, as detailed in the following sections. Chapters 2-4 address the first research question, chapter 5 the second.

Chapter 2 comprehensively assesses the extent and density of multiple drivers and impacts of land-use change. It seeks to answer the following research questions:

- How are competing land uses driven by human activities affecting the food production landscape?
- What are the geographical hotspots of land conversion?
- What is the direct and indirect impact of human activity?

The study combines and reanalyzes spatially explicit data of global land use change 2000-2010 for population, livestock, cropland, terrestrial carbon, and biodiversity. This is supplemented by a detailed region-specific literature review. It reveals significant co-occurrences of expanding human activities and pervasive pressure on biodiversity. Patterns of land use change vary, with the biggest changes observed in developing regions. This article highlights the need for a more detailed and spatially explicit understanding of competing land use dynamics driven by human activities, thus setting the stage for the next chapter.

Chapter 3 examines the implications of urban areas expansion on croplands at the global level, addressing the following research questions:

- Where are croplands most vulnerable to conversion due to future urban expansion?
- What is the magnitude of cropland loss, especially of prime cropland, due to future urban expansion?
- How will the loss of croplands affect total cropland area and relative economic importance of agriculture for different countries?

This article provides the first global estimate of the urbanization of croplands. It uses a probabilistic map of future urban area expansion and combines it with spatial datasets on cropland area and cropland productivity. It shows that while cropland losses are marginal at the global level and can likely be compensated by the global food system, they are very relevant in some of the rapidly urbanizing regions of Africa and Asia. The implications are potentially far-reaching, affecting livelihoods and dimensions of food security. In this context, some countries are likely to lose their food self-sufficiency and will have to resort increasingly to imports.

Chapter 4 builds on some of the findings from the previous chapter and explores the risks associated with high import dependencies on key staple crops for developing countries. It seeks to answer the following set of questions:

- Which countries have a strong dietary reliance on specific crops that they also need to import?
- What happens in the case of supply shocks, for example if exporting countries introduce restrictive trade policies?
- What would be the effect on the calorie supply of the poorest people in these countries?

It analyzes how high dependency on imports of staple crops could potentially affect the calorie supply in developing countries. The analysis reveals that high import dependency exposes the poorest part of the population to teleconnected food supply shocks, threatening the calorie supply of up to 200 million people below the poverty line, 90% of which live in Sub-Saharan Africa. This article shows that while trade is undoubtedly an important factor in providing enough food in the future, it will be essential to mitigate the risks associated with import dependence.

Chapter 5 provides a change in perspective and focuses on the implications of urbanization on food consumption. It addresses the following questions:

- What is driving urban food consumption patterns?
- Is there an urban effect on diets that is not income related?
- What are the consequences of an urban effect on diets?

This chapter explores the empirical relationships between urban development and packaged food, processed food, and food away from home consumption at different spatial scales, using country level data for a global analysis and household level data for India. This analysis reveals that the level of urban development affects the consumption of packaged foods at the country level. Further, it shows variations in processed food and food away from home consumption at different levels of urban development within India. These urban effects vary significantly between metropolitan cities and non-metropolitan urban areas. While income is still the most important driver for changing food consumption, the findings of this chapter underline the importance of urbanization.

Chapter 6 summarizes the results of the previous chapters, discusses the relevance of the findings of this thesis, and lays out questions for further research.

In this dissertation, I apply methods from different disciplines. Chapters 2 and 3 rely mostly on geographic information systems (GIS). In these chapters, I use ArcGIS to process and analyze spatial data. In chapter 4, I use empirical and analytical methods to model the potential implications of food supply shocks. In chapter 5, I empirically analyze country level and household-survey data, also employing econometric concepts.

References

Ahmad, S., Avtar, R., Sethi, M., Surjan, A., 2016. Delhi's land cover change in post transit era. Cities 50, 111–118. doi:10.1016/j.cities.2015.09.003

Alexandratos, N., Bruinsma, J., 2012. World agriculture towards 2030/2050: the 2012 revision. ESA Working paper.

Asseng, S., Foster, I., Turner, N.C., 2011. The impact of temperature variability on wheat yields. Glob. Change Biol. 17, 997–1012. doi:10.1111/j.1365-2486.2010.02262.x

Bagan, H., Yamagata, Y., 2014. Land-cover change analysis in 50 global cities by using a combination of Landsat data and analysis of grid cells. Environ. Res. Lett. 9, 064015. doi:10.1088/1748-9326/9/6/064015

Bettencourt, L., West, G., 2010. A unified theory of urban living. Nature 467, 912–913.

Bettencourt, L.M.A., Lobo, J., Helbing, D., Kühnert, C., West, G.B., 2007. Growth, innovation, scaling, and the pace of life in cities. Proc. Natl. Acad. Sci. 104, 7301–7306. doi:10.1073/pnas.0610172104

Burchi, F., De Muro, P., 2016. From food availability to nutritional capabilities: Advancing food security analysis. Food Policy 60, 10–19.

Chen, J., 2007. Rapid urbanization in China: A real challenge to soil protection and food security. CATENA, Influences of rapid urbanization and industrialization on soil resource and its quality in China 69, 1–15. doi:10.1016/j.catena.2006.04.019

Cohen, M.J., Garrett, J.L., 2010. The food price crisis and urban food (in)security. Environ. Urban. 22, 467–482. doi:10.1177/0956247810380375

Creutzig, F., 2017. Govern land as a global commons. Nature 546, 28.

Creutzig, F., Baiocchi, G., Bierkandt, R., Pichler, P.-P., Seto, K.C., 2015. Global typology of urban energy use and potentials for an urbanization mitigation wedge. Proc. Natl. Acad. Sci. 112, 6283–6288. doi:10.1073/pnas.1315545112

Erb, K.-H., Lauk, C., Kastner, T., Mayer, A., Theurl, M.C., Haberl, H., 2016. Exploring the biophysical option space for feeding the world without deforestation. Nat Commun 7.

Ericksen, P.J., 2008. Conceptualizing food systems for global environmental change research. Glob. Environ. Change 18, 234–245.

FAO, 2016. News Article: UN General Assembly proclaims Decade of Action on Nutrition [WWW Document]. URL http://www.fao.org/news/story/en/item/408970/icode/ (accessed 10.14.17).

FAO, 2011. Food, Agriculture and Cities - Challenges of food and nutrition security, agriculture and ecosystem management in an urbanizing world, FAO Food for the Cities multi-disciplinary initiative position paper.

FAO, 1996. Declaration on World Food Security and World Food Summit Plan of Action. Rome FAO.

FAO, IFAD and WFP, 2016. The State of Food Insecurity in the World 2015. Meeting the 2015 international hunger targets: taking stock of uneven progress. FAO Rome.

FAO, IFAD, UNICEF, WFP and WHO, 2017. The State of Food Security and Nutrition in the World 2017. Building resilience for peace and food security. FAO, Rome.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342. doi:10.1038/nature10452

Gaiha, R., Jha, R., Kulkarni, V.S., 2009. How Pervasive is Eating Out in India? The Australian National University, Australia South Asia Research Centre.

Garnett, T., 2016. Plating up solutions. Science 353, 1202. doi:10.1126/science.aah4765

Global Panel on Agriculture and Food Systems for Nutrition, 2017. Food systems and diets: Facing the challenges of the 21st century. London, UK.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. science 327, 812–818.
Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., Briggs, J.M., 2008. Global Change and the Ecology of Cities. Science 319, 756–760. doi:10.1126/science.1150195
Grubler, A., Bai, X., Buettner, T., Dhakal, S., Fisk, D.J., Ichinose, T., Keirstead, J.E., Sammer, G., Satterthwaite, D., Schulz, N.B., Shah, N., Steinberger, J., Weisz, H., 2012. Chapter 18 - Urban Energy Systems, in: Global Energy Assessment - Toward a Sustainable Future. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 1307–1400.
IFPRI, 2017. 2017 Global Food Policy Report. International Food Policy Research Institute, Washington, DC. doi:10.2499/9780896292529
Ingram, J., 2017. Perspective: Look beyond production. Nature 544, S17–S17.
Ingram, J., 2011. A food systems approach to researching food security and its interactions with global environmental change. Food Secur. 3, 417–431.
Jackson, R.B., Farley, K.A., Hoffmann, W.A., Jobbágy, E.G., McCulley, R.L., 2007. Carbon and water tradeoffs in conversions to forests and shrublands, in: Terrestrial Ecosystems in a Changing World. Springer, pp. 237–246.
Kalkuhl, M., 2014. How Strong Do Global Commodity Prices Influence Domestic Food Prices in Developing Countries? A Global Price Transmission and Vulnerability Mapping Analysis. Glob. Price Transm. Vulnerability Mapp. Anal. May 2014 ZEF-Discuss. Pap. Dev. Policy.
Kastner, T., Rivas, M.J.I., Koch, W., Nonhebel, S., 2012. Global changes in diets and the consequences for land requirements for food. Proc. Natl. Acad. Sci. 109, 6868–6872. doi:10.1073/pnas.1117054109
Kornher, L., Kalkuhl, M., 2013. Food price volatility in developing countries and its determinants. Q. J. Int. Agric. 52, 277–308.
Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. Proc. Natl. Acad. Sci. 108, 3465–3472. doi:10.1073/pnas.1100480108
Licker, R., Johnston, M., Foley, J.A., Barford, C., Kucharik, C.J., Monfreda, C., Ramankutty, N., 2010. Mind the gap: how do climate and agricultural management explain the 'yield gap'of croplands around the world? Glob. Ecol. Biogeogr. 19, 769–782.
Lobell, D.B., 2011. Climate trends and global crop production since 1980. Science 333, 616–620. doi:10.1126/science.1204531
Lobell, D.B., Burke, M.B., Tebaldi, C., Mastrandrea, M.D., Falcon, W.P., Naylor, R.L., 2008. Prioritizing Climate Change Adaptation Needs for Food Security in 2030. Science 319, 607–610. doi:10.1126/science.1152339
Lobell, D.B., Field, C.B., 2007. Global scale climate–crop yield relationships and the impacts of recent warming. Environ. Res. Lett. 2, 014002. doi:10.1088/1748-9326/2/1/014002
Lobell, D.B., Hammer, G.L., McLean, G., Messina, C., Roberts, M.J., Schlenker, W., 2013. The critical role of extreme heat for maize production in the United States. Nat. Clim. Change 3, 497–501. doi:10.1038/nclimate1832
Ma, H., Huang, J., Fuller, F., Rozelle, S., 2006. Getting rich and eating out: consumption of food away from home in urban China. Can. J. Agric. Econ. Can. Agroeconomie 54, 101–119.
Mendez, M., Popkin, B., 2004. Globalization, urbanization and nutritional change in the developing world. Glob. Food Syst. Dev. Ctries. Impact Food Secur. Nutr. 55–80.
Morisset, M., Kumar, P., 2008. Structure and performance of the food processing industry in India. Mimeo.

Mueller, N.D., Gerber, J.S., Johnston, M., Ray, D.K., Ramankutty, N., Foley, J.A., 2012. Closing yield gaps through nutrient and water management. Nature 490, 254–257. doi:10.1038/nature11420

Ng, M., Fleming, T., Robinson, M., Thomson, B., Graetz, N., Margono, C., Mullany, E.C., Biryukov, S., Abbafati, C., Abera, S.F., 2014. Global, regional, and national prevalence of overweight and obesity in children and adults during 1980–2013: a systematic analysis for the Global Burden of Disease Study 2013. The lancet 384, 766–781.

Parry, M.., Rosenzweig, C., Iglesias, A., Livermore, M., Fischer, G., 2004. Effects of climate change on global food production under SRES emissions and socio-economic scenarios. Glob. Environ. Change 14, 53–67. doi:10.1016/j.gloenvcha.2003.10.008

Pingali, P., 2007. Westernization of Asian diets and the transformation of food systems: Implications for research and policy. Food Policy 32, 281–298. doi:10.1016/j.foodpol.2006.08.001

Popkin, B.M., 2001. The nutrition transition and obesity in the developing world. J. Nutr. 131, 871S–873S.

Popkin, B.M., 1999. Urbanization, Lifestyle Changes and the Nutrition Transition. World Dev. 27, 1905–1916. doi:10.1016/S0305-750X(99)00094-7

Popkin, B.M., 1994. The nutrition transition in low-income countries: an emerging crisis. Nutr. Rev. 52, 285–298.

Porter, J.R., Xie, L., Challinor, A.J., Cochrane, K., Howden, S.M., Iqbal, M.M., Lobell, D.B., Travasso, M.I., 2014. Food Security and Food Production Systems, in: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (Eds.)]. Cambridge University Press.

Pothukuchi, K., Kaufman, J.L., 2000. The food system: A stranger to the planning field. J. Am. Plann. Assoc. 66, 113–124.

Puma, M.J., Bose, S., Chon, S.Y., Cook, B.I., 2015. Assessing the evolving fragility of the global food system. Environ. Res. Lett. 10, 024007.

Reardon, T., 2015. The hidden middle: the quiet revolution in the midstream of agrifood value chains in developing countries. Oxf. Rev. Econ. Policy 31, 45–63.

Reardon, T., Berdegue, J.A., 2002. The rapid rise of supermarkets in Latin America: challenges and opportunities for development. Dev. Policy Rev. 20, 371–388.

Reardon, T., Timmer, C.P., 2014. Five inter-linked transformations in the Asian agrifood economy: Food security implications. Glob. Food Secur. 3, 108–117. doi:10.1016/j.gfs.2014.02.001

Reardon, T., Timmer, C.P., Barrett, C.B., Berdegué, J., 2003. The rise of supermarkets in Africa, Asia, and Latin America. Am. J. Agric. Econ. 85, 1140–1146.

Reardon, T., Timmer, C.P., Minten, B., 2012. Supermarket revolution in Asia and emerging development strategies to include small farmers. Proc. Natl. Acad. Sci. 109, 12332–12337. doi:10.1073/pnas.1003160108

Reardon, T., Tschirley, D., Dolislager, M., Snyder, J., Hu, C., White, S., 2014. Urbanization, diet change, and transformation of food supply chains in Asia. Mich. Glob. Cent. Food Syst. Innov.

Richards, P., Reardon, T., Tschirley, D., Jayne, T., Oehmke, J., Atwood, D., 2016. Cities and the future of agriculture and food security: a policy and programmatic roundtable. Food Secur. 8, 871–877. doi:10.1007/s12571-016-0597-3

Schlenker, W., Lobell, D.B., 2010. Robust negative impacts of climate change on African agriculture. Environ. Res. Lett. 5, 014010. doi:10.1088/1748-9326/5/1/014010

Seto, K.C., Dhakal, S., Bigio, A., Blanco, H., Delgado, G.C., Dewar, D., Huang, L., Inaba, A., Kansal, A., Lwasa, S., McMahon, J., Müller, D.B., Murakami, J., Nagendra, H., Ramaswami, A., 2014. Human settlements, infrastructure and spatial planning, in: Climate Change 2014: Mitigation of Climate

Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Seto, K.C., Fragkias, M., Güneralp, B., Reilly, M.K., 2011. A meta-analysis of global urban land expansion. PloS One 6, e23777.

Seto, K.C., Guneralp, B., Hutyra, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proc. Natl. Acad. Sci. 109, 16083–16088. doi:10.1073/pnas.1211658109

Seto, K.C., Ramankutty, N., 2016. Hidden linkages between urbanization and food systems. Science 352, 943–945. doi:10.1126/science.aaf7439

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J.I., Jafari, M., Masera, O., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Tubiello, F.N., 2014. Agriculture, Forestry and Other Land Use (AFOLU), in: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Smith, P., Gregory, P.J., Vuuren, D. van, Obersteiner, M., Havlík, P., Rounsevell, M., Woods, J., Stehfest, E., Bellarby, J., 2010. Competition for land. Philos. Trans. R. Soc. B Biol. Sci. 365, 2941–2957. doi:10.1098/rstb.2010.0127

Thebo, A.L., Drechsel, P., Lambin, E.F., 2014. Global assessment of urban and peri-urban agriculture: irrigated and rainfed croplands. Environ. Res. Lett. 9, 114002. doi:10.1088/1748-9326/9/11/114002

Tilman, D., Clark, M., 2014. Global diets link environmental sustainability and human health. Nature 515, 518–522. doi:10.1038/nature13959

United Nations, 2015. RES/70/1. Transforming our world: the 2030 agenda for sustainable development. Seventieth U. N. Gen. Assem. N. Y. 25.

United Nations, 2014. World Urbanization Prospects: The 2014 Revision, Highlights. Department of Economic and Social Affairs. Popul. Div. U. N.

United Nations, 2012. World Population Prospects: The 2012 Revision (Report), World Urbanization Prospects. United Nations, Department of Economic and Social Affairs, Population Division.

van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance—a review. Field Crops Res. 143, 4–17.

West, P.C., Gerber, J.S., Engstrom, P.M., Mueller, N.D., Brauman, K.A., Carlson, K.M., Cassidy, E.S., Johnston, M., MacDonald, G.K., Ray, D.K., Siebert, S., 2014. Leverage points for improving global food security and the environment. Science 345, 325–328. doi:10.1126/science.1246067

PART I

Chapter 2

2. Assessing human and environmental pressures of global land-use change 2000-2010*

Felix Creutzig
Christopher Bren d'Amour
Ulf Weddige
Sabine Fuss
Tim Beringer
Anne Glaeser
Matthias Kalkuhl
Jan C. Steckel
Alexander Radebach
Ottmar Edenhofer

*Currently under review as F. Creutzig, C. Bren d'Amour, U. Weddige, S. Fuss, T. Beringer, A. Glaeser, M. Kalkuhl, J.C. Steckel, A. Radebach, O. Edenhofer: Assessing human and environmental pressures of global land-use change 2000-2010.

Assessing human and environmental pressures of global land-use change 2000-2010

Felix Creutzig[1,2,*], Christopher Bren d'Amour[1,2], Ulf Weddige[1], Sabine Fuss[1], Tim Beringer[1], Anne Glaeser[1], Matthias Kalkuhl[1,3], Jan Steckel[1,2], Alexander Radebach[1,2], Ottmar Edenhofer[1,2,4]

Abstract

Global land turns into an increasingly scarce resource. Here we present a comprehensive assessment of the extent and intensity of multiple drivers and impacts of land use change. We combine and reanalyze data of global land use change 2000-2010 for population, livestock, cropland, terrestrial carbon, and biodiversity. We find pervasive pressure on biodiversity but differentiated types of gross land-use changes across world regions. The 'consumers' type, displayed in Europe, and North America, features high land footprints, reduced direct human pressures, corresponding to intensification of agriculture, and increased reliance on imported goods, enabling a partial recovery of terrestrial carbon and biodiversity. In the 'producer' type, most clearly epitomized by Latin America, telecoupled land-use links drive biodiversity and carbon loss. In the 'mover' type, we find strong direct domestic pressures but with wide variety of outcomes, ranging from a concurrent expansion of population, livestock, and croplands in Sub-Saharan Africa at costs of natural habitats to strong pressure on cropland by urbanization in Eastern Asia. In addition, anthropogenic climate change already leaves a distinct footprint in global land use change. Our data- and literature-based assessment reveals region-specific opportunities for managing global land-use change.

[1]Mercator Research Institute on Global Commons and Climate Change, 10829 Berlin, Germany
[2]Department Economics of Climate Change, Technische Universität Berlin, 10623 Berlin, Germany
[3]Faculty of Economic and Social Sciences, University of Potsdam, D-14482 Potsdam, Germany
[4]Potsdam Institute for Climate Impact Research, D-14412 Potsdam, Germany
[*]Author to whom any correspondence should be addressed.

2.1. Introduction

Demand for land is continuously rising globally (Foley et al., 2005). This is characterized by both intensification and extensification of food production (FAO, 2014), by urbanization (Seto et al., 2012), by the onset of modern bioenergy (Chum et al., 2011; Creutzig et al., 2014), by preservation of nature and biodiversity (Newbold et al., 2015), and, more recently, by afforestation to sequester CO_2 on land (Canadell and Raupach, 2008). Projected additional land demand could exceed available land by a factor of 3-7 by 2050 (Canadell and Schulze, 2014). Even when accounting for plausible multi-purpose allocation, this future demand is unlikely to be matched by available land resources (Davis et al., 2016). Imperatively, as global land emerges as a scarce resource, the importance of land for various and interconnected aspects of human well-being is emerging, raising normative and ethical questions (Creutzig, 2017; Risse, 2008). A few studies have investigated total area demands for various purposes and have provided long-term outlooks (Hurtt et al., 2011; Lambin and Meyfroidt, 2011; Smith et al., 2010). But a holistic understanding of geographical patterns of the most recent land system dynamics that investigates both location and intensity of land use changes for human needs (food, shelter), and biophysical stability (biodiversity, climate stabilization) across scales is missing. This paper investigates global land-use change across different purposes and perspectives between 2000 and 2010 with harmonized metrics. It investigates effects of direct and telecoupled land demand (defined as socioeconomic and environmental interaction over long distances, including trade and climate change (J. Liu et al., 2013) presenting a comprehensive, but spatially and regionally differentiated picture of global demand for land.

Land-use change has been associated with human activities for millennia and, prior to industrialization, was dominated by deforestation induced by population pressure and corresponding demand for cropland, closely following the ascent and descent of civilizations (Kaplan et al., 2009). With the industrialization, fossil fuel substituted for wood fuel, and the nexus between population pressure and deforestation was broken, at least regionally (Krausmann et al., 2008). However, current trends indicate that a re-transition to more land-use intensive economies may exceed global biophysical limits (Rockström et al., 2009; Steffen et al., 2015). First, at the current rate of technological change, croplands will most likely need to increase by 10-25% until 2050 to feed a growing and more affluent population demanding more land-intensive nutrition (Schmitz et al., 2014). Second, human settlements expand, demanding an unprecedented area of land that is on average about twice as agriculturally productive as world average cropland (Bren d'Amour et al., 2017). Third, energy production has started to shift back from fossil- to land-intensive fuels, a development potentially desirable to reduce counterfactual greenhouse gas emissions (Creutzig et al., 2014), or to even generate so-called negative emissions (Fuss et al., 2014; Smith et al., 2016). Fourth, land could provide the space for an enhanced terrestrial carbon sink, e.g. by afforestation, thus contributing to the mitigation of climate change. Fifth, ecosystems need to be stabilized across the globe to avoid unprecedented human-made biodiversity loss. As decision-makers become aware of climate change and biodiversity concerns, previously low-value residual land increases in value, limiting the availability for other purposes. At the same time, anthropogenic climate change itself affects the 'supply side' of land-use, e.g. by changing temperature and precipitation patterns or CO_2-fertilization, in part reducing counterfactual crop yields (Lobell, 2011). In short, developing human land pressures encounter global biophysical constraints and threaten global common goods, such as biodiversity and climate. The overall spatial patterns of these changes requires an updated analysis and assessment.

Clearly, it does not simply matter how land is allocated, but also how well it is utilized for different purposes and objectives. For example, land allocated to crop production could be used to varying degrees of efficiency, depending on management techniques and technology (West et al., 2014). It is hence equally important to measure the quality of land use, using *intensity* metrics normalized per unit area (Erb et al., 2013; Kuemmerle et al., 2013), as also realized from a different perspective in ecological and land footprint analysis (Galli et al., 2014; Wackernagel et al., 2002; Weinzettel et al., 2013). To use common language across dimensions, we also refer to population density and species richness as intensities if used per unit of area.

In this assessment and review, we comprehensively evaluate regional variation of global land use change patterns, addressing the following questions: 1) which kind of spatially distinct land-use transitions coincide? 2) At what intensity of use do land-use transitions occur and where are the hotspots of rapidly changing land-use dynamics located? 3) What kind of types of land use transitions can be distinguished across world regions? To answer these questions, we comprehensively reanalyze existing data on land use change in the specific categories of population, pasture, cropland, biodiversity and terrestrial carbon for 2000 and 2010. Compiling available data from different sources, we 1) evaluate the change dynamics between 2000 and 2010; 2) calculate global and regionally varying co-occurrence dynamics; 3) compute land-use intensity curves for population, pasture and cropland, biodiversity, and terrestrial carbon; and 4) identify underlying drivers drawing from the region-specific literature. We understand our paper as an assessment of recent land-use change dynamics (2000 – 2010). With the goal of comprehensively understanding land use dynamics in this limited, but important time range, we combine and reanalyze published data and review region-specific literature. This assessment is relevant in that there is an emerging class of global land assessments, including the *Global Land Outlook*, and the *IPCC's special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SR2).* It is our intention to provide input and background to these assessment reports.

The data analysis makes use of the best data available for 2000-2010. Nonetheless, the data analysis part is limited by the spatial resolution, and accuracy of available datasets; data on vegetation and soil carbon stocks, and cropland suitability are modeled, and the biodiversity data are downscaled proxy data. In addition, there might be disagreements between different datasets of the same dimension, exemplified by considerable differences between different cropland extent datasets (Anderson et al., 2015; Fritz et al., 2015). The resolution (approximately 50x50 km^2) is insufficient for reporting shifts in land use change on identical patches of land. To handle the resulting uncertainty, we cross-validate our results - co-occurring land use changes patterns in particular regions and cross effects - by a detailed review of region-specific relevant literature.

2.2. Results

We first investigate the change in intensity of land use for human pressures from population growth, expanding pastures and croplands, as well as their impacts on the biophysical metrics carbon density and biodiversity (Fig. 1, Table1). We rely on intensity metrics, here always understood as units (population, tC, livestock unit, cropland area fraction, carbon storage by using tones of terrestrial carbon stored/km^2 and biodiversity intactness weighted by species richness/km^2) per area (km^2), see Methods. Intensity hotspot analysis (top 10%) corresponds to the top decile of all grid cells with an intensity change between 2000 and 2010 (ranked by absolute density delta). Overall land-use change analysis focuses on 80% of grid cells with the highest absolute density change, *notable change pixels*, filtering out land-use change of low magnitudes. We designate *hotspots* as areas where 10% of the highest absolute changes in intensity occur and *notable change areas* where 80% of the highest absolute changes in intensity occur. When not explicitly described as hotspots, land-use dynamics are represented by notable change areas. Population density is increasing on 76% of land (within notable change areas), and on 91% of the hotspot areas (Table 1). Population growth is most substantial on the Indian subcontinent, Northern Africa and Western Asia, West Africa, the Lake Victoria region, and around the Sao Paolo mega-urban regions. Population density is decreasing in parts of Eastern Europe, and rural China. The cropland area fraction is increasing in hotspot areas (on 61% of hotspot area), but overall, cropland area fraction is decreasing in a slight majority of places (53% Table 1). Cropland is expanding most prominently in Mato Grosso, Brazil, the Guinean Savannah zone and Sumatra (South East Asia), but is declining across large parts of the Northern hemisphere. Sub-Saharan Africa is the region showing greatest human pressures as population density increased on average by 27%, and cropland expanded by 18%, between 2000 and 2010 (cf. Table S5). After population, the greatest increase is in livestock (on 62% of land). The most notable increases in livestock density appear in China, Brazil and parts of Sub-Saharan Africa, but there are decreases in parts of Europe, too. Worldwide, a small majority of places demonstrate an increase in land carbon stock (55%), notably in the Northern hemisphere and in tropical rain forests (parts of the Amazon, Congo and Indonesia). In contrast, decreases occur in most of South America, Sub-Saharan Africa, Sumatra, and some North-American regions (e.g., Alberta). Notably, 57% of global net terrestrial carbon loss took place in Sub-Saharan Africa and Latin America, together with 68% of global net cropland expansion (Table S5). With rare exceptions, biodiversity is decreasing worldwide (90%, and 98% of hotspots).

Notably, biofuel production was responsible for about half the global cropland expansion of about 44Mha between 2000 and 2010; it increased more than 4-fold between 2000 and 2010 and, by 2010, biofuels required about 30Mha of land (Bruinsma, 2009; Lambin and Meyfroidt, 2011). This expansion has mostly taken place on low-intensively used pasture land in Brazil, but also involves about 2.3Mha biodiversity-rich prairie land in the US (Lark et al., 2015), and, in total, >8Mha of palm oil (only partially used as fuel) in Sumatra, Borneo and Malaysia (Koh et al., 2011).

Table 1. Gain/loss per land use dimension with density change above threshold between 2000 and 2010 (2000 and 2005 for livestock). Density units: 1) Population: population/km²; 2) Livestock: livestock units/km²; 3) Cropland: cropland area fraction (here defined as percentage of cropland in a grid cell); 4) Carbon: tC/ha; 5) Biodiversity: Intactness/km² (weighted with species richness). *Intactness* measures the degree to which the original biodiversity of a terrestrial site remains unimpaired in the face of human land use and related pressures. Threshold refers to changes in intensity between 2010 (2005 for livestock) and 2000: Top 10% = hotspots areas of intensity changes, Top 80% = areas with notable changes.

Dimension	**Threshold (only cells with absolute changes above threshold considered)**	**Share of area with gain**	**Share of area with loss**	**Average density 2000**	**Average density change for areas with gain**	**Average density change for areas with loss**	**Average density 2010 (and change compared to 2000)**
Population	Top 10%	91%	9%	311.2	55.3 (+18%)	-29.2 (-9%)	357.2 (+15%)
	Top 80%	76%	24%	64.6	12.0 (+19%)	-2.7 (-4%)	72.1 (+12%)
Livestock	Top 10%	86%	14%	45.0	7.2 (+16%)	-5.7 (-13%)	49.8 (+11%)
	Top 80%	62%	38%	12.5	1.8 (+14%)	-0.8 (-6%)	13.2 (+5%)
Cropland	Top 10%	61%	39%	0.46	0.1 (+21%)	-0.09 (-19%)	0.47 (+4%)
	Top 80%	47%	53%	0.21	0.03 (+13%)	-0.02 (-10%)	0.21 (-0.1%)
Carbon	Top 10%	55%	45%	257.1	11.1 (+4%)	-12.9 (-5%)	259.0 (+1%)
	Top 80%	56%	44%	262.3	4.0 (+2%)	-3.8 (-1%)	263.3 (+0.4%)
Biodiversity	Top 10%	2%	98%	0.14	0.004 (+3%)	-0.0065 (-5%)	0.13 (-4%)
	Top 80%	10%	90%	0.11	0.0005 (+0.4%)	-0.0016 (-1%)	0.11 (-1%)

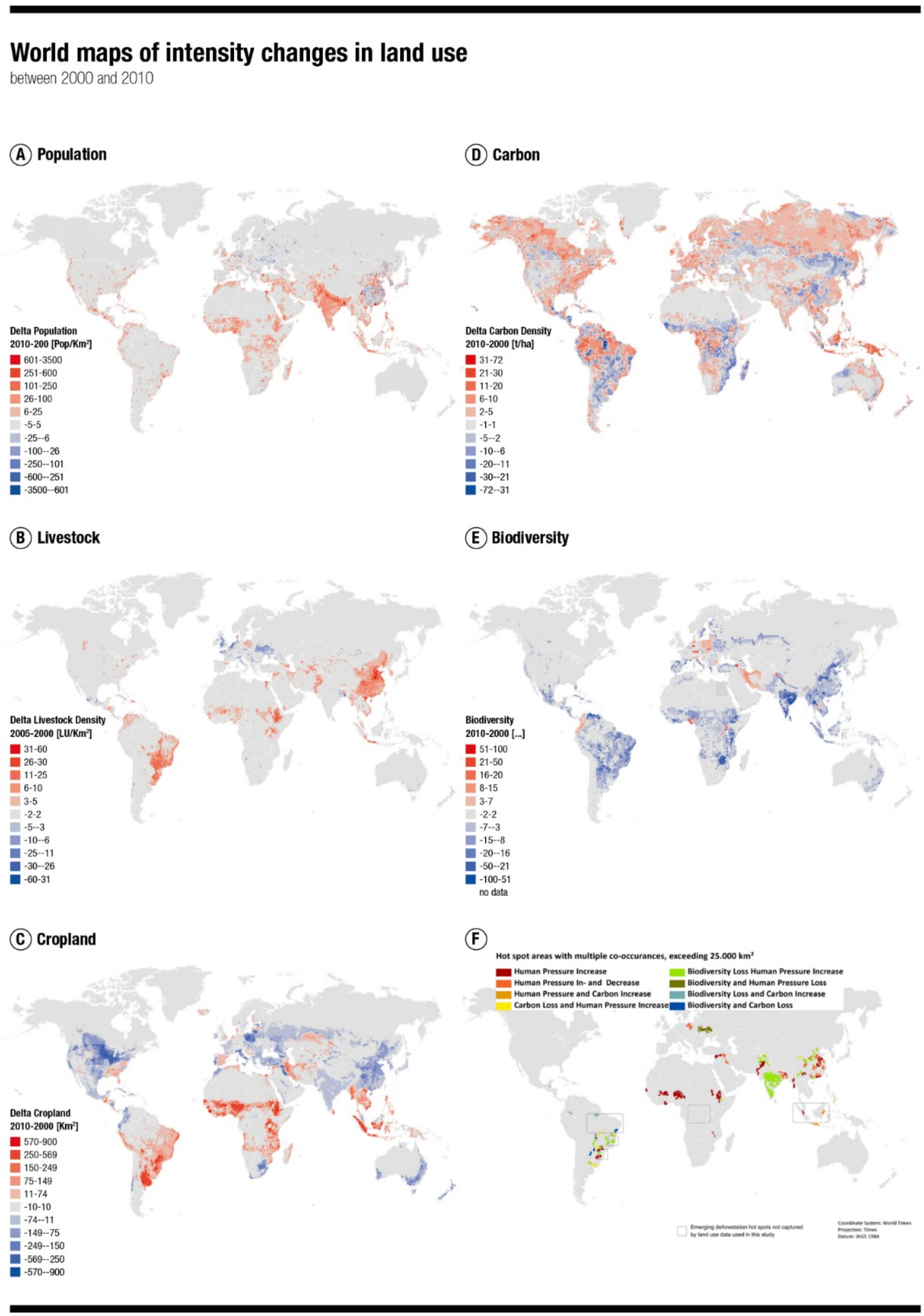

Figure 1. Change in intensity of land use between 2000 and 2010. A) Population density. B) Livestock density (for 2000 and 2005). C) Cropland area fraction D) Terrestrial carbon density E) Biodiversity intactness (proxy for biodiversity) F) Hotspot with multiple co-occurrences where human pressures (population, cropland, livestock) are aggregated to reduce complexity; rectangular areas denote hotspots of deforestation as identified by Harris et al., (2017a). All data are processed and mapped into 30 arc-minute (0.5

degree) grid (63879 data points), corresponding to ≈50x50km at equator, and finer resolution at higher latitudes. Data sources are summarized in Table S1.

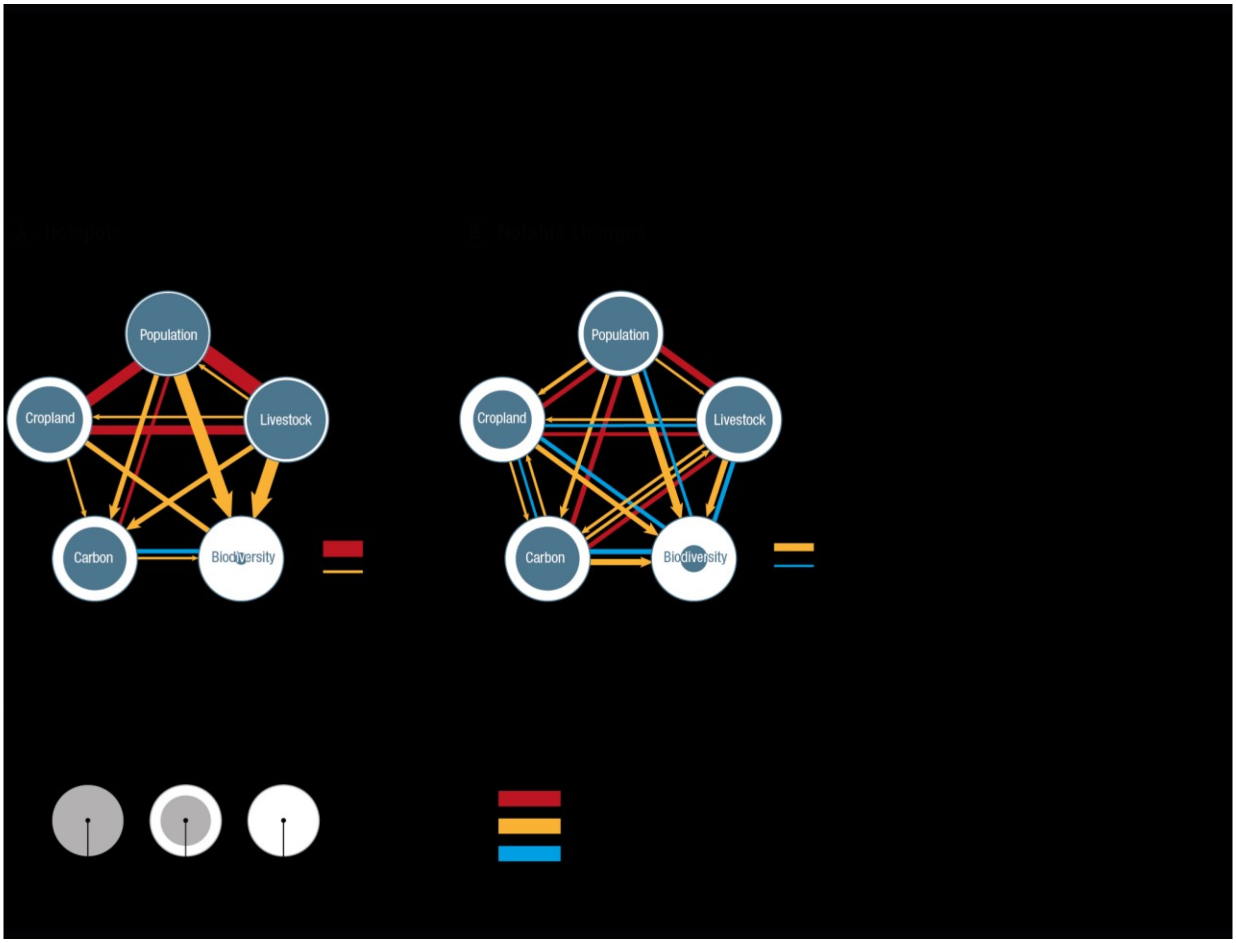

Figure 2. Co-occurrences of land use changes between 2000 and 2010 (population, cropland, carbon, biodiversity) and 2000 and 2005 (livestock), respectively, within grid cells for (A) hotspots, and (B) notable change regions. Solid circle filling represents the area that experienced intensity increases or decreases within each type of land use. Links between types of land use depict pair-wise co-occurrences. Undirected red (blue) links represent mutual increase (decrease) in intensity. Reported are gross changes. For example, in some parts of the world, both cropland and livestock decrease simultaneously. In others, it increases simultaneously. This results in both red and blue lines between cropland land livestock in panel B. Directed yellow links represent an intensity increase in source land use, and decrease in target land use. Co-occurrences measured at 0.5° grid resolution. Width of the links show the respective total area of pair-wise co-occurrence. Links smaller than 2% of total co-occurrence area are omitted. The hotspot analysis (top 10%) corresponds to the top decile of all grid cells with an intensity change between 2000 and 2010 (ranked by absolute density delta). Overall land-use change analysis focuses on 80% of grid cells with the highest absolute density change, *notable change pixels*, filtering out land-use change of low magnitudes.

Next, we analyze the spatial co-occurrence of land-use changes by aggregating the area of grid cells on which land-use changes co-occur (Fig. 2). We find that human activities (population, livestock, cropland) tend to grow together. This is confirmed by a Principal Component Analysis (PCA), in which the first eigenvector clearly distinguishes between increasing human direct pressures and negative impact on biophysical dimensions (Fig. S1-S2, Table S2). The second eigenvector describes that, after accounting for the first eigenvector that explains the largest share of data variation, increases in population density and terrestrial carbon tend to co-occur with losses in cropland area, biodiversity, and, to a lower extent, livestock. This reflects on the one hand cropland and biodiversity reduction due to urban expansion (c.f. Bren d'Amour et al., 2017) and population growth (India), and on the other hand increased carbon stocks in Europe, the US and in remote areas of the boreal and tropical biomes due to reduced agricultural activity (US, Europe) and CO_2-fertilization, respectively.

Biodiversity reduction co-occurs pervasively with intensity increases for all other land uses (Fig. 2). The land carbon stock is partially reduced where human activities expand; there is an increase in land carbon stock in other areas most likely related to CO_2-fertilization, longer growing periods, or increased precipitation. In hotspots, population and livestock increase, but carbon stock and especially biodiversity is reduced (Fig. 2A). Population exerts a dominant pressure over all land use changes (Fig. 2B). Increases in population where densities are high (urbanization) lead to cropland losses measurable on a global scale. In other instances, cropland expansion and biodiversity loss often coincide.

Changes of land use are concentrated in specific intensity bands (Fig. 3). An analysis of the magnitude of intensity shift for all land areas reveals that more than 90% of the shifts have an absolute value of <10% of their respective scales as presented in Fig. 3; population and livestock shifts tend to be positive, while biodiversity shifts are strongly negative (Fig. S2). We cross-validated results with a world-region specific literature (Tab. 2). Pristine land becomes populated, reflecting human land take in Sub-Saharan Africa, the Arabian Peninsula, and in a few scarcely populated areas of the Americas (Fig. 3A, Fig. S3a, Tab. 2). The area of high population concentration (>900 pop/km^2) increases, reflecting urbanization in the Bengal delta, coastal China, the Nile delta, and Java (Fig. 3A, Fig. S3b, Tab. 2). Livestock land use follows a negative exponential function with large areas of land being used for very low-intensive husbandry (Fig. 3B). Livestock is increasing in areas of very low density, i.e. mostly in Brazil, Northern China, and the Guinean Savannah, but there is less husbandry in Eastern Europe (Fig, 3B, Fig. S3c, Tab. 2). Livestock is also increasing in areas of higher density, reflecting industrial livestock breeding in Shandong, Hebei, and Henan provinces in China and around Sao Paulo, Brazil (Fig. 1, Fig. 3B, Fig. S3d, Tab. 2). There is an expansion of cropland of medium suitability in the Guinean Savannah and South America, but there is a loss of cropland in the USA and Eastern Europe (Fig. 3, Fig. S3e, Tab. 2). Land of very high suitability was utilized less for agriculture in the US Mid-West in 2010, while cropland has expanded in the highly suitable Chaco region of Argentina producing soybean for exports (Fig. 3C, Fig. S3f, Tab. 2), while some land of low suitability has been abandoned (Fig. 3C). Most land has less than 50tC/ha carbon stock, which is low compared to the peak value of 1,850tC/ha (Keith et al., 2009) (Fig. 3D). The change in intensity of terrestrial carbon is complex, but there is a distinct increase in carbon stored by land at <100tC/ha, particularly close to the Arctic Circle (Fig. 3D, S3g). There is also an increase of terrestrial carbon stored at around 400tC/ha in boreal areas and in the tropics (Fig. 3D, Fig. S3h, Tab. 1). Areas of medium-high species intactness are lost, particularly in South Asia (India and Pakistan) and the Chaco region, Argentina (Fig. 3E, Fig. S3i, Tab. 2).

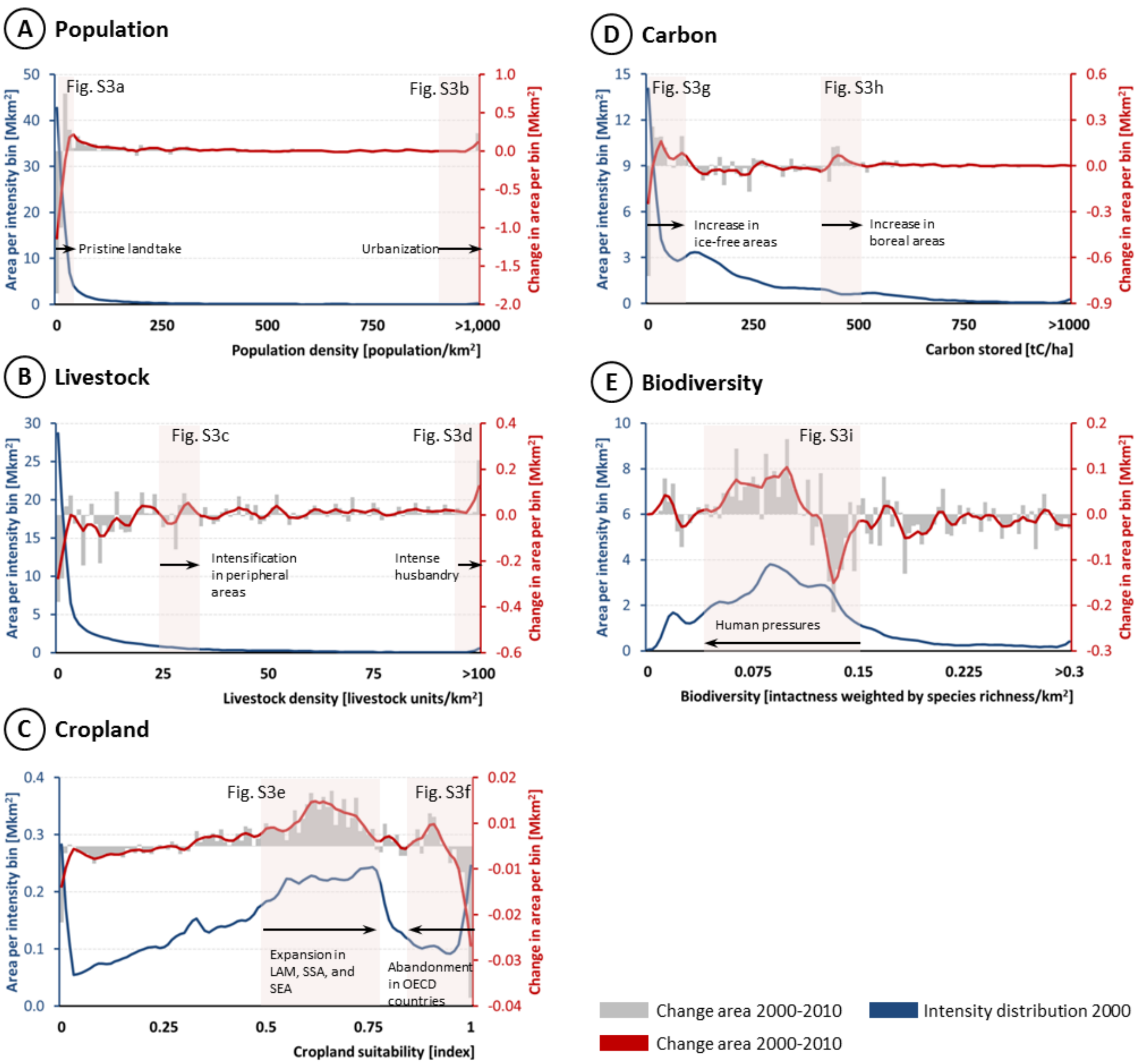

Figure 3. Distribution of changes in the intensity of land use between 2000 and 2010 for population (A), livestock (B), cropland (C), carbon (D), and biodiversity (E). Bin sizes are 0.01. Lines represent 5-bin weighted mean average. The blue lines represent frequency of land (total area) within each bin; the red lines changes in frequency. Red boxes indicate intensity bins of special interest and are substantiated with maps in Fig. S3 in the SI for analysis of spatial patterns, and by the world-region specific review (Table 1 and SI).

A world-region specific analysis of co-occurring land-use changes (Fig. 4), substantiated by literature review (Tab. 2, Supplementary Information for detailed discussion), and an analysis of the increasingly important role of international trade (Tab. S3) reveals that regions can be associated with at least one of three types of land-use dynamics (Fig. 5). Archetype A is characterized by a large land footprint but at most moderate population growth ('Consumers'). Europe fits best into this archetype, with stagnating population, intensification of agriculture, and increased reliance on imported foods. Europe outsourced land-intensive food production at a scale corresponding to up-to-half of their domestic cropland use (Fig. 5, Table S3). On its own territory, these factors enabled a partial recovery of terrestrial carbon and biodiversity. North America and Oceania also have high footprints, but also have moderate population growth and high biocapacity enabling exports of its agricultural surplus. Human pressure and losses of ecosystem services have decoupled only in few instances: land carbon stock and biodiversity are partially co-improving in Europe and Oceania. A possible explanation for the improvement in Europe and Oceania is the emergence of new institutions and policies, as for example, in EU-accession countries from Eastern Europe.

Archetype B is defined by high export shares (>5% of land is used for export) as enabled by high capacity relative to overall population ('Producers'). Notably, this involves Latin America that increasingly serves the consumer needs of Europe and Eastern Asia. Specifically, South America and Russia increased their cropland embedded in net exports by 24 and 16 percentage points, respectively (Table S3). But also Eastern Europe and Central Asia, witnessing decreasing population, sees an increasing share of land used for exports. The consumer world-regions of North America and Oceania belong simultaneously to the producers, exporting high margins to other world regions. Importantly, telecoupled and trade-induced land-use links drive biodiversity and carbon loss, epitomized by Latin America, notably in parts of Brazil and the Argentian Chaco region (Tab. 2 & S3). In addition, export of palm oil from Indonesia is a major driver for biodiversity loss and deforestation in South-East Asia (Tab. 2 & S3). Overall, exports are responsible for 17% of species loss, with highest impact embodied in exports from Indonesia to the US and China (Chaudhary and Kastner, 2016).

Archetype C is characterized by high population growth (>5%) and limited land used for export (export share of land <5% and increased imports in 2009 compared to 2000). We denote this type as 'movers' reflecting their dynamic population and economic growth, and their expected future global influence on global land use change. Land use change is dominated by direct regional demands, feeding a growing and more affluent population. 83% of species loss is attributed to agriculture devoted for domestic consumption (Chaudhary and Kastner, 2016), and demand is increasingly driven by growing affluence and dietary change rather than population growth (Kastner et al., 2012). Most of Asia and Africa belongs to this archetype. But the variety of 'mover' world regions is considerable, ranging from a concurrent expansion of population, livestock, and croplands in Sub-Saharan Africa at costs of natural habitats to strong pressure on cropland by urbanization in Eastern Asia (Fig. 2&4). In fact, a detailed companion study finds that urbanization consumes around 2-3% of global agricultural land between 2000 and 2030, mostly in East Asia; this is prime agricultural land and is nearly twice as productive as average agricultural land, implying a productivity loss of 4-5% (Bren d'Amour et al., 2017). Eastern Asia and the Middle East and North Africa import a high proportion of land-based products from elsewhere, similar to Europe. The

Middle East and North Africa are in the most precarious situation with high population growth and strong reliance on imported food and other land produce (Fig. 5).

Anthropogenic climate change is associated with region-specific dynamics that have a total effect comparable to that of direct human pressures. Carbon fertilization has especially affected carbon stocks in the intact tropical rainforests, such as in Congo, and the boreal zone, including Siberia (Zhu et al., 2016). Increased precipitation in the Sahel zone (Park et al., 2016) and Central Africa enabled higher carbon stocks, while prolonged drought conditions contributed to salinization (Gallant et al., 2012) and reduced cropland density in Oceania by 11% (cf. Table S5).

The analysis of drivers from the literature reveals the importance of institutional drivers, including agricultural policies in Europe and North America, afforestation programs in China, conservation in India, forest protection in the Amazon, and the legal underpinnings of international trade (Tab. 2).

Land-use change co-occurrences in world regions

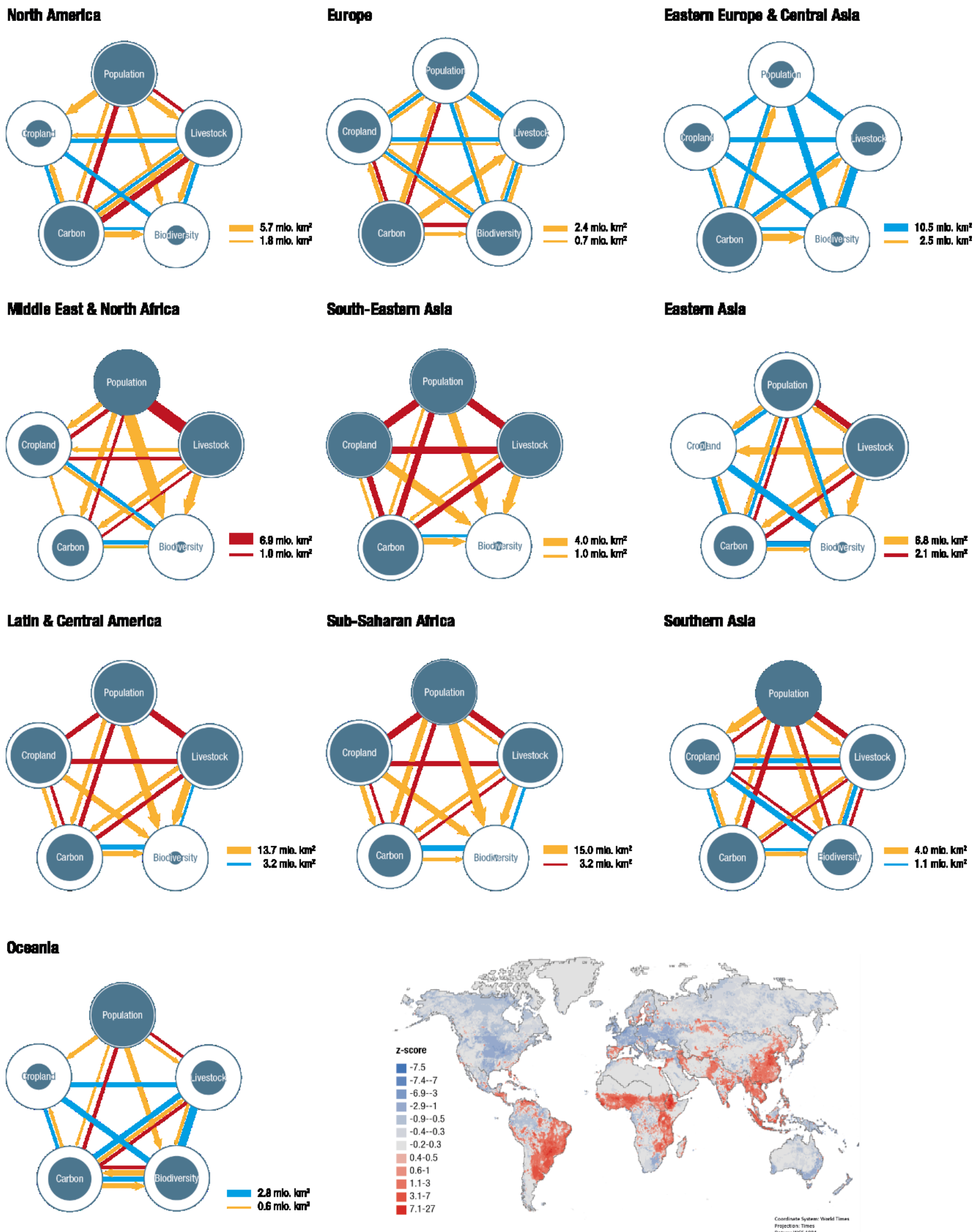

Figure 4. Co-occurrence of notable land use changes within regions. See caption of Fig. 2 for explanation of co-occurrence figures. The map shows the z-scores from the product of the first eigenvector from the PCA with the standardized data of intensity changes. Blue colors indicate that increases in carbon stocks and biodiversity are

relatively strong while red colors indicate that population, cropland and livestock gains dominate (relative to the mean change).

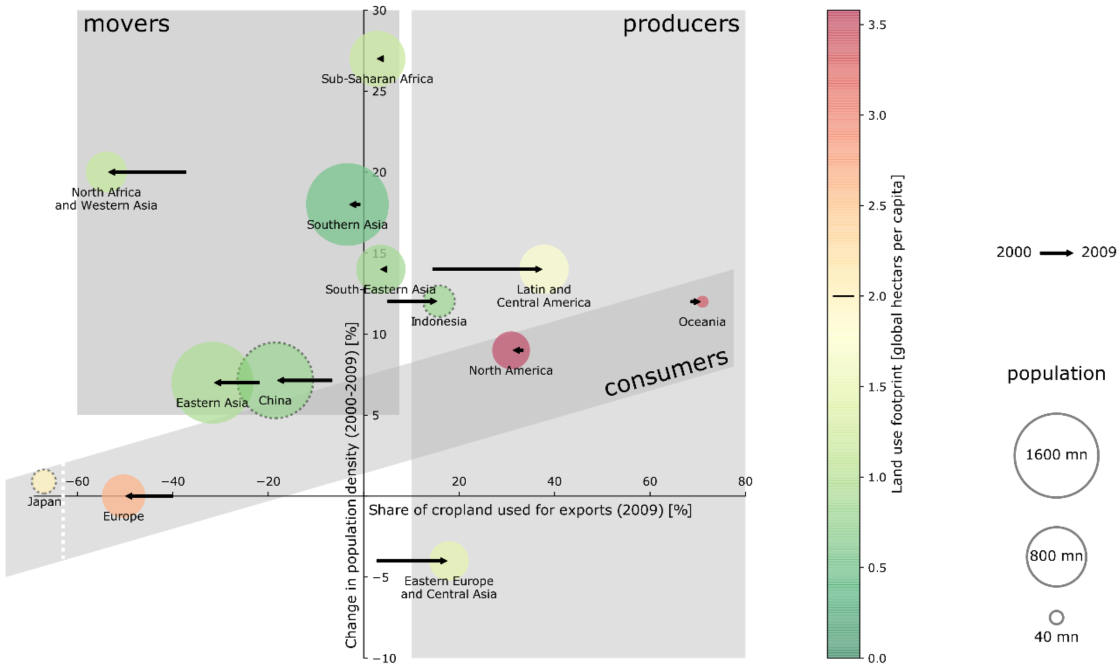

Figure 5. Land use change across world regions belong to different archetypes. Type A (Consumers): High land footprint, moderate population growth (Europe, North America, Oceania). Type B (Producers): High biocapacity and institutional capacity that enables a share of cropland >5% being exported (Eastern Europe and Central Asia, Latin America, North America, Oceania, South-East Asia). Type C (Movers): Population growth>5% and export share <5%: (North Africa and Western Asia, Southern Asia, Eastern Asia, Sub-Saharan Africa, South-Eastern Asia). Data from (Kastner et al., 2014; Weinzettel et al., 2013).

World region	Key observations	Explanations
Europe (without Eastern Europe)	Low population pressures go along with an abandonment of cropland and co-occur with increases in land carbon stock (84% of area), and declines in biodiversity (albeit increases in biodiversity occur in some places such as Germany) (Fig. 4). Livestock density is decreasing by 94% in hotspots and 76% in areas with notable changes (cf. Table S4&S5).	Aging populations, and established urbanization patterns point to low population pressures. Technological and institutional drivers underlie location-specific agricultural intensification in Europe; economic factors, including urbanization, and changes in the European Common Agricultural Policy explain location-specific reductions in intensity (van Vliet et al., 2015). Both agricultural intensification of the most productive lands (e.g. in Denmark) and farmland abandonment in marginal, less competitive regions are driven by the globalization of agricultural markets (Kuemmerle et al., 2016; van Vliet et al., 2015). Europe is strongly outsourcing land-intensive crop production through international trade; the share of 'imported' cropland, driven by dietary change (Galli et al., 2017), grew by 20% from 2000 to 2009 and by then corresponded to more than half of the cropland under domestic production (cf: Table S3).
Eastern Europe and Central Asia	The stock of terrestrial carbon increases in many areas (with the exception of South-East Siberia) (Fig. 1D), including, at low intensities, close to the Arctic Circle (Fig. 3D, S3g). At the top decile, carbon stock gains outweigh losses by 517Mt CO_2 in Eastern Europe and Central Asia (cf. Table S4). Those effects co-occur with cropland, pastures and livestock declines (Fig. 4). Cropland intensity in Eastern Europe and Central Asia dropped by 18% in hotspots (cf. Table S4), despite the region having become an effective exporter of crops (cf. Table S3)	The increase of forests on abandoned farmland after the collapse of the Soviet Union (>30Mha) contributed substantially to carbon stock gains. In former socialist countries restitution, low competitiveness, and rural emigration led to the abandonment of farms (Kuemmerle et al., 2016). There is, however, substantial variation between the countries, attributed to strong differences in market reform (Alcantara et al., 2013). In European Russia the gain amounts to more than 44tCO_2/ha during our observation period, which makes it outstanding as a sink in the boreal region and comparable to sinks in the temperate biome (Pan et al., 2011). After land is abandoned, soil loses carbon before reforestation dynamics emerge, increasing terrestrial carbon. Hence, varied patterns exist in carbon stock changes, partially depending on the order of land abandonment (cf Schierhorn et al., 2013). South-East Siberia displays carbon loss, linked to deforestation and timber exports to China, and demand for products sold globally (Liang et al., 2016). In large parts of Siberia, global warming enables longer periods of plant growth and photosynthesis (increased land carbon stock) (Zhu et al., 2016), while wild fires reduce the land carbon stock in some other parts (see SI).
South Asia	Strong concurrent increases in population, cropland, and livestock are combined with a loss in biodiversity at hotspots (Fig. 4). Population increases by 18% (India, North-east Pakistan), cropland expands by 17% (Pakistan Afghanistan) and livestock by 3% (North-east Pakistan) at	Strong population growth (250 million from 2000 to 2010) dominates land use changes. In India, agricultural land loss due to urbanization led to a reduction of the harvested area of rice by 4%, while yields increased by 15% between 2000 and 2010 (SI). Urbanization also emerged as a key pressure affecting biodiversity loss, but

	hotspots (Fig. 1, Table S4). Cropland decreases with urbanization, but increases in wider urban regions (SI, cf Bren d'Amour et al., 2017). Biodiversity density loss amounts to 8% at hotspots and 3% at notable changes all over India and East Pakistan. Global share in biodiversity intensity loss is 13%.	conservation programs and a switch away from traditional fuels ameliorated the loss of biodiversity (Nagendra et al., 2013; Reddy et al., 2015).
South-East Asia	Strong co-occurring intensity increases in human settlements (14%), cropland (18%), livestock (14%), and, less so, carbon stock (2%), abundant losses of biodiversity (-2%) (Fig. 4, Table S5). The region accommodates 19% of global cropland expansion, with high contributions from Sumatra, Vietnam and central Myanmar (Table S5, Fig. 1). Human activities have triggered increasing pressure on biodiversity (Fig. 4). 97% of all land with biodiversity change show loss, concentrated in Sumatra, the North of Thailand, Cambodia and Vietnam (Table S4, Fig. 1).	The severe loss of biodiversity is mostly driven by deforestation for commercial agriculture (Hosonuma et al., 2012), particularly for palm oil (more than 30% for international markets (Wilcove et al., 2013)) and forest plantations (explaining the more modest effect on land carbon stock, cf. Stibig et al., 2014), sometimes related to large-scale land acquisitions (Davis et al., 2015). Draining and burning of peatland constitute a major source of carbon release in South East Asia, especially in Sumatra, and to lesser degree in Borneo (Wilcove et al., 2013). Peak emission rates exceeding those of the European Union fossil fuel burning occurred in 2015 (Huijnen et al., 2016). Growth in population in cities (by > 31%) as well as urban land (by 22 %) has been significant, with the highest rates observed in Malaysia, Vietnam, Cambodia, the Philippines and Laos (Schneider et al., 2015). Growth in incomes has resulted in an increasing consumption of meat across the entire region (Thornton, 2010).
East Asia	Population and livestock expand, partially co-occurring, while cropland and biodiversity losses are massive; terrestrial carbon dynamics are mixed (Fig 4). East Asia shows 15% of population and 30% of livestock growth as global shares (Table S5, Fig 3B, S3d). Ongoing urbanization in East Asia leads to high population decreases in rural areas (44% of global total negative, Table S5) mainly. Loss of cropland is 19% of global cropland loss; loss of biodiversity is 9% of global biodiversity loss, (Table S5, Fig. 1).	Rapid urbanization and population growth around big metropolitan and urban centers between 2000 and 2010 led to pressures on other land use types, e.g., consuming productive croplands (Bren d'Amour et al., 2017; Chen, 2007; Galli et al., 2015). Urbanization has also been the most important driver of biodiversity losses; e.g., in the Pearl River delta, 26% of natural habitat and 42% of local wetlands have been prey to increasing urban land (He et al., 2014). In the biodiversity-rich Chinese Yunnan province cash crop plantations, notably rubber, cause biodiversity loss (X. Liu et al., 2013). Net changes of terrestrial carbon have been negative in the region, with a highly diversified regional pattern (Calle et al., 2016). Afforestation and restored grassland on degraded agricultural land in rural areas (e.g., Tibet, Inner Mongolia) increased terrestrial carbon stock (Deng et al., 2014), while cropland extensification, e.g. in the Sichuan basin and Heilongjiang, increased emissions from land use change (Zhang et al., 2015). Rapidly increasing meat demand in East Asia is mostly satisfied by industrialized

		livestock breeding, particular in urban areas (Bai et al., 2014). Increasing fodder imports, particularly maize and soybean, for livestock production have raised land-use pressures elsewhere as the proportion of indirect cropland imports grew (Table S3).
Middle East and North Africa	Increasing population (Fig. 3 & S3b) is associated with growing livestock densities at the expense of biodiversity (Fig. 4). The region records high relative population density growth (20%), and accounts for 9% of total global positive changes in population, and 6% of global positive livestock changes, mainly concentrated at Nile river delta and South-west Yemen. The region depicts cropland loss (7% of global total) in Morocco, East Iraq, Turkey, as well as cropland gain (4% of global total) in the Nile river delta, North of Syria and Mediterranean Algeria (Table S4&S5, Fig. 1).	Human and economic activities congregate around the available, but scarce water resources, mostly rivers, deltas, and oases, but also coastal zones; the competition between land uses is particularly fierce, best exemplified by the Nile river in Egypt, where urban area expansion is forecasted to engulf more than a quarter of valuable croplands (Bren d'Amour et al., 2017). In Marocco, food demand multiplied driven by population growth (160% in 1961-2009) and per capita demand (>50% in 1961-2009, c.f. Galli, 2015). The region outsources land-intensive production by imports, which have increased substantially between 2000 and 2010 (cf. Galli et al., 2017 and Table S3), increasing the risk for telecoupled food supply shocks (Bren d'Amour et al., 2016). In Turkey, biodiversity loss appears where important wetlands, grasslands, and even rivers are disappearing due to human activities (Şekercioğlu et al., 2011). Pristine land take on the Arabian peninsula is closely related to population growth, and agricultural expansion, fostered by unsustainable reliance on fossil water reserves (Odhiambo, 2016).
Sub-Saharan Africa	Strong concurrent human pressures dominate (Fig 1,3A&4, Fig S3a). Population is increasing mostly in the Lake Victoria region and West Africa, cropland expansion is pervasive across the entire Guinean Savannah, and livestock expansion is concentrated in East Africa (Ethiopia, Lake Victoria region), representing 39% of global cropland expansion (Table S5). Biodiversity is decreasing pervasively (Fig. 1&4). Fertile savannahs, offering a large untapped potential for agriculture, display increased crop production representing 25% of the world's fastest changing croplands (hotspots, Table S4), co-occurring with rural population growth and carbon loss (Fig. 4).	Population dynamics are characterized by high fertility rates and rural-urban migration (Buhaug and Urdal, 2013), driven by population growth in resource constrained rural areas rather than urban agglomerations (Holden and Otsuka, 2014). Local cropland losses (South Africa) are related to the concurrent expansion of horticulture (Liebenberg and Pardey, 2010). The co-occurrent population and crop yield growth in the Guinean Savannah is in line with existing evidence on Boserupian intensification in Africa (Jayne et al., 2014). Cropland expansion, however, also results into a reduction in land carbon stock (cf. Searchinger et al., 2015). Land-use emissions for savannah burning exceed those of fossil fuels in Sub-Saharan Africa (Ciais et al., 2011). In contrast, carbon fertilization and increased precipitation generated an increase in land carbon stock in forest areas (Ciais et al., 2011). Most Sub-Sahara African countries have been poorly integrated into to the world agricultural market

		because of a lack of infrastructure and low investment rates resulting from poor institutional quality (Barrett, 2008; Kalkuhl, 2016). Hence, cropland dynamics have so far largely been driven by local factors rather than by international trade (cf. Table S3). Pristine land take and biodiversity loss is most strongly associated with population pressure, but also with cropland expansion (cf. Searchinger et al., 2015).
Oceania	Cropland and livestock reduction appears more pervasively than biodiversity or carbon loss (Fig. 4). Cropland intensity decreased by 11% (Table S5).	Salinization and droughts, partially attributed to anthropogenic climate change (Gallant et al., 2012), compromised more than half of the farmland and crop production in Australia (MSEIC, 2010). Local biodiversity loss in Australia has mostly been attributed to agricultural pressures (Steffen et al., 2009).
Latin and Central America	Population growth is pronounced mostly in Central America and in coastal parts of South America (Fig. 1A). Crop and livestock densities rose by 16% and 24%, respectively, in Latin American hotspot areas between 2000 and 2010 (Table S4), including the Chaco region, Argentina (Fig. 3E, Fig. S3i). 28% of global land area with notable reduction in biodiversity is located in Latin America (Table S5). Carbon losses are concentrated in the most carbon-rich regions (in hotspots, Table S4). This explains the observed co-occurrences (Fig. 4): a dominance of human pressures in Central America and part of Latin America (mainly Brazil), and a recovery of carbon and biodiversity in the North.	Direct human pressures are less dominant as the continent had already been mostly urbanized before 2000. In South America, cattle ranching intensified, especially in the Brazilian subtropics, and is no longer only associated with deforestation (Lapola et al., 2014); the combination of the availability of fertile land and low production costs has led to deforestation through export-oriented industrial agriculture, especially in the peripheral Amazon basin (cf. Fig 1 and Grau and Aide, 2008), even as deforestation rates in Brazil declined after 2005 (Nepstad et al., 2014). Declining deforestation arose from better monitoring and more rigorous enforcement. Soy and maize was increasingly produced, and exported to Europe and East Asia (cf. Table S5; cf. Kastner et al., 2014). Notable, the Argentinian Chaco region experienced an acceleration of dry forest clearing for soybean production for international markets (Gasparri and Grau, 2009). A combination of agricultural modernization and rural-urban migration caused land to be abandoned, enabling ecosystem recovery, especially in parts of the Caribbean and Central America (Grau and Aide, 2008).
North America	North America records population growth (9%) accompanied by urbanization, partly at the expense of livestock and cropland area (Fig. 4, Table S5). It shows cropland depletion of 10% and 31% total global share (Table S4). On cropland biodiversity is reduced. North America is a large land-exporting region, with 34% (2000) and 31% (2009) net export as share of cropland under domestic production (Table S3). Share of the total	Cropland loss occurred with the intensification of agriculture and the expansion of urban areas (Sleeter et al., 2013). High commodity prices driven by the rising demand for biofuel feedstocks since the late 2000s provided new incentives to expand crop production (Wright and Wimberly, 2013). Consequently, wide-spread conversion of grasslands, shrublands, and wetlands to agricultural uses reappeared across the United States with hot-spots of change located in the

	global positive carbon stock density increase by 20% in vast parts of Alaska, Canada, and the Mid-West USA (Table S5, Fig. 1). Carbon increase coincides with cropland abandonment, afforestation, and cropland intensification (Fig. 1&4).	Corn Belt and the Lake States. Corn caused most of recent land use change through its displacement of other crops (Lark et al., 2015; Mladenoff et al., 2016). Between 2006 and 2008 the area harvested for corn and soybean in the United States increased by 3.2Mha (Wallander et al., 2011) with another 5Mha increase occurring between 2008 and 2012 mostly at the expense of grasslands (Faber et al., 2012; Lark et al., 2015). This new wave of expanding corn and soy production occurred most rapidly on land less suitable for agriculture, characterized by high erosion risk, shallow soils, and drought vulnerability (Lark et al., 2015).

Table 2. Land-use change dynamics in world regions 2000-2010. See SI and associated online information for more background. Table S7 separately list key references for each world region.

2.3. Discussion and conclusion

Our data and literature-based assessment reveals that the regionally diverging patterns of global land use change, grounded in direct human pressures, telecoupled land demand by international trade, and varying climate change impacts. We identify three crude types of world regions: A) 'consumers', characterized by high per capita land footprint; B) 'producers', characterized by high export share of land; and C) 'movers', characterized by high population growth, and increasing demand for land outside their own regions. Due to its population and dynamic change, the 'movers' will have the most import role in future global land use change.

Managing global land use change requires an explicit consideration of the differences between world regions. Our analysis and resulting typology demonstrates that a successful management of global land use is closely linked to SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), and SDG 15 (Life on Land), and attached to SDG 13 (Climate Action) both on the mitigation and impact side. The strong telecoupling, both by international trade and climate change, substantiate the need for international cooperation to manage global land (Creutzig, 2017; Magalhães et al., 2016). Plausible global cooperation on land-use management includes measures particularly suited for different types of world regions. In consumer regions, such as Europe, sustainability certificates and dietary change could foster a shift to sustainable land use on the demand side (Galli et al., 2017; Tayleur et al., 2016). In producer regions, in particular those with rich biodiversity, harmonization of ecosystem protection measures and financing of nature conversation (Waroux et al., 2016), and an upscaling of international payment for ecosystem services schemes (Rands et al., 2010) would be a crucial component of protecting intact ecosystems. As carbon stock movements are not always related to biodiversity, it is crucial for the design of environmental policies, such as REDD+, to differentiate between land carbon stock and biodiversity (Phelps et al., 2012). Our data reveals that in Sub-Saharan Africa and Latin America rural population growth is accompanied by an increase in cropland, and a reduction in biodiversity (Fig. 5), pointing to potential efficiency gains in agriculture due to population pressure (cf. Boserup, 2005). Specific measures to further improve efficient land use involve intensification that complies with the protection of important ecosystems, soil carbon, and water resources (Garnett et al., 2013); multi-purpose systems that integrate several land uses, an approach called land sharing (Fischer et al., 2014; Lambin and Meyfroidt, 2011); and compact urbanization that preserves cropland (Bren d'Amour et al., 2017). Prioritizing a small set of leverage points could greatly increase the sustainability and efficiency of food production (West et al., 2014).

Our synthesis of the literature on the drivers of land-use change indicates also that institutions are crucial for preserving biodiversity-rich land, for example in Europe and in particular instances in South Asia. The current land-use change observed in our analysis suggests that economic pressures of direct human needs trump sustainability concerns, or, in other words, that institutions are poorly suited to preserve biophysical assets, and in particular, biodiversity. The fact that the highest pressures on land can be found in the developing world where institutional quality is very heterogeneous needs to be taken as a strong warning signal that, at least in the near future, increasing human activities will continue to put high pressure on natural systems. Improving institutional capacity will be a key factor in realizing nature conservation and efficient land use. Especially in mover regions, highly efficient land uses could be further fostered by technological transfer and institutional capacity building.

Our emerging view differs from both Malthus (population rises until limited by resource availability) and Condorcet (the human race is capable of unlimited progress), who both see human-nature interactions in terms of natural laws. Instead, human actions, particularly in terms of institutional design, including markets, cultures, and regulations, will decide whether direct human needs and sustainability objectives can be simultaneously achieved. The *global* dimension of land use is not only founded in transboundary externalities of emission reductions and biodiversity protection; it is also that underlying drivers such as rural-urban migration, trade in land-intensive goods, and more indirectly, poverty reduction efforts and education improvements, go beyond the immediate jurisdictions of the nation state and require some form of international cooperation. Local land use changes are therefore part of a multilayered biophysical-socioeconomic system. This perspective of globally integrated land use could more effectively translate into local and globally coordinated action to make the best use of land for direct human needs and foster biophysical stability.

2.4. Methods

2.4.1. Data and data processing

This study combines gridded datasets of different land use dimensions and their respective intensities (Table S1). Data selection is based on quality and availability for the year 2000 and 2010. All data are processed and mapped into 30 arc-minute (0.5 degree) grid, corresponding to ≈50x50km at equator, and finer resolution at higher latitudes. The sample size ensures statistical relevant measurements of co-occurrences of land use change and statistical analysis on world region scale. The resolution is insufficiently high for reporting shifts in land use change on identical patches of land. Instead, the analysis reveals co-occurring land use changes in particular regions, and by this, statistical inference of cross effects. Spatially explicit reported data are used for all dimensions in the year 2000. Data are only partially availably for

2010. Specifically, established datasets on livestock (Robinson et al., 2014) only go as far as 2005. Some data (e.g. population, livestock) are based on census data. Not all countries provide frequently updated censuses, therefore are some of the estimates based on a single census year, while others have had adjustments applied to normalize the data from different census years to a common set of boundaries. Data should be taken with care in inter-annual comparison as changes can be matter from adjustments or reflections of national or regional growth rates rather than e.g. net migration or population growth. Hence, differences between the observed points in time, 2000 and 2010 should be taken with care and seen as indicators rather than fixed values. Nevertheless these were the best available data, on global level, at this time. This study combines gridded datasets of different land use dimensions and their respective intensities (Table S1). It focuses exclusively on land-use dynamics and does not cover water as additional component, which is beyond the scope of this study.

Cropland data is based on HYDE 3.1 (Klein Goldewijk et al., 2011) and the GAEZ product (IIASA, 2012, see also Table S1). Other cropland maps, e.g. (Fritz et al., 2015), offer higher resolution, but are not available for 2010.

All data were read in, re-sampled (if applicable), and compiled into a single dataset for subsequent analysis, using zonal statistics in ArcGIS. Additional processing steps were required for the data used in livestock and biodiversity dimensions:

Livestock datasets of the most important livestock types (poultry, pigs, goats, sheep, and cattle) were read in as layers and re-sampled to 2.5' Arc Minute. The aggregate Livestock Unit (LU) Layer was generated with the raster calculator tool using the Livestock Layers and Livestock Unit Conversion Factors (poultry: 0.01, pigs: 0.225, goats: 0.1, sheep: 0.1, and cattle: 0.7; derived from http://www.lrrd.org/lrrd18/8/chil18117.htm).

Biodiversity is defined as the stock of plants (including trees) and animals (including fish), fungi and bacteria (e.g. for food, fuels, fiber and medicine, genetic resources for developing new crops or medicines, or as a tourism asset etc.) following the official SEEA (System of Environmental Economic Accounting) definition (United Nations, 2014). The focus is on terrestrial biodiversity, thus including fish (in rivers, lakes etc.), but not offshore marine life. The map of species richness by UNEP/WCMC is used which covers the taxonomic groups of birds, mammals and amphibians, based on the Predicts model (Newbold et al., 2014). Species richness can be interpreted as the potential number of different species in one grid cell, thus measuring actual diversity and not absolute numbers. From species richness, we compute 'intactness' as proxy for the biodiversity dimension. The intactness of a grid cell is an index of how much of the initial species richness of a grid cell (untouched, i.e. in 100% 'primary' vegetation) is impacted by other land uses. The intactness for a given year is computed by factoring in gridded land use data (for both 2000 and 2010). Every land use type in a grid cell (in fractions of a grid cell) gets assigned a different impact on the original, initial species richness in that cell, methodologically following Newbold et al. (2015). Newbold et al. differentiate between different intensities of land use types (minimal, light, intense use) and, in the case of secondary vegetation, different maturities (young, intermediate, mature). These will have an impact on the effect of the land use type on the species richness. In the calculations, the intensity of the land use type is assumed to be light (not minimal or intense). The light intensity allows for relatively high species richness, independent of the land use type it is associated with. The resulting estimate can be regarded as relatively conservative since it would be in the lower range of the potential effects on species richness. Using these inputs, the intactness of each grid cell is computed. The resulting intactness is weighted with the species richness of the cell and divided by the corresponding area of the cell. In other words, if intactness is considerably impacted in a region with very low species richness, the intactness density metric will be comparatively low. The resulting biodiversity density metric is: intactness weighted by species richness/km^2.

We use the process-based dynamic global vegetation model LPJmL (Bondeau et al., 2007; Gerten et al., 2004; Sitch et al., 2003) to estimate land carbon stocks in vegetation and soils. LPJmL is a global, grid-based biogeography–biogeochemistry model, simulates terrestrial carbon pools and fluxes and the biogeographical distribution of natural vegetation. The representation of agricultural land driven by land use data allows for the quantification of the impacts of land use on water and carbon cycles. Here we used observation-based monthly temperature and cloud cover time series provided by the Climatic Research Unit (CRU TS version 3.21; see CRU et al., 2013; Harris et al., 2014) and monthly gridded precipitation data based on the Global Precipitation Climatology Centre (GPCC) Full Data Reanalysis Version 6.0 (Becker et al., 2013; Schneider et al., 2011). In this study, we calculate terrestrial carbon storage as the sum of all above- and belowground carbon stocks in vegetation and soil.

LPJmL uses a land use data set based on the HYDE 3.1 that provides gridded cropland and pasture land use from 10000 B.C. to 2005 A.D. (Klein Goldewijk et al., 2011). Detailed information on the distribution of crop types is taken from Monfreda et al. (Monfreda et al., 2008). In order to run the model until 2010 LPJmL applies linear extrapolation of recent land change dynamics for the years 2006-2010. Updating the LPJmL land use data with HYDE 3.2 (Klein Goldewijk et al., 2016) or other more recent data sets was not possible within the scope of this study. We were aware that the reduced temporal coverage may limit our ability to capture the most recent and emerging patterns of deforestation and other non-linear changes in land use. In order to evaluate possible shortcomings of our analysis due to data used we compared patterns of expanding human land use in the LPJmL data with a recent analysis of emerging deforestation hot spots (Harris et al., 2017b).

Figure S4 shows areas with decreasing shares of natural vegetation in the LPJmL data colored in shades of blue. Countries and regions with emerging hot spots of forest loss since the year 2000 according to Harris et al. (2017b) are highlighted with a red border. In Brazil, both data sets show forest cover loss in the Cerrado and the Mata Atlantica biomes, but LPJmL misses hot spots in the most southern parts of Brazil. Forest loss in Kalimantan and Sumatra is prevalent in both data sets, but the spatial patterns are different. This is also caused by the different spatial resolution of the two data sets. While Harris et al. (2017b) use satellite data with 30m resolution, LPJmL uses land use information at a resolution of 0.5° equivalent to about 55km at the equator. Spatial patterns of land use change will therefore be much more detailed in Harris et al. (2017b). In the case of the Democratic Republic of Congo, LPJmL completely misses emerging patterns of forest loss. While LPJmL assumes slight losses of natural vegetation in the south, the hot spot analysis of Harris et al. shows new forest loss in the northern part of the country.

However, it is also not possible to directly apply the Global Forest Watch data used by Harris et al. to improve the LPJmL simulations, because this data does not discriminate between clear cuts, forest thinnings, and changes in management. Once this information becomes available, it will be possible to improve the estimates of carbon stock changes with LPJmL.

2.4.2. Intensity curves

Intensity curves are constructed to depict the distribution of the land use dimensions in terms of area and intensity (Fig. 3 of the manuscript). To this end, areas (in km^2) of grid cells that fall into the respective intensity bins were aggregated. To measure the spatial concentration of land use we computed the Gini coefficient of the five dimensions.

2.4.3. Intensity change

Intensity change refers to the respective land-use dimension (Table S1) in a grid cell between 2000 and 2010, e.g. the change in population density (population/ km^2) in a grid cell. First, we calculate the intensity for each land use dimension. Second, we compute the change for each grid cell between 2000 and 2010. We calculate both relative and absolute intensity change to identify where and to what extent specific changes occurred, respectively how much area was affected and at which magnitude.

2.4.4. Principle Component Analysis

Principle Component Analysis (PCA) was performed using STATA 14 to identify major underlying patterns of land-use changes. The PCA is a statistical technique to reduce the dimensions of large datasets by orthogonal transformations to a lower-dimensional space (Jolliffe, 2002). Particularly, we are interested in the first principal component which accounts for the largest variance in the data with considering only one dimension. The first component is the eigenvector of the correlation matrix, which corresponds to the largest eigenvalue. We perform the PCA with STATA 14. The results are shown in Table S2.

The first component Fig. S1a) indicates that the variables can be grouped into those with positive signs (population density, crop area and livestock density) and with negative signs (carbon, biodiversity). These two groups have a clear interpretation as they correspond to direct human pressures (positive sign) and the nature-related residual (negative sign) which means that categorizing dynamics among this dimension allows to explain the largest share of the variability in the data. Adding additional orthogonal components (e.g. component 2, Fig. S1b) would increase explanatory power; the second component is, however, difficult to interpret. We therefore restrict only to the first component, which has high statistical power as well as a clear interpretation.

In order to visualize overall land-use dynamics according to the first principal component (the 'human-vs-nature' dimension), the corresponding eigenvector is multiplied with the normalized data. The normalization to zero mean and one standard deviation variance is necessary to convert the different variables and dimensions to one comparable metric. The resulting scores indicate whether overall land-use changes are related to human drivers (high positive score) or to the nature residual (large negative score). As the scores result from the normalized data, they must be interpreted relative to the overall land-use dynamics. Hence, a negative score does not mean that nature-related land-use changes are 'stronger' than human-related land-use changes. Rather, large positive and negative values indicate regions where human or natural forces are particularly strong.

For interpretation and in-depth understanding of observed co-occurring global land use change between 2000 and 2010, we perform an in-depth literature research on regional drivers of land-use dynamics, explaining hotspots and their regional and global relevance (see SI and associated online material).

2.4.5. Land embodied in crop trade

Our detailed spatial analysis focuses on local dynamics. For discussing the results, referring to spatial linkages particularly through trade is useful because trade in agricultural products links local land-use decisions to far-distant or global demand changes. Trade in agricultural products involves implicit trade of the production factors that are used to produce the traded good. The concept of factors embodied in trade is particularly used for analyzing virtual water trade (Dalin et al., 2012; Hoekstra and Hung, 2005), carbon emissions embodied in trade (Peters and Hertwich, 2008) and, more recently, also for quantifying crop land that is associated to trade (Kastner et al., 2014). Based on bilateral virtual land trade data (Kastner et al., 2014), we calculate in Table S3 the share of the cropland in our world regions that is associated to net exports in the years 2000 and 2009. The Oceana region is, for example, a large land exporter as roughly 70 % of the cropland is associated to net exports of crops. Hence, local land-use dynamics can be expected to be strongly influenced by international markets. Contrary, Sub-Saharan Africa, South-Eastern Asia and Southern Asia are largely land self-sufficient. Note that this can be consistent with large food trade flows (as we look only on exports net of imports) and trade deficits or surpluses which are measured in monetary terms and quantities of particular food items (and not land). Finally, Europe, Eastern Asia and Middle East and North Africa rely on large land imports. For these three regions, dependency on imported land has substantially increased.

References

Alcantara et al., 2013. Mapping the extent of abandoned farmland in Central and Eastern Europe using MODIS time series satellite data. Environ. Res. Lett. 8.

Anderson, W., You, L., Wood, S., Wood-Sichra, U., Wu, W., 2015. An analysis of methodological and spatial differences in global cropping systems models and maps. Glob. Ecol. Biogeogr. 24, 180–191.

Bai, Z.H., Ma, L., Qin, W., Chen, Q., Oenema, O., Zhang, F.S., 2014. Changes in Pig Production in China and Their Effects on Nitrogen and Phosphorus Use and Losses. Environ. Sci. Technol. 48, 12742–12749. https://doi.org/10.1021/es502160v

Barrett, C.B., 2008. Smallholder market participation: Concepts and evidence from eastern and southern Africa. Food Policy 33, 299–317.

Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., Schamm, K., Schneider, U., Ziese, M., 2013. A description of the global land-surface precipitation data products of the Global Precipitation Climatology Centre with sample applications including centennial (trend) analysis from 1901–present. Earth Syst. Sci. Data 5, 71–99. https://doi.org/10.5194/essd-5-71-2013

Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., Smith, B., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Glob. Change Biol. 13, 679–706. https://doi.org/10.1111/j.1365-2486.2006.01305.x

Boserup, E., 2005. The Conditions of Agricultural Growth: The Economics of Agrarian Change Under Population Pressure. Transaction Publishers.

Bren d'Amour, C., Reitsma, F., Baiocchi, G., Barthel, S., Güneralp, B., Erb, K.-H., Haberl, H., Creutzig, F., Seto, K.C., 2017. Future urban land expansion and implications for global croplands. Proc. Natl. Acad. Sci. 114, 8939–8944. https://doi.org/10.1073/pnas.1606036114

Bren d'Amour, C., Wenz, L., Kalkuhl, M., Steckel, J.C., Creutzig, F., 2016. Teleconnected food supply shocks. Environ. Res. Lett. 11, 035007.

Bruinsma, J., 2009. The Resource Outlook to 2050: By How Much do Land, Water and Crop Yields Need to Increase by 2050? Presented at the FAO Expert Meeting, 24-26 June on "How to Feed the World in 2050, Rome.

Buhaug, H., Urdal, H., 2013. An urbanization bomb? Population growth and social disorder in cities. Glob. Environ. Change 23, 1–10.

Calle, L., Canadell, J.G., Patra, P., Ciais, P., Ichii, K., Tian, H., Kondo, M., Piao, S., Arneth, A., Harper, A.B., Ito, A., Kato, E., Koven, C., Sitch, S., Stocker, B.D., Vivoy, N., Wiltshire, A., Zaehle, S., Poulter, B., 2016. Regional carbon fluxes from land use and land cover change in Asia, 1980–2009. Environ. Res. Lett. 11, 074011. https://doi.org/10.1088/1748-9326/11/7/074011

Canadell, J., Raupach, M., 2008. Managing forests for climate change mitigation. science 320, 1456–1457.

Canadell, J.G., Schulze, E.D., 2014. Global potential of biospheric carbon management for climate mitigation. Nat. Commun. 5.

Chaudhary, A., Kastner, T., 2016. Land use biodiversity impacts embodied in international food trade. Glob. Environ. Change 38, 195–204.

Chen, J., 2007. Rapid urbanization in China: A real challenge to soil protection and food security. CATENA, Influences of rapid urbanization and industrialization on soil resource and its quality in China 69, 1–15. https://doi.org/10.1016/j.catena.2006.04.019

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Dong, H., Gabrielle, B., Goss Eng, G., Lucht, W., Mapako, M., Masera Cerutti, O., McIntyre, T., Minowa, T., Pingoud, K., 2011. Bioenergy, in: IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R.

Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (Eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Ciais, P., Bombelli, A., Williams, M., Piao, S., Chave, J., Ryan, C., Henry, M., Brender, P., Valentini, R., 2011. The carbon balance of Africa: synthesis of recent research studies. Philos. Trans. R. Soc. Lond. Math. Phys. Eng. Sci. 369, 2038–2057.

Creutzig, F., 2017. Govern land as a global commons. Nature 546, 28.

Creutzig, F., Ravindranath, N., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., Chum, H., Corbera, E., Delucchi, M., Faaij, A., Fargione, J., Haberl, H., Heath, G., Lucon, O., Plevin, R., Popp, A., Robledo Abad, C., Rose, S., Smith, P., StrØmman, A.H., Suh, S., Masera, O., 2014. Bioenergy and climate change mitigation: an assessment. GCB Bioenergy 7, 916–944.

CRU, University of East Anglia Climatic Research Unit, Jones P D, Harris I, 2013. Climatic Research Unit (CRU) Time-Series (TS) Version 3.21 of High Resolution Gridded Data of Month-by-month Variation in Climate (January 1901–December 2012).

Dalin, C., Konar, M., Hanasaki, N., Rinaldo, A., Rodriguez-Iturbe, I., 2012. Evolution of the global virtual water trade network. Proc. Natl. Acad. Sci. 109, 5989–5994.

Davis, K.F., Gephart, J.A., Emery, K.A., Leach, A.M., Galloway, J.N., D'Odorico, P., 2016. Meeting future food demand with current agricultural resources. Glob. Environ. Change 39, 125–132. https://doi.org/10.1016/j.gloenvcha.2016.05.004

Davis, K.F., Yu, K., Rulli, M.C., Pichdara, L., D'Odorico, P., 2015. Accelerated deforestation driven by large-scale land acquisitions in Cambodia. Nat. Geosci. 8, 772–775.

Deng, L., Liu, G., Shangguan, Z., 2014. Land-use conversion and changing soil carbon stocks in China's 'Grain-for-Green' Program: a synthesis. Glob. Change Biol. 20, 3544–3556. https://doi.org/10.1111/gcb.12508

Erb, K.-H., Haberl, H., Jepsen, M.R., Kuemmerle, T., Lindner, M., Müller, D., Verburg, P.H., Reenberg, A., 2013. A conceptual framework for analysing and measuring land-use intensity. Curr. Opin. Environ. Sustain., Human settlements and industrial systems 5, 464–470. https://doi.org/10.1016/j.cosust.2013.07.010

Faber, S., Rundquist, S., Male, T., 2012. Plowed under: how crop subsidies contribute to massive habitat loss. Environmental Working Group.

FAO, I., 2014. WFP. The State of Food Insecurity in the World 2014 strengthening the enabling environment for food security and nutrition. FAO Rome Italy.

Fischer, J., Abson, D.J., Butsic, V., Chappell, M.J., Ekroos, J., Hanspach, J., Kuemmerle, T., Smith, H.G., von Wehrden, H., 2014. Land Sparing Versus Land Sharing: Moving Forward. Conserv. Lett. 7, 149–157. https://doi.org/10.1111/conl.12084

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global Consequences of Land Use. Science 309, 570–574. https://doi.org/10.1126/science.1111772

Fritz, S., See, L., McCallum, I., You, L., Bun, A., Moltchanova, E., Duerauer, M., Albrecht, F., Schill, C., Perger, C., Havlik, P., Mosnier, A., Thornton, P., Wood-Sichra, U., Herrero, M., Becker-Reshef, I., Justice, C., Hansen, M., Gong, P., Abdel Aziz, S., Cipriani, A., Cumani, R., Cecchi, G., Conchedda, G., Ferreira, S., Gomez, A., Haffani, M., Kayitakire, F., Malanding, J., Mueller, R., Newby, T., Nonguierma, A., Olusegun, A., Ortner, S., Rajak, D.R., Rocha, J., Schepaschenko, D., Schepaschenko, M., Terekhov, A., Tiangwa, A., Vancutsem, C., Vintrou, E., Wenbin, W., van der Velde, M., Dunwoody, A., Kraxner, F., Obersteiner, M., 2015. Mapping global cropland and field size. Glob. Change Biol. 21, 1980–1992. https://doi.org/10.1111/gcb.12838

Fuss, S., Canadell, J.G., Peters, G.P., Tavoni, M., Andrew, R.M., Ciais, P., Jackson, R.B., Jones, C.D., Kraxner, F., Nakicenovic, N., 2014. Betting on negative emissions. Nat. Clim. Change 4, 850–853.

Gallant, A., Kiem, A., Verdon-Kidd, D., Stone, R., Karoly, D., 2012. Understanding hydroclimate processes in the Murray-Darling Basin for natural resources management. Hydrol. Earth Syst. Sci. 16, 2049–2068.

Galli, A., 2015. On the rationale and policy usefulness of Ecological Footprint Accounting: The case of Morocco. Environ. Sci. Policy 48, 210–224.

Galli, A., Halle, M., Grunewald, N., 2015. Physical limits to resource access and utilisation and their economic implications in Mediterranean economies. Environ. Sci. Policy 51, 125–136.

Galli, A., Iha, K., Halle, M., El Bilali, H., Grunewald, N., Eaton, D., Capone, R., Debs, P., Bottalico, F., 2017. Mediterranean countries' food consumption and sourcing patterns: An Ecological Footprint viewpoint. Sci. Total Environ. 578, 383–391.

Galli, A., Wackernagel, M., Iha, K., Lazarus, E., 2014. Ecological footprint: Implications for biodiversity. Biol. Conserv. 173, 121–132.

Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P.K., Toulmin, C., Vermeulen, S.J., Godfray, H.C.J., 2013. Sustainable Intensifi cation in Agriculture: Premises and Policies. Science 341, 33–34.

Gasparri, N.I., Grau, H.R., 2009. Deforestation and fragmentation of Chaco dry forest in NW Argentina (1972–2007). For. Ecol. Manag., Ecology and regeneration of tropical dry forests in the Americas: Implications for management 258, 913–921. https://doi.org/10.1016/j.foreco.2009.02.024

Gerten, D., Schaphoff, S., Haberlandt, U., Lucht, W., Sitch, S., 2004. Terrestrial vegetation and water balance—hydrological evaluation of a dynamic global vegetation model. J. Hydrol. 286, 249–270. https://doi.org/10.1016/j.jhydrol.2003.09.029

Grau, H.R., Aide, M., 2008. Globalization and land-use transitions in Latin America. Ecol. Soc. 13, 16.

Harris, I., Jones, P.D., Osborn, T.J., Lister, D.H., 2014. Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset. Int. J. Climatol. 34, 623–642. https://doi.org/10.1002/joc.3711

Harris, N.L., Goldman, E., Gabris, C., Nordling, J., Minnemeyer, S., Stephen Ansari, Lippmann, M., Bennett, L., Raad, M., Hansen, M., Potapov, P., 2017a. Using spatial statistics to identify emerging hot spots of forest loss. Environ. Res. Lett. 12, 024012. https://doi.org/10.1088/1748-9326/aa5a2f

Harris, N.L., Goldman, E., Gabris, C., Nordling, J., Minnemeyer, S., Stephen Ansari, Lippmann, M., Bennett, L., Raad, M., Hansen, M., Potapov, P., 2017b. Using spatial statistics to identify emerging hot spots of forest loss. Environ. Res. Lett. 12, 024012. https://doi.org/10.1088/1748-9326/aa5a2f

He, C., Liu, Z., Tian, J., Ma, Q., 2014. Urban expansion dynamics and natural habitat loss in China: a multiscale landscape perspective. Glob. Change Biol. 20, 2886–2902. https://doi.org/10.1111/gcb.12553

Hoekstra, A.Y., Hung, P.Q., 2005. Globalisation of water resources: international virtual water flows in relation to crop trade. Glob. Environ. Change 15, 45–56.

Holden, S.T., Otsuka, K., 2014. The roles of land tenure reforms and land markets in the context of population growth and land use intensification in Africa. Food Policy 48, 88–97.

Hosonuma, N., Herold, M., De Sy, V., De Fries, R.S., Brockhaus, M., Verchot, L., Angelsen, A., Romijn, E., 2012. An assessment of deforestation and forest degradation drivers in developing countries. Environ. Res. Lett. 7, 044009. https://doi.org/10.1088/1748-9326/7/4/044009

Huijnen, V., Wooster, M.J., Kaiser, J.W., Gaveau, D.L.A., Flemming, J., Parrington, M., Inness, A., Murdiyarso, D., Main, B., van Weele, M., 2016. Fire carbon emissions over maritime southeast Asia in 2015 largest since 1997. Sci. Rep. 6, 26886. https://doi.org/10.1038/srep26886

Hurtt, G.C., Chini, L.P., Frolking, S., Betts, R.A., Feddema, J., Fischer, G., Fisk, J.P., Hibbard, K., Houghton, R.A., Janetos, A., 2011. Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. Clim. Change 109, 117–161.

IIASA, F., 2012. Global Agro-ecological Zones (GAEZ v3. 0). IIASA Laxenburg Austria FAO Rome Italy.

Jayne, T., Chamberlin, J., Headey, D.D., 2014. Land pressures, the evolution of farming systems, and development strategies in Africa: A synthesis. Food Policy 48, 1–17.

Jolliffe, I., 2002. Principal component analysis. Wiley Online Library.

Kalkuhl, M., 2016. How strong do global commodity prices influence domestic food prices in developing countries? A global price transmission and vulnerability mapping analysis, in: Food Price Volatility and Its Implications for Food Security and Policy. Springer, pp. 269–301.

Kaplan, J.O., Krumhardt, K.M., Zimmermann, N., 2009. The prehistoric and preindustrial deforestation of Europe. Quat. Sci. Rev. 28, 3016–3034.

Kastner, T., Erb, K.-H., Haberl, H., 2014. Rapid growth in agricultural trade: effects on global area efficiency and the role of management. Environ. Res. Lett. 9, 034015.

Kastner, T., Rivas, M.J.I., Koch, W., Nonhebel, S., 2012. Global changes in diets and the consequences for land requirements for food. Proc. Natl. Acad. Sci. 109, 6868–6872.

Keith, H., Mackey, B.G., Lindenmayer, D.B., 2009. Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests. Proc. Natl. Acad. Sci. 106, 11635–11640. https://doi.org/10.1073/pnas.0901970106

Klein Goldewijk, K., Beusen, A., Doelman, J., Stehfest, E., 2016. New anthropogenic land use estimates for the Holocene; HYDE 3.2. Earth Syst. Sci. Data Discuss. 1–40. https://doi.org/10.5194/essd-2016-58

Klein Goldewijk, K., Beusen, A., van Drecht, G., de Vos, M., 2011. The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. Glob. Ecol. Biogeogr. 20, 73–86. https://doi.org/10.1111/j.1466-8238.2010.00587.x

Koh, L.P., Miettinen, J., Liew, S.C., Ghazoul, J., 2011. Remotely sensed evidence of tropical peatland conversion to oil palm. Proc. Natl. Acad. Sci. 108, 5127–5132. https://doi.org/10.1073/pnas.1018776108

Krausmann, F., Schandl, H., Sieferle, R.P., 2008. Socio-ecological regime transitions in Austria and the United Kingdom. Ecol. Econ. 65, 187–201. https://doi.org/10.1016/j.ecolecon.2007.06.009

Kuemmerle, T., Erb, K., Meyfroidt, P., Müller, D., Verburg, P.H., Estel, S., Haberl, H., Hostert, P., Jepsen, M.R., Kastner, T., Levers, C., Lindner, M., Plutzar, C., Verkerk, P.J., van der Zanden, E.H., Reenberg, A., 2013. Challenges and opportunities in mapping land use intensity globally. Curr. Opin. Environ. Sustain., Human settlements and industrial systems 5, 484–493. https://doi.org/10.1016/j.cosust.2013.06.002

Kuemmerle, T., Levers, C., Erb, K., Estel, S., Jepsen, M.R., Müller, D., Plutzar, C., Stürck, J., Verkerk, P., Verburg, P.H., 2016. Hotspots of Land Use Change in Europe. Environ. Res. Lett. 11.

Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. Proc. Natl. Acad. Sci. 108, 3465–3472.

Lapola, D.M., Martinelli, L.A., Peres, C.A., Ometto, J.P.H.B., Ferreira, M.E., Nobre, C.A., Aguiar, A.P.D., Bustamante, M.M.C., Cardoso, M.F., Costa, M.H., Joly, C.A., Leite, C.C., Moutinho, P., Sampaio, G., Strassburg, B.B.N., Vieira, I.C.G., 2014. Pervasive transition of the Brazilian land-use system. Nat. Clim. Change 4, 27–35. https://doi.org/10.1038/nclimate2056

Lark, T.J., Salmon, J.M., Gibbs, H.K., 2015. Cropland expansion outpaces agricultural and biofuel policies in the United States. Environ. Res. Lett. 10, 044003. https://doi.org/10.1088/1748-9326/10/4/044003

Liang, S., Guo, S., Newell, J.P., Qu, S., Feng, Y., Chiu, A.S.F., Xu, M., 2016. Global Drivers of Russian Timber Harvest. J. Ind. Ecol. 20, 515–525. https://doi.org/10.1111/jiec.12417

Liebenberg, F., Pardey, P.G., 2010. South African agricultural production and productivity patterns., in: The Shifting Patterns of Agricultural Production and Productivity Worldwide. The Midwest Agribusiness Trade Research and Information Center, Iowa State University, Ames, Iowa.

Liu, J., Hull, V., Batistella, M., DeFries, R., Dietz, T., Fu, F., Hertel, T., Izaurralde, R.C., Lambin, E., Li, S., Martinelli, L., McConnell, W., Moran, E., Naylor, R., Ouyang, Z., Polenske, K., Reenberg, A., de Miranda Rocha, G., Simmons, C., Verburg, P., Vitousek, P., Zhang, F., Zhu, C., 2013. Framing Sustainability in a Telecoupled World. Ecol. Soc. 18. https://doi.org/10.5751/ES-05873-180226

Liu, X., Feng, Z., Jiang, L., Li, P., Liao, C., Yang, Y., You, Z., 2013. Rubber plantation and its relationship with topographical factors in the border region of China, Laos and Myanmar. J. Geogr. Sci. 23, 1019–1040. https://doi.org/10.1007/s11442-013-1060-4

Lobell, D.B., 2011. Climate trends and global crop production since 1980. Science 333, 616–620. https://doi.org/10.1126/science.1204531

Magalhães, P., Steffen, W., Bosselmann, K., Aragão, A., Soromenho-Marques, V., 2016. Cambridge Scholars Publishing. The Safe Operating Space Treaty. Cambridge Scholars Publishing, Cambridge UK.

Mladenoff, D.J., Sahajpal, R., Johnson, C.P., Rothstein, D.E., 2016. Recent Land Use Change to Agriculture in the U.S. Lake States: Impacts on Cellulosic Biomass Potential and Natural Lands. PLOS ONE 11, e0148566. https://doi.org/10.1371/journal.pone.0148566

Monfreda, C., Ramankutty, N., Foley, J.A., 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Glob. Biogeochem. Cycles 22, GB1022. https://doi.org/10.1029/2007GB002947

MSEIC, 2010. Australia and Food Security in a Changing World. The Prime Minister's Science, Engineering and Innovation Council.

Nagendra, H., Sudhira, H.S., Katti, M., Schewenius, M., 2013. Sub-regional Assessment of India: Effects of Urbanization on Land Use, Biodiversity and Ecosystem Services, in: Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P.J., McDonald, R.I., Parnell, S., Schewenius, M., Sendstad, M., Seto, K.C., Wilkinson, C. (Eds.), Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities. Springer Netherlands, pp. 65–74.

Nepstad, D., McGrath, D., Stickler, C., Alencar, A., Azevedo, A., Swette, B., Bezerra, T., DiGiano, M., Shimada, J., Motta, R.S. da, Armijo, E., Castello, L., Brando, P., Hansen, M.C., McGrath-Horn, M., Carvalho, O., Hess, L., 2014. Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. Science 344, 1118–1123. https://doi.org/10.1126/science.1248525

Newbold, T., Hudson, L.N., Hill, S.L., Contu, S., Lysenko, I., Senior, R.A., Börger, L., Bennett, D.J., Choimes, A., Collen, B., 2015. Global effects of land use on local terrestrial biodiversity. Nature 520, 45–50.

Newbold, T., Hudson, L.N., Phillips, H.R.P., Hill, S.L.L., Contu, S., Lysenko, I., Blandon, A., Butchart, S.H.M., Booth, H.L., Day, J., Palma, A.D., Harrison, M.L.K., Kirkpatrick, L., Pynegar, E., Robinson, A., Simpson, J., Mace, G.M., Scharlemann, J.P.W., Purvis, A., 2014. A global model of the response of tropical and sub-tropical forest biodiversity to anthropogenic pressures. Proc. R. Soc. Lond. B Biol. Sci. 281, 20141371. https://doi.org/10.1098/rspb.2014.1371

Odhiambo, G.O., 2016. Water scarcity in the Arabian Peninsula and socio-economic implications. Appl. Water Sci. 1–14. https://doi.org/10.1007/s13201-016-0440-1

Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A Large and Persistent Carbon Sink in the World's Forests. Science 333, 988–993. https://doi.org/10.1126/science.1201609

Park, J., Bader, J., Matei, D., 2016. Anthropogenic Mediterranean warming essential driver for present and future Sahel rainfall. Nat. Clim. Change 6, 941–945. https://doi.org/10.1038/nclimate3065

Peters, G.P., Hertwich, E.G., 2008. CO2 embodied in international trade with implications for global climate policy. Environ. Sci. Technol. 42, 1401–1407.

Phelps, J., Webb, E.L., Adams, W.M., 2012. Biodiversity co-benefits of policies to reduce forest-carbon emissions. Nat. Clim. Change 2, 497–503. https://doi.org/doi:10.1038/nclimate1462

Rands, M.R., Adams, W.M., Bennun, L., Butchart, S.H., Clements, A., Coomes, D., Entwistle, A., Hodge, I., Kapos, V., Scharlemann, J.P., others, 2010. Biodiversity conservation: challenges beyond 2010. Science 329, 1298–1303.

Reddy, C.S., Jha, C.S., Dadhwal, V.K., Krishna, P.H., Pasha, S.V., Satish, K.V., Dutta, K., Saranya, K.R.L., Rakesh, F., Rajashekar, G., Diwakar, P.G., 2015. Quantification and monitoring of deforestation in India over eight decades (1930–2013). Biodivers. Conserv. 25, 93–116. https://doi.org/10.1007/s10531-015-1033-2

Risse, M., 2008. Original ownership of the earth: a contemporary approach. John F. Kennedy School of Government, Harvard University.

Robinson, T.P., Wint, G.R.W., Conchedda, G., Boeckel, T.P.V., Ercoli, V., Palamara, E., Cinardi, G., D'Aietti, L., Hay, S.I., Gilbert, M., 2014. Mapping the Global Distribution of Livestock. PLOS ONE 9, e96084. https://doi.org/10.1371/journal.pone.0096084

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Nature 461, 472–475. https://doi.org/10.1038/461472a

Schierhorn, F., Müller, D., Beringer, T., Prishchepov, A.V., Kuemmerle, T., Balmann, A., 2013. Post-Soviet cropland abandonment and carbon sequestration in European Russia, Ukraine, and Belarus. Glob. Biogeochem. Cycles 27, 1175–1185. https://doi.org/10.1002/2013GB004654

Schmitz, C., van Meijl, H., Kyle, P., Nelson, G.C., Fujimori, S., Gurgel, A., Havlik, P., Heyhoe, E., d'Croz, D.M., Popp, A., Sands, R., Tabeau, A., van der Mensbrugghe, D., von Lampe, M., Wise, M., Blanc, E., Hasegawa, T., Kavallari, A., Valin, H., 2014. Land-use change trajectories up to 2050: insights from a global agro-economic model comparison. Agric. Econ. 45, 69–84. https://doi.org/10.1111/agec.12090

Schneider, A., Mertes, C.M., Tatem, A.J., Tan, B., Sulla-Menashe, D., Graves, S.J., Patel, N.N., Horton, J.A., Gaughan, A.E., Rollo, J.T., Schelly, I.H., Stevens, F.R., Dastur, A., 2015. A new urban landscape in East–Southeast Asia, 2000–2010. Environ. Res. Lett. 10, 034002. https://doi.org/10.1088/1748-9326/10/3/034002

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., Ziese, M., 2011. GPCC full data reanalysis version 6.0 at 0.5°: monthly land-surface precipitation from rain-gauges built on GTS-based and historic data.

Searchinger, T.D., Estes, L., Thornton, P.K., Beringer, T., Notenbaert, A., Rubenstein, D., Heimlich, R., Licker, R., Herrero, M., 2015. High carbon and biodiversity costs from converting Africa's wet savannahs to cropland. Nat. Clim. Change 5, 481–486.

Şekercioğlu, Ç.H., Anderson, S., Akçay, E., Bilgin, R., Can, Ö.E., Semiz, G., Tavşanoğlu, Ç., Yokeş, M.B., Soyumert, A., Ipekdal, K., 2011. Turkey's globally important biodiversity in crisis. Biol. Conserv. 144, 2752–2769.

Seto, K.C., Güneralp, B., Hutyra, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proc. Natl. Acad. Sci. 109, 16083–16088. https://doi.org/10.1073/pnas.1211658109

Sitch, S., Smith, B., Prentice, I.C., Arneth, A., Bondeau, A., Cramer, W., Kaplan, J.O., Levis, S., Lucht, W., Sykes, M.T., Thonicke, K., Venevsky, S., 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. Glob. Change Biol. 9, 161–185. https://doi.org/10.1046/j.1365-2486.2003.00569.x

Sleeter, B.M., Sohl, T.L., Loveland, T.R., Auch, R.F., Acevedo, W., Drummond, M.A., Sayler, K.L., Stehman, S.V., 2013. Land-cover change in the conterminous United States from 1973 to 2000. Glob. Environ. Change 23, 733–748. https://doi.org/10.1016/j.gloenvcha.2013.03.006

Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J., Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C., 2016. Biophysical and economic limits to negative CO2 emissions. Nat. Clim. Change 6, 42–50. https://doi.org/10.1038/nclimate2870

Smith, P., Gregory, P.J., Van Vuuren, D., Obersteiner, M., Havlík, P., Rounsevell, M., Woods, J., Stehfest, E., Bellarby, J., 2010. Competition for land. Philos. Trans. R. Soc. B Biol. Sci. 365, 2941–2957.

Steffen, W., Burbidge, A., Hughes, L., Kitching, R., Lindenmayer, D., Musgrave, W., Stafford Smith, M., Werner, P., 2009. Australia's biodiversity and climate change: a strategic assessment of the vulnerability of Australia's biodiversity to climate change.

Steffen, W., Richardson, K., Rockström, J., Cornell, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., de Vries, W., de Wit, C.A., others, 2015. Planetary boundaries: Guiding human development on a changing planet. Science 347, 1259855.

Stibig, H.-J., Achard, F., Carboni, S., Raši, R., Miettinen, J., 2014. Change in tropical forest cover of Southeast Asia from 1990 to 2010. Biogeosciences 11, 247–258. https://doi.org/10.5194/bg-11-247-2014

Tayleur, C., Balmford, A., Buchanan, G.M., Butchart, S.H., Ducharme, H., Green, R.E., Milder, J.C., Sanderson, F.J., Thomas, D.H., Vickery, J., others, 2016. Global Coverage of Agricultural Sustainability Standards, and Their Role in Conserving Biodiversity. Conserv. Lett.

Thornton, P.K., 2010. Livestock production: recent trends, future prospects. Philos. Trans. R. Soc. B Biol. Sci. 365, 2853–2867. https://doi.org/10.1098/rstb.2010.0134

van Vliet, J., de Groot, H., Rietveld, P., Verburg, P.H., 2015. Manifestations and underlying drivers of agricultural land use change in Europe. Landsc. Urban Plan. 133, 24–36.

Vereinte Nationen (Ed.), 2014. System of environmental-economic accounting 2012: central framework. United Nations, New York, NY.

Wackernagel, M., Schulz, N.B., Deumling, D., Linares, A.C., Jenkins, M., Kapos, V., Monfreda, C., Loh, J., Myers, N., Norgaard, R., Randers, J., 2002. Tracking the ecological overshoot of the human economy. Proc. Natl. Acad. Sci. 99, 9266–9271. https://doi.org/10.1073/pnas.142033699

Wallander, S., Claassen, R., Nickerson, C., 2011. The ethanol decade: an expansion of US corn production, 2000-09, EIB-79, U.S. Department of Agriculture, Economic Research Service.

Waroux, Y. le P. de, Garrett, R.D., Heilmayr, R., Lambin, E.F., 2016. Land-use policies and corporate investments in agriculture in the Gran Chaco and Chiquitano. Proc. Natl. Acad. Sci. 113, 4021–4026. https://doi.org/10.1073/pnas.1602646113

Weinzettel, J., Hertwich, E.G., Peters, G.P., Steen-Olsen, K., Galli, A., 2013. Affluence drives the global displacement of land use. Glob. Environ. Change 23, 433–438. https://doi.org/10.1016/j.gloenvcha.2012.12.010

West, P.C., Gerber, J.S., Engstrom, P.M., Mueller, N.D., Brauman, K.A., Carlson, K.M., Cassidy, E.S., Johnston, M., MacDonald, G.K., Ray, D.K., Siebert, S., 2014. Leverage points for improving global food security and the environment. Science 345, 325–328. https://doi.org/10.1126/science.1246067

Wilcove, D.S., Giam, X., Edwards, D.P., Fisher, B., Koh, L.P., 2013. Navjot's nightmare revisited: logging, agriculture, and biodiversity in Southeast Asia. Trends Ecol. Evol. 28, 531–540. https://doi.org/10.1016/j.tree.2013.04.005

Wright, C.K., Wimberly, M.C., 2013. Recent land use change in the Western Corn Belt threatens grasslands and wetlands. Proc. Natl. Acad. Sci. 110, 4134–4139. https://doi.org/10.1073/pnas.1215404110

Zhang, M., Huang, X., Chuai, X., Yang, H., Lai, L., Tan, J., 2015. Impact of land use type conversion on carbon storage in terrestrial ecosystems of China: A spatial-temporal perspective. Sci. Rep. 5, 10233. https://doi.org/10.1038/srep10233

Zhu, Z., Piao, S., Myneni, R.B., Huang, M., Zeng, Z., Canadell, J.G., Ciais, P., Sitch, S., Friedlingstein, P., Arneth, A., Cao, C., Cheng, L., Kato, E., Koven, C., Li, Y., Lian, X., Liu, Y., Liu, R., Mao, J., Pan, Y., Peng, S., Peñuelas, J., Poulter, B., Pugh, T.A.M., Stocker, B.D., Viovy, N., Wang, X., Wang, Y., Xiao, Z., Yang, H., Zaehle, S., Zeng, N., 2016. Greening of the Earth and its drivers. Nat. Clim. Change 6, 791–795. https://doi.org/10.1038/nclimate3004

2.5 Supplementary Information

Supplementary Information Guide

This documents entails information regarding

Figures S1-4

Tables S1-7

Supplementary Information text

2.5.1. Figures

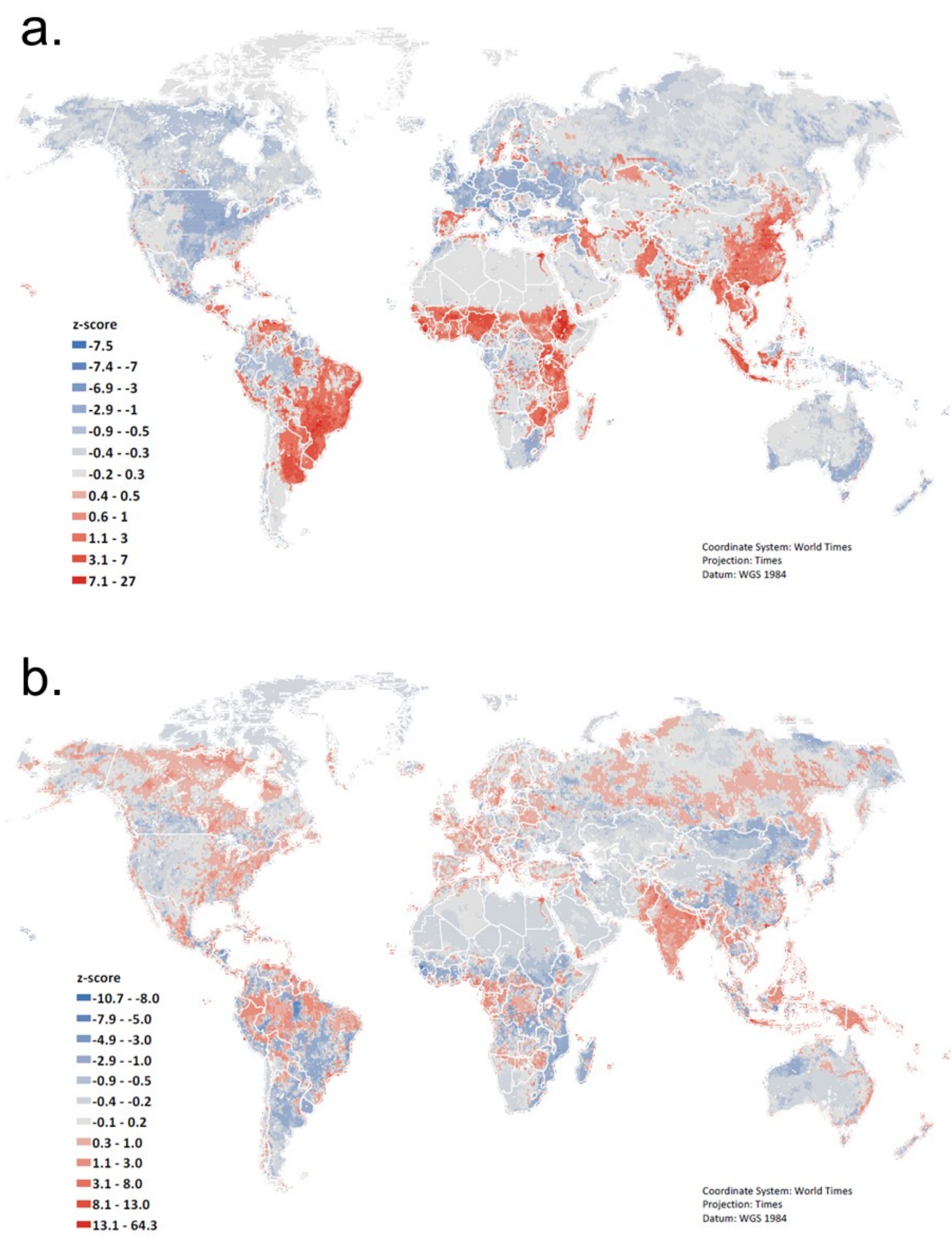

Figure S1 – Principal Component Analysis. This figure contains maps of the Z-scores of the PCA for **a)** component 1 **b)** component 2. Z-scores are calculated as the product of the eigenvectors from the PCA with the standardized data of intensity changes. They show the reduction of the underlying data to the lower-dimensional space (here: two dimensions as we consider only the first two components) while maintaining highest explanatory power.

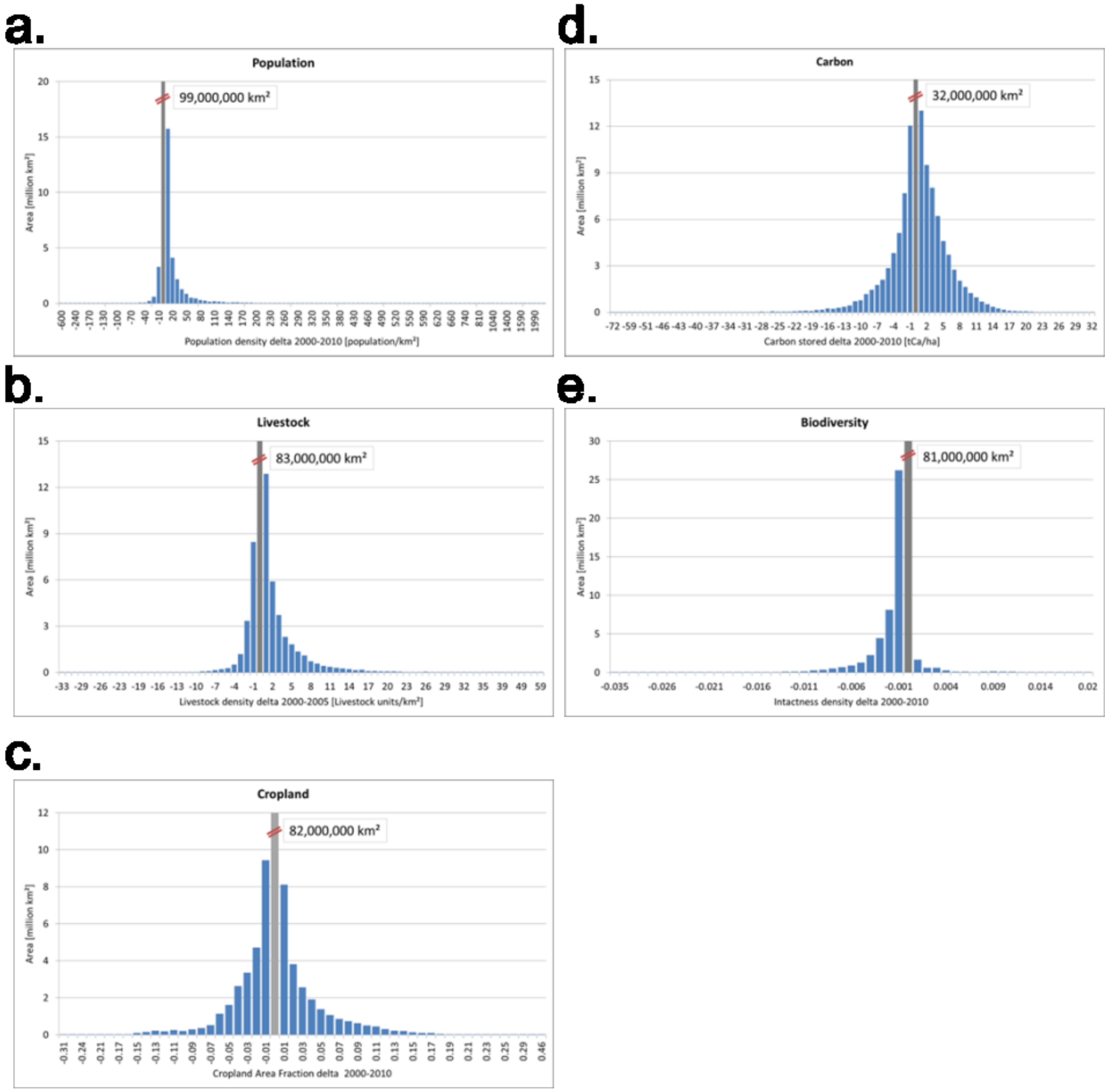

Figure S2 – Shift diagrams. The shift diagrams depict the frequency distribution in terms of area of the intensity changes between 2000 and 2010 from negative (on the left) to positive (on the right) for **a)** population density; **b)** livestock density; **c)** cropland area fraction; **d)** carbon stock; **e)** Intactness. The grey bar represents the area without notable changes.

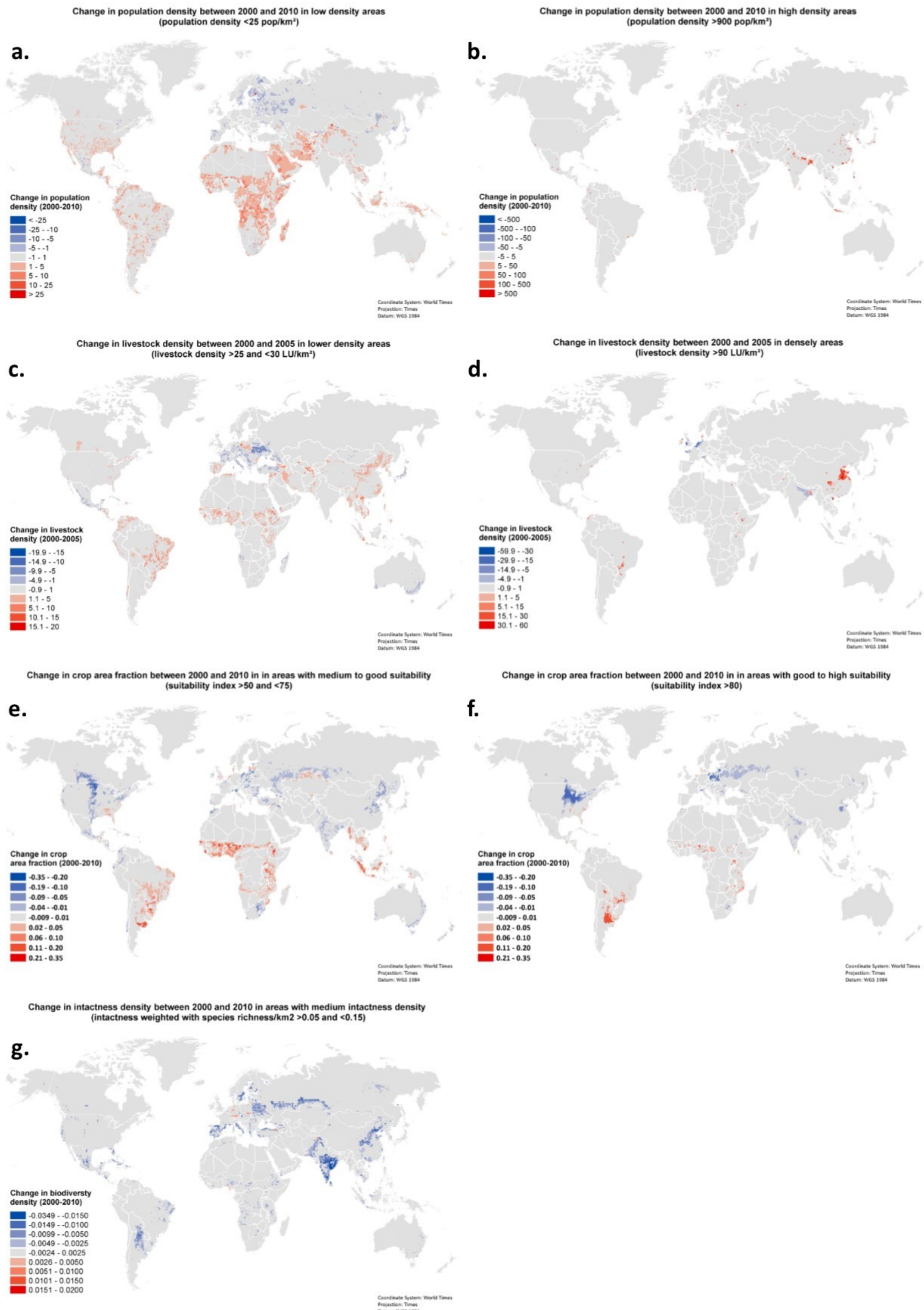
Change in population density between 2000 and 2010 in low density areas
(population density <25 pop/km²)
a.
Change in population density (2000-2010)
< -25
-25 - -10
-10 - -5
-5 - -1
-1 - 1
1 - 5
5 - 10
10 - 25
> 25
Coordinate System: World Times
Projection: Times
Datum: WGS 1984
Change in population density between 2000 and 2010 in high density areas
(population density >900 pop/km²)
b.
Change in population density (2000-2010)
< -500
-500 - -100
-100 - -50
-50 - -5
-5 - 5
5 - 50
50 - 100
100 - 500
> 500
Coordinate System: World Times
Projection: Times
Datum: WGS 1984
Change in livestock density between 2000 and 2005 in lower density areas
(livestock density >25 and <30 LU/km²)
c.
Change in livestock density (2000-2005)
-19.9 - -15
-14.9 - -10
-9.9 - -5
-4.9 - -1
-0.9 - 1
1.1 - 5
5.1 - 10
10.1 - 15
15.1 - 20
Coordinate System: World Times
Projection: Times
Datum: WGS 1984
Change in livestock density between 2000 and 2005 in densely areas
(livestock density >90 LU/km²)
d.
Change in livestock density (2000-2005)
-59.9 - -30
-29.9 - -15
-14.9 - -5
-4.9 - -1
-0.9 - 1
1.1 - 5
5.1 - 15
15.1 - 30
30.1 - 60
Coordinate System: World Times
Projection: Times
Datum: WGS 1984
Change in crop area fraction between 2000 and 2010 in in areas with medium to good suitability
(suitability index >50 and <75)
e.
Change in crop area fraction (2000-2010)
-0.35 - -0.20
-0.19 - -0.10
-0.09 - -0.05
-0.04 - -0.01
-0.009 - 0.01
0.02 - 0.05
0.06 - 0.10
0.11 - 0.20
0.21 - 0.35
Coordinate System: World Times
Projection: Times
Datum: WGS 1984
Change in crop area fraction between 2000 and 2010 in in areas with good to high suitability
(suitability index >80)
f.
Change in crop area fraction (2000-2010)
-0.35 - -0.20
-0.19 - -0.10
-0.09 - -0.05
-0.04 - -0.01
-0.009 - 0.01
0.02 - 0.05
0.06 - 0.10
0.11 - 0.20
0.21 - 0.35
Coordinate System: World Times
Projection: Times
Datum: WGS 1984
Change in intactness density between 2000 and 2010 in areas with medium intactness density
(intactness weighted with species richness/km2 >0.05 and <0.15)
g.
Change in biodiversty density (2000-2010)
-0.0349 - -0.0150
-0.0149 - -0.0100
-0.0099 - -0.0050
-0.0049 - -0.0025
-0.0024 - 0.0025
0.0026 - 0.0050
0.0051 - 0.0100
0.0101 - 0.0150
0.0151 - 0.0200
Coordinate System: World Times
Projection: Times
Datum: WGS 1984

Figure S3 – Intensity change maps. The following maps show the spatial distribution of the areas in intensity bins of interest (red boxes) as identified in Fig. 3 of the manuscript. **a) Pristine land take:** Change in population density between 2000 and 2010 in low density areas (population density <25 pop/km2); **b) Urbanization:** Change in population density between 2000 and 2010 in high density areas (population density >900 pop/km2); **c) Intensification in peripheral areas:** Change in livestock density between 2000 and 2010 in lower density areas (livestock density >25 and <30 LU/km2); **d) Intense husbandry:** Change in livestock density between 2000 and 2010 in higher density areas (livestock density >90 LU/km2); **e) Expansion in LAM, SSA and SEA:** Change in cropland area fraction between 2000 and 2010 in areas with medium to good suitability (suitability index >50 and <75); **f) Cropland abandonment in OECD countries:** Change in cropland area fraction between 2000 and 2010 in areas with medium to high suitability (suitability >80); **g) Increase in ice-free areas:** Change in carbon stock between 2000 and 2010 in areas with low carbon stock (tC/ha <80); **h) Increase in boreal areas:** Change in carbon stock between 2000 and 2010 in areas with medium carbon stock (tC/ha >400 and <500); **i) Human pressures:** Change in intactness density between 2000 and 2010 in areas with medium intactness density (intactness weighted with species richness/km2 >0.05 and <0.15).

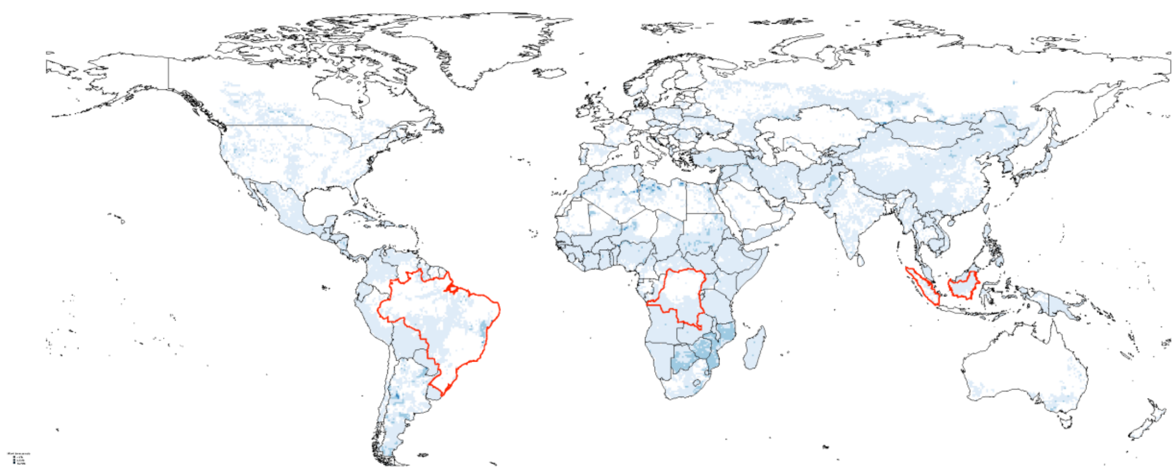

Figure S4. Comparison of LJP with deforestation hotspots. Blue areas denote a reduction of vegetation between 2000 and 2010 according to LPJ. Red areas denote deforestation hotspots between 2000 and 2014 according to **Harris et al. (2017)**, including deforestation dynamics after 2010. LPJ likely underestimates deforestation loss due to deforestation, especially in Congo.

2.5.2. Tables

Table S1 – Overview over datasets. Data selection is based on quality and availability for the year 2000 and 2010. Modelled data is only used if alternatives were unavailable.

	Name of dataset	Resolution	Comments	Units	Points in time	Source/Link
Population	SEDAC's Gridded Population of the World (GPW), v3 (Center for International Earth Science Information Network - CIESIN - Columbia University and Centro Internacional de Agricultura Tropical - CIAT, 2005)	50x50km (5x5km possible)	The projected grid for 2010 was produced in collaboration with the United Nations Food and Agriculture Program (FAO) as Population Count and Density Grid Future Estimates.	Total population, Population density (pop/km^2)	2000 and 2010 (projected)	(Gridded Population of the World, Version 3 (GPWv3): Population Count Grid. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). http://dx.doi.org/10.7927/H4639MPP. Accessed, Jan 2016) (We used Version v3 which got recently updated to v4 in June 2016.)
Livestock	Gridded Livestock of the World (GLW) (Robinson et al., 2014; Wint et al., 2007)	5x5 arc-minute	Aggregate Livestock units compromise different livestock types	Livestock units, livestock density (LU/km^2)	2000 and 2005	http://www.fao.org/ag/againfo/resources/en/glw/GLW_dens.html
Cropland	History Database of the Global Environment (HYDE) (Klein Goldewijk et al., 2011); Global Agro-Ecological Zones (GAEZ) (IIASA, 2012)	0.5x 0.5 degree	HYDE data is based on FAO's categories 'Arable land and permanent crops' GAEZ suitability for cereals only, high input level	Crop area fraction, i.e. percentage of a grid cell Suitability Index [from 0-1]	2000 and 2010 2000 (for suitability)	ftp://ftp.pbl.nl/hyde/hyde3.2/ http://themasites.pbl.nl/tridion/en/themasites/hyde/ http://gaez.fao.org/Main.html#

Carbon Storage	Lund-Potsdam-Jena managed Land model (LPJ) (Bondeau et al., 2007)	0.5x 0.5 degree	Modelled data.	tC stored (total, and per ha)	2000 and 2010	https://www.pik-potsdam.de/research/projects/activities/biosphere-water-modelling/lpjml
Biodiversity	Predicts database (Hudson et al., 2014) Newbold et al. (Newbold et al., 2015) (SI) LUHa_u2t1 Land Use Harmoni-zation (Hurtt et al., 2011)		See SI text for further explanation on data processing. Partially, pre-processed data by Newbold et al.	Species Richness Intactness Land Uses	n/a n/a 2000 and 2010	http://www.predicts.org.uk/ http://www.biodiversityinfo.org/spcdownload/r5h8a1/ http://www.nature.com/nature/journal/v520/n7545/full/nature14324.html http://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=about
Land embodied in trade	Kastner et al, 2014 (Kastner et al., 2014)	Country level	Used to account for teleconnected land uses	Net share of croplands used for exports	2000 and 2009	Data (Kastner et al, 2014(Kastner et al., 2014)(SI)): http://iopscience.iop.org/1748-9326/9/3/034015/media
Land footprint	Weinzettel et al, 2013 (Weinzettel et al., 2013)	Country level	Used for Fig. 5	global hectares (gha) per capita	2004	http://www.sciencedirect.com/science/article/pii/S0959378012001501

Table S2 - First two components (eigenvectors) of the Principle Component Analysis. The eigenvector with the highest eigenvector is the principle component which gives a one-dimensional reduction of the data that explains the highest share of the variation. Adding further eigenvectors allows to account for more variability (but increases also dimensionality). The eigenvectors are used to calculate the z-scores.

Variable	Component 1	Component 2	Unexplained
Population	0.2671	0.7195	0.3801
Carbon	-0.276	0.6849	0.4227
Crop area	0.5239	-0.0679	0.6218
Livestock	0.5666	-0.0232	0.5625
Biodiversity	-0.507	-0.0898	0.642

Table S3 - Cropland associated to trade (net exports) as a share of the cropland under domestic production [in %]. (a) relative to total regional cropland in 2000. (b) relative to total regional cropland in 2009. Numbers are calculated using detailed country data from the Supplementary Appendix in Kastner et al. (2014) which contains land embedded in crop trade flows. As data for 2009 is the most recent available, we use 2009 data instead of 2010. Entries are ordered according to the largest changes between 2009 and 2000 (last column). Positive (negative) numbers for the year 2000 and 2009 indicate that a country is a net land exporter (importer), with the net export share of land on total cropland represented by the respective entries. The last column shows the change of the land net export share.

Region	2000	2009 (a)	2009 (b)	Change (2000 vs 2009 (a))
Latin and Central America	14.0	37.8	31.2	23.8
Eastern Europe & Central Asia	2.3	17.9	16.7	15.7
Oceania	68.1	71.0	62.6	2.9
South-Eastern Asia	4.1	3.6	3.0	-0.5
Sub-Saharan Africa	3.6	2.9	2.4	-0.7
Southern Asia	-0.3	-3.4	-3.2	-3.0
North America	33.9	30.9	31.8	-3.1
Eastern Asia	-21.4	-31.7	-30.0	-10.3
Europe	-39.5	-50.3	-53.0	-10.8
Middle East and North Africa	-36.8	-53.9	-52.0	-17.1

Table S4 - Regional overview over gain/loss per land use dimension in hotspots (top 10%) between 2000 and 2010 (2000 and 2005 for livestock). Units used are 1) Population (Pop): population/km2 (density) and million people (total); 2) Livestock (Livest): livestock units/km2 (density and million livestock units (total); 3) Cropland (Crop): cropland area fraction (% of cropland in a grid cell, density) and '000 km2 (total); 4) Carbon: tC/ha (density) and megatons Carbon (total); 5) Biodiversity: Intactness/km2 (weighted with species richness, density) and Intactness weighted with species richness (total).

Top 10%	Dimension	Share of area with gain	Average density 2000	Average density 2010	Density 2010 – density 2000	Change in intensity (%)	Average density change for areas with gain	Share of global area with gain	Average density change for areas with loss	Share of global area with loss
Eastern Asia	Pop	59%	505.7	556.8	51.1	10%	117	14%	-19	30%
	Livest	98%	52.1	59.5	7.3	14%	32	26%	0	1%
	Crop		0.6	0.5	-0.1	-11%	0	0%	-34	4%
	Carbon	20%	280.7	274.4	-6.3	-2%	238	1%	-919	5%
	Bio		0.109	0.103	0.0	-5%	0	0%	-7	4%
Eastern Europe & Central Asia	Pop	37%	256.1	245.8	-10.2	-4%	7	1%	-9	14%
	Livest	35%	22.5	20.9	-1.6	-7%	2	2%	-4	13%
	Crop	7%	0.5	0.4	-0.1	-18%	2	0%	-31	4%
	Carbon	60%	294.5	298.0	3.5	1%	382	2%	-240	1%
	Bio	3%	0.117	0.111	0.0	-5%	0	4%	-7	5%
Europe (excl. Eastern Europe)	Pop	60%	463.2	470.3	7.1	2%	6	1%	-4	5%
	Livest	6%	72.2	65.9	-6.3	-9%	0	0%	-4	14%
	Crop	1%	0.5	0.4	-0.1	-17%	0	0%	-25	3%
	Carbon	89%	162.4	170.2	7.8	5%	241	1%	-36	0%
	Bio	10%	0.104	0.097	0.0	-7%	0	6%	-5	3%
Latin America	Pop	100%	294.8	342.5	47.7	16%	54	6%	0	0%
	Livest	94%	40.8	47.5	6.7	16%	28	23%	-1	4%
	Crop	96%	0.4	0.5	0.1	24%	146	16%	-4	0%
	Carbon	54%	261.9	261.9	0.0	0%	2,905	12%	-3,178	17%
	Bio		0.171	0.165	0.0	-3%	0	1%	-28	19%
Western Asia and Northern Africa	Pop	99%	216.9	264.0	47.1	22%	56	7%	0	1%
	Livest	96%	37.1	42.1	5.0	13%	4	3%	0	0%
	Crop	46%	0.4	0.4	0.0	-4%	15	2%	-19	2%
	Carbon	9%	131.2	122.0	-9.1	-7%	9	0%	-126	1%
	Bio	11%	0.083	0.079	0.0	-5%	0	3%	-1	1%
North America	Pop	100%	414.5	459.5	45.0	11%	18	2%	0	0%
	Livest	99%	56.3	60.8	4.5	8%	1	1%	0	0%
	Crop	1%	0.7	0.6	-0.1	-14%	1	0%	-158	20%
	Carbon	92%	244.9	253.0	8.2	3%	1,327	6%	-159	1%
	Bio		0.105	0.099	0.0	-6%	0	0%	-1	1%
Oceania	Pop	100%	251.0	283.3	32.3	13%	2	0%	0	0%
	Livest	28%	63.0	62.9	-0.1	0%	0	0%	0	1%
	Crop	0%	0.5	0.4	-0.1	-16%	0	0%	-19	2%
	Carbon	79%	311.6	321.2	9.7	3%	852	4%	-178	1%

	Bio		0.118	0.113	0.0	-4%	0	0%	-1	0%
South -Eastern Asia	Pop	99%	322.8	370.9	48.2	15%	61	7%	-1	1%
	Livest	97%	27.7	33.4	5.7	21%	5	4%	0	1%
	Crop	100%	0.3	0.4	0.1	27%	111	12%	0	0%
	Carbo n	81%	302.6	311.2	8.5	3%	1,537	7%	-492	3%
	Bio		0.181	0.175	0.0	-3%	0	0%	-6	4%
South ern Asia	Pop	100%	357.4	420.6	63.2	18%	243	29%	0	0%
	Livest	73%	71.8	74.0	2.3	3%	3	3%	-1	4%
	Crop	99%	0.4	0.5	0.1	17%	13	1%	0	0%
	Carbo n	43%	189.3	188.4	-0.8	0%	74	0%	-120	1%
	Bio	2%	0.104	0.096	0.0	-8%	0	4%	-18	12%
Sub-Saharan Africa	Pop	99%	131.5	170.4	39.0	30%	128	15%	-1	2%
	Livest	99%	33.7	40.7	7.0	21%	13	11%	0	0%
	Crop	93%	0.4	0.4	0.1	23%	232	26%	-14	2%
	Carbo n	29%	208.0	201.8	-6.1	-3%	932	4%	- 2,894	16%
	Bio	4%	0.168	0.162	0.0	-4%	0	6%	-13	8%

Table S5 - Regional overview over gain/loss per land use dimension (top 80%) between 2000 and 2010 (2000 and 2005 for livestock). Units used are 1) Population (Pop): population/km2 (density) and million people (total); 2) Livestock (Livest): livestock units/km2 (density and million livestock units (total); 3) Cropland (Crop): cropland area fraction (% of cropland in a grid cell, density) and '000 km2 (total); 4) Carbon: tC/ha (density) and megatons Carbon (total); 5) Biodiversity: Intactness/km2 (weighted with species richness, density) and Intactness weighted with species richness (total).

Top 80%	Dimension	Share of area with gain	Average density 2000	Average density 2010	Density 2010 – Density 2000	Change in intensity (%)	Average density change for areas with gain	Share of global area with gain	Average density change for areas with loss	Share of global area with loss
Eastern Asia	Pop	63%	154.2	164.4	10.3	7%	126	15%	-29	44%
	Livest	82%	22.5	25.4	2.9	13%	36	30%	-2	7%
	Crop	2%	0.2	0.2	0.0	-10%	1	0%	-152	19%
	Carbon	38%	173.5	172.1	-1.4	-1%	1,127	5%	-2,520	14%
	Bio	3%	0.095	0.094	0.0	-2%	0	1%	-13	9%
Eastern Europe & Central Asia	Pop	17%	22.1	21.3	-0.8	-4%	11	1%	-21	32%
	Livest	27%	4.3	4.0	-0.3	-7%	4	4%	-9	29%
	Crop	20%	0.3	0.3	0.0	-5%	22	2%	-128	16%
	Carbon	69%	426.2	427.5	1.3	0%	3,804	16%	-1,494	8%
	Bio	5%	0.112	0.111	0.0	-1%	1	16%	-20	13%
Europe (excl. Eastern Europe)	Pop	34%	104.3	104.8	0.5	0%	10	1%	-8	13%
	Livest	24%	24.8	23.4	-1.3	-5%	1	1%	-6	21%
	Crop	43%	0.2	0.2	0.0	-3%	12	1%	-40	5%
	Carbon	84%	208.9	211.8	3.0	1%	1,286	5%	-166	1%
	Bio	48%	0.094	0.092	0.0	-2%	1	17%	-6	4%
Latin America	Pop	85%	35.9	40.8	5.0	14%	77	9%	-2	3%
	Livest	80%	15.4	17.1	1.7	11%	36	30%	-3	10%
	Crop	74%	0.1	0.1	0.0	13%	258	29%	-38	5%
	Carbon	52%	192.8	193.0	0.2	0%	5,517	23%	-5,438	29%
	Bio	4%	0.164	0.162	0.0	-1%	1	11%	-42	28%
Western Asia and Northern Africa	Pop	98%	39.9	47.9	8.0	20%	76	9%	-1	2%
	Livest	88%	9.4	10.1	0.7	7%	7	6%	-1	3%
	Crop	39%	0.2	0.2	0.0	-2%	39	4%	-53	7%
	Carbon	32%	47.2	46.4	-0.8	-2%	214	1%	-641	3%
	Bio	3%	0.054	0.053	0.0	-2%	0	4%	-6	4%
North America	Pop	88%	38.9	42.3	3.4	9%	28	3%	0	1%
	Livest	54%	6.8	6.9	0.1	2%	3	2%	-1	4%
	Crop	17%	0.3	0.2	0.0	-10%	15	2%	-248	31%
	Carbon	72%	336.1	338.7	2.7	1%	4,598	20%	-1,005	5%
	Bio	9%	0.105	0.105	0.0	0%	0	2%	-5	3%
Oceania	Pop	92%	17.7	19.9	2.2	12%	4	0%	0	0%
	Livest	28%	7.7	7.4	-0.3	-4%	0	0%	-2	6%
	Crop	16%	0.2	0.2	0.0	-11%	2	0%	-56	7%
	Carbon	44%	97.4	98.7	1.3	1%	1,413	6%	-853	5%

	Bio	46%	0.074	0.074	0.0	-1%	0	7%	-4	2%
South -Eastern Asia	Pop	94%	134.9	153.7	18.8	14%	72	9%	-1	1%
	Livest	90%	10.3	11.7	1.4	14%	9	7%	0	2%
	Crop	93%	0.2	0.3	0.0	18%	168	19%	-4	0%
	Carbon	73%	271.5	276.3	4.8	2%	2,282	10%	-749	4%
	Bio	2%	0.149	0.147	0.0	-2%	0	1%	-10	7%
Southern Asia	Pop	100%	221.0	259.7	38.8	18%	254	30%	0	0%
	Livest	51%	37.1	37.2	0.1	0%	5	5%	-4	15%
	Crop	30%	0.4	0.4	0.0	0%	33	4%	-37	5%
	Carbon	60%	70.1	70.7	0.6	1%	638	3%	-417	2%
	Bio	31%	0.092	0.089	0.0	-3%	1	28%	-20	13%
Sub-Saharan Africa	Pop	94%	34.9	44.5	9.5	27%	173	21%	-3	4%
	Livest	71%	10.0	11.1	1.1	11%	20	16%	-1	4%
	Crop	82%	0.1	0.2	0.0	18%	354	39%	-31	4%
	Carbon	42%	144.0	142.6	-1.5	-1%	2,570	11%	-5,092	28%
	Bio	1%	0.121	0.119	0.0	-1%	0	9%	-25	17%

Table S6 – Supporting data for Figure 5 of the manuscript. Numbers on the share of croplands used for exports are calculated using detailed country data from the Supplementary Appendix in Kastner et al. (2014) which contains land embedded in crop trade flows. As data for 2009 is the most recent available, we use 2009 data instead of 2010. Entries are ordered according to table S3. Positive (negative) numbers for the year 2000 and 2009 indicate that a country is a net land exporter (importer), with the net export share of land on total cropland represented by the respective entries. Population density growth is computed from GPW data (Center for International Earth Science Information Network - CIESIN - Columbia University and Centro Internacional de Agricultura Tropical - CIAT, 2005). The land use footprint is based on data from Weinzettel et al. (2013). South-Eastern Asia and Eastern Asia a further supplemented with disaggregated country level data on Indonesia, China, and Japan.

Region	**Share of croplands used for exports (net)**	**Share of croplands used for exports (net)**	**Population density growth**	**land use footprint**
	2000	2009	in %	(global hectares per capita)
Latin and Central America	14	38	14	1.7
Eastern Europe & Central Asia	2	18	-4	1.4
Oceania	68	71	12	3.4
South-Eastern Asia	4	4	14	0.8
Indonesia	5	16	12	0.8
Sub-Saharan Africa	4	3	27	1.2
Southern Asia	0	-3	18	0.5
North America	34	31	9	3.6
Eastern Asia	-21	-32	7	0.9
China	-6	-19	7	0.8
Japan	-554	-486	1	2.0
Europe	-40	-50	0	2.7
North Africa and Western Asia	-37	-54	20	1.1

Table S7 – Overview over references from Table 2 of the manuscript. The list is non exhaustive and only lists the references from Table 2 of the manuscript. Additional references can be found in the Supplementary Information Text, which provides a more detailed overview over the different world regions.

World region	Key references from table 2
Multiple regions	Kastner, T., Rivas, M. J. I., Koch, W. & Nonhebel, S. Global changes in diets and the consequences for land requirements for food. Proc. Natl. Acad. Sci. 109, 6868–6872 (2012). Chaudhary, A. & Kastner, T. Land use biodiversity impacts embodied in international food trade. Glob. Environ. Change 38, 195–204 (2016). West, P. C. et al. Leverage points for improving global food security and the environment. Science 345, 325–328 (2014). Weinzettel, J., Hertwich, E. G., Peters, G. P., Steen-Olsen, K. & Galli, A. Affluence drives the global displacement of land use. Glob. Environ. Change 23, 433–438 (2013). Bren d'Amour, C., Reitsma, F., Baiocchi, G., Barthel, S., Güneralp, B., Erb, K.-H., Haberl, H., Creutzig, F., Seto, K.C., 2017. Future urban land expansion and implications for global croplands. Proc. Natl. Acad. Sci. 114, 8939–8944.
Europe w/o Eastern Europe	van Vliet, J., de Groot, H., Rietveld, P. & Verburg, P. H. Manifestations and underlying drivers of agricultural land use change in Europe. *Landsc. Urban Plan.* **133,** 24–36 (2015). Kuemmerle, T. *et al.* Hotspots of Land Use Change in Europe. *Environ. Res. Lett.* **11,** (2016). Galli, A. et al. Mediterranean countries' food consumption and sourcing patterns: An Ecological Footprint viewpoint. Sci. Total Environ. 578, 383–391 (2017).
Eastern Europe and Central Asia	Kuemmerle, T. *et al.* Hotspots of Land Use Change in Europe. *Environ. Res. Lett.* **11,** (2016). Alcantara et al. Mapping the extent of abandoned farmland in Central and Eastern Europe using MODIS time series satellite data. *Environ. Res. Lett.* **8,** (2013). Pan, Y. *et al.* A Large and Persistent Carbon Sink in the World's Forests. *Science* **333,** 988–993 (2011). Schierhorn, F. *et al.* Post-Soviet cropland abandonment and carbon sequestration in European Russia, Ukraine, and Belarus. *Glob. Biogeochem. Cycles* **27,** 1175–1185 (2013). Liang, S. *et al.* Global Drivers of Russian Timber Harvest. *J. Ind. Ecol.* **20,** 515–525 (2016). Zhu, Z. *et al.* Greening of the Earth and its drivers. *Nat. Clim. Change* **6,** 791–795 (2016).
Southern Asia	Reddy, C. S. *et al.* Quantification and monitoring of deforestation in India over eight decades (1930–2013). *Biodivers. Conserv.* **25,** 93–116 (2015). Nagendra, H., Sudhira, H. S., Katti, M. & Schewenius, M. in *Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities* (eds. Elmqvist, T. et al.) 65–74 (Springer Netherlands, 2013).
South-East Asia	Hosonuma, N. *et al.* An assessment of deforestation and forest degradation drivers in developing countries. *Environ. Res. Lett.* **7,** 044009 (2012). Wilcove, D. S., Giam, X., Edwards, D. P., Fisher, B. & Koh, L. P. Navjot's nightmare revisited: logging, agriculture, and biodiversity in Southeast Asia. *Trends Ecol. Evol.* **28,** 531–540 (2013).

	Stibig, H.-J., Achard, F., Carboni, S., Raši, R. & Miettinen, J. Change in tropical forest cover of Southeast Asia from 1990 to 2010. *Biogeosciences* **11,** 247–258 (2014). Davis, K. F., Yu, K., Rulli, M. C., Pichdara, L. & D'Odorico, P. Accelerated deforestation driven by large-scale land acquisitions in Cambodia. *Nat. Geosci.* **8,** 772–775 (2015). Huijnen, V. *et al.* Fire carbon emissions over maritime southeast Asia in 2015 largest since 1997. *Sci. Rep.* **6,** 26886 (2016). Schneider, A. *et al.* A new urban landscape in East–Southeast Asia, 2000–2010. *Environ. Res. Lett.* **10,** 034002 (2015). Thornton, P. K. Livestock production: recent trends, future prospects. *Philos. Trans. R. Soc. B Biol. Sci.* **365,** 2853–2867 (2010).
East Asia	Chen, J. Rapid urbanization in China: A real challenge to soil protection and food security. *CATENA* **69,** 1–15 (2007). He, C., Liu, Z., Tian, J. & Ma, Q. Urban expansion dynamics and natural habitat loss in China: a multiscale landscape perspective. *Glob. Change Biol.* **20,** 2886–2902 (2014). Liu, X. *et al.* Rubber plantation and its relationship with topographical factors in the border region of China, Laos and Myanmar. *J. Geogr. Sci.* **23,** 1019–1040 (2013). Calle, L. *et al.* Regional carbon fluxes from land use and land cover change in Asia, 1980–2009. *Environ. Res. Lett.* **11,** 074011 (2016). Deng, L., Liu, G. & Shangguan, Z. Land-use conversion and changing soil carbon stocks in China's 'Grain-for-Green' Program: a synthesis. *Glob. Change Biol.* **20,** 3544–3556 (2014). Zhang, M. *et al.* Impact of land use type conversion on carbon storage in terrestrial ecosystems of China: A spatial-temporal perspective. *Sci. Rep.* **5,** 10233 (2015). Bai, Z. H. *et al.* Changes in Pig Production in China and Their Effects on Nitrogen and Phosphorus Use and Losses. *Environ. Sci. Technol.* **48,** 12742–12749 (2014).
North Africa and Western Asia	Bren d'Amour, C., Wenz, L., Kalkuhl, M., Steckel, J. C. & Creutzig, F. Teleconnected food supply shocks. *Environ. Res. Lett.* **11,** 035007 (2016). Şekercioğlu, Ç. H. *et al.* Turkey's globally important biodiversity in crisis. *Biol. Conserv.* **144,** 2752–2769 (2011). Odhiambo, G. O. Water scarcity in the Arabian Peninsula and socio-economic implications. *Appl. Water Sci.* 1–14 (2016). doi:10.1007/s13201-016-0440-1. Galli, A. et al. Mediterranean countries' food consumption and sourcing patterns: An Ecological Footprint viewpoint. Sci. Total Environ. 578, 383–391 (2017). Galli, A., Halle, M. & Grunewald, N. Physical limits to resource access and utilisation and their economic implications in Mediterranean economies. Environ. Sci. Policy 51, 125–136 (2015). Galli, A. On the rationale and policy usefulness of Ecological Footprint Accounting: The case of Morocco. Environ. Sci. Policy 48, 210–224 (2015).
Sub-Saharan Africa	Buhaug, H. & Urdal, H. An urbanization bomb? Population growth and social disorder in cities. *Glob. Environ. Change* **23,** 1–10 (2013).

	Holden, S. T. & Otsuka, K. The roles of land tenure reforms and land markets in the context of population growth and land use intensification in Africa. *Food Policy* **48,** 88–97 (2014). Liebenberg, F. & Pardey, P. G. in *The Shifting Patterns of Agricultural Production and Productivity Worldwide.* (The Midwest Agribusiness Trade Research and Information Center, Iowa State University, 2010). Jayne, T., Chamberlin, J. & Headey, D. D. Land pressures, the evolution of farming systems, and development strategies in Africa: A synthesis. *Food Policy* **48,** 1–17 (2014). Searchinger, T. D. *et al.* High carbon and biodiversity costs from converting Africa/'s wet savannahs to cropland. *Nat. Clim. Change* **5,** 481–486 (2015). Ciais, P. *et al.* The carbon balance of Africa: synthesis of recent research studies. *Philos. Trans. R. Soc. Lond. Math. Phys. Eng. Sci.* **369,** 2038–2057 (2011). Barrett, C. B. Smallholder market participation: Concepts and evidence from eastern and southern Africa. *Food Policy* **33,** 299–317 (2008). Kalkuhl, M. in *Food Price Volatility and Its Implications for Food Security and Policy* 269–301 (Springer, 2016).
Oceania	Gallant, A., Kiem, A., Verdon-Kidd, D., Stone, R. & Karoly, D. Understanding hydroclimate processes in the Murray-Darling Basin for natural resources management. *Hydrol. Earth Syst. Sci.* **16,** 2049–2068 (2012). MSEIC. *Australia and Food Security in a Changing World*. (The Prime Minister's Science, Engineering and Innovation Council, 2010). Steffen, W. *et al.* Australia's biodiversity and climate change: a strategic assessment of the vulnerability of Australia's biodiversity to climate change. (2009).
South and Central America	Lapola, D. M. *et al.* Pervasive transition of the Brazilian land-use system. *Nat. Clim. Change* **4,** 27–35 (2014). Grau, H. R. & Aide, M. Globalization and land-use transitions in Latin America. *Ecol. Soc.* **13,** 16 (2008). Nepstad, D. *et al.* Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. *Science* **344,** 1118–1123 (2014). Kastner, T., Erb, K.-H. & Haberl, H. Rapid growth in agricultural trade: effects on global area efficiency and the role of management. *Environ. Res. Lett.* **9,** 034015 (2014). Gasparri, N. I. & Grau, H. R. Deforestation and fragmentation of Chaco dry forest in NW Argentina (1972–2007). *For. Ecol. Manag.* **258,** 913–921 (2009).
North America	Sleeter, B. M. *et al.* Land-cover change in the conterminous United States from 1973 to 2000. *Glob. Environ. Change* **23,** 733–748 (2013). Wright, C. K. & Wimberly, M. C. Recent land use change in the Western Corn Belt threatens grasslands and wetlands. *Proc. Natl. Acad. Sci.* **110,** 4134–4139 (2013). Lark, T. J., Salmon, J. M. & Gibbs, H. K. Cropland expansion outpaces agricultural and biofuel policies in the United States. *Environ. Res. Lett.* **10,** 044003 (2015). Mladenoff, D. J., Sahajpal, R., Johnson, C. P. & Rothstein, D. E. Recent Land Use Change to Agriculture in the U.S. Lake States: Impacts on Cellulosic Biomass Potential and Natural Lands. *PLOS ONE* **11,** e0148566 (2016).

	Wallander, S., Claassen, R. & Nickerson, C. *The ethanol decade: an expansion of US corn production, 2000-09*. (2011). Faber, S., Rundquist, S. & Male, T. Plowed under: how crop subsidies contribute to massive habitat loss. (Environmental Working Group, 2012).

2.5.3. Supplementary Information text

Here we provide an in-depth overview over region-specific land-use dynamics as summarized in Table 2 of the manuscript. This information can also be found on the website.

Region-specific analysis

The following includes a description of observed land-use dynamics in the 10 world regions analysed. If not indicated otherwise, data reported refer to Table S5.

Sub-Saharan Africa

Description of key dynamics

Sub-Saharan Africa experiences large changes over all land-use dimensions and could therefore be considered as a major hotspot region. Generally, **population** density shows increasing trends, in particular in coastal areas in West Africa as well as large parts of Nigeria, Ghana and Burkina Faso and East-African countries like Ethiopia, Uganda and Rwanda. **Livestock** density increased particularly in East Africa (Ethiopia, Uganda, Kenya and Rwanda) as well as Burkina Faso in West Africa. **Cropland** grew strongly in the Guinean Savannah regions of West Africa, East Africa as well as Southeast Africa and decreased particularly in South Africa. 38% of the world's cropland extensification happened in Sub-Saharan Africa. **Carbon** density shows mixed and dispersed dynamics with mostly decreases in the Guinean Savannah and increases in tropical forest areas. 28% of the global net reduction in terrestrial carbon happened in Sub-Saharan Africa. **Biodiversity** decreases in most areas except some coastal areas in Nigeria as well as parts of Togo, Uganda, Rwanda and Burundi, which experienced major increases.

Main Drivers

Population dynamics are characterized by high fertility rates as well as migration from sparsely populated rural areas to urban areas (Buhaug and Urdal, 2013). Urbanization in SSA is driven by population growth in resource constrained rural areas rather than economic growth in cities that attract labour for higher wages (Holden and Otsuka, 2014).

Land reforms which give private property rights to individuals at the expense of communal land induced a structural change in the **livestock** sector from nomadic pastoralism to more intense agricultural and livestock systems (Andela and van der Werf, 2014). Like other developing countries, Africa also experiences stronger demand increases for meat products than developed countries where demand saturated (Thornton, 2010). Beyond its role for income generation and food production, livestock is considered as asset and insurance in many traditional societies, reflecting also wealth and social status (Thornton, 2010).

Regarding the **agricultural land dynamics** in South Africa, the horticulture sector increased strongly at the expense of conventional staple food production and large commercial farms replaced small-scale and subsistence farming by intensified and farming processes (Liebenberg and Pardey, 2010). These processes may explain the reduction of cropland visible, which corresponds to national statistics on cropland dynamics (FAOSTAT, 2015). Contrary to South Africa, cropland expanded strongly in the Guinean Savannah regions that are considered as potential breadbasket of Africa (Morris et al., 2009). Roughly two thirds of the Savannah region could be used for agriculture while only 10% is currently used for agricultural production (Morris et al., 2009). The increase in cropland expansion in this area therefore mirrors not only the biophysical feasibility but also the economic attractiveness of using the Savanna lands for agricultural production. This attractiveness is, in turn, also influenced by international demand (high crop prices in 2007/08), changing political and institutional environments (e.g. facilitating foreign land investments, (Deininger and Byerlee, 2011; Kuusela and Amacher, 2015)) and improved access and infrastructure to remote areas(Chamberlin et al., 2014). Recent cross-country and household survey evidence suggests that rural population growth is also a driver of higher cropping intensities (so-called 'Boserupian intensification, see Jayne et al., 2014).

Above-ground **carbon** changes are very heterogeneous. Large carbon releases occur in the Savannah regions which simultaneously experience cropland expansion. Simulated conversion from Savannah wet lands to maize or soybean crop land indicate major carbon releases (Searchinger et al., 2015). Fires have been a common tool to convert bushland into cropland as well as grazing land practiced by small-holder farmers (Andela and van der Werf, 2014). Changes in fire incidence are, however, also associated to precipitation dynamics, in particular the ENSO phenomenon (Andela and van der Werf, 2014). Globally, 40% of fire-related CO_2 emissions are linked to Savannah burning and land-use emissions are in SSA higher than emissions from burning fossil fuels (Ciais et al., 2011). Contrary to Savannah regions, tropical forest areas show increases in carbon stocks (despite large heterogeneity). The main factors for increased carbon in SSA forest areas are carbon fertilization and increased precipitation trends (Ciais et al., 2011).

Drivers of **biodiversity** changes are difficult to assess. Reductions in intactness are correlated to increases in cropland. As the Savannah regions are rich in species, cropland expansion may reduce biodiversity substantially (Searchinger et al., 2015). The few and very small hotspots of increasing biodiversity are difficult to explain and we could not find studies providing explanations for these dynamics. One possible reason for increased biodiversity is the establishment and improved enforcement of protected areas and national parks in East African countries that may attract further wildlife as a 'save haven'.

South-East Asia

Description of key dynamics

South-East Asia has experienced major changes in all land-use dimensions and can generally be described as a hotspot region in terms of land-use change and competition. Severe losses in **biodiversity** occurred in Sumatra, the Malaysian peninsula, parts of Borneo, North Western Thailand, Cambodia and Vietnam (98% of all land with notable biodiversity changes displays loss). At the same time, those regions (with the exception of the Malaysian Peninsula) have also experienced a large extension of **croplands** (altogether in 93% of all areas with notable changes). In population centres, particular Java and the Mekong Delta region, **livestock density** has increased, while it has remained relatively constant in the rest of the region (altogether 90% of land areas with notable changes). **Population** has increased largely around urban centres, including Kuala Lumpur (Malaysia), the densely populated island of Java (Indonesia), Bangkok (Thailand), Saigon (Vietnam), Phnom Penh (Cambodia) and Manila (The Philippines), and in the Southern and Eastern parts of Sumatra (Indonesia), altogether in 94% of land areas. For **carbon intensity** a rather mixed picture evolves. While it increases in Borneo, Java and Papua New Guinea (both parts), it decreases in Sumatra and the Malaysian Peninsula.

Main drivers

The scientific literature has highlighted the prominent role of deforestation in South East Asia. The most important driver for deforestation in South East Asia is commercial **agriculture** (Hosonuma et al., 2012), particularly driven by increasing production of cash crops (palm-oil), logging and transformation of natural forests to forest plantations (Stibig et al., 2014). The former is satisfying an international market, with >30% of palm oil produced for the world market now stemming from South East Asia , while the latter is also driven by an increasing pulp-and paper industry in the region (Wilcove et al., 2013). Davis et al. (2015 for the case of Cambodia) find that increasing land acquisitions are a major driver of deforestation.

Transformation of primary forest has severe implications for **biodiversity** (Phalan et al., 2013), with different impacts of new plantations on various species. Palm oil plantations are in particular damaging for biodiversity, while logging (in particular selected logging as practiced, inter alia, in Myanmar) has less consequences for most species in the region (Wilcove et al., 2013).

Draining and burning of peatlands has been the largest source of **carbon** in the region, corresponding to nearly twice the carbon that has been released by forest conversion to shifting cultivation and cropland, respectively (Houghton, 2012). Carbon-intensive peat swamps in particular have experienced a higher rate of deforestation than lowland or forests or montane forests. Highest rates (-5.2% yr^{-1}) are reported in Sumatra, followed by Borneo (Wilcove et al., 2013). Deforestation of peatland forest is found to increase the likelihood of forest fires, again holding implications for human health (Turetsky et al., 2014).

Between 2000 and 2010 **population growth** in South East Asia has been mainly driven by growth of urban agglomerations. While the urban population climbed by > 31%, urban land area increased by 22% in the East-South-East-Asian region. Population growth has been in particular strong (with cities growing at an average rate between 3 and 7.8%) in Malaysia, Vietnam, Cambodia and Laos, while urban land has grown particular strong (higher than 2% per year) in the Philippines, Cambodia and Laos(Schneider et al., 2015).

Increasing urbanization and income is generally related to **dietary shifts** towards more demand for meat, a pattern that can also be observed in South East Asia (Thornton, 2010). Lipoeto et al. (2013) find that traditional food still plays a major role within the region, with a rapid transition towards Western-style food predominantly in urban areas.

Eastern Europe and Central Asia (Russia)

Description of key dynamics

Moving from 2000 to 2010, the Russian Federation has been characterized by a stagnating – if not declining - **population** with increases only in the major cities (83% of land has reduction in population density). This is also the general trend observed for **livestock density** (73% of land area has reduced livestock density). There is also a significant decline in **cropland** (80% of all land area has less cropland), specifically in the Central, Volga and South Federal Districts (between the Black and Caspian Sea) and in Southern Siberia and Southern Ural (bordering Kazakhstan and part of Mongolia).

However, this decline has not translated into a recovery of nature in Southern Siberia and Southern Ural, as both **carbon stocks** and species intactness have been developing negatively in these regions. On the other hand, large parts of Northern and Central Russia have experienced improvements in carbon density during the observation period. Altogether 69% of land displays an increase in terrestrial carbon. **Biodiversity** has seen a decline in the Far-Eastern Russia (around the Yakutsk region).

Main drivers

The lack of **population** growth and slow urbanization during the observation period can be attributed to, inter alia, low fertility in urban areas (about 1 compared to 1.55 in rural areas in 2000) and the fact that by 2009 life expectancy at birth for males was still more than a decade less than in Europe, the US, Japan or Korea. In addition, urbanization rates were already above 70% in 2000 (Becker et al., 2012). Russia often serves as the prime example of a region where birth rates have fallen behind death rates (Bongaarts, 2009).

The large overall increase in **carbon density** between 2000 and 2010 is consistent with the findings by Pan et al. (2011a) for forest carbon in European Russia, which the authors attribute to several factors: increased areas of forests after agricultural abandonment (31.3 million ha), reduced harvesting, and changes of forest age structure to more productive stages, particularly for deciduous forest. In European Russia the carbon gain amounts to more than 44 tons of CO_2 per hectare during our observation period, which makes it outstanding as a sink in the boreal region and comparable to sinks in the temperate biome. However, Pan et al. (2011a) find a stable sink over the same time period for Asian Russia, which is not matched by our data, which show an increase. This could be due to the increased carbon stock in dead wood and on-ground litter (Dolman et al., 2012) that could have at least balanced reductions in carbon stocks from disturbances that can be connected to climate change, e.g. large wildfires in Siberia and Far-Eastern Russia (Kukavskaya et al., 2012; Shvidenko et al., 2011; van der Werf et al., 2010), which are not captured in the model providing our carbon data. The damage from these disturbances could, however be limited, by an improvement in institutions and policies, not only for prevention and increased response times, but also for better management on the hitherto unused increment (Petrov and Lobovikov, 2012). What the model does capture, however, is the beneficial increase of CO_2 fertilization on biomass in the region, not included in other publications that report NPP (Dolman et al., 2012).

Finally, carbon density losses in the South East bordering China are also increasingly driven by consumption of wood products abroad (see e.g. Liang et al., 2016, on timber demand) and might, to a large extent, be associated with illegal deforestation for timber exports to China, for which there is anecdotal evidence. Our observation period is characterized by the large Russian roundwood footprints of China, the United States, Japan, Finland, and Germany, where China is not only the most important Russian timber importer, but also the largest foreign final consumer driving Russian timber harvest (Liang et al., 2016). This indicates the strong role that institutions and policies can play in this context. Consumption-side measures in importing countries could lead to substantial improvements, e.g. by “taking shared responsibility and improving the production efficiency of key sectors in consuming nations” (Liang et al., 2016).

The apparent contradiction between the cropland abandonment in Southern Siberia and Southern Ural and decrease in carbon density might be explained by the lag in the sequestration response (Schierhorn et al., 2013). A similarly slow recovery might be the case for **biodiversity**. Again, one has to keep in mind that the map shows an absolute change from 2000 to 2010 and that those areas showing a negative change actually do not imply that intactness has crossed a critical level (e.g. the extinction of a species). In fact, the boreal area and tundra have been least affected by land use pressures in 2005 and are still within planetary boundaries, whereas many tropical, subtropical and temperate biomes have already declined beyond planetary boundary limits (Newbold et al., 2016).

Oceania

Description of key dynamics

Oceania experiences little (population, biodiversity, livestock) to moderate (cropland, carbon) changes. Generally, **population** hotspots are located where major cities are and indicate continued urbanization rates. **Livestock** density is reduced in 72% of all areas. **Cropland** reduces in the South West and South East of Australia as well as in New Zealand. Altogether 84% of all areas experience cropland loss, with overall 11% less cropland. **Carbon** density shows mixed and dispersed dynamics with increases in the North West of Australia and reductions in the costal South East Australia. In comparison to other world regions, **biodiversity** is less affected with only 54% of all areas with notable changes displaying biodiversity loss, which remains also relatively small.

Main Drivers

Cropland in Australia is subject to strong salinization which affects roughly 50% of the farmland in Western Australia and even 85% of the farmland related to grain production (ABS [Australian Bureau of Statistics], 2003). Hence, productive land shows diminishing trends due to continuing land degradation which is partly irreversible (MSEIC, 2010). Additionally, changed precipitation patterns and continued drought conditions between 1995 and 2007 had strong impacts on crop production in the entire Oceania region (Gallant et al., 2012; MSEIC, 2010). Hence, local environmental changes can be considered as main driver for cropland reduction, which may be partly also related to anthropogenic climate change (Gallant et al., 2012).

Population hotspots are clearly located where major cities are and indicate continued urbanization rates.

Livestock density shows no major changes.

Carbon: mixed dynamics. Changes in biomass (and thus, carbon) are highly driven by heterogeneous rainfall trends with northern Australia getting wetter and southeast Australia dryer (Liu et al., 2015). Apart from the impact on natural vegetation, growth of forest plantations may also contribute to changes in carbon stocks. Carbon sequestration in forest plantations responds to rainfall variability (Paul et al., 2008). Forest plantations almost doubled in Australia (1.54% of total forest area in 2010) while total forest area declined by 4.4% and total carbon in forests above ground remained constant. In New Zealand, forest area remained constant but carbon above ground increased by 4% (FAO, 2015). Forest plantations in Australia are located in coastal areas in Southwest and Southeast and correspond partly to increases in carbon in our hot spot map (ASFB, 2013). The inclusion of forestry into carbon markets led to additional increases in forest plantations (‘carbon forestry’) of about 65,000 ha in Australia (equal to 3.4% of the area of total forest plantations, see Mitchell et al., 2012). New Zealand introduced an emissions trading scheme in 2009 and included the forestry sector, leading to a doubling in forest plantations in 2011 compared to the previous year (Rhodes and Stephens, 2014).

Biodiversity: Major reasons for decrease in biodiversity related to agricultural issues: Land clearing for agriculture, changes in water availability due to agricultural land uses; application of fertilizers; introduction of new species (mammals but also weeds) to the sensitive ecosystem that evolved largely isolated from other continental systems (Steffen et al., 2009).

North America

Description of key dynamics

The **population** of the United States grew from 283 Million to 310 Million between 2000 and 2010 (FAO, 2016). Urbanization trends continued as reflected by rising population densities in urban areas along the coasts and some interior metropolitan areas. Spatial patterns of urbanization are also the main driver of **biodiversity** loss in the United States during our study period. **Livestock densities** remained constant during this period while total **cropland** area declined especially in the northeast and increased in the southeast – overall cropland was lost in 83% of areas. Persistent carbon sinks in the World's forests (Pan et al., 2011b) explain the spatial pattern of growing in **carbon stocks** concentrated in the large forest areas of the eastern United States (72% of all areas gain terrestrial carbon in North America).

Main Drivers

The United States went through three distinct phases of land use change. Large-scale deforestation for agricultural lands and cultivation of prairie soils accompanied the expansion of European settlements across the continent with a peak in total cropland area around 1940 (Houghton et al., 1999; Waisanen and Bliss, 2002). Farm abandonment in the second half of the 20th century resulted in several decades of cropland area decline, reforestation, and the rapid expansion of developed lands (Lark et al., 2015; Sleeter et al., 2013). Increasing forest area and recovering forests contribute to the widespread increase in carbon density that was also driven by enhanced plant growth due to CO_2 fertilization and nitrogen deposition. Average carbon gains in forests of the United States amount to 38 tons of CO_2 per hectare in recent years (Pan et al., 2011b). At the same time, drought stress, pest infestations and fire events affected forests in the western United States over the past few decades and reduced their capacity to sequester carbon or even resulted in carbon losses from vegetation and soils.

High commodity prices driven by the rising demand for biofuel feedstocks since the late 2000s provided new incentives to expand crop production (Lark et al., 2015; Wright and Wimberly, 2013). Consequently, wide-spread conversion of grasslands, shrublands, and wetlands to agricultural uses reappeared across the United States with hot-spots of change located in the Corn Belt and the Lake States. In addition, federally subsidized crop insurance mitigated the risk of farming even in less productive areas characterized by high erosion risk, shallow soils, and drought vulnerability (Feng et al., 2013).

Corn was the most common crop cultivated on new agricultural land followed by soy and wheat. Corn was also responsible for the majority of recent land use change through its displacement of other crops (Lark et al., 2015; Mladenoff et al., 2016). Between 2006 and 2008 the area harvested for corn and soybean in the United States increased by 3.2 Mha (Wallander et al., 2011) and another 5 Mha between 2008 and 2012 mostly at the expense of grasslands (Faber et al., 2012; Lark et al., 2015). This new wave of expanding corn and soy production occurred most rapidly on land less suitable for agriculture characterized by high erosion risk, shallow soils, and drought vulnerability (Lark et al., 2015). The concentration of grassland conversion in the Corn Belt around wetlands threatens wildlife habitats and may also increase flood risk (Wright and Wimberly, 2013). In some regions of the Western Corn Belt rates of grassland conversion were comparable to deforestation rates in Brazil, Malaysia, and Indonesia (Wright and Wimberly, 2013) and the ongoing loss of grassland is expected to create adverse effects on native biodiversity (Meehan et al., 2010).

Increased market demand for biofuels feedstocks also triggered crop switching, especially from wheat to corn and soybean, which forces wheat production to expand onto other land. Cascading land replacements occurred in some areas where land cover change from agricultural land to developed land was offset by a conversion of open lands to agricultural lands. In other areas open lands were converted to developed lands to offset the conversion of developed lands to agricultural lands (Mladenoff et al., 2016).

Overall, recent patterns of land use change lead to further simplification and homogenization of mixed-use landscapes to large-scale cultivation of annual crops displaces the former crop to other locations (Meehan and Gratton, 2015; Wright, 2015).

These most recent land use dynamics are not visible in our analysis due to two factors. First, switching from one crop to another does not change cropland area. Second, total cropland continued to decrease in the United States in recent years (USDA, 2016) and this trend may outweigh and hence hide grassland expansion under the coarse resolution of the land use data we analysed here.

North Africa and Western Asia

Description of key dynamics

Population density growth has been concentrated along the coastlines of the Mediterranean, and the river valleys and deltas. The **livestock** density remained more or less stable in most of the region but increased along the Nile River, in Syria and to some extent in North-Western Iran as well as in Yemen. Slight increases were observed in Turkey. Overall livestock density increased by 7%. Along the Mediterranean coastline, the **cropland** area fraction has largely increased. Morocco's cropland area fraction has decreased. The biggest changes, however, took place in Iraq and Iran. The cropland area fraction decrease substantially in Iraq's east, in the fertile region along the Euphrates and Tigris valleys, while it increased in Iran's west and north. Croplands decreased in the semiarid mountainous regions of Turkey and its Mediterranean coastline. The region's **carbon** intensity has been largely constant with the exception of Turkey, Algeria, Morocco and Tunisia, with different, heterogeneous dynamics displayed. Despite considerable human activity in the MENA region, **biodiversity** was not impacted significantly, the only exception being the stretch of land in Algeria's Northern Sahara as well as Turkeys coastlines with the Black Sea and the Mediterranean.

Main drivers

The MENA region is characterized by arid to semi-arid climate and is one of the world's most water-scarce regions. Human and economic activities are concentrated around the few water sources, mostly rivers, deltas, oases, but also coastal zones, and the competition between land uses is particularly fierce. Wherever there is access to fresh water, there is a high competition due to the accumulation of anthropogenic activities, best exemplified by the river Nile and the Nile delta in Egypt, where urban area expansion is forecast to convert valuable croplands (Bren d'Amour et al., 2017). The MENA region is also expected to be among the most adversely affected by Climate Change: heat extremes are likely to increase across the entire region (Lelieveld et al., 2016), while precipitation is forecast to decrease in the Western Asian part (Evans, 2009), potentially leading to increasing levels of desertification. Sea-level rise and the sinking of deltas will further increase the risk for the flood-prone urban coastal zones (Bohannon, 2010). Attempts to resettle are underway, but have yet to prove to be efficient (Bohannon, 2010). Biodiversity remains largely unchanged with the exception of Turkey, where important wetlands, grasslands, even rivers are disappearing due to human activities (Şekercioğlu et al., 2011).

Regardless of any biophysical constraints, the **population** grew by 19% to a total of more than 200 million in Northern Africa compared to 2000 levels, and by 25% in Western Asia, totalling 230 million in 2010 ("World Population Prospects - Population Division - United Nations," n.d.). The population has quadrupled in the second half of the last century. Fertility rates have slowed but the population is still expected to reach almost 700 million by 2050 (Roudi-Fahimi and Kent, 2007). More than 50% of the population lived in urban areas in Northern Africa in 2010, and more than 68% in Western Asia. Both urbanization rates are expected to increase further. Population increases mostly take place in and around major cities as well as larger villages in the more rural areas. The MENA region still contains a significant number of pastoralists and the pastoral farming system can be found across almost a quarter of the land area (Dixon et al., 2001). Seasonal migration, also across borders, plays an important role for the often small herds of goats and sheep, depending on the availability of grass and water.

We observe co-occurrences of significant population and **livestock** increases across the region, and of population and **croplands** in Northern Africa. In Western Asia, population growth mostly takes place at the expense of croplands, and we can expect similar dynamics for Northern Africa, as urban areas continue to increase (Bren d'Amour et al., 2017). In the second half of the century, Climate Change impacts are likely to have reduced the little lands viable for rain-fed agriculture by over 170.000 km^2 across the region (Evans, 2009). Croplands can be very productive, especially in Northern Africa, but rely largely on complex irrigation systems (Fetzel et al., 2016). While the magnitude of the competition in areas with competing land uses in the MENA region can be very strong, it is also contained to a relatively small fraction of the total area. Large expanses are still not impacted by human activity, mostly because they are uninhabitable.

The above-ground **carbon** stored in the MENA region will decrease, albeit for different reasons. In Northern Africa, this dynamic is driven by population growth whereas in Western Asia, it is driven by cropland expansion. **Biodiversity** will also be affected by the increase in anthropogenic land uses, mostly by population and livestock intensification (in Western Asia). For Northern Africa, we see an increase in biodiversity which is mostly driven by Egypt which showed an almost country wide transition from plantation to secondary vegetation. This development would substantially affect the intactness factor but might be an artefact.

Latin America and the Caribbean

Description of key dynamics

Population growth in Latin America and the Caribbean between 2000 and 2010 has been less pronounced than in Sub-Saharan Africa and large parts of Asia (population growth in 85% of all areas). It has been mostly concentrated in Central (Guatemala, Honduras, El Salvador, Nicaragua and parts of Costa Rica and

Panama) and Southern America (mainly the coastal areas in the North West Venezuela, Colombia, Ecuador, Peru and large parts of Eastern Brazil), and some hotspots where urban areas had already expanded before (e.g. Buenos Aires in Argentina or São Paulo in Brazil, which is also apparent in the dynamic described in the main text, cf. Fig. 1A).

Areas dedicated to growing **crops** have increased in Brazil, parts of Chile, Uruguay, Honduras, El Salvador, Nicaragua, Northern Colombia and Venezuela. Interestingly, much of Central America, Northern Colombia, Ecuador and central Chile feature the opposite picture, i.e., a decrease in cropland intensity. **Livestock** intensity generally increased in the same period (80% of all area). We also observe an expansion of livestock density for Brazil, Uruguay, Argentina, Paraguay, Bolivia and Peru. Even though the Caribbean islands are less prominent in terms of absolute numbers, there seems to be a shift from cropland to larger areas dedicated to livestock on some islands.

This pressure from human demands (shelter/infrastructure, livestock, cropland) has come at the cost of **biodiversity** losses across the whole of Latin America and the Caribbean, as is apparent from the Latin American panel in Fig. 4 (indicating a co-occurrence of increases in the three human demands with decreases in biodiversity). In 96% of all areas biodiversity is lost, representing 28% of the global biodiversity loss. The density of **carbon**, on the other hand, has been evolving in a much more dispersed way, with gains in Mexico, Panama, Costa Rica, but also Colombia, Peru, Guyana, Suriname, French Guiana and Brazil. Much of the carbon increases in Brazil coincide with the Amazon Basin, where we also partially observe lower than expected biodiversity losses compared to other parts. This is also reflected in the more mixed pattern for carbon in Fig. 4. Nonetheless 29% of the global net loss in terrestrial carbon is attributed to Latin America.

The latter regions (Mexico and El Salvador, parts of Costa Rica and Panama, parts of the Amazon Basin, Ecuador and Colombia, Northern Guyana, Suriname and French Guiana, small parts of Peru, Bolivia and Argentina and large parts of Chile) are characterized by an improvement in nature (cf. Principal Component Analysis in main text), while most of middle and Southern Brazil, Uruguay, coastal Peru, Venezuela, mid-Central America and Caribbean are dominated by the influence of human pressures.

Main Drivers

The observed **population dynamics** can mainly be explained by reference to three drivers: Latin America has – in contrast to Sub-Saharan Africa – seen a decline in fertility rates (Cohen, 2006). Partially counteracting this trend is the fact that Latin America has been a front-runner in catching up with Northern mortality rates. Indeed, the projections for our period of investigation (made in 1990) indicated that in 2015, Latin America would have a rate of around 29 deaths of children under 1 for every 1,000 born alive, whereas new estimates show that this rate has dropped to 19 deaths on a regional average in 2015 (Observatorio Demográfico de América Latina y el Caribe, 2014). Regional variations are large and range from 5.4 in Cuba to 41.3 in Haiti. With a high level of **urbanization** in Southern America, which has matched Northern levels already at the beginning of our observation period, it is no surprise that the rate of (further) urbanization is relatively low compared to other regions (Cohen, 2006) and growth is no longer predominantly driven by rural-urban migration for economic motives, but also by natural population growth in the cities and migration between cities (Cerrutti and Bertoncello, 2003). These larger urban populations in turn can be associated with increased demand for food and especially meat (Thornton, 2010) and more inefficient agricultural practices (Grau and Aide, 2008), explaining parts of the observed increases in **cropland and livestock density**. In Central America, rural-urban migration still plays a bigger role in urbanization, but the effects are more heterogeneous here. For example, Mexico and El Salvador see lower **losses of biodiversity** and partially gains in **carbon density**, which some authors have explained by the positive correlation between remittances and forest recovery (e.g. Hecht and Saatchi 2008). In Southern America, the roots of deforestation are no longer only associated with the traditional development pattern shifting agriculture and cattle ranching. Instead, the combination of the availability of fertile land and low production costs has led to deforestation through **export-oriented industrial agriculture** (Grau and Aide, 2008). Both in terms of species intactness and carbon density, the hotspots of the past can still be singled out for the period 2000-2010 (the Amazon Basin in Ecuador, Columbia and Venezuela, Southern Guyana/Rio Negro, Acre, the Peruvian Amazon and Mato Grosso, cf. Grau and Aide, 2008). Still, the change from 2000 to 2010 appears to be less pronounced in parts of Brazil, which can be attributed to a substantial decrease in deforestation rates during the time (Gibbs et al., 2015; Nepstad et al., 2014).

In addition, it has been observed that the combination of agricultural modernization and rural-urban migration has led to abandonment of marginal cropland and pastures, enabling ecosystem recovery (Grau and Aide, 2008). Grau and Aide (2008) provide an overview of the literature on the recovery of degraded forests in Puerto Rico and the Dominican Republic in the Caribbean, in Mexico, El Salvador, Honduras, Costa Rica and Panama in Central America and in parts of South America.

This points to an important role for institutions and policy, where the Latin American experience has been two-sided: on the one hand, our observation period has seen a decrease in deforestation rates due to enhanced monitoring and enforcement in Brazil (Nepstad et al., 2009). On the other hand, most of the current deforestation in Latin America is related to meat production, either by planting pastures for livestock or by planting soybean to supply feed for animals (Aide et al., 2013), which confronts decision-makers with new institutional challenges and points towards the need for transboundary governance concepts.

Southern Asia

Description of key dynamics

The world map demonstrates that the world's highest **population growth** takes places in the Indian subcontinent (India, Pakistan, Bangladesh, Nepal), with highest change along the Southern Himalayan range (100% of areas with notable changes display population growth). Suitable **cropland** is slightly decreasing across South Asia (at 70% of area), and it the most frequent co-occurrence is with increase in population. However, at hotspots (i.e. where absolute cropland intensity changes belong to the highest 10% globally), there is strong co-occurrence of cropland increase and population growth.

Livestock increases together with population, but also is reduced with population increase in other places. Livestock has a mostly balanced interaction with other land-uses, co-occurring both with positive and negative changes, and approximately increasing in as many areas as it is decreasing. Hotspots of livestock increase co-occur with population. The land **carbon stock** is both increasing (60% of all area with notable changes) and decreasing (40%), with both dynamics co-occurring with population growth. **Biodiversity** is reduced across the subcontinent (69% of all areas), mostly where there is also relevant population growth but not along the Himalaya ranges.

Main drivers

India's land use challenge is dominated by a rapidly growing **population** and ensuing land use change. Population is expected to grow from 1.3 billion in 2016 to 1.7 billion in 2050; India is expected to overtake China as the world's most populous country in 2022 (US Census Bureau, n.d.). The total urban population is expected to nearly double from 420 million in 2015 to about 814 million in 2050 (United Nations, 2014). This urbanization translates into large urban land expansion, which is mostly driven by population growth, and less by economic growth (Seto et al., 2011). While the total urban land expansion is uncertain, it is estimated that in 2030 more than 100.000 km2 will be urbanized with likelihood higher than 75% (in 2000 30.000 km2 were urbanized, see Seto et al., 2012). There is lower probability of urbanization but for much larger area along the Himalayan range, reflecting the rapid population growth of mostly rural populations. Growing population will increase demand for food; it is expected that likely rice yield increases of about 1%/year would be sufficient to maintain per capita consumption rates (Ray et al., 2013).

FAO data demonstrate the total area harvested for key **crops** like rice and sugarcane decreased by 4.1% and 1.1% respectively. A case study of Delhi highlights that urban and infrastructure land take predominantly correlates with agricultures land loss, and to lesser degree with dense forest loss (Jain et al., 2016). This area loss was compensated by yield increases per ha of 15% for rice, but yields for sugarcane kept constant (FAOSTAT, 2015). Differing land property rights originating from colonial times lead to very different outcomes in agricultural productivity and well-being in the long run (Banerjee and Iyer, 2005). Crucially, the data used in our analysis (cropland suitability) display the reduced area, but not the increasing yields.

Deforestation due to human pressures has been the leading cause for **biodiversity** but deforestation has significantly decelerated due to effective conversation programs (Reddy et al., 2015). In some areas of the Doda region in the Western Himalaya, anthropogenic pressures on forest systems compromise plant biodiversity (Rashid et al., 2013). Urbanization emerges as a key treat to biodiversity; however, the shift from traditional fuels (wood) to modern fuels accompanying urbanization let to reduced pressure on peri-urban forests and mangroves (Nagendra et al., 2013). The transition from subsistence farming to cash-crop systems leads to loss in agro-biodiversity (Pande et al., 2016). However, conservation with a high level of community involvement is proving to be an effective way to conserve forests, especially if motivation for conversation is coupled with social and economic benefits (Allendorf et al., 2013).

Europe

Description of key dynamics

The PCA map shows a clear dominance of the "nature" dimension, albeit with important exceptions such as in Spain, along the Mediterranean and around the Baltic Sea and the Gulf of Bothnia, where "nature" recedes.

Biodiversity decline dominates, most prominently in Spain, Italy and Belarus. Biodiversity has increased in Poland and Germany. Strong declines in **agricultural area** can be observed in Poland, Lithuania, Italy and

Portugal. Decline in cropland tends to coincide with increasing carbon and decreasing population and livestock. Agricultural area increased in Denmark, the Netherlands and Latvia. With regard to **livestock**, a decrease in intensity dominates in Europe, most strongly in the UK, the Netherlands, Belgium and Ukraine, while pockets of substantial intensification exist in Denmark and Poland. Looking at Europe without the Eastern European countries, 76% of the area in which significant changes occur, manifest a decrease in livestock density. 21% of the global livestock decrease occurs in this region (Europe excl. Eastern Europe).

Population trends are mixed with a tendency for decreasing densities in the East and increasing densities towards the West. Overall, increasing densities in major urban agglomerations (Istanbul, London etc.) are visible. **Carbon** increases dominate the region, coinciding with biodiversity loss in Eastern and Southern Europe and biodiversity gains in Northern and Western Europe. 84% of the area in Europe (excl. Eastern Europe) where significant carbon changes occur, show a gain in land carbon stocks (see Region brief Eastern Europe/ Russia for more details concerning that region).

Main drivers

Land-use change in Europe is characterised by increasing specialisation and polarisation. Key trends involve **agricultural intensification** on the most productive lands (e.g. in Denmark) and **farmland abandonment** in marginal, less competitive regions (e.g. in some former Soviet countries). Both developments are driven by the globalization of agricultural markets resulting in increased competition and (agricultural) land use displacement outside Europe (Cosor, 2014; Kuemmerle et al., 2016; van Vliet et al., 2015). Drivers of **farmland abandonment** in particular include societal change in the form of increasing urbanization and demographic change resulting in rural depopulation (Cosor, 2014; van Vliet et al., 2015). Farmland abandonment and a strong decline in capital-intensive farming practices have been particularly significant in the **former socialist countries** where the process of restitution, low competitiveness and rural outmigration were important drivers (Kuemmerle et al., 2016; van Vliet et al., 2015). After the Soviet Union collapsed prices for inputs and outputs were liberalised, former markets disappeared and international competition increased. Moreover, land ownership changed, often leading to tenure insecurity (Baumann et al., 2011). The great heterogeneity in the extent of abandonment within Eastern and Central Europe results from strong differences in agricultural sector reforms ranging from full-scale market liberalisation in Poland and Romania to gradual reforms in Belarus and Ukraine; stark differences in state support; different approaches concerning land reforms (ranging from restitution to continuing state ownership); and EU accession of some countries (Alcantara et al., 2013). On the other hand, in some former socialist countries, e.g. Poland, a lower baseline level of intensification compared to other regions, technological change enabling increasing mechanization and rising labour costs resulted in intensification in the form of increasing livestock densities (Kuemmerle et al., 2016).

In some EU countries such as the Netherlands and Belgium, P and N application standards and manure fees led many holdings to decrease their **livestock concentrations** (European Commission, DG Agriculture, 2004; Kuemmerle et al., 2016). The 2003 reform of the EU's Common Agricultural Policy which decoupled farm subsidies from output contributed to declining agricultural intensification (WWF, 2010). According to a systematic review of case studies concerning Europe by van Vliet et al. (2015), technological and institutional drivers (incl. subsidies and land-use planning) dominate when it comes to agricultural intensification, while economic (incl. globalization and urbanization) and institutional drivers as well as location factors (incl. topography and soil) dominate with respect to agricultural dis-intensification (van Vliet et al., 2015).

Biodiversity loss due to pollution, habitat loss and fragmentation, invasive species and climate change is widespread throughout the region. Both agricultural intensification and abandonment contribute to the observed decline (European Environment Agency, 2015). In Belarus in particular, biodiversity decline associated with farmland abandonment could be observed (visible in our maps). Expansion of tourism and associated infrastructure development is a strong driver of biodiversity loss along the Mediterranean coast. Underlying causes include governance and market failures (European Commission, DG Environment 2009). Notable exceptions are Poland and Germany where conservation programs were implemented and secondary vegetation established itself after agricultural monoculture and former industrial sites were abandoned (Kolecka et al., 2015).

The observed **urbanization** patterns reflect rural-to-urban migration, the attraction of large urban centres and rural depopulation driven by societal and demographic change.

Carbon stock increases have resulted from forest regrowth on abandoned farmland and afforestation (Cosor, 2014; European Environment Agency, 2015; Kuemmerle et al., 2016). This dynamic is largely responsible for the "nature" dominance in the principal component analysis, which prevails in most of the region.

East Asia

Description of key dynamics

East Asia has experienced land use changes between 2000 and 2010 to various extents. Very prominently, **population** has grown in big metropolitan and urban areas, e.g., in Guangzhou, Chengdu, Shanghai or Beijing in China, as well as in Seoul and Pusan in South Korea. At the same time, the hinterland regions of large metropolitan areas have experienced decreases in population density indicating a rural exodus and inner regional migration in particular in China, and in South Korea. Cities in remote areas, e.g. in Xinjiang province in China and in Mongolia have also grown significantly. The overall net effect on average population densities has been positive, as the rural exodus is more than offset by increases in the high density regions around existing urban areas. 15% of global population growth took place in East Asia.

Population growth has gone hand-in-hand with large increases in **livestock.** 30% of all growth in livestock density took place in East Asia. **Cropland** has decreased in the entire region – 98% of all notable changes in cropland are negative. **Carbon** intensity shows a rather mixed picture, with increases in Eastern China, the Tibetan Plateau, as well as Yunnan. Decreases of carbon intensity can mainly be found in Taiwan, Sichuan and the Southern Chinese provinces as well as in the Northern part of the region, including Mongolia, the Northern Chinese provinces (Heilongjiang, Jilin and Inner Mongolia) and North Korea. **Biodiversity** has decreased mainly in the South of China (across the border to South East Asian countries Myanmar, Laos and Vietnam), as well as in a corridor reaching approximately from Chengdu to the greater Beijing area, covering the provinces of Hubei, Henan Shanxi and Hebei. Altogether 97% of all notable changes in biodiversity are negative.

Main drivers

The literature identifies **population dynamics** to be largely driven by urbanization. In fact, East Asia is among the world regions with the strongest urbanization dynamics, both in terms of scale and pace. From

2000 to 2010, urban **population** in China grew by 3.3% per annum on average (World Bank, 2015), whereas the growth rate of the total population averaged 0.5% ("World Population Prospects - Population Division - United Nations," n.d.). In the same decade, urban areas expanded by 3.1% p.a. Accordingly, urban population densities mostly increased, moderately remained stable, or even decreased (e.g., in Shanghai).

In China, 87% of urban expansion occurred on arable land which had important implications for agricultural production (World Bank, 2015). There is evidence that the rapid urban area expansion poses substantial threats to China's most productive **croplands** (Chen, 2007). By 2030, China is expected to have urbanized more than 5% of its prime croplands which were used to produce 9% of crop production in 2000 (Bren d'Amour et al., 2017). However, observed decreases in cropland are partly also due to efforts to fight soil erosion (Deng et al., 2014).

Livestock densities increased in much of East Asia, mostly driven by surges in demand for pig meat and poultry (Thornton, 2010). Increasingly, confined livestock production systems are established to meet this demand; metropolitan areas like Shanghai, Beijing, and Guangdong increasingly rely on industrial pig production (Bai et al., 2014) This very intensive form of livestock production has allowed for significant simultaneous increases in both population and livestock.

Terrestrial **carbon Strange** is decreasing in 62% of Land in East Asia (Table S5, cf. Calle et al., 2016). However, decomposing those changes, significant differences can be identified, both related to land use types as well as across regions. Decreases in Northern China and Mongolia are predominantly rooted in deforestation. Increases in cropland have led to high decreases in terrestrial carbon in Sichuan and Heilongjiang (Zhang et al., 2015). Afforestation and an increase of grassland areas have contributed to increases in stored terrestrial carbon, particularly in Tibet. Parts of that can be attributed to China's fight against soil erosion ("green-for-grain" program), aiming to restore degraded agricultural land by grasslands or afforestation (Deng et al., 2014). However, afforestation does not always lead to increased terrestrial carbon storage; in Inner Mongolia, for example, increasing carbon intensity by afforestation has been compensated by losses in grasslands (Zhang et al., 2015).

Biodiversity losses can to a large extent be attributed to land increasingly being consumed by urban areas, particular in China (He et al., 2014). For example, in the Pearl River delta, 26% of natural habitat and 42% of local wetlands have been prey to urbanization. In particular in Yunnan the loss of primary forest and biodiversity is due to logging and cash crop plantations, particularly rubber (Liu et al., 2013).

References

ABS [Australian Bureau of Statistics], 2003. Salinity and land management on Western Australian farms.
Aide, T.M., Clark, M.L., Grau, H.R., López-Carr, D., Levy, M.A., Redo, D., Bonilla-Moheno, M., Riner, G., Andrade-Núñez, M.J., Muñiz, M., 2013. Deforestation and Reforestation of Latin America and the Caribbean (2001–2010). Biotropica 45, 262–271. https://doi.org/10.1111/j.1744-7429.2012.00908.x
Alcantara et al., 2013. Mapping the extent of abandoned farmland in Central and Eastern Europe using MODIS time series satellite data. Environ. Res. Lett. 8.
Allendorf, T.D., Das, R., Bose, A., Ray, B., Chaudhuri, K.D., Brock, S., Horwich, R.H., 2013. Motivations of the community forest protection forces of the Manas Biosphere Reserve in Assam, India. Int. J. Sustain. Dev. World Ecol. 20, 426–432. https://doi.org/10.1080/13504509.2013.816890
Andela, N., van der Werf, G.R., 2014. Recent trends in African fires driven by cropland expansion and El Nino to La Nina transition. Nat. Clim. Change 4, 791–795.
ASFB, 2013. Australia's State of the Forests Report.
Bai, Z.H., Ma, L., Qin, W., Chen, Q., Oenema, O., Zhang, F.S., 2014. Changes in Pig Production in China and Their Effects on Nitrogen and Phosphorus Use and Losses. Environ. Sci. Technol. 48, 12742–12749. https://doi.org/10.1021/es502160v
Banerjee, A., Iyer, L., 2005. History, Institutions, and Economic Performance: The Legacy of Colonial Land Tenure Systems in India. Am. Econ. Rev. 95, 1190–1213. https://doi.org/10.1257/0002828054825574
Baumann et al., 2011. Patterns and drivers of post-socialist farmland abandonment in Western Ukraine. Land Use Policy 28, 552–562.
Becker, A., Inoue, S., Fischer, M., Schwegler, B., 2012. Climate change impacts on international seaports: knowledge, perceptions, and planning efforts among port administrators. Clim. Change 110, 5–29.
Bohannon, J., 2010. The Nile Delta's Sinking Future. Science 327, 1444–1447. https://doi.org/10.1126/science.327.5972.1444
Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W., Cramer, W., Gerten, D., Lotze-Campen, H., Müller, C., Reichstein, M., Smith, B., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Glob. Change Biol. 13, 679–706. https://doi.org/10.1111/j.1365-2486.2006.01305.x
Bongaarts, J., 2009. Human population growth and the demographic transition. Philos. Trans. R. Soc. Lond. B Biol. Sci. 364, 2985–2990. https://doi.org/10.1098/rstb.2009.0137
Bren d'Amour, C., Reitsma, F., Baiocchi, G., Barthel, S., Güneralp, B., Erb, K.-H., Haberl, H., Creutzig, F., Seto, K.C., 2017. Future urban land expansion and implications for global croplands. Proc. Natl. Acad. Sci. 114, 8939–8944. https://doi.org/10.1073/pnas.1606036114
Buhaug, H., Urdal, H., 2013. An urbanization bomb? Population growth and social disorder in cities. Glob. Environ. Change 23, 1–10.
Calle, L., Canadell, J.G., Patra, P., Ciais, P., Ichii, K., Tian, H., Kondo, M., Piao, S., Arneth, A., Harper, A.B., Ito, A., Kato, E., Koven, C., Sitch, S., Stocker, B.D., Vivoy, N., Wiltshire, A., Zaehle, S., Poulter, B., 2016. Regional carbon fluxes from land use and land cover change in Asia, 1980–2009. Environ. Res. Lett. 11, 074011. https://doi.org/10.1088/1748-9326/11/7/074011
Center for International Earth Science Information Network - CIESIN - Columbia University, Centro Internacional de Agricultura Tropical - CIAT, 2005. Gridded Population of the World, Version 3 (GPWv3): Population Density Grid.
Cerrutti, M., Bertoncello, R., 2003. Urbanization and internal migration patterns in Latin America. Cent. Estud. Poblac. Argent.

Chamberlin, J., Jayne, T., Headey, D., 2014. Scarcity amidst abundance? Reassessing the potential for cropland expansion in Africa. Food Policy 48, 51–65.
Chen, J., 2007. Rapid urbanization in China: A real challenge to soil protection and food security. CATENA, Influences of rapid urbanization and industrialization on soil resource and its quality in China 69, 1–15. https://doi.org/10.1016/j.catena.2006.04.019
Ciais, P., Bombelli, A., Williams, M., Piao, S., Chave, J., Ryan, C., Henry, M., Brender, P., Valentini, R., 2011. The carbon balance of Africa: synthesis of recent research studies. Philos. Trans. R. Soc. Lond. Math. Phys. Eng. Sci. 369, 2038–2057.
Cohen, B., 2006. Urbanization in developing countries: Current trends, future projections, and key challenges for sustainability. Technol. Soc., Sustainable Cities 28, 63–80. https://doi.org/10.1016/j.techsoc.2005.10.005
Cosor, G., 2014. Visions of Land Use Transitions in Europe.
Davis, K.F., Yu, K., Rulli, M.C., Pichdara, L., D'Odorico, P., 2015. Accelerated deforestation driven by large-scale land acquisitions in Cambodia. Nat. Geosci. 8, 772–775.
Deininger, K., Byerlee, D., 2011. Rising global interest in farmland: can it yield sustainable and equitable benefits? World Bank Publications.
Deng, L., Liu, G., Shangguan, Z., 2014. Land-use conversion and changing soil carbon stocks in China's 'Grain-for-Green' Program: a synthesis. Glob. Change Biol. 20, 3544–3556. https://doi.org/10.1111/gcb.12508
Dixon, J.A., Gibbon, D.P., Gulliver, A., 2001. Farming systems and poverty: improving farmers' livelihoods in a changing world. Food & Agriculture Org.
Dolman, A.J., Shvidenko, A., Schepaschenko, D., Ciais, P., Tchebakova, N., Chen, T., vander Molen, M.K., Belelli Marchesini, L., Schulze, E.-D., 2012. An estimate of the terrestrial carbon budget of Russia using inventory-based, eddy covariance and inversion methods. Biogeosciences 9, 5323–5340. https://doi.org/doi:10.5194/bg-9-5323-2012
European Commission, DG Agriculture, 2004. The meat sector in the European Union.
European Environment Agency, 2015. The European Environment. State and Outlook 2015.
Evans, J.P., 2009. 21st century climate change in the Middle East. Clim. Change 92, 417–432.
Faber, S., Rundquist, S., Male, T., 2012. Plowed under: how crop subsidies contribute to massive habitat loss. Environmental Working Group.
FAO, 2016. FAOSTAT [WWW Document]. URL http://faostat3.fao.org (accessed 9.13.16).
FAO, 2015. Global Forest Resources Assessment 2015. FAO, Rome.
FAOSTAT, F., 2015. Food and Agriculture Organization of the United Nations Statistics Division. Rome FAO.
Feng, H., Hennessy, D.A., Miao, R., 2013. The Effects of Government Payments on Cropland Acreage, Conservation Reserve Program Enrollment, and Grassland Conversion in the Dakotas. Am. J. Agric. Econ. 95, 412–418. https://doi.org/10.1093/ajae/aas112
Fetzel, T., Niedertscheider, M., Haberl, H., Krausmann, F., Erb, K.-H., 2016. Patterns and changes of land use and land-use efficiency in Africa 1980–2005: an analysis based on the human appropriation of net primary production framework. Reg. Environ. Change 16, 1507–1520.
Gallant, A., Kiem, A., Verdon-Kidd, D., Stone, R., Karoly, D., 2012. Understanding hydroclimate processes in the Murray-Darling Basin for natural resources management. Hydrol. Earth Syst. Sci. 16, 2049–2068.
Gibbs, H.K., Rausch, L., Munger, J., Schelly, I., Morton, D.C., Noojipady, P., Soares-Filho, B., Barreto, P., Micol, L., Walker, N.F., 2015. Brazil's Soy Moratorium. Science 347, 377–378. https://doi.org/10.1126/science.aaa0181
Grau, H.R., Aide, M., 2008. Globalization and land-use transitions in Latin America. Ecol. Soc. 13, 16.

Harris, N.L., Goldman, E., Gabris, C., Nordling, J., Minnemeyer, S., Stephen Ansari, Lippmann, M., Bennett, L., Raad, M., Hansen, M., Potapov, P., 2017. Using spatial statistics to identify emerging hot spots of forest loss. Environ. Res. Lett. 12, 024012. https://doi.org/10.1088/1748-9326/aa5a2f

He, C., Liu, Z., Tian, J., Ma, Q., 2014. Urban expansion dynamics and natural habitat loss in China: a multiscale landscape perspective. Glob. Change Biol. 20, 2886–2902. https://doi.org/10.1111/gcb.12553

Holden, S.T., Otsuka, K., 2014. The roles of land tenure reforms and land markets in the context of population growth and land use intensification in Africa. Food Policy 48, 88–97.

Hosonuma, N., Herold, M., De Sy, V., De Fries, R.S., Brockhaus, M., Verchot, L., Angelsen, A., Romijn, E., 2012. An assessment of deforestation and forest degradation drivers in developing countries. Environ. Res. Lett. 7, 044009. https://doi.org/10.1088/1748-9326/7/4/044009

Houghton, R.., 2012. Carbon emissions and the drivers of deforestation and forest degradation in the tropics. Curr. Opin. Environ. Sustain. 4, 597–603. https://doi.org/10.1016/j.cosust.2012.06.006

Houghton, R.A., Hackler, J.L., Lawrence, K.T., 1999. The U.S. Carbon Budget: Contributions from Land-Use Change. Science 285, 574–578. https://doi.org/10.1126/science.285.5427.574

Hudson, L.N., Newbold, T., Contu, S., Hill, S.L.L., Lysenko, I., De Palma, A., Phillips, H.R.P., Senior, R.A., Bennett, D.J., Booth, H., Choimes, A., Correia, D.L.P., Day, J., Echeverría-Londoño, S., Garon, M., Harrison, M.L.K., Ingram, D.J., Jung, M., Kemp, V., Kirkpatrick, L., Martin, C.D., Pan, Y., White, H.J., Aben, J., Abrahamczyk, S., Adum, G.B., Aguilar-Barquero, V., Aizen, M.A., Ancrenaz, M., Arbeláez-Cortés, E., Armbrecht, I., Azhar, B., Azpiroz, A.B., Baeten, L., Báldi, A., Banks, J.E., Barlow, J., Batáry, P., Bates, A.J., Bayne, E.M., Beja, P., Berg, Å., Berry, N.J., Bicknell, J.E., Bihn, J.H., Böhning-Gaese, K., Boekhout, T., Boutin, C., Bouyer, J., Brearley, F.Q., Brito, I., Brunet, J., Buczkowski, G., Buscardo, E., Cabra-García, J., Calviño-Cancela, M., Cameron, S.A., Cancello, E.M., Carrijo, T.F., Carvalho, A.L., Castro, H., Castro-Luna, A.A., Cerda, R., Cerezo, A., Chauvat, M., Clarke, F.M., Cleary, D.F.R., Connop, S.P., D'Aniello, B., da Silva, P.G., Darvill, B., Dauber, J., Dejean, A., Diekötter, T., Dominguez-Haydar, Y., Dormann, C.F., Dumont, B., Dures, S.G., Dynesius, M., Edenius, L., Elek, Z., Entling, M.H., Farwig, N., Fayle, T.M., Felicioli, A., Felton, A.M., Ficetola, G.F., Filgueiras, B.K.C., Fonte, S.J., Fraser, L.H., Fukuda, D., Furlani, D., Ganzhorn, J.U., Garden, J.G., Gheler-Costa, C., Giordani, P., Giordano, S., Gottschalk, M.S., Goulson, D., Gove, A.D., Grogan, J., Hanley, M.E., Hanson, T., Hashim, N.R., Hawes, J.E., Hébert, C., Helden, A.J., Henden, J.-A., Hernández, L., Herzog, F., Higuera-Diaz, D., Hilje, B., Horgan, F.G., Horváth, R., Hylander, K., Isaacs-Cubides, P., Ishitani, M., Jacobs, C.T., Jaramillo, V.J., Jauker, B., Jonsell, M., Jung, T.S., Kapoor, V., Kati, V., Katovai, E., Kessler, M., Knop, E., Kolb, A., Kőrösi, Á., Lachat, T., Lantschner, V., Le Féon, V., LeBuhn, G., Légaré, J.-P., Letcher, S.G., Littlewood, N.A., López-Quintero, C.A., Louhaichi, M., Lövei, G.L., Lucas-Borja, M.E., Luja, V.H., Maeto, K., Magura, T., Mallari, N.A., Marin-Spiotta, E., Marshall, E.J.P., Martínez, E., Mayfield, M.M., Mikusinski, G., Milder, J.C., Miller, J.R., Morales, C.L., Muchane, M.N., Muchane, M., Naidoo, R., Nakamura, A., Naoe, S., Nates-Parra, G., Navarrete Gutierrez, D.A., Neuschulz, E.L., Noreika, N., Norfolk, O., Noriega, J.A., Nöske, N.M., O'Dea, N., Oduro, W., Ofori-Boateng, C., Oke, C.O., Osgathorpe, L.M., Paritsis, J., Parra-H, A., Pelegrin, N., Peres, C.A., Persson, A.S., Petanidou, T., Phalan, B., Philips, T.K., Poveda, K., Power, E.F., Presley, S.J., Proença, V., Quaranta, M., Quintero, C., Redpath-Downing, N.A., Reid, J.L., Reis, Y.T., Ribeiro, D.B., Richardson, B.A., Richardson, M.J., Robles, C.A., Römbke, J., Romero-Duque, L.P., Rosselli, L., Rossiter, S.J., Roulston, T.H., Rousseau, L., Sadler, J.P., Sáfián, S., Saldaña-Vázquez, R.A., Samnegård, U., Schüepp, C., Schweiger, O., Sedlock, J.L., Shahabuddin, G., Sheil, D., Silva, F.A.B., Slade, E.M., Smith-Pardo, A.H., Sodhi, N.S., Somarriba, E.J., Sosa, R.A., Stout, J.C., Struebig, M.J., Sung, Y.-H., Threlfall, C.G., Tonietto, R., Tóthmérész, B., Tscharntke, T., Turner, E.C., Tylianakis, J.M., Vanbergen, A.J., Vassilev, K., Verboven, H.A.F., Vergara, C.H., Vergara, P.M., Verhulst, J., Walker, T.R., Wang, Y., Watling, J.I., Wells, K., Williams, C.D., Willig, M.R., Woinarski, J.C.Z., Wolf, J.H.D., Woodcock, B.A., Yu, D.W., Zaitsev, A.S., Collen, B., Ewers, R.M., Mace, G.M., Purves, D.W., Scharlemann, J.P.W., Purvis, A., 2014. The PREDICTS database: a global database of how local terrestrial biodiversity responds to human impacts. Ecol. Evol. 4, 4701–4735. https://doi.org/10.1002/ece3.1303

Hurtt, G.C., Chini, L.P., Frolking, S., Betts, R.A., Feddema, J., Fischer, G., Fisk, J.P., Hibbard, K., Houghton, R.A., Janetos, A., 2011. Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. Clim. Change 109, 117–161.

IIASA, F., 2012. Global Agro-ecological Zones (GAEZ v3. 0). IIASA Laxenburg Austria FAO Rome Italy.

Jain, M., Dawa, D., Mehta, R., Dimri, A.P., Pandit, M.K., 2016. Monitoring land use change and its drivers in Delhi, India using multi-temporal satellite data. Model. Earth Syst. Environ. 2, 1–14. https://doi.org/10.1007/s40808-016-0075-0

Jayne, T., Chamberlin, J., Headey, D.D., 2014. Land pressures, the evolution of farming systems, and development strategies in Africa: A synthesis. Food Policy 48, 1–17.

Kastner, T., Erb, K.-H., Haberl, H., 2014. Rapid growth in agricultural trade: effects on global area efficiency and the role of management. Environ. Res. Lett. 9, 034015.

Klein Goldewijk, K., Beusen, A., van Drecht, G., de Vos, M., 2011. The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. Glob. Ecol. Biogeogr. 20, 73–86. https://doi.org/10.1111/j.1466-8238.2010.00587.x

Kolecka, N., Kozak, J., Kaim, D., Dobosz, M., Ginzler, C., Psomas, A., 2015. Mapping Secondary Forest Succession on Abandoned Agricultural Land with LiDAR Point Clouds and Terrestrial Photography. Remote Sens. 7, 8300–8322. https://doi.org/10.3390/rs70708300

Kuemmerle, T., Levers, C., Erb, K., Estel, S., Jepsen, M.R., Müller, D., Plutzar, C., Stürck, J., Verkerk, P., Verburg, P.H., 2016. Hotspots of Land Use Change in Europe. Environ. Res. Lett. 11.

Kukavskaya, E.A., Soja, A.J., Petkov, A.P., Ponomarev, E.I., Ivanova, G.A., Conard, S.G., 2012. Fire emissions estimates in Siberia: evaluation of uncertainties in area burned, land cover, and fuel consumption. Can. J. For. Res. 43, 493–506. https://doi.org/10.1139/cjfr-2012-0367

Kuusela, O.-P., Amacher, G.S., 2015. Changing Political Regimes and Tropical Deforestation. Environ. Resour. Econ. 1–19.

Lark, T.J., Salmon, J.M., Gibbs, H.K., 2015. Cropland expansion outpaces agricultural and biofuel policies in the United States. Environ. Res. Lett. 10, 044003. https://doi.org/10.1088/1748-9326/10/4/044003

Lelieveld, J., Proestos, Y., Hadjinicolaou, P., Tanarhte, M., Tyrlis, E., Zittis, G., 2016. Strongly increasing heat extremes in the Middle East and North Africa (MENA) in the 21st century. Clim. Change 137, 245–260. https://doi.org/10.1007/s10584-016-1665-6

Liang, S., Guo, S., Newell, J.P., Qu, S., Feng, Y., Chiu, A.S.F., Xu, M., 2016. Global Drivers of Russian Timber Harvest. J. Ind. Ecol. 20, 515–525. https://doi.org/10.1111/jiec.12417

Liebenberg, F., Pardey, P.G., 2010. South African agricultural production and productivity patterns., in: The Shifting Patterns of Agricultural Production and Productivity Worldwide. The Midwest Agribusiness Trade Research and Information Center, Iowa State University, Ames, Iowa.

Lipoeto, N.I., Geok Lin, K., Angeles-Agdeppa, I., 2013. Food consumption patterns and nutrition transition in South-East Asia. Public Health Nutr. 16, 1637–1643. https://doi.org/10.1017/S1368980012004569

Liu, X., Feng, Z., Jiang, L., Li, P., Liao, C., Yang, Y., You, Z., 2013. Rubber plantation and its relationship with topographical factors in the border region of China, Laos and Myanmar. J. Geogr. Sci. 23, 1019–1040. https://doi.org/10.1007/s11442-013-1060-4

Liu, Y.Y., Van Dijk, A.I., De Jeu, R.A., Canadell, J.G., McCabe, M.F., Evans, J.P., Wang, G., 2015. Recent reversal in loss of global terrestrial biomass. Nat. Clim. Change 5, 470–474.
Meehan, T.D., Gratton, C., 2015. A consistent positive association between landscape simplification and insecticide use across the Midwestern US from 1997 through 2012. Environ. Res. Lett. 10, 114001. https://doi.org/10.1088/1748-9326/10/11/114001
Meehan, T.D., Hurlbert, A.H., Gratton, C., 2010. Bird communities in future bioenergy landscapes of the Upper Midwest. Proc. Natl. Acad. Sci. 107, 18533–18538. https://doi.org/10.1073/pnas.1008475107
Mitchell, C.D., Harper, R.J., Keenan, R.J., 2012. Current status and future prospects for carbon forestry in Australia. Aust. For. 75, 200–212.
Mladenoff, D.J., Sahajpal, R., Johnson, C.P., Rothstein, D.E., 2016. Recent Land Use Change to Agriculture in the U.S. Lake States: Impacts on Cellulosic Biomass Potential and Natural Lands. PLOS ONE 11, e0148566. https://doi.org/10.1371/journal.pone.0148566
Morris, M.L., Binswanger-Mikhize, H.P., Byerlee, D., 2009. Awakening Africa's sleeping giant: prospects for commercial agriculture in the Guinea Savannah Zone and beyond. World Bank Publications.
MSEIC, 2010. Australia and Food Security in a Changing World. The Prime Minister's Science, Engineering and Innovation Council.
Nagendra, H., Sudhira, H.S., Katti, M., Schewenius, M., 2013. Sub-regional Assessment of India: Effects of Urbanization on Land Use, Biodiversity and Ecosystem Services, in: Elmqvist, T., Fragkias, M., Goodness, J., Güneralp, B., Marcotullio, P.J., McDonald, R.I., Parnell, S., Schewenius, M., Sendstad, M., Seto, K.C., Wilkinson, C. (Eds.), Urbanization, Biodiversity and Ecosystem Services: Challenges and Opportunities. Springer Netherlands, pp. 65–74.
Nepstad, D., McGrath, D., Stickler, C., Alencar, A., Azevedo, A., Swette, B., Bezerra, T., DiGiano, M., Shimada, J., Motta, R.S. da, Armijo, E., Castello, L., Brando, P., Hansen, M.C., McGrath-Horn, M., Carvalho, O., Hess, L., 2014. Slowing Amazon deforestation through public policy and interventions in beef and soy supply chains. Science 344, 1118–1123. https://doi.org/10.1126/science.1248525
Nepstad, D., Soares-Filho, B.S., Merry, F., Lima, A., Moutinho, P., Carter, J., Bowman, M., Cattaneo, A., Rodrigues, H., Schwartzman, S., McGrath, D.G., Stickler, C.M., Lubowski, R., Piris-Cabezas, P., Rivero, S., Alencar, A., Almeida, O., Stella, O., 2009. The End of Deforestation in the Brazilian Amazon. Science 326, 1350–1351. https://doi.org/10.1126/science.1182108
Newbold, T., Hudson, L.N., Arnell, A.P., Contu, S., Palma, A.D., Ferrier, S., Hill, S.L.L., Hoskins, A.J., Lysenko, I., Phillips, H.R.P., Burton, V.J., Chng, C.W.T., Emerson, S., Gao, D., Pask-Hale, G., Hutton, J., Jung, M., Sanchez-Ortiz, K., Simmons, B.I., Whitmee, S., Zhang, H., Scharlemann, J.P.W., Purvis, A., 2016. Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment. Science 353, 288–291. https://doi.org/10.1126/science.aaf2201
Newbold, T., Hudson, L.N., Hill, S.L., Contu, S., Lysenko, I., Senior, R.A., Börger, L., Bennett, D.J., Choimes, A., Collen, B., 2015. Global effects of land use on local terrestrial biodiversity. Nature 520, 45–50.
Observatorio Demográfico de América Latina y el Caribe, 2014. Proyecciones de población [WWW Document]. URL http://repositorio.cepal.org/bitstream/handle/11362/39228/1/S1500643_mu.pdf (accessed 9.20.16).
Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011a. A Large and Persistent Carbon Sink in the World's Forests. Science 333, 988–993. https://doi.org/10.1126/science.1201609
Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A.,

Sitch, S., Hayes, D., 2011b. A Large and Persistent Carbon Sink in the World's Forests. Science 333, 988–993. https://doi.org/10.1126/science.1201609
Pande, P.C., Vibhuti, V., Awasthi, P., Bargali, K., Bargali, S.S., 2016. Agro-Biodiversity of Kumaun Himalaya, India: A Review. Curr. Agric. Res. J. 4, 16–34. https://doi.org/10.12944/CARJ.4.1.02
Paul, K., Jacobsen, K., Koul, V., Leppert, P., Smith, J., 2008. Predicting growth and sequestration of carbon by plantations growing in regions of low-rainfall in southern Australia. For. Ecol. Manag. 254, 205–216.
Petrov, A., Lobovikov, M., 2012. The Russian Federation Forest Sector: Outlook Study to 2030. FAO Rome.
Phalan, B., Bertzky, M., Butchart, S.H.M., Donald, P.F., Scharlemann, J.P.W., Stattersfield, A.J., Balmford, A., 2013. Crop Expansion and Conservation Priorities in Tropical Countries. PLoS ONE 8, e51759. https://doi.org/10.1371/journal.pone.0051759
Rashid, I., Romshoo, S.A., Vijayalakshmi, T., 2013. Geospatial modelling approach for identifying disturbance regimes and biodiversity rich areas in North Western Himalayas, India. Biodivers. Conserv. 22, 2537–2566. https://doi.org/10.1007/s10531-013-0538-9
Ray, D.K., Mueller, N.D., West, P.C., Foley, J.A., 2013. Yield Trends Are Insufficient to Double Global Crop Production by 2050. PLOS ONE 8, e66428. https://doi.org/10.1371/journal.pone.0066428
Reddy, C.S., Jha, C.S., Dadhwal, V.K., Krishna, P.H., Pasha, S.V., Satish, K.V., Dutta, K., Saranya, K.R.L., Rakesh, F., Rajashekar, G., Diwakar, P.G., 2015. Quantification and monitoring of deforestation in India over eight decades (1930–2013). Biodivers. Conserv. 25, 93–116. https://doi.org/10.1007/s10531-015-1033-2
Rhodes, D., Stephens, M., 2014. Planted forest development in Australia and New Zealand: comparative trends and future opportunities. N. Z. J. For. Sci. 44, 1.
Robinson, T.P., Wint, G.R.W., Conchedda, G., Boeckel, T.P.V., Ercoli, V., Palamara, E., Cinardi, G., D'Aietti, L., Hay, S.I., Gilbert, M., 2014. Mapping the Global Distribution of Livestock. PLOS ONE 9, e96084. https://doi.org/10.1371/journal.pone.0096084
Roudi-Fahimi, F., Kent, M.M., 2007. Challenges and opportunities: The population of the Middle East and North Africa. Popul. Bull. 62, 24.
Schierhorn, F., Müller, D., Beringer, T., Prishchepov, A.V., Kuemmerle, T., Balmann, A., 2013. Post-Soviet cropland abandonment and carbon sequestration in European Russia, Ukraine, and Belarus. Glob. Biogeochem. Cycles 27, 1175–1185. https://doi.org/10.1002/2013GB004654
Schneider, A., Mertes, C.M., Tatem, A.J., Tan, B., Sulla-Menashe, D., Graves, S.J., Patel, N.N., Horton, J.A., Gaughan, A.E., Rollo, J.T., Schelly, I.H., Stevens, F.R., Dastur, A., 2015. A new urban landscape in East–Southeast Asia, 2000–2010. Environ. Res. Lett. 10, 034002. https://doi.org/10.1088/1748-9326/10/3/034002
Searchinger, T., Edwards, R., Mulligan, D., Heimlich, R., Plevin, R., 2015. Do biofuel policies seek to cut emissions by cutting food? Science 347, 1420–1422.
Şekercioğlu, Ç.H., Anderson, S., Akçay, E., Bilgin, R., Can, Ö.E., Semiz, G., Tavşanoğlu, Ç., Yokeş, M.B., Soyumert, A., Ipekdal, K., 2011. Turkey's globally important biodiversity in crisis. Biol. Conserv. 144, 2752–2769.
Seto, K.C., Fragkias, M., Güneralp, B., Reilly, M.K., 2011. A Meta-Analysis of Global Urban Land Expansion. PLOS ONE 6, e23777. https://doi.org/10.1371/journal.pone.0023777
Seto, K.C., Guneralp, B., Hutyra, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proc. Natl. Acad. Sci. 109, 16083–16088. https://doi.org/10.1073/pnas.1211658109
Shvidenko, A., Schepaschenko, D., Sukhinin, A., McCallum, I., Maksyutov, S., 2011. Carbon emissions from forest fires in Boreal Eurasia between 1998–2010//5th Int, in: Wildland Fire Conf. Sun City, South Africa.

Sleeter, B.M., Sohl, T.L., Loveland, T.R., Auch, R.F., Acevedo, W., Drummond, M.A., Sayler, K.L., Stehman, S.V., 2013. Land-cover change in the conterminous United States from 1973 to 2000. Glob. Environ. Change 23, 733–748. https://doi.org/10.1016/j.gloenvcha.2013.03.006

Steffen, W., Burbidge, A., Hughes, L., Kitching, R., Lindenmayer, D., Musgrave, W., Stafford Smith, M., Werner, P., 2009. Australia's biodiversity and climate change: a strategic assessment of the vulnerability of Australia's biodiversity to climate change.

Stibig, H.-J., Achard, F., Carboni, S., Raši, R., Miettinen, J., 2014. Change in tropical forest cover of Southeast Asia from 1990 to 2010. Biogeosciences 11, 247–258. https://doi.org/10.5194/bg-11-247-2014

Thornton, P.K., 2010. Livestock production: recent trends, future prospects. Philos. Trans. R. Soc. B Biol. Sci. 365, 2853–2867. https://doi.org/10.1098/rstb.2010.0134

Turetsky, M.R., Benscoter, B., Page, S., Rein, G., van der Werf, G.R., Watts, A., 2014. Global vulnerability of peatlands to fire and carbon loss. Nat. Geosci. 8, 11–14. https://doi.org/10.1038/ngeo2325

United Nations, 2014. World Urbanization Prospects: The 2014 Revision, Highlights. Department of Economic and Social Affairs. Popul. Div. U. N.

US Census Bureau, n.d. Population Clock: World [WWW Document]. URL https://www.census.gov/popclock/world/in (accessed 7.17.16).

USDA, 2016. USDA - National Agricultural Statistics Service [WWW Document]. URL https://www.nass.usda.gov/ (accessed 9.13.16).

van der Werf, G.R., Randerson, J.T., Giglio, L., Collatz, G.J., Mu, M., Kasibhatla, P.S., Morton, D.C., DeFries, R.S., Jin, Y., van Leeuwen, T.T., 2010. Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009). Atmos Chem Phys 10, 11707–11735. https://doi.org/10.5194/acp-10-11707-2010

van Vliet, J., de Groot, H., Rietveld, P., Verburg, P.H., 2015. Manifestations and underlying drivers of agricultural land use change in Europe. Landsc. Urban Plan. 133, 24–36.

Waisanen, P.J., Bliss, N.B., 2002. Changes in population and agricultural land in conterminous United States counties, 1790 to 1997: AGRICULTURAL LAND CHANGE. Glob. Biogeochem. Cycles 16, 84-1-84–19. https://doi.org/10.1029/2001GB001843

Wallander, S., Claassen, R., Nickerson, C., 2011. The ethanol decade: an expansion of US corn production, 2000-09, EIB-79, U.S. Department of Agriculture, Economic Research Service.

Weinzettel, J., Hertwich, E.G., Peters, G.P., Steen-Olsen, K., Galli, A., 2013. Affluence drives the global displacement of land use. Glob. Environ. Change 23, 433–438. https://doi.org/10.1016/j.gloenvcha.2012.12.010

Wilcove, D.S., Giam, X., Edwards, D.P., Fisher, B., Koh, L.P., 2013. Navjot's nightmare revisited: logging, agriculture, and biodiversity in Southeast Asia. Trends Ecol. Evol. 28, 531–540. https://doi.org/10.1016/j.tree.2013.04.005

Wint, W., Robinson, T., de Obschatko, E., Foti, M., Román, M., Saba, S., Battro, P., Chaves Solera, M., Rodríguez Rodríguez, M., Alfaro Portuguez, R., 2007. Gridded livestock of the world 2007. FAO, Roma (Italia).

World Bank, 2015. East Asia's Changing Urban Landscape: Measuring a Decade of Spatial Growth. The World Bank.

World Population Prospects - Population Division - United Nations [WWW Document], n.d. URL https://esa.un.org/unpd/wpp/ (accessed 7.11.16).

Wright, C.K., 2015. US agricultural policy, land use change, and biofuels: are we driving our way to the next dust bowl? Environ. Res. Lett. 10, 051001. https://doi.org/10.1088/1748-9326/10/5/051001

Wright, C.K., Wimberly, M.C., 2013. Recent land use change in the Western Corn Belt threatens grasslands and wetlands. Proc. Natl. Acad. Sci. 110, 4134–4139. https://doi.org/10.1073/pnas.1215404110

WWF, 2010. Farmland Abandonment in the EU: An Assessment of Trends and Prospects.
Zhang, M., Huang, X., Chuai, X., Yang, H., Lai, L., Tan, J., 2015. Impact of land use type conversion on carbon storage in terrestrial ecosystems of China: A spatial-temporal perspective. Sci. Rep. 5, 10233. https://doi.org/10.1038/srep1023

Chapter 3

3. Future urban land expansion and implications for global croplands*

Christopher Bren d'Amour
Femke Reitsma
Giovanni Baiocchi
Stephan Barthel
Burak Güneralp
Karl-Heinz Erb
Helmut Haberl
Felix Creutzig
Karen C. Seto

* Published in the journal *Proceedings of the National Academy of Sciences of the United States of America* as C. Bren d'Amour, F. Reitsma, G. Baiocchi, S. Barthel, B. Güneralp, K.H. Erb, H. Haberl, F. Creutzig, .K. C. Seto: Future urban land expansion and implications for global croplands, *PNAS* 2017 114 (34) 8939-8944; published ahead of print December 27, 2016, https://doi.org/10.1073/pnas.1606036114

Future urban land expansion and implications for global croplands

Christopher Bren d'Amour[1,2], Femke Reitsma[3], Giovanni Baiocchi[4], Stephan Barthel[5,6], Burak Güneralp[7], Karl-Heinz Erb[8], Helmut Haberl[8], Felix Creutzig[1,2,*], Karen C. Seto[9]

Abstract

Urban expansion often occurs on croplands. However, there is little scientific understanding of how global patterns of future urban expansion will affect the world's cultivated areas. Here, we combine spatially explicit projections of urban expansion with datasets on global croplands and crop yields. Our results show that urban expansion will result in a 1.8–2.4% loss of global croplands by 2030, with substantial regional disparities. About 80% of global cropland loss from urban expansion will take place in Asia and Africa. In both Asia and Africa, much of the cropland that will be lost is more than twice as productive as national averages. Asia will experience the highest absolute loss in cropland, whereas African countries will experience the highest percentage loss of cropland. Globally, the croplands that are likely to be lost were responsible for 3–4% of worldwide crop production in 2000. Urban expansion is expected to take place on cropland that is 1.77 times more productive than the global average. The loss of cropland is likely to be accompanied by other sustainability risks and threatens livelihoods, with diverging characteristics for different megaurban regions. Governance of urban area expansion thus emerges as a key area for securing livelihoods in the agrarian economies of the Global South.

Keywords: urbanization, global land use change, livelihoods, agricultural productivity, megaurban regions

[1]Mercator Research Institute on Global Commons and Climate Change, 10829 Berlin, Germany
[2]Department Economics of Climate Change, Technische Universität Berlin, 10623 Berlin, Germany
[3]Department of Geography, Canterbury University, Christchurch 8140, New Zealand
[4]Department of Geographical Sciences, University of Maryland, College Park, MD 20742, USA
[5]University of Gävle, SE-80176, Gävle, Sweden
[6]Stockholm Resilience Centre, Stockholm University, SE-10691, Stockholm, Sweden
[7]Department of Geography, Texas A&M University, College Station, TX 77840, USA
[8]Institute of Social Ecology Vienna, Alpen-Adria Universitaet Klagenfurt, 1070 Vienna, Austria
[9]Yale School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511, USA
[*] Author to whom any correspondence should be addressed.

3.1. Statement of significance

Urbanization's contribution to land use change emerges as an important sustainability concern. Here, we demonstrate that projected urban area expansion will take place on some of the world's most productive croplands, in particular in megaurban regions in Asia and Africa. This dynamic adds pressure to potentially strained future food systems and threatens livelihoods in vulnerable regions.

3.2. Introduction

Urban land expansion—the process of creating the built environment to house urban populations and their activities—is one of the fundamental aspects of urbanization. Urban land expansion modifies habitats, biogeochemistry, hydrology, land cover, and surface energy balance (Grimm et al., 2008). In most parts of the world, urban land is expanding faster than urban populations (Seto et al., 2010). Whereas urban populations are expected to almost double from 2.6 billion in 2000 to 5 billion in 2030 (United Nations, 2014), urban areas are forecast to triple between 2000 and 2030 (Seto et al., 2012). A defining characteristic of contemporary urbanization is the rise of megaurban regions (MURs): the merging of multiple urban areas into a contiguous and continuous urban fabric. These MURs differ from megacities with populations of 10 million or more in two important and fundamental ways: administratively, they consist of multiple contiguous entities with discrete governance structures; biophysically, they are a single continuous urban area whose absolute spatial size creates challenges for urban, land, and transport governance. The rate and magnitude of urban land expansion are influenced by many macro factors, including income, economic development, and population growth, as well as a number of local and regional factors such as land use policies, the informal economy, capital flows, and transportation costs (Seto et al., 2011).

More than 60% of the world's irrigated croplands are located near urban areas (Thebo et al., 2014), highlighting the potential competition for land between agricultural and urban uses. Individual case studies show that high rates of urban expansion over the last three decades have resulted in the loss of cropland all around the world, with examples from China, the United States, Egypt, Turkey, India, and other countries (Ahmad et al., 2016; Bagan and Yamagata, 2014; Chen, 2007). Although cropland loss has become a significant concern in terms of food production and livelihoods for many countries (Brook and Dávila, 2000), there is very little scientific understanding of how future urban expansion and especially growth of MURs will affect croplands. However, this knowledge is key given the potential large-scale land conflicts between agriculture and urban uses in an era of rapid megaurbanization.

Most of the future urban population and urban area expansion are forecast to take place in Asia and Africa (Seto et al., 2012), often in places with high poverty rates and potentially prone to systemic disruptions in the food system (Bren d'Amour et al., 2016; Puma et al., 2015). For many of these countries, agriculture is a crucial economic sector in terms of income generation, percentage of total national gross domestic product (GDP), and employment source. Thus, there is a need to assess the implications of urban expansion on croplands on global, national, and subnational scales to identify potential areas of conflict as well as strategies for shaping more sustainable forms of urban expansion.

This paper fills these knowledge gaps by addressing the following questions: (i) Where are croplands most vulnerable to conversion due to future urban expansion? (ii) What is the magnitude of cropland loss, especially of prime cropland, due to future urban expansion? (iii) How will the loss of croplands affect total cropland area and relative economic importance of agriculture for different countries? Sustainability in the era of megaurbanization will require understanding the "hidden linkages" between urbanization and food systems (Seto and Ramankutty, 2016), including where and how to maintain croplands to grow food, the most basic of all human necessities. Here, we define food systems as "the chain of activities connecting food production, processing, distribution, consumption, and waste management, as well as all the associated regulatory institutions and activities" (Pothukuchi and Kaufman, 2000).

This study provides a global estimate of the loss of croplands to urban area expansion and its implications for crop production. We limit our discussion to croplands, which cover 12% of Earth's ice-free land area (Ramankutty et al., 2008), but exclude pastures. We compare spatially explicit datasets on croplands (Fritz et al., 2015; Ramankutty et al., 2008) and cropland productivity (Monfreda et al., 2008) for the year 2000 to gridded urban area projections for the year 2030 (Seto et al., 2012). Processing the cropland datasets, we generate a cropland map and intersect it with gridded data on the aggregated productivity of 16 major nutritional crops. We supplement this with a disaggregated analysis of four staple crops (maize, rice, soybean, wheat) and three cash crops (cacao, oil palm, sugarcane). We then calculate the cropland and crop production loss according to three different urbanization scenarios (low, medium, and high).

3.3. Results

Future urban expansion is highly likely to occur in areas currently under cultivation (Fig. 1). Globally, 46 Mha (medium scenario; range from low to high scenario: 43–55 Mha) of croplands in 2000 are located in areas that are expected to be urbanized by 2030, corresponding to 3.2% (3.0–3.8%) of existing cultivated land. However, urban agriculture is known to be significant in many cities. Hence, we account for urban agriculture by overlaying maps of urban areas and croplands for the year 2000, and find that, on average, 36% of all urban areas are used for crop production. We assume this percentage of urban agriculture to prevail when urban area expands but account for regional variation (for example, 41% in Asia and 32% in Africa; see Supporting Information for details). Accounting for these prevailing cropland fractions, total cropland loss amounts to 2.0% (1.8–2.4%) of the global total—around 30 Mha (27–35 Mha), with countries such as China, Vietnam, and Pakistan ranging between 5 and 10% (Table 1).

Although the aggregate impact of urban expansion on global cropland is modest, regional impacts will be acute and differentiated. In the medium urbanization scenario, Asia and Africa will experience around 80%, or roughly 24 Mha, of the total global cropland loss. The most affected regions in Africa include Egypt, Nigeria, and the region surrounding Lake Victoria Basin in Eastern Africa (Fig. 1). In Asia, the hot spots of cropland loss are river valleys and coastlines, many of which are in the vicinity of MURs, such as the Bohai Economic Rim and the Yangtze River Delta in China, or Java Island in Indonesia (Fig. 2).

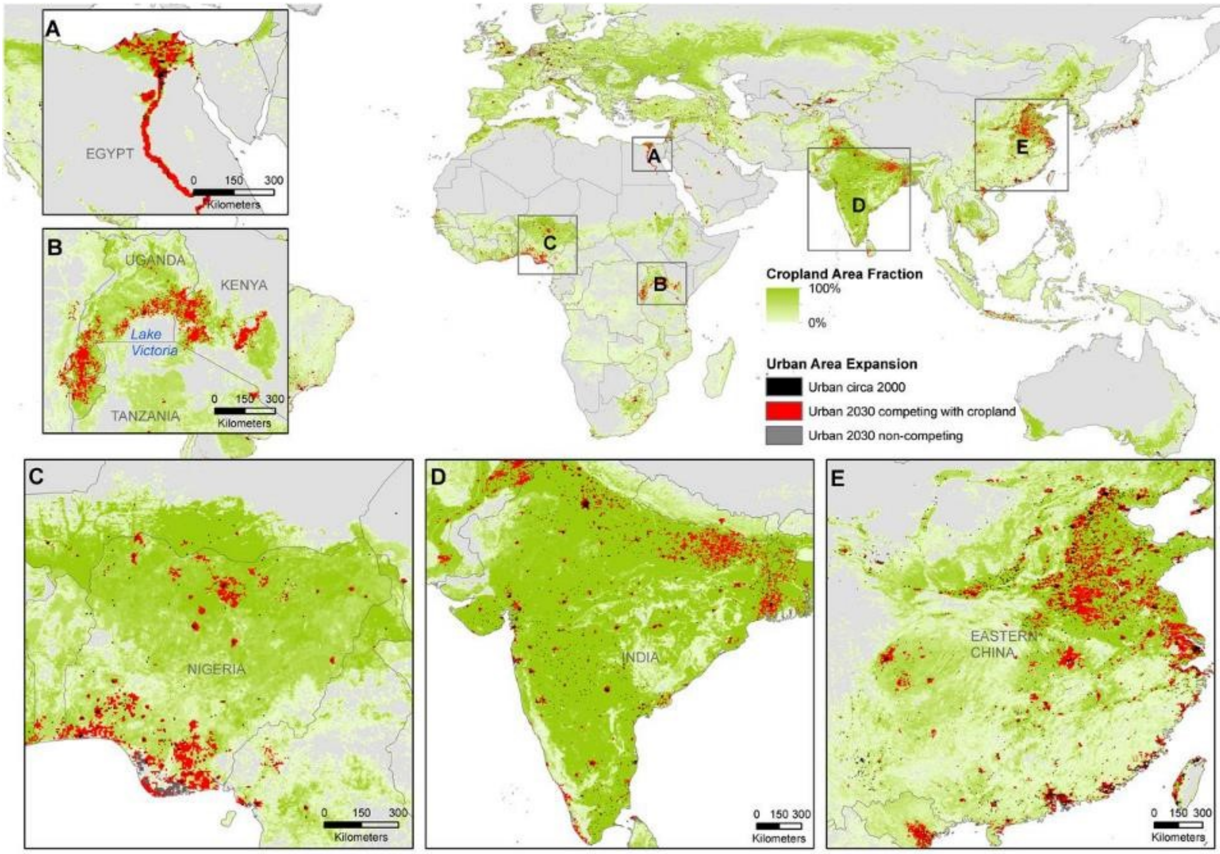

Figure 1 – Maps show where projected urban expansion until 2030 is expected to result in cropland loss. Competing areas (red) hold croplands but have a high probability (>75%; medium scenario) of becoming urbanized by 2030. (A–E) Close-ups of urban area expansion hot spots. Data on urban expansion are from Seto et al. (2012), and data on cropland are from Fritz et al. (2015).

One-fourth of total global cropland loss will occur in China. Urban expansion in China is taking place in the country's most productive farmland and over large areas. Therefore, urban expansion could pose a threat to domestic crop production. In contrast, India, the United States, and Brazil will also experience high losses in absolute terms, but here urban expansion leaves large expanses of croplands untouched, and is therefore less likely to threaten domestic crop production (Table 1).

Future urban land expansion will continue to take place on prime agricultural lands. We observe a total loss of crop production of 3.7% (3.4–4.2%) due to urban expansion. On average, the cropland lost to urban expansion is 1.77 times as productive as the average global croplands. Our results hence confirm evidence from local case studies (Ahmad et al., 2016; Bagan and Yamagata, 2014; Chen, 2007), indicating that urban agglomerations are surrounded by croplands with above average productivity.

Our analysis shows that 84% of global production losses are expected to occur in Africa and Asia (Table 1). The 3% cropland loss in Asia translates into a 6% production loss (Table 1). In Africa, the effects are tripled: a 3% cropland loss translates into a 9% crop production reduction, most of which will take place in Egypt and Nigeria. Only a few countries display urbanized cropland with below national average agricultural productivity, the United States being the most prominent example. China and India will continue to urbanize rapidly, but with different spatial patterns and development dynamics. China's croplands are concentrated along the coastal areas and in the east of the country (Fig. 1). By 2030, most of the urban land cover expansion is expected to occur in that region.

Table 1 - Regional and national implications of urban area expansion on croplands and crop production.

	Expected cropland loss	Relative cropland loss	Production loss	Production loss	Productivity in conflicting cells
	Mha	% of cropland	Tera Cal yr-1	% of total crop production	relative to domestic/regional average
World	**30 (27-35)**	**2.0 (1.8-2.4)**	**333 (308-378)**	**3.7 (3.4-4.2)**	**1.77**
Asia	18 (16-21)	3.2 (2.9-3.7)	231 (214-264)	5.6 (5.1-6.3)	1.59
Africa	6 (5-6)	2.6 (2.4-3)	49 (45-52)	8.9 (8.3-9.4)	3.32
Europe	2 (2-3)	0.5 (0.5-0.9)	17 (16-23)	1.2 (1.1-1.5)	2.18
Americas	5 (4-5)	1.2 (1.1-1.4)	35 (32-40)	1.3 (1.2-1.5)	1.09
Australasia	0.1 (0-0.1)	0.2 (0.1-0.3)	0.3 (0.1-0.3)	0.2 (0.1-0.3)	0.94
Top 10					
China	7.6 (7.1-8.6)	5.4 (5-6.1)	137 (128-153)	8.7 (8.2-9.8)	1.53
India	3.4 (3.3-3.7)	2.0 (1.9-2.2)	34 (32-38)	3.9 (3.7-4.3)	1.61
Nigeria	2.1 (1.8-2.5)	5.7 (5-6.9)	16 (15-17)	11.7 (10.7-12.6)	1.82
Pakistan	1.8 (1.7-2)	7.6 (7.2-8.6)	9 (9-10)	8.8 (8.4-9.9)	1.22
United States	1.5 (1.4-1.6)	0.8 (0.8-0.9)	11 (11-12)	0.7 (0.7-0.8)	0.90
Brazil	1.0 (0.9-1.2)	2.0 (1.7-2.4)	10 (9-12)	2.4 (2.1-2.8)	1.22
Egypt	0.8 (0.7-0.8)	34.1 (31.6-35.8)	25 (23-26)	36.5 (34-38)	1.07
Viet Nam	0.8 (0.7-0.8)	10.3 (9.3-11.2)	15 (15-17)	15.9 (15.2-17.2)	1.41
Mexico	0.7 (0.6-0.8)	1.9 (1.7-2.3)	4 (4-5)	3.7 (3.2-4.4)	1.91
Indonesia	0.6 (0.5-0.7)	1.1 (0.9-1.3)	10 (8-11)	2.3 (2-2.7)	2.03

Cropland and production losses are generated using data from refs. 4, 15, and 17. We differentiate between different urbanization probability thresholds (50, 75, and 87.5%). Depending on the corresponding threshold, we define cropland loss scenarios as follows: low (>87.5%), medium (>75%), and high (>50%). Medium-scenario results are reported, and ranges indicate low- to high-scenario results. The 10 countries with the highest absolute crop production losses are presented in descending order.

The analysis reveals relative cropland losses of 5–6% (8–9 Mha) and productivity losses of 8–10% (128–153 Pcal) between 2000 and 2030 (Table 1). Results for India are markedly different. Total urban extent in 2000 is an order of magnitude smaller than in China (3 Mha compared with 8 Mha), and absolute urban area expansion until 2030 is expected to cover one-half as much area as in China (3–4 Mha compared with 7–8 Mha). This difference in urban expansion is in large part explained by very different urbanization and urban expansion trends (United Nations, 2014). Whereas China's urban population exceeded its rural population in 2012 and is expected to be 75% of the total population by 2050, India's urban population is currently less than one-third of the total population and by 2050 will just be over one-half. Furthermore, as of 2011, 79% of India's total population resided in settlements of 100,000 or fewer, and 52% of the country lived in towns and villages with populations fewer than 5,000 (Mitra et al., 2016). This is in stark contrast to China. Although cropland loss is currently not an issue in India (about 2% by 2030; Table 1), other studies corroborate that it is likely to become more significant in the future when the country's urban expansion begins to accelerate (Pandey and Seto, 2015).

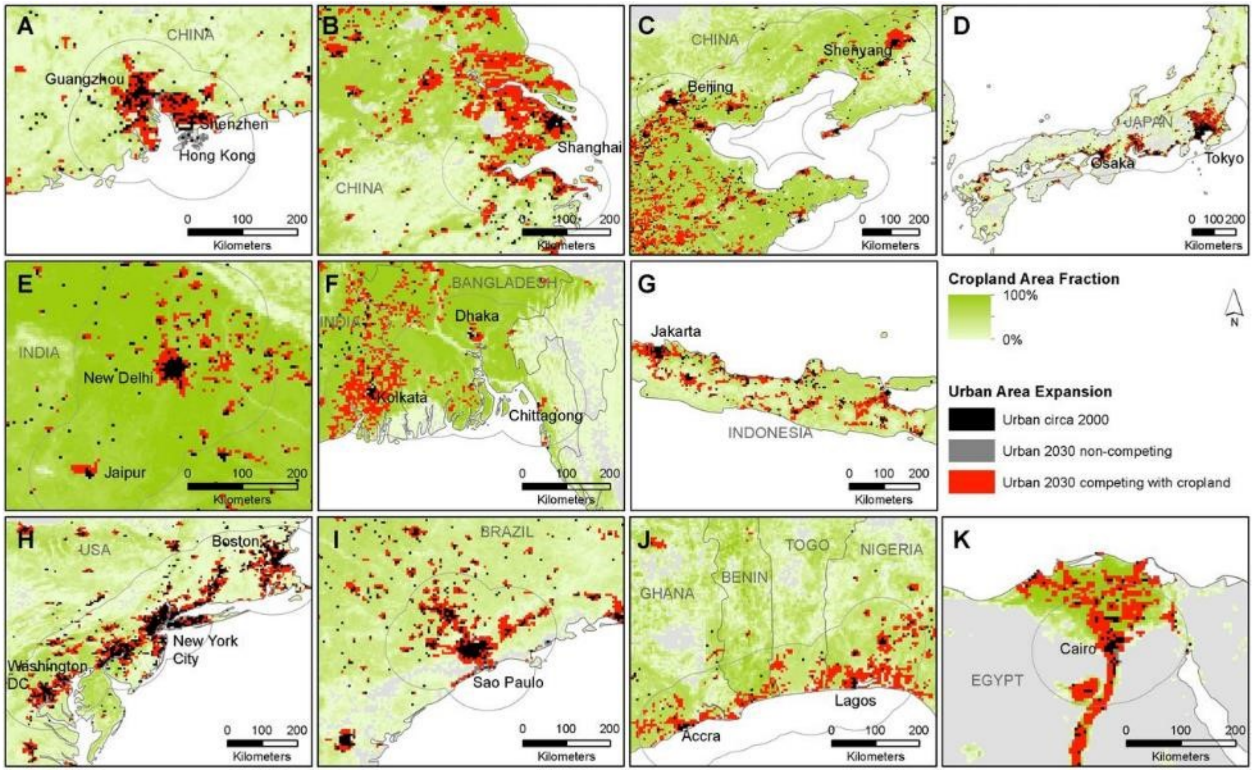

Figure 2 – Competition between croplands and urban expansion in select MURs. The maps show where projected urbanization until 2030 is expected to result in cropland loss. Competing areas (red) hold croplands but have a high probability (>75%; medium scenario) of becoming urbanized by 2030. MURs displayed are (A) Pearl River Delta, (B) Yangtze River Delta, (C) Bohai Economic Rim, (D) Tokaido Corridor, (E) Delhi National Capital Region and Jaipur, (F) Ganges-Brahmaputra Delta (Kolkata, Dhaka, and Chittagong Region), (G) Java, (H) Northeast Megalopolis, (I) Expanded Metropolitan Complex of São Paulo, (J) Greater Ibadan Lagos Accra Corridor (GILA), and (K) Greater Cairo Region. See Supporting Information for more details.

In African countries, there will be significant variation in the geographic distribution and rates of cropland loss. Croplands in less arid zones are expected to be relatively less affected by urbanization. Nigeria, Africa's most populous country, will experience high rates of urban expansion and 5–7% cropland loss (Table 1). Urban expansion will be concentrated along the continent's coastlines, whereas the majority of cropland lies inland (Fig. 1). The region around Lake Victoria will experience the highest rates of urban expansion. In particular, for Burundi and Rwanda, the high rates of expected cropland conversion to urban (∼28 and 34%) reflect the limited availability of land in those countries.

Our disaggregated analysis for individual staple crops shows their relative importance in urbanizing areas. In 2000, 4% of maize, 9% of rice, 2% of soybean, and 7% of global wheat production were grown in areas that are forecast to be urbanized (Table S1). Although the results for Europe (range between 2 and 3%), the Americas (1–2%), and Australasia (all <1%) indicate low competition for these key staples, the findings for Asia and Africa suggest significant losses of specific crops. In Asia, 10% of maize, 9% of rice, 7% of soybean, and 13% of wheat production were produced in areas that will be urbanized by 2030. In Africa, these shares range from 11% of soybean production to 26% of the continent's wheat production (14% maize, 19% rice).

We further analyzed cropland loss for a selection of MURs, defined as continuous urban regions with multiple urban centers and a combined population greater than 20 million, often expanding over 10,000 km2. Prime agricultural lands are especially vulnerable to conversion in MURs with estimated cropland losses between 0.1 and 1.2 Mha for the 11 case studies (Fig. 2 and Table S2). With the exception of the US Northeast, the productivity of the cropland converted in MUR is higher than national averages (Table S2). Notably, in MURs of India, Bangladesh, and Indonesia, the relative productivity is >2 (Fig. 2 E–G). In Chinese MURs, the relative productivity is 1.05–2.05 (Fig. 2 A–C).

To understand agricultural production patterns around these evolving MURs, we analyzed the harvested area fraction (HAF)—the ratio of harvested area of a specific crop over the total harvested area—in competing areas of the abovementioned staple crops and a selection of cash crops specific to some of the MURs (cacao, oil palm, sugarcane; Table S2). The aggregated HAF for these crops is high in most of the MURs. In the Yangtze River Delta around Shanghai, for example, the combined HAF of rice and wheat accounts for 50% of total area harvested in competing areas. In contrast, the combined HAF is very low for the United States, Brazil, and Japan, indicating that these areas are used to grow other crops such as vegetables. HAF is also low for the Greater Ibadan Lagos Accra (GILA) corridor in Western Africa, where these crops only contribute marginally to diets. The prevalence of the cash crops analyzed is comparatively low (the exception is sugarcane around Delhi with HAF of 18%).

The spatial pattern of urban expansion plays an important role in cropland loss. MURs are often characterized by multiple urban centers, with productive cropland distributed throughout the urban fabric. Although the aggregate amount of cropland in these regions may be high, each patch of cropland is relatively small and thus vulnerable to urban envelopment (Pearl River Delta, Fig. 2A). In regions with a single dominant urban center, such as Greater Delhi (Fig. 2E), urban envelopment of cropland is still contained around the urban core, with little evidence of large-scale continuous urban fabric development. Cropland in these regions will continue to be converted (Pandey and Seto, 2015), but not at the same magnitude as in multinodal urban regions.

As urban areas expand, the remaining croplands and farmers at the periurban interface experience greater competition for water and increased exposure to climate hazards. The urban expansion into the Ganges-Brahmaputra Delta, for example, has resulted in the loss of wetlands and water bodies that serve as flood protection (Dewan et al., 2012). In addition, cropland conversion led to a sinking of the delta due to a combination of sediment loading, compaction, ground water extraction, and reduced aggradation. This makes the delta increasingly vulnerable to hazards associated with climate change, such as sea level rise (Higgins et al., 2014), and threatens not only urban areas but also the remaining croplands that were largely used to feed the regional population with rice (HAF of rice >83%; Table S2).

Sea level rise and subsidence are also significant concerns for Greater Cairo, because a considerable fraction of the Nile Delta is already near or below sea level and expected to sink further (Syvitski et al., 2009). Diminishing sediment discharge due to dams in the south will increase the pressure on the delta, which will eventually decrease in size (Redeker and Kantoush, 2014). Our results show that urbanization converts precarious croplands at high rates along the Nile even though they are important for maintaining food supply of the urban centers [combined HAF for wheat and maize, 49% (Table 1 and Table S2)]. Efforts to divert urbanization away from the fertile lands into the deserts are underway but have been less effective than hoped (Redeker and Kantoush, 2014).

3.4. Discussion

Our study shows that future urban expansion is expected to convert 27–35 Mha of croplands (1.8–2.4% of global cropland and 3.4–4.2% of the yearly production) globally between 2000 and 2030, adding an additional component to the emerging global consequences of land use (Turner et al., 2007). On average, this amounts to an annual land consumption of 1 Mha, which is almost a third of the annual agricultural expansion between 1961 and 2009 of 3.38 Mha·y−1 (FAOSTAT, 2015). Our study is limited by the spatial resolution of the analysis; although higher-resolution data would generate more detailed insights, these results provide a global assessment of the patterns of likely cropland loss due to urban expansion.

3.4.1. Compensating Cropland Loss

On aggregate, the loss of cropland can be compensated by the global food system, but the effects will not be distributed equally. Many less developed and emerging countries will face acute losses, both in absolute and relative terms (Table 1 and Table S3). In principle, cropland loss could be compensated by intensifying existing production or expanding cropland. However, the domestic adaptation potential varies substantially by country and may be limited. For example, many sub-Saharan countries have ample potential for extensification and could additionally aim to close their yield gap by improving agricultural management and technology (West et al., 2014). The option to expand cropland is constrained in other regions, such as Southern Asia, where much of the suitable land is already under intense, multicropping cultivation. Expansion in these regions is likely to occur in less suitable areas, thus requiring disproportionately more land (Wirsenius et al., 2010). Other countries in arid regions, especially Northern Africa and the Middle East, have nearly reached their maximum potential (Fetzel et al., 2016). The option to expand is likely to be constrained further as climate change is expected to decrease the amount of suitable croplands throughout Africa, and Southern and Southeast Asia (Fischer et al., 2002). Climate change is also expected to adversely affect yields (Challinor et al., 2014), making it harder for countries in the tropical regions of Asia and Africa to compensate for cropland losses via intensification.

The loss of croplands and associated food production could also be offset by global agricultural markets and trade. Regardless of cropland loss to urbanization, the total volume of global trade is likely to rise, and many developing regions will see a decrease in food self-sufficiency (Erb et al., 2016). Many African countries as well as China have experienced a decline in the production-to-consumption ratio of food in the last decade, indicating rising imports (Fukase and Martin, 2016). Countries with limited extensification and intensification potential, such as Egypt, are likely to resort to trade to compensate for cropland loss, which could make them more susceptible to international food supply shocks (Bren d’Amour et al., 2016).

3.4.2. Food System Transition

Beyond the direct loss of cropland, the growth of MURs has other important implications for food systems, especially for smallholder farmers (Masters et al., 2013). Worldwide, there are about 500 million small farms and an estimated 2–2.5 billion smallholder farmers who cultivate farms of 2 ha or smaller. Large urban areas have seen a growth in supermarkets replacing locally owned or small-scale food retail stores (Hu et al., 2004; Reardon and Berdegue, 2002). This trend is occurring throughout the developing world, particularly in East Asia, where the growth of large cities and rising household incomes converge to create new demands for “modern” food retail supply chains. Additionally, supermarkets have gained greater market shares over traditional stores in big cities (Neven and Reardon, 2004). Thus, as MURs continue to grow in number and size, food retail is likely to become increasingly dominated by large supermarket chains. This has important implications for traditional retailers, small-scale producers, traditional food brokers, and the entire supply chain. In larger cities, decentralized systems of food procurement (individual stores and their buyers work directly with producers or food brokers) shift to a more centralized system focused on large distribution centers. To protect small-scale producers and traditional retailers, governments may intervene. India, for example, has strictly regulated foreign direct investment into multibrand retail (the Indian equivalent to large supermarkets). Still, there is evidence of an “emerging supermarket revolution in India” (Reardon and Minten, 2011), driven by domestic capital. The loss of local food chains might compromise food accessibility in markets as local food chains historically have shown to build resilience against price spikes (Mukherjee, 2015). Local producers typically keep prices low, to maintain customers, a mechanism supporting resilient food security (Keck and Etzold, 2013).

3.4.3. Livelihoods and Food Security

The dynamics of agricultural livelihood transformation are complex and involve dispossession of peasants by agrobusinesses (Ross, 2003). Urban land expansion also coincides with the loss of income and displacement of periurban livelihoods (Simon, 2008). However, economic development and the accompanying structural change are likely to provide sufficient job opportunities. The transformation of food supply chains around evolving cities, for example, offers ample nonfarm employment opportunities along the food chain— in processing, logistics, and wholesale (Reardon, 2015). A study from Ghana shows that more than 50% of households that lost access to agricultural land engage in trading and other activities, such as construction, whereas 28% become unemployed (Kasanga, 1998). As only 11% of households try to replace the land they had lost, the overwhelming majority would aim to enter the nonfarm labor market. Livelihood and food insecurity could become an issue for the households that do not find employment. Generally, urban food security depends not only on the availability of foods in the markets, but ultimately on the ability of households to access food on their income (Cohen and Garrett, 2010). Hence, poor urban or periurban households, entailing the displaced farmers that are unemployed, are at risk of becoming food insecure (Crush et al., 2012). There is a myriad of other factors to account for to assess whether households would be better or worse off. However, such investigations are beyond the scope of this study.

3.4.4. Governance

To meet the twin goals of urban development to house the growing urban population and preserve prime cropland, it will be imperative to guide and shape future urban expansion to more sustainable forms. Different approaches to safeguard agricultural land have been tried around the world, with different outcomes. For example, despite numerous edicts from the central government to protect agricultural land from conversion, agricultural land in China continues to be converted (Jiang et al., 2012). Regardless of approach, good governance is a necessary condition for sustainable urbanization and critical for successfully shaping urban expansion (Koroso et al., 2013). The quality of governance in countries with important cropland losses, however, tends to be medium to low in emerging economies and low for developing countries (Kaufmann et al., 2011, and table S4). A factor specific to MURs is that they often consist of multiple contiguous entities with discrete governance structures. More comprehensive governance regimes could be helpful to mitigate pressures from urbanization on food systems and ecosystems in urban hinterlands (Barthel et al., 2013).

Urban policy makers and planners play a crucial role in managing urban area expansion. Containing the expansion of urban areas is a well-established planning approach to encourage compact, public transport-oriented urban forms, crucial for securing long-term climate mitigation goals (Creutzig et al., 2016). The same approach also preserves agricultural lands in periurban areas (Daniels, 1999). However, the effectiveness of urban containment strategies around the world is mixed, and its success depends on many factors, including the willpower of policy makers, and geographic and institutional contexts (Dawkins and Nelson, 2002). An alternative approach involves selective protection of open space from urban encroachment (Angel et al., 2011). One policy instrument to use in this respect may be transfer of development rights that effectively redirects new growth from areas to be protected (e.g., prime agricultural fields) to areas where more development is desired (Johnston and Madison, 1997). However, national policy makers are also important by designing crucial economic incentives. In particular, fuel taxes have also both empirically and theoretically been shown to induce more compact urban form and preserve open space (Creutzig, 2014; Creutzig et al., 2015).

3.5. Conclusion

As Seitzinger et al. (2012) argue, “Urban regions must take an increased responsibility for motivating and implementing solutions that take into account their profound connections with and impacts on the rest of the planet.” Nowhere is this more evident than at the interface of urban areas and croplands. The next few decades will be a period of large-scale urban expansion, and in many parts of the world, this will take place on prime cropland. Our findings show that, for a few countries, the loss of cropland will significantly reduce the total share of national cropland. As most of the cropland expected to be converted is more productive than the global average, efforts will need to compensate for that loss, whether by intensifying remaining cropland or by expanding agricultural production into new areas. The results suggest that strategies and policies to effectively steer patterns of urban expansion will be critical for preserving cropland. In an increasingly interconnected world, the sustainability of urban areas cannot be considered in isolation from the sustainability of resources and livelihoods elsewhere.

3.6. Materials and Methods

We base our study on a spatially explicit urban area expansion probability dataset (Seto et al., 2012) and two gridded datasets on global croplands in 2000 (Ramankutty et al., 2008) and 2005 (Fritz et al., 2015). We use a dataset on gridded global crop yields in 2000 (Monfreda et al., 2008) to calculate the productivity of the displaced land. Yields of the 16 most important crops (listed in Supporting Information) are converted to calories and aggregated in a single dataset, weighted with area harvested. We supplement this with a disaggregated analysis of four staple crops (maize, rice, soybean, and wheat) and three cash crops (cacao, oil palm, and sugarcane). We assess the impact of urban area expansion by intersecting three distinct urbanization projections for the year 2030 with the cropland dataset for the year 2000. The resulting cropland and production loss scenarios are "low" (with a restrictive threshold including only grid cells exceeding 87.5% urbanization probability), "medium" (>75% urbanization probability), and "high" (>50% urbanization probability). As a "best guess," we assume that all grid cells with >75% probability of becoming urbanized (medium scenario) will be affected by urbanization until 2030. Please see Supporting Information for a detailed description.

Acknowledgements

We acknowledge the contribution of Ulf Weddige from the Mercator Research Institute on Global Commons and Climate Change, Graham Furniss from the University of Canterbury, and Sung Bae from the BlueFern Supercomputing Services. We thank the EarthStat team for support in data-related inquiries. Thanks to Stockholm Resilience Centre, University of Gävle, and Formas for funding S.B.; Stiftung der Deutschen Wirtschaft for funding C.B.d.; ERC-2010-stg-263522 LUISE for funding K.-H.E.; and NASA Grants NNX15AD43G and NNX11AE88G for supporting B.G. and K.C.S.

References

Ahmad, S., Avtar, R., Sethi, M., Surjan, A., 2016. Delhi's land cover change in post transit era. Cities 50, 111–118. https://doi.org/10.1016/j.cities.2015.09.003

Angel, S., Parent, J., Civco, D.L., Blei, A., Potere, D., 2011. The dimensions of global urban expansion: Estimates and projections for all countries, 2000–2050. Prog. Plan., The dimensions of global urban expansion: Estimates and projections for all countries, 2000–2050 75, 53–107. https://doi.org/10.1016/j.progress.2011.04.001

Bagan, H., Yamagata, Y., 2014. Land-cover change analysis in 50 global cities by using a combination of Landsat data and analysis of grid cells. Environ. Res. Lett. 9, 064015. https://doi.org/10.1088/1748-9326/9/6/064015

Barthel, S., Parker, J., Ernstson, H., 2013. Food and green space in cities: a resilience lens on gardens and urban environmental movements. Urban Stud. 0042098012472744.

Bren d'Amour, C., Wenz, L., Kalkuhl, M., Christoph Steckel, J., Creutzig, F., 2016. Teleconnected food supply shocks. Environ. Res. Lett. 11, 035007. https://doi.org/10.1088/1748-9326/11/3/035007

Brook, R.M., Dávila, J.D., 2000. The peri-urban interface: a tale of two cities. School of Agricultural and Forest Sciences, University of Wales.

Challinor, A.J., Watson, J., Lobell, D.B., Howden, S.M., Smith, D.R., Chhetri, N., 2014. A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Change 4, 287–291. https://doi.org/10.1038/nclimate2153

Chen, J., 2007. Rapid urbanization in China: A real challenge to soil protection and food security. CATENA, Influences of rapid urbanization and industrialization on soil resource and its quality in China 69, 1–15. https://doi.org/10.1016/j.catena.2006.04.019

Cohen, M.J., Garrett, J.L., 2010. The food price crisis and urban food (in)security. Environ. Urban. 22, 467–482. https://doi.org/10.1177/0956247810380375

Creutzig, F., 2014. How fuel prices determine public transport infrastructure, modal shares and urban form. Urban Clim. 10, 63–76.

Creutzig, F., Agoston, P., Minx, J.C., Canadell, J.G., Andrew, R.M., Le Quéré, C., Peters, G.P., Sharifi, A., Yamagata, Y., Dhakal, S., 2016. Urban infrastructure choices structure climate solutions. Nat. Clim. Change 6, 1054–1056.

Creutzig, F., Baiocchi, G., Bierkandt, R., Pichler, P.-P., Seto, K.C., 2015. Global typology of urban energy use and potentials for an urbanization mitigation wedge. Proc. Natl. Acad. Sci. 112, 6283–6288. https://doi.org/10.1073/pnas.1315545112

Crush, J., Frayne, B., Pendleton, W., 2012. The crisis of food insecurity in African cities. J. Hunger Environ. Nutr. 7, 271–292.

Daniels, T., 1999. When city and country collide: Managing growth in the metropolitan fringe. Island Press.

Dawkins, C.J., Nelson, A.C., 2002. Urban containment policies and housing prices: an international comparison with implications for future research. Land Use Policy 19, 1–12.

Dewan, A.M., Yamaguchi, Y., Rahman, M.Z., 2012. Dynamics of land use/cover changes and the analysis of landscape fragmentation in Dhaka Metropolitan, Bangladesh. GeoJournal 77, 315–330.

Erb, K.-H., Lauk, C., Kastner, T., Mayer, A., Theurl, M.C., Haberl, H., 2016. Exploring the biophysical option space for feeding the world without deforestation. Nat Commun 7.

FAOSTAT, F., 2015. Food and Agriculture Organization of the United Nations Statistics Division. Rome FAO.

FAOSTAT, F.B.S., 2005. Food and agriculture organization. URL Httpfaostat Fao Orgfaostat 1990–1993.

Fetzel, T., Niedertscheider, M., Haberl, H., Krausmann, F., Erb, K.-H., 2016. Patterns and changes of land use and land-use efficiency in Africa 1980–2005: an analysis based on the human appropriation of net primary production framework. Reg. Environ. Change 16, 1507–1520.
Fischer, G., Shah, M., Van Velthuizen, H., 2002. Climate Change and Agricultural Vulnerability, A Special Report Prepared as a Contribution to the World Summit on Sustainable Development. Int. Inst. Appl. Syst. Anal. Laxenburg Austria.
Fritz, S., See, L., McCallum, I., You, L., Bun, A., Moltchanova, E., Duerauer, M., Albrecht, F., Schill, C., Perger, C., Havlik, P., Mosnier, A., Thornton, P., Wood-Sichra, U., Herrero, M., Becker-Reshef, I., Justice, C., Hansen, M., Gong, P., Abdel Aziz, S., Cipriani, A., Cumani, R., Cecchi, G., Conchedda, G., Ferreira, S., Gomez, A., Haffani, M., Kayitakire, F., Malanding, J., Mueller, R., Newby, T., Nonguierma, A., Olusegun, A., Ortner, S., Rajak, D.R., Rocha, J., Schepaschenko, D., Schepaschenko, M., Terekhov, A., Tiangwa, A., Vancutsem, C., Vintrou, E., Wenbin, W., van der Velde, M., Dunwoody, A., Kraxner, F., Obersteiner, M., 2015. Mapping global cropland and field size. Glob. Change Biol. 21, 1980–1992. https://doi.org/10.1111/gcb.12838
Fukase, E., Martin, W., 2016. Who Will Feed China in the 21st Century? Income Growth and Food Demand and Supply in China. J. Agric. Econ. 67, 3–23.
Grimm, N.B., Faeth, S.H., Golubiewski, N.E., Redman, C.L., Wu, J., Bai, X., Briggs, J.M., 2008. Global Change and the Ecology of Cities. Science 319, 756–760. https://doi.org/10.1126/science.1150195
Higgins, S.A., Overeem, I., Steckler, M.S., Syvitski, J.P., Seeber, L., Akhter, S.H., 2014. InSAR measurements of compaction and subsidence in the Ganges-Brahmaputra Delta, Bangladesh. J. Geophys. Res. Earth Surf. 119, 1768–1781.
Hu, D., Reardon, T., Rozelle, S., Timmer, P., Wang, H., 2004. The emergence of supermarkets with Chinese characteristics: challenges and opportunities for China’s agricultural development. Dev. Policy Rev. 22, 557–586.
Jiang, L., Deng, X., Seto, K.C., 2012. Multi-level modeling of urban expansion and cultivated land conversion for urban hotspot counties in China. Landsc. Urban Plan. 108, 131–139.
Johnston, R.A., Madison, M.E., 1997. From land marks to landscapes: a review of current practices in the transfer of development rights. J. Am. Plann. Assoc. 63, 365–378.
Kasanga, K., 1998. Rapid Urbanization, Land Markets and Gender Insecurity in Peri-Urban Kumasi, Ghana. Kumasi Inst. Land Manag. Dev. UST.
Kaufmann, D., Kraay, A., Mastruzzi, M., 2011. The worldwide governance indicators: methodology and analytical issues. Hague J. Rule Law 3, 220–246.
Keck, M., Etzold, B., 2013. RESILIENCE REFUSED WASTED POTENTIALS FOR IMPROVING FOOD SECURITY IN DHAKA. Erdkunde 75–91.
Koroso, N.H., van der Molen, P., Tuladhar, A.M., Zevenbergen, J.A., 2013. Does the Chinese market for urban land use rights meet good governance principles? Land Use Policy 30, 417–426.
Masters, W.A., Djurfeldt, A.A., De Haan, C., Hazell, P., Jayne, T., Jirström, M., Reardon, T., 2013. Urbanization and farm size in Asia and Africa: Implications for food security and agricultural research. Glob. Food Secur. 2, 156–165. https://doi.org/10.1016/j.gfs.2013.07.002
Mitra, C., Pandey, B., Allen, N.B., Seto, K.C., 2016. Contemporary Urbanization in India, in: The Routledge Handbook of Urbanization and Global Environmental Change. Routledge, pp. 64–76.
Monfreda, C., Ramankutty, N., Foley, J.A., 2008. Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. Glob. Biogeochem. Cycles 22, GB1022. https://doi.org/10.1029/2007GB002947
Mukherjee, J., 2015. Beyond the urban: rethinking urban ecology using Kolkata as a case study. Int. J. Urban Sustain. Dev. 7, 131–146.

Neven, D., Reardon, T., 2004. The rise of Kenyan supermarkets and the evolution of their horticulture product procurement systems. Dev. Policy Rev. 22, 669–699.
Pandey, B., Seto, K.C., 2015. Urbanization and agricultural land loss in India: Comparing satellite estimates with census data. J. Environ. Manage., Land Cover/Land Use Change (LC/LUC) and Environmental Impacts in South Asia 148, 53–66. https://doi.org/10.1016/j.jenvman.2014.05.014
Pothukuchi, K., Kaufman, J.L., 2000. The food system: A stranger to the planning field. J. Am. Plann. Assoc. 66, 113–124.
Puma, M.J., Bose, S., Chon, S.Y., Cook, B.I., 2015. Assessing the evolving fragility of the global food system. Environ. Res. Lett. 10, 024007.
Ramankutty, N., Evan, A.T., Monfreda, C., Foley, J.A., 2008. Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. Glob. Biogeochem. Cycles 22, GB1003. https://doi.org/10.1029/2007GB002952
Reardon, T., 2015. The hidden middle: the quiet revolution in the midstream of agrifood value chains in developing countries. Oxf. Rev. Econ. Policy 31, 45–63.
Reardon, T., Berdegue, J.A., 2002. The rapid rise of supermarkets in Latin America: challenges and opportunities for development. Dev. Policy Rev. 20, 371–388.
Reardon, T., Minten, B., 2011. Surprised by supermarkets: diffusion of modern food retail in India. J. Agribus. Dev. Emerg. Econ. 1, 134–161. https://doi.org/10.1108/20440831111167155
Redeker, C., Kantoush, S.A., 2014. The Nile Delta: urbanizing on diminishing resources. Built Environ. 40, 201–212.
Ross, E.B., 2003. Malthusianism, capitalist agriculture, and the fate of peasants in the making of the modern world food system. Rev. Radic. Polit. Econ. 35, 437–461.
Seitzinger, S.P., Svedin, U., Crumley, C.L., Steffen, W., Abdullah, S.A., Alfsen, C., Broadgate, W.J., Biermann, F., Bondre, N.R., Dearing, J.A., others, 2012. Planetary stewardship in an urbanizing world: Beyond city limits. Ambio 41, 787–794.
Seto, K.C., Fragkias, M., Güneralp, B., Reilly, M.K., 2011. A meta-analysis of global urban land expansion. PloS One 6, e23777.
Seto, K.C., Guneralp, B., Hutyra, L.R., 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proc. Natl. Acad. Sci. 109, 16083–16088. https://doi.org/10.1073/pnas.1211658109
Seto, K.C., Ramankutty, N., 2016. Hidden linkages between urbanization and food systems. Science 352, 943–945. https://doi.org/10.1126/science.aaf7439
Seto, K.C., Sánchez-Rodríguez, R., Fragkias, M., 2010. The New Geography of Contemporary Urbanization and the Environment. Annu. Rev. Environ. Resour. 35, 167–194. https://doi.org/10.1146/annurev-environ-100809-125336
Simon, D., 2008. Urban Environments: Issues on the Peri-Urban Fringe. Annu. Rev. Environ. Resour. 33, 167–185. https://doi.org/10.1146/annurev.environ.33.021407.093240
Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Day, J., Vorosmarty, C., Saito, Y., Giosan, L., Nicholls, R.J., 2009. Sinking deltas due to human activities. Nat. Geosci 2, 681–686. https://doi.org/10.1038/ngeo629
The World Bank, 2015. World Development Indicators | The World Bank [WWW Document]. URL http://wdi.worldbank.org/table/3.1# (accessed 9.26.15).
Thebo, A.L., Drechsel, P., Lambin, E.F., 2014. Global assessment of urban and peri-urban agriculture: irrigated and rainfed croplands. Environ. Res. Lett. 9, 114002. https://doi.org/10.1088/1748-9326/9/11/114002

Turner, B.L., Lambin, E.F., Reenberg, A., 2007. The emergence of land change science for global environmental change and sustainability. Proc. Natl. Acad. Sci. 104, 20666–20671. https://doi.org/10.1073/pnas.0704119104
United Nations, 2014. World Urbanization Prospects: The 2014 Revision, Highlights. Department of Economic and Social Affairs. Popul. Div. U. N.
West, P.C., Gerber, J.S., Engstrom, P.M., Mueller, N.D., Brauman, K.A., Carlson, K.M., Cassidy, E.S., Johnston, M., MacDonald, G.K., Ray, D.K., Siebert, S., 2014. Leverage points for improving global food security and the environment. Science 345, 325–328. https://doi.org/10.1126/science.1246067
Wirsenius, S., Azar, C., Berndes, G., 2010. How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agric. Syst. 103, 621–638. https://doi.org/10.1016/j.agsy.2010.07.005

3.7. Supplementary Information

Data Inputs and Processing

We base our study on a spatially explicit urban area expansion probability dataset (Seto et al., 2012), projected in Goode's Homolosine Equal-Area projection. The dataset uses urban extent in 2000 as baseline and forecasts urban area expansion for the year 2030. We use two gridded datasets on global croplands in 2000 and 2005 [from EarthStat and from the International Institute for Applied Systems Analysis and the International Food Policy Research Institute, IIASA–IFPRI]. The EarthStat cropland map by Ramankutty et al. (2008) combines agricultural inventory and satellite-derived land cover data in a 5-min grid (∼10 km at the equator). We integrate a newly developed high-resolution map of global cropland from IIASA–IFPRI by Fritz et al. (2015) (∼1 km) into our analysis. Both datasets are in GCS_WGS_1984 projection. We use the EarthStat dataset on gridded global crop yields by Monfreda et al. (2008) in 2000 to calculate the productivity of the displaced land. Yields of 16 important food crops (barley, cassava, groundnut, maize, millet, oil palm, potato, rapeseed, rice, rye, sorghum, soybean, sugarbeet, sugarcane, sunflower, and wheat) are converted to calories and aggregated in a single dataset. We supplement this with a disaggregated analysis of four staple crops (maize, rice, soybean, and wheat) and three cash crops (cacao, oil palm, and sugarcane). The dataset uses GCS_WGS_1984 projection with a spatial resolution of 5 min. We reproject the urban expansion dataset to fit GCS_WGS_1984 projection. We aggregate the IIASA–IFPRI map to the same resolution as the initial urban expansion forecast by assigning the mean values of the ∼1-km pixels to the resultant ∼5-km pixel. We create separate shapefile layers for a selection of megaurban regions (MURs) by creating a 100-km buffer around the geographic centers of the most prominent urban centers of each region. For Java, we take the administrative boundaries of the island. We define MURs as continuous urban regions with multiple urban centers and a combined population greater than 20 million, often expanding over 10,000 km2 or more (with the exception of Greater Cairo). Our selection is based on our cropland loss findings and mostly entails countries from developing or emerging regions. For comparison, we supplement them with MURs from developed regions (the United States and Japan). Note: this list of MURs is not comprehensive. We further include World Bank (2015) data on poverty and FAOSTAT data from the Food and Agriculture Organization of the United Nations (2015) to supplement our findings (Table S3).

Analyzing the Cropland and Crop Production Losses

We assess the impact of urban area expansion by intersecting three distinct urbanization projections for the year 2030 with the EarthStat cropland dataset for the year 2000 (at 5-min resolution). The resulting cropland and production loss scenarios are "low" (with a restrictive threshold including only grid cells exceeding 87.5% urbanization probability), "medium" (>75% urbanization probability), and "high" (>50% urbanization probability). As a "best guess," we assume that all grid cells with >75% probability of becoming urbanized (medium scenario) will be affected by urbanization until 2030.

If the urbanization probability of a grid cell exceeds one of the predefined thresholds, it is assumed that it will be urbanized. Loss of cropland due to urban area expansion is only calculated for grid cells with a cropland area fraction >0%. The corresponding cropland areas (and corresponding production metrics) are aggregated and subsequent calculations made at national level (for the MURs at the corresponding regional level). We assume that cropland area is partially maintained within the predominantly urbanized regions to account for the potential of urban agriculture. For each country, we assume that cropland area is only lost to the extent that it exceeds the prevailing fraction of the initial cropland area. This prevailing fraction is estimated for each country by intersecting urban areas around the year 2000 with the cropland map for the year 2000. For example, if croplands cover 25% of urbanized areas in a country in 2000, we assume that 25% of the initial cropland area in the newly urbanized area is maintained, whereas the remaining cropland area is lost.

A similar procedure is applied for calculating the corresponding production losses. We use the aggregate production in urban areas in 2000 to calculate the average productivity in million calories per km2 of croplands in urban areas in 2000. This average productivity is then used to compute the crop production on the prevailing cropland in competing areas. Loss of production due to urban expansion is the total production in competing areas minus the so-computed production on the remaining croplands. We assume that the production is spread equally over the cropland of a grid cell.

For the disaggregated crop specific analysis, we abstract from calculating actual losses. Instead, we use the amount of crop production [and the average harvested area fraction (HAF) for the MURs] in competing grid cells as an indicator of the relevance of a specific crop in a specific area. We intersected the urban area expansion dataset with the production and HAF datasets of the respective crops. The HAF represents the ratio of area harvested of a specific crop over the total area harvested in a grid cell. We aggregated the production in the grid cells with an urbanization probability >75% (medium scenario) and compare it to the total production of the country/region. For the HAF, we computed the average in all competing pixel per MUR.

We cross-check our cropland loss estimates by intersecting the urban area expansion forecasts with the generated cropland map at ∼5-km resolution (Table S5), finding little to no variation on aggregate (both 29.9 Mha of total cropland loss; medium scenario). Some variation was visible in Africa and Asia (6.1 vs. 5.6, and 17 vs. 17.9, Mha, medium scenario, high- to lower-resolution analysis), which can be explained by the differences between the two cropland datasets as discussed in detail by Fritz et al. (2015).

Table S1. Disaggregated crop analysis

	Maize production in competing cells		Rice production in competing cells		Soybean production in competing cells		Wheat production in competing cells	
	Megatons	Share of total production (%)	Megatons	Share of total production (%)	Megatons	Share of total production (%)	Megatons	Share of total production (%)
World	**25.8**	**4.3**	**51.8**	**9.1**	**3.3**	**2.1**	**39.6**	**7.1**
Asia	15.1	9.6	48.2	9.2	1.7	7.0	31.9	12.9
Africa	5.1	14.1	2.9	18.8	0.1	11.2	4.0	26.0
Europe	1.0	1.5	0.1	2.2	0.1	2.8	2.7	1.6
Americas	4.6	1.4	0.6	2.2	1.5	1.1	0.9	0.9
Australasia	0.0	0.7	0.0	0.0	0.0	0.2	0.0	0.1
Top 10								
China	12.7	10.9	18.7	10.2	1.4	9.0	20.6	20.5
India	0.7	6.5	10.5	8.3	0.1	2.2	5.7	8.2
Nigeria	0.5	11.7	0.5	17.5	0.0	11.6	0.0	10.4
Pakistan	0.2	13.0	0.8	12.2	0.0	13.2	3.1	16.7
United States	2.1	0.9	0.1	0.9	0.6	0.8	0.4	0.6
Brazil	0.7	1.9	0.2	1.8	0.4	1.3	0.1	2.2
Egypt	3.8	63.3	2.3	41.2	0.0	53.3	3.7	59.5
Viet Nam	0.3	14.7	7.5	27.1	0.0	24.3	-	-
Mexico	0.9	4.9	0.0	4.3	0.0	0.9	0.2	5.4
Indonesia	0.7	7.3	4.5	9.2	0.1	9.2	-	-

Overview over the disaggregated production analysis for a selection of staple crops. Provided are the production in competing areas (medium scenario, urbanization probability >75% and Cropland Area Fraction >0%), both in total (megatons) and as share of total for the year 2000. Note: not all this production is necessarily lost. This is supposed to serve as indication of which crops are grown around urban areas.

Table S2. Mega urban regions.

MUR	Expected cropland loss	Productivity relative to regional/domestic average	Crop type	Production in competing cells	Average harvested area fraction in competing cells
	Mha			Megatons yr-1	%
Bohai Economic Rim	1.2 (1.1-1.4)	1.47	Maize	3.8	22
			Wheat	3.4	19
			Soybean	0.2	3
			Rice	0.7	3
Delhi National Capital Region and Jaipur	0.3 (0.3-0.4)	2.71	Wheat	1.1	38
			Sugarcane	9.5	18
			Rice	0.4	14
			Maize	0.0	2
Expanded Metropolitan Complex of São Paulo	0.1 (0.1-0.1)	1.68	Sugarcane	5.8	7
				0.1	2
Ganges-Brahmaputra Delta	0.6 (0.5-0.7)	2.34	Rice	3.3	83
				0.1	3
Greater Cairo	0.3 (0.3-0.3)	1.12	Maize	1.6	25
			Wheat	1.3	24
			Rice	1.1	14
			Sugarcane	3.0	3
Greater Ibadan Lagos Accra Corridor	0.5 (0.5-0.6)	1.50	Maize	0.2	10
			Cacao	0.0	8
			Oilpalm	0.3	5
Java	0.5 (0.4-0.6)	2.05	Rice	4.3	49
			Maize	0.6	11

			Soybean	0.1	4
Northeast Megalopolis	0.2 (0.2-0.2)	0.75	Maize	0.2	2
			Soybean	0.1	1
Pearl River Delta	0.2 (0.2-0.2)	1.05	Rice	0.9	23
			Sugarcane	0.9	2
Tokaido Corridor	0.1 (0.1-0.1)	1.17	Rice	0.6	7
Yangtze River Delta	0.9 (0.8-1)	2.05	Rice	6.4	35
			Wheat	1.6	15
			Soybean	0.2	3
			Maize	0.3	2

Medium scenario results are reported, ranges indicate low to high scenario results. Average productivity reported represents the medium scenario. Crop specific analysis is conducted with a sample of staple crops (maize, rice, soybean, wheat) and cash crops (cacao, oil palm, sugarcane) that are characteristic for specific MUR. Harvested area fraction is the fraction of total area harvested used to grow a specific crop. Only crops with a HAF of minimum 1% are reported.

Table S3. Governance indicators of selected countries.

Country	Control of corruption	Government Effectiveness	Regulatory Quality	Rule of Law
Brazil	47	48	51	53
China	48	63	44	42
Egypt	33	20	27	34
India	40	50	36	55
Indonesia	34	49	48	40
Japan	93	96	84	90
Mexico	30	62	67	37
Nigeria	9	15	24	12
Pakistan	21	25	28	23
United States	88	90	88	90
Viet Nam	38	51	31	44

Selection of countries based on Table 1 of the manuscript and Table S2 of the SI. Governance indicators are derived from the World Bank's World Governance Indicators (Kaufmann et al., 2011). Numbers represent percentile ranks which indicate the country's rank among all countries covered by the aggregate indicator, with 0 corresponding to lowest rank, and 100 to highest rank. Values represent three year averages for the years 2013-2015.

Table S4. Cropland and productivity loss estimates for countries.

Country	Abs cropland loss	Relative cropland loss	Abs production loss	Relative production loss	Poor Pop (< $1.90/d)	CIDR	Agricultural employment	Rural population	Agricultural value added to GDP
	('000 ha)	(%)	(Mega Cal)	(%)	(million)	(%)	(%)	(%)	(%)
Angola	1	0.04	5	0.06	7.8	50.5	48	69	18
Argentin	304	0.92	2,678	1.21	0.8	-100	10	25	10
Armenia	9	1.65	21	1.63	0.1	55.7	17	15	5
Azerbaija	14	0.71	38	0.72	0	37.7	77	73	36
Banglade	289	3.43	3,783	3.48	69.4	10.8	63	80	34
Belarus	5	0.08	12	0.06	0	1.4	-	78	54
Benin	39	1.45	0	0.00	5.6	22.2	11	42	5
Bolivia	14	0.44	37	0.35	0.8	18.7	36	82	46
Botswan	5	0.52	0	0.00	0.3	80.8	51	69	18
Brazil	1,004	2.00	9,929	2.39	10	-3	39	49	14
Bulgaria	13	0.36	79	0.40	0.2	-92.2	71	66	32
Burkina Faso	23	0.53	61	0.76	7.8	9.8	79	67	27
Burundi	177	28.07	461	26.93	8.8	21.4	64	84	31
Cambodi	31	0.80	159	1.36	0.9	-1.4	66	63	39
Cameroo	79	1.08	532	4.83	6.3	25.8	70	83	35
Central African Republic	2	0.12	8	0.49	3	21.4	57	82	38
Chad	1	0.03	2	0.05	5.2	9.6	44	63	24
Chile	62	2.65	293	2.88	0.2	38.8	13	39	3
China	7,631	5.39	136,57	8.74	152.5	2.1	31	55	14
Colombi	222	6.16	2,509	6.99	2.9	63.3	5	37	3
Congo	1	0.22	0	0.00	1.3	92.9	70	71	31
Costa	5	1.00	53	1.00	0.1	82.4	54	62	37
Côte d'Ivoire	58	0.86	108	0.87	4.2	52.4	23	29	9
Croatia	2	0.10	14	0.11	0	-12.4	72	85	26
Czech Republic	6	0.18	19	0.08	0	-44	49	69	19

Dominican	81	5.12	204	4.93	0.2	73.9	38	46	7
Ecuador	54	2.05	324	2.15	0.7	36.4	20	55	14
Egypt	774	34.08	24,717	36.53	1.5	44.2	45	58	26
El	39	4.24	231	5.54	0.2	41.8	36	33	13
Ethiopia	94	0.88	150	0.77	32.5	10.7	-	61	9
Gabon	10	2.11	14	2.07	0.1	81.9	-	89	41
Georgia	21	1.97	53	1.95	0.5	68.6	-	48	23
Ghana	210	3.54	912	4.31	6.7	26.1	-	61	55
Guatema	41	2.06	269	2.32	1.9	43	12	11	4
Guinea	1	0.09	8	0.09	4.3	13.8	29	37	10
Haiti	5	0.45	10	0.45	5.7	53.9	20	35	12
Hondura	15	0.92	70	1.03	1.5	56.5	48	49	29
Hungary	3	0.05	51	0.12	0	-81.1	34	50	12
India	3,413	2.01	33,966	3.89	275.3	-3.1	-	54	46
Indonesi	556	1.06	9,517	2.29	40.5	12.7	21	29	7
Iran	331	2.34	1,831	3.08	0.1	28.7	61	76	27
Iraq	316	5.50	239	11.39	1.4	56.8	34	65	24
Jamaica	16	5.84	38	5.77	0.1	99.5	18	43	11
Jordan	42	11.17	3	1.12	0	96.2	14	22	3
Kazakhst	10	0.04	14	0.03	0	-50.6	37	31	17
Kenya	383	7.27	979	7.67	15.1	36.4	41	42	14
Kyrgyzst	15	1.05	63	0.96	0.2	23.4	-	69	28
Laos	0	0.04	3	0.04	2	-5.1	29	42	19
Latvia	0	0.02	1	0.02	0	-72.2	49	56	28
Lesotho	4	1.24	0	0.00	1.3	78.2	34	55	12
Liberia	6	1.60	39	2.28	3.7	61.1	77	75	34
Madagascar	2	0.06	32	0.34	19.3	8.7	32	82	10
Malawi	59	4.37	390	6.77	11.8	1.6	53	73	24
Malaysia	69	0.93	2,821	0.93	0.5	76	-	64	21
Mali	6	0.13	16	0.24	8.7	4.7	1	9	8
Mauritan	2	0.22	4	0.79	0.8	74	7	27	6
Mexico	683	1.90	4,130	3.73	3.4	30.7	5	31	4
Mongoli	6	0.30	2	0.29	0	35.1	29	46	6
Morocco	198	2.16	512	2.83	2.1	36.4	10	33	4
Mozambique	9	0.21	36	0.44	16.5	27.3	28	41	21

Namibia	0	0.04	0	0.03	0.6	55.9	8	26	4
Nepal	68	2.87	591	2.77	4.2	3.9	22	45	10
Nicaragu	16	0.72	62	1.51	0.9	31.5	4	46	4
Niger	31	0.22	22	0.26	9.6	7.3	41	55	10
Nigeria	2,070	5.70	16,016	11.71	110.1	21.7	18	31	9
Pakistan	1,754	7.58	9,296	8.81	15.4	-12.2	10	5	9
Panama	1	0.12	1	0.07	0.1	71.4	-	59	-
Paraguay	10	0.34	114	0.56	0.1	-100	41	37	20
Peru	51	1.19	181	1.30	1.2	48.4	28	44	3
Philippin	252	2.90	2,851	4.84	13	21.9	18	25	7
Poland	13	0.09	81	0.09	0	-2.5	35	36	4
Russian Federati	28	0.02	65	0.03	0.1	-27.5	-	49	23
Rwanda	259	33.47	465	26.18	6.8	23.7	-	23	4
Senegal	40	1.66	97	1.86	5.6	46.9	14	25	7
Sierra Leone	2	0.41	14	0.73	3.3	19.7	54	47	10
Slovakia	7	0.48	84	0.69	0	-27.5	-	47	-
Slovenia	1	0.37	8	0.40	0	36.9	37	48	13
South Africa	265	1.77	1,477	3.21	8.9	2.8	23	31	
Sri Lanka	248	13.00	580	6.95	0.4	25.4	19	46	6
Tajikista	35	3.38	72	3.42	0.5	43.7	12	75	8
Tanzania	29	0.57	109	0.67	24.2	13.2	47	52	-
Thailand	150	0.90	1,780	1.26	0	-41.6	13	28	10
Togo	25	0.95	166	4.43	3.9	14	-	43	23
Tunisia	73	3.17	126	3.06	0.2	55.3	9	60	4
Turkey	429	1.97	2,597	2.30	0.2	0.8	7	37	10
Uganda	288	3.54	427	3.25	12.6	9.1	27	57	9
Ukraine	22	0.06	64	0.05	0	-60.3	16	35	5
Uruguay	21	1.48	23	0.39	0	-100	9	23	8
Uzbekist	450	8.76	1,355	8.75	20.9	18.2	40	58	16
Venezuel	116	3.39	412	3.23	5.2	56.6	-	79	7
Viet Nam	759	10.34	15,445	15.86	2.9	-11	17	34	9
Yemen	40	2.70	59	2.51	2.6	81.2	9	11	5
Zambia	4	0.07	9	0.18	10.1	-8.2	25	68	10

This table contains estimates of cropland loss for countries with available World Bank data on poverty (medium scenario, estimated cropland loss >0). The last columns present additional information on the structure of the population and the importance of agriculture for the respective country (FAOSTAT, 2005; The World Bank, 2015). More information on other countries is also available on request.

Table S5 - Comparison of aggregated cropland losses for different spatial resolution.

	Higher Resolution (in Mha) (3)			Lower resolution (in Mha) (2)		
	Low	Medium	High	Low	Medium	High
World	**27.3**	**29.9**	**35.4**	**27.3**	**29.9**	**35.4**
Asia	15.5	17.0	20.0	16.3	17.9	21.0
Africa	5.6	6.1	7.0	5.1	5.6	6.4
Europe	1.6	1.7	2.8	1.5	1.6	2.7
Americas	4.5	4.9	5.4	4.3	4.7	5.3
Australasia	0.0	0.1	0.2	0.0	0.1	0.1

Comparison between cropland loss calculations with the higher (approx. 5km at the equator) and the lower resolution (approx. 10km at the equator, used in main analysis) cropland products. Low, medium, high refer to the urbanization scenarios from the main analysis.

Chapter 4

4. Teleconnected food supply shocks*

Christopher Bren d'Amour
Leonie Wenz
Matthias Kalkuhl
Jan C. Steckel
Felix Creutzig

* Published in the journal *Environmental Research Letters* as C. Bren d'Amour, L. Wenz, M. Kalkuhl, J.C. Steckel, F. Creutzig: Teleconnected food supply shocks, *Environ. Res. Lett.*, 11 (2016), p. 035007.
https://doi.org/10.1088/1748-9326/11/3/035007

Teleconnected food supply shocks

Christopher Bren d'Amour*[1,2] Leonie Wenz[1,3,4] Matthias Kalkuhl[1,3] Jan C. Steckel[1,2,3] Felix Creutzig[1,2]

Abstract

The 2008–2010 food crisis might have been a harbinger of fundamental climate-induced food crises with geopolitical implications. Heat-wave-induced yield losses in Russia and resulting export restrictions led to increases in market prices for wheat across the Middle East, likely contributing to the Arab Spring. With ongoing climate change, temperatures and temperature variability will rise, leading to higher uncertainty in yields for major nutritional crops. Here we investigate which countries are most vulnerable to teleconnected supply-shocks, i.e. where diets strongly rely on the import of wheat, maize, or rice, and where a large share of the population is living in poverty. We find that the Middle East is most sensitive to teleconnected supply shocks in wheat, Central America to supply shocks in maize, and Western Africa to supply shocks in rice. Weighing with poverty levels, Sub- Saharan Africa is most affected. Altogether, a simultaneous 10% reduction in exports of wheat, rice, and maize would reduce caloric intake of 55 million people living in poverty by about 5%. Export bans in major producing regions would put up to 200 million people below the poverty line at risk, 90% of which live in Sub-Saharan Africa. Our results suggest that a region-specific combination of national increases in agricultural productivity and diversification of trade partners and diets can effectively decrease future food security risks.

Keywords: food security, trade shocks, vulnerability, climate change, teleconnections

[1] Mercator Research Institute on Global Commons and Climate Change, D-10829 Berlin, Germany
[2] Technische Universität Berlin, D-10623 Berlin, Germany
[3] Potsdam Institute for Climate Impact Research, D-14412 Potsdam, Germany
[4] Institute of Physics and Astronomy, University of Potsdam, D-14476 Potsdam, Germany
[5] Faculty of Economic and Social Sciences, University of Potsdam, D-14482 Potsdam, Germany
[*] Author to whom any correspondence should be addressed.

4.1. Introduction

The future of food security in a changing climate is of global concern. Existing analyses of the impacts of climate change on food security focus typically on food production by quantifying to what extent changing temperature and precipitation patterns affect global or country-specific crop yields (Jones and Thornton, 2003; Lobell, 2011; Lobell and Field, 2007; Nelson et al., 2010). Models have advanced substantially in refined consideration of CO2 fertilizing effects as well as nonlinearities in heat stress (Asseng et al., 2015; Challinor et al., 2014; Schlenker et al., 2013; Schlenker and Roberts, 2009). Most works conclude that, globally, average crop yields will decrease as the positive fertilizing effect is more than offset by unfavorable climate conditions. But, global warming not only influences mean total yields; recent work also highlights that crop yields become more variable (Asseng et al., 2011; Porter et al., 2014; Urban, 2012) as climatic extremes become more frequent (Rahmstorf and Coumou, 2011). Supply shocks due to adverse weather conditions may therefore become more common.

Variability in production is not per se a threat to food security. Grain storage and international trade are important tools to stabilize food supply by influencing grain supply inter-temporally or spatially. Many governments hold grain reserves for emergency or price stabilization purposes. But past efforts to liberalize grain markets (Galtier, 2013), high costs, and governance problems of public storage (Rashid et al., 2008; Rashid and Jayne, 2010) have led to a substantial reduction of public grain stocks. This reduction has only partially been compensated by speculative grain storage by private sector corporations (Fraser et al., 2015). Contrary to public storage, speculative grain storage has relatively modest stabilizing effects on price volatility as only low stock levels are profitable (Gouel, 2013). Due to missing insurance markets between consumers and stockholders, speculative grain storage tends to be too low from a social welfare perspective (Gouel 2013).

Apart from storage, international trade is able to diversify idiosyncratic production risks at comparably low costs. But, trade makes importing countries also vulnerable to teleconnected supply shocks resulting from e.g. harvest failures in distant producing regions, which limits their scope of domestic policy intervention. These supply shortages would mostly be mediated by price-effects. Several works study the transmission of prices and price volatility from international to domestic markets (Baquedano and Liefert, 2014; Kalkuhl, 2014; Kornher and Kalkuhl, 2013). Such spatially disconnected climate events and market reactions, combined with the governance obstacles to adequately respond, are considered to have played an important role in the Arab Spring (Sternberg, 2012; Werrell and Femia, 2013). Weather-related production shocks in far-distant producer regions alone have not been exceptional in 2010. However, their impact on food prices in food importing countries, exacerbated by a cascade of counter-cyclical trade policies may have altered the conditions for political change. Political and economic motives are still dominant forces of political instability, and must be addressed directly (De Châtel, 2014). But taken together, events like these can create a mixture of conditions that could provide a window of opportunity for riots and revolution in the Arab world and other countries (Bellemare, 2015).

Our article is motivated by the observation that exports of major food commodities are concentrated in few countries (table 1). For maize, for example, the global export market is largely dominated by the United States (Lobell et al., 2014), with Central American countries depending on US imports. This raises the general question whether countries that heavily rely on imports are increasingly vulnerable to localized extreme events in supplying regions, especially since trade flows have become less reliable in past years and exporting countries often applied restricting trade policies to stabilize their domestic supply at the expense of world market supply (Fellmann et al., 2014; Headey and Fan, 2008; Jensen and Anderson, 2015; Martin and Anderson, 2011).

Table 1 – Export shares of top five exporters on globally traded grains. The top five exporters of maize, rice and wheat account for more than two third of the total export volume (average for 2000–2012; source: FAOSTAT 2015).

Maize		**Rice**		**Wheat**	
Country	Share	Country	Share	Country	Share
United States	50%	Thailand	27%	United States	21%
Argentina	13%	Vietnam	16%	France	13%
Brazil	7%	India	14%	Canada	13%
France	7%	United States of America	10%	Australia	11%
China	5%	Pakistan	9%	Russia	8%
Top 5	82%	Top 5	77%	Top 5	66%

The aim of this study is to develop a methodology to identify most vulnerable countries to teleconnected food-supply shocks. There is a broad range of literature on the concept of vulnerability (see e.g. Adger 2006 for a review and Fraser et al 2013 for an exemplarily application). In this study, vulnerability is measured by two dimensions: (1) the extent to which a shock on the international grain market translates to the domestic grain market and (2) the number of poor people affected. The first dimension is relevant for policy makers as disruptions in food supply can induce turmoil and political instabilities (von Braun et al 2014). The second dimension is important for an appropriate understanding of the aggregate relevance of global market interruptions. By focusing on abrupt market shocks rather than slowly changing long-term dynamics, we take an explicit short-term perspective on events lasting several months up to one year.

Vulnerability is related to supply shocks in export markets as follows: supply shocks can be caused by harvest failures but also by policy interventions that can be partly understood as endogenous reactions to the domestic and international supply situation (von Braun et al., 2014). The extent to what supply shocks in exporting countries transmit to the caloric food availability in importing countries depends on several factors, like market share of the exporter, import deficit, diet composition and possible secondary equilibrium responses at the international market. We identify countries with critical caloric trade dependency and map these countries to the total number of people living in poverty. We then determine trade dependencies for the countries identified, by linking them to their major suppliers. Finally, we calculate the calorie-supply implications for stylized supply shock scenarios, resulting in (i) a 10% reduction in availability of grains at world export markets, and (ii) export bans of maize in the US, of wheat in Russia, and of rice in Thailand. We conclude by pointing to measures that could reduce vulnerabilities. Our analysis complements previous climate impact studies on food availability by incorporating trade-related aspects.

4.2. Methods

We define country *j*'s vulnerability V_j to tele-connected trade shocks as two dimensional vector $V_j = (\nu_j, \rho_j)$ of a supply shock transmission indicator υ_j and the number of people living below the international poverty line ρ_j. The transmission of a relative (exogenous) supply shock of crop c from exporter *i* on domestic calorie availability of importer *j*, is expressed by

$$\tilde{v}_{ijc} = \theta_{jc}\, s_{ijc}\, \mathrm{IDR}_{jc}\, w_{jc.} \qquad (1)$$

Parameter θ_{jc} indicates the endogenous market adjustment of the world export market of crop *c* and importer *j* to an exogenous relative total supply shock

[1]. The exogenous relative supply shock can be driven by a production shock (harvest) or policy shock (in particular, trade policy). The share country *i* holds on all imports of crop c of country *j* is given by s_{ijc}. The import dependency ratio IDR_{jc} represents that part of the domestic supply of crop *c* that has been produced outside country *j* itself. Finally, w_{jc} measures the share crop *c* holds on country *j*'s total calorie consumption. The higher $\tilde{v}_{ijc}$, the more vulnerable country j is to tele-connected trade shocks. To the contrary, $\tilde{v}_{ijc} \approx 0$ implies independence on tele-connected shocks.

While $s_{ijc}, \mathrm{IDR}_{jc}$ and w_{jc} can be directly obtained from available data, θ_{jc} is a behavioral response parameter that is related to the underlying economic structure of exporting and importing countries. For iso-elastic supply and demand functions,

$$\theta_{jc} = \frac{-\eta_j}{\varepsilon - \eta_j}$$

holds with $\eta_j < 0$ being the price elasticity of demand in the importing country j and ε being the price elasticity of supply in the exporting countries (see SI). Because of the uncertainties associated with the estimation of θ_{jc} and its relatively low impact on moderating tele-connected shocks in the short-run (see SI), we abstract from its role and focus in our vulnerability analysis on the simplified version of (1) that considers only first-round effects of trade shocks:

$$v_{ijc} = s_{ijc}\, \mathrm{IDR}_{jc}\, w_{jc}.$$

The crops considered here are wheat, maize and rice. The *IDR* is calculated from FAOSTAT's Food Balance Sheets (FAOSTAT, 2005) as ratio of imported crops to total domestic supply (sum of production and import, net of export); the trade shares *s* are calculated by averaging annual export data from the FAO database for the years 2007-2011. In case there are no data available for a country, we derive the information from the GTAP 8.1 dataset for 2007 (Aguiar et al., 2012)[2]. The calorie share *w* of crop *c* on total food consumption and, alternatively, on total cereals consumption is calculated from FAO's Balance Sheets. The poverty index ρ is defined as the number of people living on less than \$1.90 a day, based on World Bank data (The World Bank, 2015).

---

[1] The endogenous market adjustment rate θ_{jc} measures to what extent an exogenous relative shock in supply of exporting countries is moderated by market reactions. For example, consider a 10% aggregate supply shock in all exporting countries due to harvest failures. Reducing exports by 10% would lead to a price increase on the international market which, in turn, would increase profitability of exports. As a response, exports increase and the original supply shock of 10% is moderated to $10 \cdot \theta_{jc}$ %.

[2] Please note in this case data refer to the year 2007 only as GTAP does not provide annual time series.

In the following analysis, we decompose this transmission indicator into several components: The factor s_{ijc} measures to what extent a supply shock in exporter country *i* affects country *j*; the product $\mathrm{IDR}_{jc} \cdot w_{jc}$ measures the impact on the domestic calorie base. The different components can be addressed by different policies (see Discussion).

Subsequently, we present results related to the following analysis:

1) **Vulnerability due to caloric trade deficiency:** We identify countries with $\mathrm{IDR}_{jc} \geq \frac{1}{4}$ and $w_{jc} \geq \frac{1}{4}$ (Fig 1 and Fig 2) and add the poverty population index;
2) **Trade dependency:** The countries selected by (1) are linked to their major exporter (i.e. $\max_i\{s_{ijc}\}$) (Fig. 3) as well as the three major exporting countries (Fig. S1-S3 in SI);
3) **Continuous vulnerability mapping for specific trade shock scenarios:** We map aggregate values and variants of v_{ijc} to population below the poverty line ρ_j. Here, we include all countries with available World Bank data on poverty.

4.3. Results

The results of this study show that there are many countries with both a high dependency on a single staple crop for supply of calories and a high dependency on imports, often from a very small supplier base. Our findings indicate that countries vulnerable to supply shocks of a specific crop are often clustered geographically.

4.3.1. Countries vulnerable due to large caloric trade deficits

We find that the most vulnerable countries are mainly located in Africa. The number of vulnerable countries varies by staple crop, i.e. we identify a total of 33 vulnerable countries, 21 of which depend on wheat, seven on maize and five on rice (figure 1). Since countries with similar vulnerabilities pattern cluster geographically, major supply disruptions are likely to affect entire regions rather than just single countries.

Wheat is particularly important for diets in the Middle East and Northern Africa (MENA region) as well as some regions in Central Asia (figure 2). As most of these regions are characterized by arid desert climate and have very little suitable croplands, import dependencies are often high (>50%). Maize is an important staple crop in Central America and Southern African countries (figure 2). Both regions neighbor major producing countries (the USA and South Africa). With the exception of Malaysia and Brunei Darussalam, there are no countries in Asia that import more than 25% of their rice supply, even though rice is by far the most important staple crop of the region. The rice-consuming countries that qualify under our definition as vulnerable are instead mostly located in Western Africa.

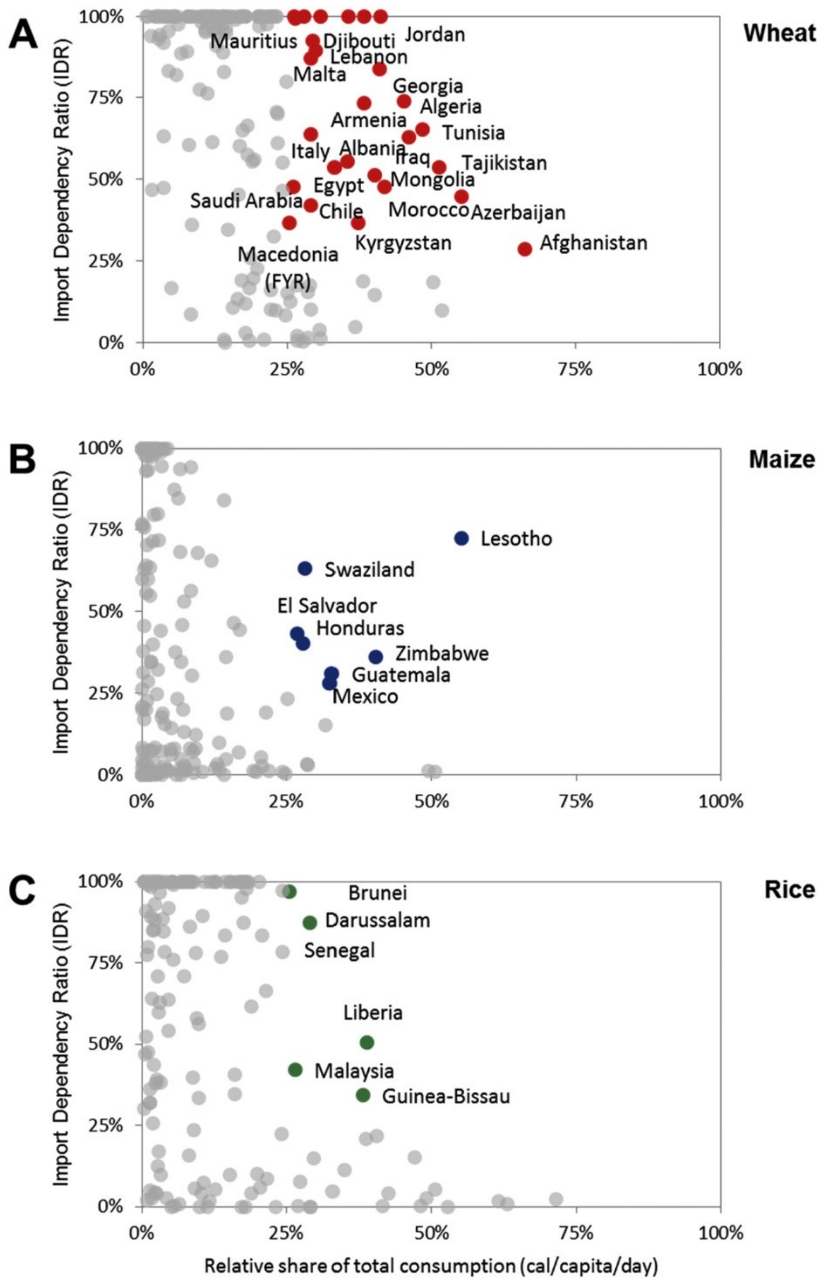

Figure 1 – Caloric trade dependency panels. The horizontal axis indicates a countries' reliance on a specific crop (w_{jc}), the vertical axis its Import Dependency Ratio (IDR_{jc}). Analyzed crops are wheat (A), maize (B), and rice (C). Countries where both ratios are $\geq$ 25% are highlighted.

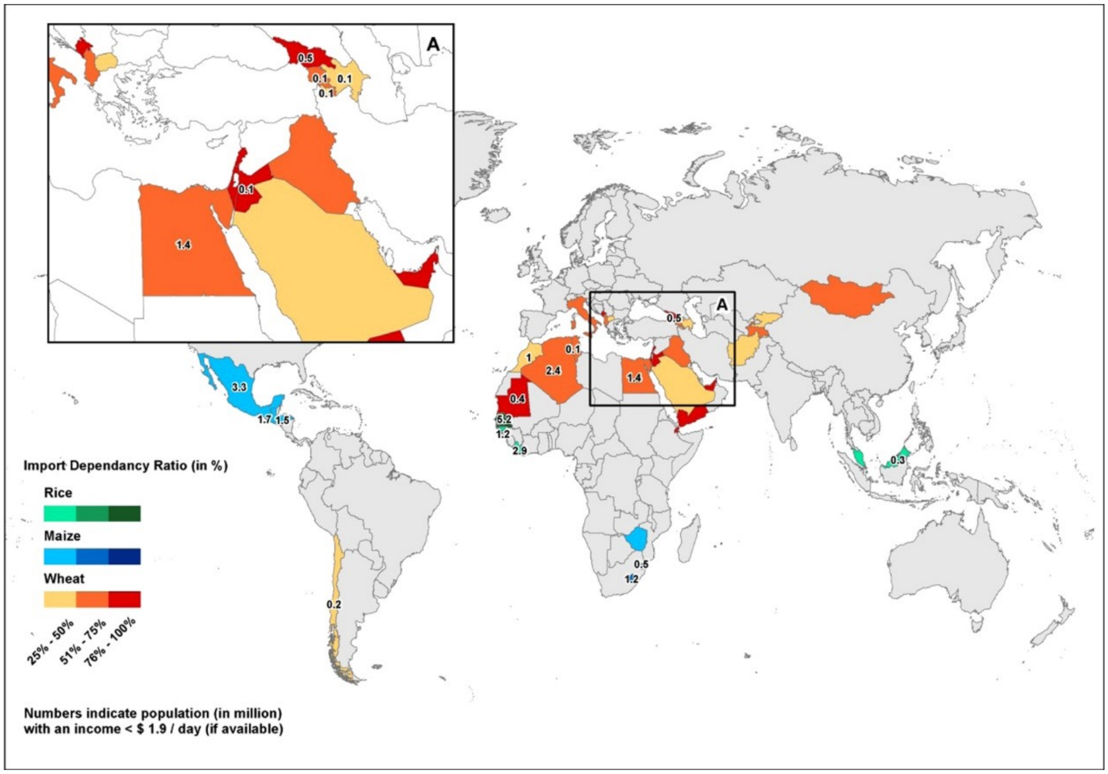

Figure 2 – Caloric trade deficits and poverty levels. Countries with an Import Dependency Ratio and dietary reliance on wheat, maize, or rice of at least 25%, respectively, are highlighted. Black numbers indicate the number of people (in million) living on less than US $1.90 a day. Panel A provides a close up of the Middle Eastern region.

4.3.2. Trade dependencies

Our results show that most of the countries identified receive their imports from just a few dominant producing countries, in some cases only a single one (figure 3). Wheat is mainly sourced from former Soviet republics (Russia, Kazakhstan, and Ukraine), Western Europe, and North America. Most MENA countries obtain the largest share of their imports from Russia and Western Europe (mostly France). The US and Canada are important suppliers for some of the Gulf States while Kazakhstan is a very important supplier for the countries in Central Asia (figure 3). Overall, Russia is the most important exporter for the countries identified (table S1).

The world market for maize is largely dominated by the US. Virtually all imports of the Central American countries come from the US. The countries in Southern Africa are the exception in that they receive almost all of their imports from the regional hegemon South Africa, the most important producer of the region (figure 3). Thailand and Vietnam dominate rice exports[3].

[3] After lifting an export ban, India's exports exceeded those of Vietnam and Thailand in 2012. These recent shifts in global trade are not considered in our analysis, which is based on the years 2007–2011.

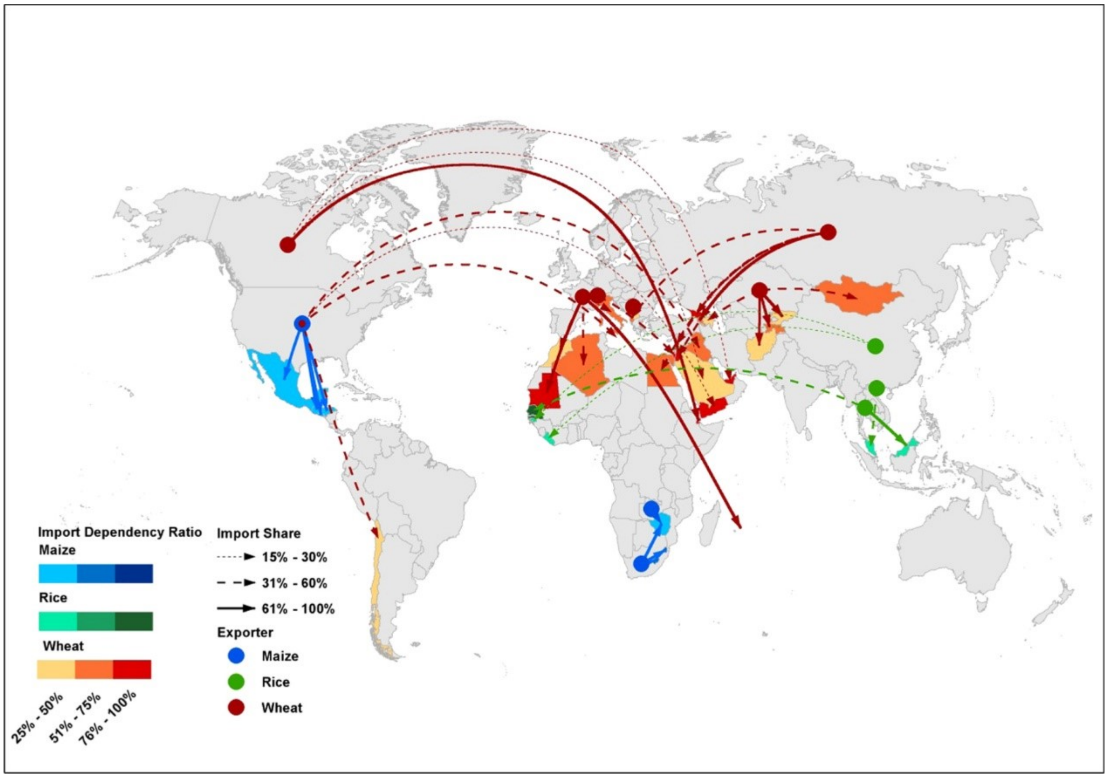

Figure 3 – Major crop import flows for caloric trade dependent countries. Countries are colored according to the crop they are importing. The color intensification signifies the import dependency ratio. Each country is linked to its major supplier via an import arrow. The thicker the arrow, the higher the share the exporting country has on the import volume of that country.

4.3.3. Continuous vulnerability mapping for specific trade shock scenarios

We now analyze how many poor people would be affected by supply-side shocks in food-producing countries. To this end we investigate the import-effects of a climate hazard that reduces global exports of maize, of wheat, and of rice by 10%, respectively, and map the cumulative effect on the population below the international poverty line (figure 4). Note that the 10% reduction can be understood as either a 10% supply shock with no market adjustment on global markets, or as a supply shock greater than 10% with an endogenous market response that leads ultimately to 10% lower global exports. Such a reduction can have different underlying causes such as production shocks or restricting trade policies in important exporting countries. We chose a 10% reduction scenario as it is easily scalable and still realistic[4]. We find that a simultaneous 10% reduction in international market supply of the three crops reduces domestic calorie supply in total food by at least 5% for 6.3 million people below the poverty line in 19 countries. When considering cereals as most important staple group, calorie supply decreases at least by 5% in 58 countries and 55 million people are affected (figure 4A). The standalone impact on the poor population of a 10% supply reduction of each of the three crops separately is comparable: almost seven million people below

[4] For example, rice exports collapsed by 12% in 2008 after various export bans (FAOSTAT 2015).

the poverty line are impacted by at least 5% (6.8 million people for wheat, 6.5 for rice, and 6.8 for maize) (figure 4B).

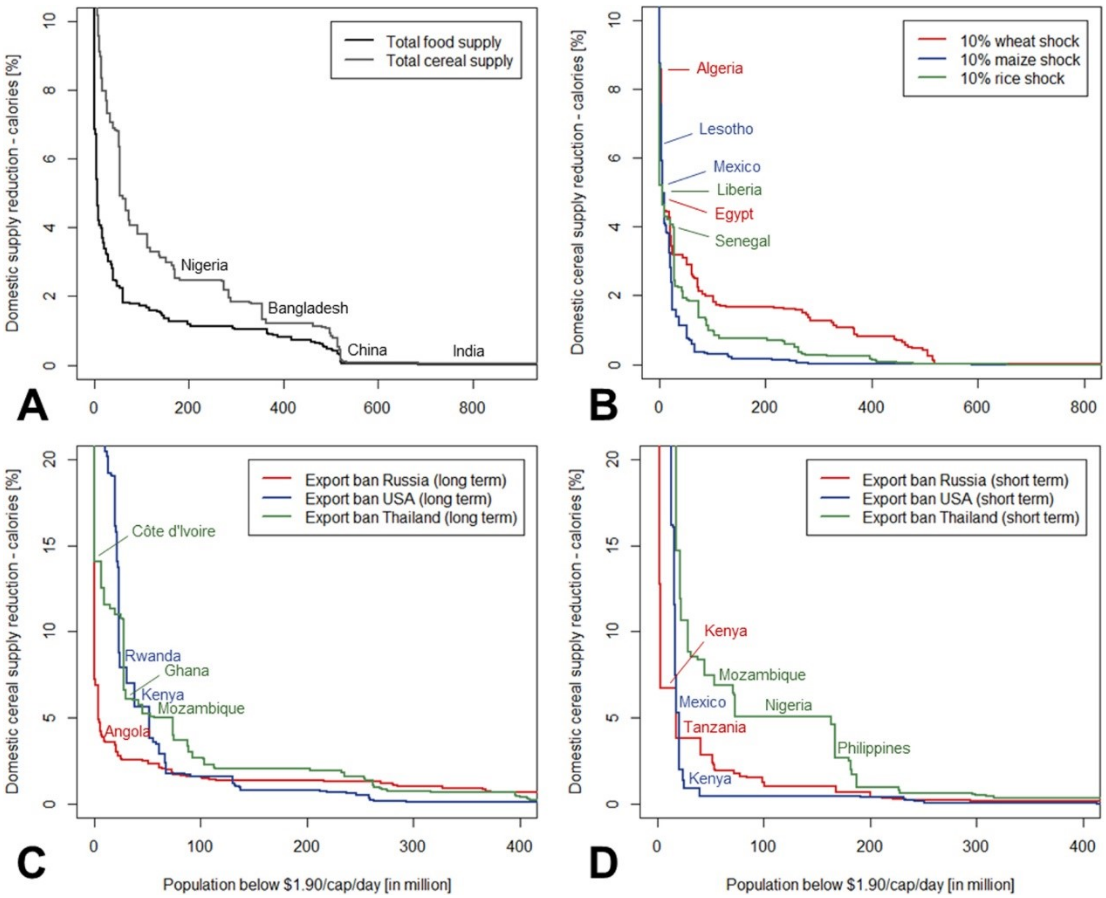

Figure 3 – Exposure of people living below the international poverty line to different supply shock scenarios. Countries are sorted in descending order with respect to the size of the effect (y-axis). The horizontal length of the graphs indicates the number of poor people living in a particular country. We exclude transit from the analysis, i.e. use net imports in our calculations. A) A 10% simultaneous reduction in trade cereals (rice, wheat maize) (formally: $V_j = (\nu_j, \rho_j)$ with $\nu_j := \sum_i \sum_c \upsilon_{ijc} \cdot 10\% = \sum_c \mathrm{IDR}_{jc}\, w_{jc} \cdot 10\%$). B) A 10% reduction for individual grains ($V_{jc} = (\nu_{jc}, \rho_j)$ with $\nu_{jc} := \sum_i \upsilon_{ijc} \cdot 10\% = \mathrm{IDR}_{jc}\, w_{jc} \cdot 10\%$). C) Long term impacts of export bans in important producing regions (a reduction of 8% in wheat, 27% in rice and 50% in maize): perfect compensation of trade flows leads to an equal distribution of shocks among all importing countries affecting all importers proportionally(formally $\bar{V}_{ij} = (\bar{\nu}_{ij}, \rho_j)$ with $\bar{\nu}_{ij} := \nu_j(1 - x_i)$). D) Short term impacts of scenario C: export bans affect only direct trade partners ($V_{ij} = (\nu_{ij}, \rho_j)$ with $\nu_{ij} := \sum_{l \neq i} \sum_c \upsilon_{ljc} = \sum_{l \neq i} \sum_c s_{ijc} \mathrm{IDR}_{jc}\, w_{jc}$). Included are all countries with available World Bank data on poverty.

Next, we consider export restrictions in major exporting countries with strong trade relations to import-dependent countries: i.e. an export restriction for wheat in Russia, for rice in Thailand, and for maize in the United States (figure 4C, D). We chose these three countries as illustration for our methodological approach which can be easily extended to other countries and scenarios[5]. In a first scenario, we model the immediate short term impacts by looking at the bilateral trade relations only (figure 4D, tables S1–3). An export ban in Russia would reduce cereal supply by more than 5% for 18 million people under the international poverty line. An export ban for maize in the USA would reduce cereal supply by at least 5% for 21 million people, mostly in the Central Americas or the Caribbean. An export ban on rice in Thailand would expose 163 million people in Sub-Saharan Africa (SSA) to a cereal supply reduction of more than 5%, 29 million of which to a reduction of 10% or more. Altogether, 200 million poor would be put at risk in the short term, most of which live in SSA (90%). Other vulnerable regions include South America (4%), Central America and the Caribbean (3%), and Northern Africa (3%).

In a second scenario, we model the impacts of such a reduction on the world markets. We consider them to be long term impacts as the supply reductions are mediated proportionally among all importing countries, independent of actual trade relations. The export ban in Russia translates into an 8% reduction in global wheat exports which in turn impacts 4.2 million people under the poverty line by at least 5%. An export ban in Thailand reduces global rice exports by 27%. We find that this reduction decreases cereal supply of 74 million by at least 5%. The impact in terms of population affected is particularly strong in SSA while we observe the highest supply reduction rates on small island states. Due to the high market concentration, an export ban on maize in the United States would curtail global exports of maize by 50%. We find that this reduction decreases cereal supply by at least 5% for 52.4 million people below the poverty line, which can be attributed to spillover effects into Africa where most of the poor live. Still, the highest reduction rates are in Middle America and the Caribbean. Cereal supply would, for instance, decrease by 25% in Mexico and by 45% in Panama. A total of 120 million poor people would be affected in this instance. We find that 76% of these people live in SSA, 11% in Central America and the Caribbean, 7% in South America, and 4% in Northern Africa.

Of the five countries with the highest absolute population below international poverty lines, namely India, China, Nigeria, Bangladesh, and the Democratic Republic of the Congo (DRC; excluded from analysis due to lack of data), which together account for about 70% of the world's poor, only Nigeria and Bangladesh show marginal impacts. India and China are not affected by teleconnected supply shocks due to their strong self-sufficiency.

4.4. Discussion

In this paper, we reported the exposure of caloric trade dependent countries to supply-side shocks. If global exports were simultaneously reduced by 10%, we find that cereal supply in 58 countries would decrease by at least 5%. Considering poverty levels, we find that—dependent on the scenario—up to 200 million poor people are potentially vulnerable to trade-related food supply shocks. While some of these supply reduction numbers seem to be small on the first sight, their implications can be substantial. Own-

[5] Russia is a large exporter and several countries' imports depend strongly on Russian exports; additionally, Russia used export bans in the past to insulate domestic markets from global markets. Thailand has been the largest rice exporter in 2000–2012 (see table 1) with a fragile political system. The US is the largest exporter of maize; although the country is unlikely to use export bans in the future, a strong reduction of exports can also result from an ambitious biofuel policy in addition to a positive oil price shock (which makes ethanol production from maize highly profitable).

price elasticities of cereal demand range from −0.5 to −0.3 for low and middle income countries (Seale et al 2003). A 5% supply reduction can therefore imply a price increase in the range of 10%–17%[6]. In the following, we will first discuss potential future implications of our results for specific staple crops, rice, wheat and maize, and will then discuss policy implications that could generally reduce vulnerability to trade-related supply shocks.

Rice appears as essential crop in our vulnerability analysis. It provides up to 50% of the calories for Asia's poor population and matures into a major staple of African diets (Muthayya et al., 2014). Our findings indicate that supply shortages have severe implications for African countries, especially in the short term. West African rice importers suffer most from unreliable international markets, notably in the short term as exemplified by an export ban in Thailand. The international rice market has historically always been dominated by few exporters, notably Thailand, Vietnam and, India, that often apply restricting trade policies to stabilize domestic markets (Dawe, 2002).

Wheat has the lowest market concentration of the three staple crops and has a relatively diverse supplier base (table 1). Yet, import dependencies are high for many countries that rely on wheat as most important calorie source (figure 1A). These preconditions lead to a high level of vulnerability to teleconnected supply shocks in the wheat market. While the yields in the major producing regions in the US and Western Europe are close to their maximum potential (West et al., 2014), wheat production in Russia remains below its high potential. Recurring droughts cause high fluctuations in actual and potential yields, especially under rainfed conditions (Schierhorn et al., 2014). In times of bad harvests, Russia is likely to introduce export restrictions to keep domestic prices stable (Fellmann et al., 2014). Global warming may further reduce wheat yields in Russia and Eastern Europe and increase their volatility (Alcamo et al., 2007). At the same time, diet shifts towards a higher relevance of meat in China (and potentially other Asian regions) accompanied by reduced food production areas due to urbanization are likely to induce a redirection of Russian wheat exports from the Middle East to China. In this scenario, the Middle East and especially Egypt would suffer dramatically from food price spikes, and food shortages.

As maize use can be flexibly directed into the food, feed or ethanol sector, demand shocks on oil markets translate stronger to food markets (Abbott, 2013; Serra and Zilberman, 2013). Ethanol mandates further constitute an inelastic demand factor which amplifies the relative magnitude of harvest shocks in terms of maize availability for non-biofuel use (Abbott 2013). Thus, particularly Central American countries, such as Mexico and El Salvador, become more susceptible to supply-side shocks in the US[7]. Additionally, global warming is projected to reduce US maize yields by up to 40%–80% compared to a scenario of no warming by the end of this century (Schlenker and Roberts 2009), affecting Central American countries even further. Not only do yields decrease, variability in harvests also increases due to the highly non-linear response of plant growth to temperature shocks.

Generally, besides natural harvest variability, sudden trade restrictions like export bans are considered to be an important factor explaining the price spikes in 2007/08 and 2010, in particular for rice in 2008 (Abbott 2012, Headey 2011) and wheat (Fellmann et al 2014). So far, neither the international community,

[6] An own-price elasticity of −0.3 implies a 0.3% demand reduction in reaction to a 1% price increase. In turn, a 5% reduction in demand would lead to a 17% price increase (or 10% increase for an own-price elasticity of −0.5). Contrary, supply elasticities for food crops range from 0.02 (rice) to 0.27 (maize) (Haile et al 2016).

[7] As biofuel production diverts crops and agricultural land away from food production to non-food uses, it tends to reduce total availability of food which might also have adverse distributional impacts (Fraser et al 2016).

nor the WTO, nor the G20 have developed an effective mechanism to prevent such beggar-they-neighbor behavior (Bouët and Debucquet, 2016). Hence, there remain substantial risks of future trade disruptions by exporting countries, depending on domestic and world market prices as well as their prevailing political situation.

Different measures besides poverty reduction could reduce this vulnerability: (i) reducing the scale of supply shocks in exporting countries, (ii) increasing the endogenous market response to shocks, (iii) reducing the trade share from volatile exporting countries, (iv) diversifying diets away from internationally traded and volatile grains, and (v) reducing import dependency. All of these measures are associated to additional costs and benefits. While equation (1) allows to systematically address these measures, a full discussion and assessment lies beyond the scope of this paper. A brief discussion is provided in the following.

The use of food crops or agricultural land for biofuel production has been identified as a major concern for food security (Creutzig et al., 2015; Fraser et al., 2016; Tilman et al., 2009), reducing the supply of major exporting countries (ad i). Biofuel policies are considered to have contributed to price increases of several food crops in 2007/08 (Wright, 2014).

Endogenous market response (ad ii) can be augmented with increased use of multi-seasonal cropping regimes, in particular in tropical and subtropical regions (potentially facilitated by irrigation). Multiple harvesting seasons enable a relatively quick response to global scarcities. An additional measure would be higher storage capacities, which would increase inter-temporal flexibility.

Diversification of imports (ad iii) can substantially reduce vulnerability to bi-lateral trade shocks but is of little effectiveness for global supply shocks. Also, diversification can be costly if it implies imports from far-distant exports. With respect to diets (ad iv), increasing incomes are expected to lead to more dietary diversification, i.e. towards higher protein consumption (ad iv). However, recent trends of wheat, maize, and rice consumption point to continuous demand growth for these crops and a streamlining of diets in developing regions at the cost of scarcely traded crops such as millet (Kearney, 2010). This could imply an increasing exposure to world market volatility.

The scarcity of water and arable land is one reason for the high import dependency (ad v) in the MENA region. A good fiscal situation in many of the mostly oil exporting Gulf States allows to cover potentially harmful consequences of these problematic preconditions (Lampietti et al., 2011). Countries with fiscal deficits however, which are mostly found in Northern Africa, have shown to be very vulnerable to food price increases (Werrell and Femia 2013) even though the region has a low share of population living below international poverty lines.

Finally, even though most of the global poor live in SSA, it has not been identified to be particularly vulnerable in our study (with the exception of rice in Western African countries). It however constitutes a special case as the three crops analyzed in this study contribute only 31% to the calories consumed by the poor in SSA (Lobell et al., 2008) whereas they represent roughly half of the calories consumed by the world's poor in general. The most important calorie providers in most of SSA are other cereals like millet and sorghum, starchy roots, and pulses, which are almost exclusively grown domestically. Hence, major trade dependencies do not exist yet. However, as income levels rise, per capita consumption of wheat, maize, and rice is expected to increase rapidly in SSA, while the consumption of e.g. millet is expected to decrease (Kearney 2010). Most of the increase in wheat consumption is expected to come from non-SSA countries (Mason et al., 2012). At the same time, research indicates that SSA and South Asia will likely suffer from negative climate impacts on several crops that are important for food security (Lobell *et al 2008*), which could also lead to higher reliance on imported staples.

4.5 Conclusion

This study indicates that the problematic confluence of strong and mostly bilateral import dependence and a high dietary reliance on specific crops is a common occurrence and is often regionally concentrated. Climate change is likely to further aggravate the situation.

Import dependent countries can implement measures to prevent extreme food shortages, and mediate food import dependency, some of which have been discussed. First, closing yield gaps can reduce reliance on international markets especially for African countries (West et al 2014), but may also involve high costs and face limitations by land and water constraints as, for example, in Egypt. Second, diversification of trading partners but also of diets can reduce risks to sudden supply shocks. Third, regional trade agreements combined with regional grain emergency reserves can be a promising tool to stabilize food supply at low costs (Kornher and Kalkuhl, 2016). It depends on the specific characteristics of each country, which of these strategies, or which combination of strategies, will be optimal.

Acknowledgements

We thank Ulf Weddige for support with designing the figures. Jan Steckel and Leonie Wenz gratefully acknowledge financial support from Deutsche Forschungsgemeinschaft Collaborative Research Center 1026 and Deutsche Bundesstiftung Umwelt, Christopher Bren d'Amour financial support from Stiftung der Deutschen Wirtschaft. We thank Ottmar Edenhofer for his valuable comments and support.

References

Abbott, P., 2013. Biofuels, binding constraints and agricultural commodity price volatility. National Bureau of Economic Research.

Adger, W.N., 2006. Vulnerability. Glob. Environ. Change 16, 268–281.

Aguiar, A., McDougall, R., Narayanan, B., 2012. Global trade, Assistance, and production: the GTAP 8 data base. Cent. Glob. Trade Anal. Purdue Univ.

Alcamo, J., Dronin, N., Endejan, M., Golubev, G., Kirilenko, A., 2007. A new assessment of climate change impacts on food production shortfalls and water availability in Russia. Glob. Environ. Change 17, 429–444. https://doi.org/10.1016/j.gloenvcha.2006.12.006

Asseng, S., Ewert, F., Martre, P., Rötter, R.P., Lobell, D.B., Cammarano, D., Kimball, B.A., Ottman, M.J., Wall, G.W., White, J.W., Reynolds, M.P., Alderman, P.D., Prasad, P.V.V., Aggarwal, P.K., Anothai, J., Basso, B., Biernath, C., Challinor, A.J., De Sanctis, G., Doltra, J., Fereres, E., Garcia-Vila, M., Gayler, S., Hoogenboom, G., Hunt, L.A., Izaurralde, R.C., Jabloun, M., Jones, C.D., Kersebaum, K.C., Koehler, A.-K., Müller, C., Naresh Kumar, S., Nendel, C., O'Leary, G., Olesen, J.E., Palosuo, T., Priesack, E., Eyshi Rezaei, E., Ruane, A.C., Semenov, M.A., Shcherbak, I., Stöckle, C., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Thorburn, P.J., Waha, K., Wang, E., Wallach, D., Wolf, J., Zhao, Z., Zhu, Y., 2015. Rising temperatures reduce global wheat production. Nat. Clim. Change 5, 143–147. https://doi.org/10.1038/nclimate2470

Asseng, S., Foster, I., Turner, N.C., 2011. The impact of temperature variability on wheat yields. Glob. Change Biol. 17, 997–1012. https://doi.org/10.1111/j.1365-2486.2010.02262.x

Baquedano, F.G., Liefert, W.M., 2014. Market integration and price transmission in consumer markets of developing countries. Food Policy 44, 103–114.

Bellemare, M.F., 2015. Rising food prices, food price volatility, and social unrest. Am. J. Agric. Econ. 97, 1–21.

Bouët, A., Debucquet, D.L., 2016. Food Crisis and Export Taxation: Revisiting the Adverse Effects of Noncooperative Aspect of Trade Policies, in: Food Price Volatility and Its Implications for Food Security and Policy. Springer, pp. 167–179.

Challinor, A.J., Watson, J., Lobell, D.B., Howden, S.M., Smith, D.R., Chhetri, N., 2014. A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Change 4, 287–291. https://doi.org/10.1038/nclimate2153

Creutzig, F., Ravindranath, N.H., Berndes, G., Bolwig, S., Bright, R., Cherubini, F., Chum, H., Corbera, E., Delucchi, M., Faaij, A., Fargione, J., Haberl, H., Heath, G., Lucon, O., Plevin, R., Popp, A., Robledo-Abad, C., Rose, S., Smith, P., Stromman, A., Suh, S., Masera, O., 2015. Bioenergy and climate change mitigation: an assessment. GCB Bioenergy 7, 916–944. https://doi.org/10.1111/gcbb.12205

Dawe, D., 2002. The changing structure of the world rice market, 1950–2000. Food Policy 27, 355–370.

De Châtel, F., 2014. The role of drought and climate change in the Syrian uprising: Untangling the triggers of the revolution. Middle East. Stud. 50, 521–535.

FAOSTAT, F., 2015. Food and Agriculture Organization of the United Nations Statistics Division. Rome FAO.

FAOSTAT, F.B.S., 2005. Food and agriculture organization. URL Httpfaostat Fao Orgfaostat 1990–1993.

Fellmann, T., Hélaine, S., Nekhay, O., 2014. Harvest failures, temporary export restrictions and global food security: the example of limited grain exports from Russia, Ukraine and Kazakhstan. Food Secur. 6, 727–742.

Fraser, E., Legwegoh, A., KC, K., CoDyre, M., Dias, G., Hazen, S., Johnson, R., Martin, R., Ohberg, L., Sethuratnam, S., Sneyd, L., Smithers, J., Van Acker, R., Vansteenkiste, J., Wittman, H., Yada, R., 2016. Biotechnology or organic? Extensive or intensive? Global or local? A critical review of

potential pathways to resolve the global food crisis. Trends Food Sci. Technol. 48, 78–87. https://doi.org/10.1016/j.tifs.2015.11.006
Fraser, E.D., Legwegoh, A., Krishna, K., 2015. Food stocks and grain reserves: evaluating whether storing food creates resilient food systems. J. Environ. Stud. Sci. 5, 445–458.
Fraser, E.D., Simelton, E., Termansen, M., Gosling, S.N., South, A., 2013. "Vulnerability hotspots": Integrating socio-economic and hydrological models to identify where cereal production may decline in the future due to climate change induced drought. Agric. For. Meteorol. 170, 195–205.
Galtier, F., 2013. Managing food price instability: Critical assessment of the dominant doctrine. Glob. Food Secur. 2, 72–81. https://doi.org/10.1016/j.gfs.2013.02.001
Gouel, C., 2013. Optimal food price stabilisation policy. Eur. Econ. Rev. 57, 118–134. https://doi.org/10.1016/j.euroecorev.2012.10.003
Headey, D., Fan, S., 2008. Anatomy of a crisis: the causes and consequences of surging food prices. Agric. Econ. 39, 375–391. https://doi.org/10.1111/j.1574-0862.2008.00345.x
Jensen, H.G., Anderson, K., 2015. Grain price spikes and beggar-thy-neighbor policy responses: A global economywide analysis. World Bank Econ. Rev. 31, 158–175.
Jones, P.G., Thornton, P.K., 2003. The potential impacts of climate change on maize production in Africa and Latin America in 2055. Glob. Environ. Change 13, 51–59. https://doi.org/10.1016/S0959-3780(02)00090-0
Kalkuhl, M., 2014. How Strong Do Global Commodity Prices Influence Domestic Food Prices in Developing Countries? A Global Price Transmission and Vulnerability Mapping Analysis. Glob. Price Transm. Vulnerability Mapp. Anal. May 2014 ZEF-Discuss. Pap. Dev. Policy.
Kearney, J., 2010. Food consumption trends and drivers. Philos. Trans. R. Soc. Lond. B Biol. Sci. 365, 2793–2807. https://doi.org/10.1098/rstb.2010.0149
Kornher, L., Kalkuhl, M., 2016. The costs and benefits of regional cooperation on grain reserves: the case of ECOWAS, in: Food Price Volatility and Its Implications for Food Security and Policy. Springer, pp. 353–384.
Kornher, L., Kalkuhl, M., 2013. Food price volatility in developing countries and its determinants. Q. J. Int. Agric. 52, 277–308.
Lampietti, J.A., Michaels, S., Magnan, N., McCalla, A.F., Saade, M., Khouri, N., 2011. A strategic framework for improving food security in Arab countries. Food Secur. 3, 7–22.
Lobell, D.B., 2011. Climate trends and global crop production since 1980. Science 333, 616–620. https://doi.org/10.1126/science.1204531
Lobell, D.B., Burke, M.B., Tebaldi, C., Mastrandrea, M.D., Falcon, W.P., Naylor, R.L., 2008. Prioritizing Climate Change Adaptation Needs for Food Security in 2030. Science 319, 607–610. https://doi.org/10.1126/science.1152339
Lobell, D.B., Field, C.B., 2007. Global scale climate–crop yield relationships and the impacts of recent warming. Environ. Res. Lett. 2, 014002. https://doi.org/10.1088/1748-9326/2/1/014002
Lobell, D.B., Roberts, M.J., Schlenker, W., Braun, N., Little, B.B., Rejesus, R.M., Hammer, G.L., 2014. Greater Sensitivity to Drought Accompanies Maize Yield Increase in the U.S. Midwest. Science 344, 516–519. https://doi.org/10.1126/science.1251423
Martin, W., Anderson, K., 2011. Export restrictions and price insulation during commodity price booms. Am. J. Agric. Econ. 94, 422–427.
Mason, N.M., Jayne, T.S., Shiferaw, B.A., 2012. Wheat consumption in sub-Saharan Africa: Trends, drivers, and policy implications. Michigan State University, Department of Agricultural, Food, and Resource Economics.
Muthayya, S., Sugimoto, J.D., Montgomery, S., Maberly, G.F., 2014. An overview of global rice production, supply, trade, and consumption. Ann. N. Y. Acad. Sci. 1324, 7–14.

Nelson, G.C., Rosegrant, M.W., Palazzo, A., Gray, I., Ingersoll, C., Robertson, R., Tokgoz, S., Zhu, T., Sulser, T.B., Ringler, C., Msangi, S., You, L., 2010. Food Security, Farming, and Climate Change to 2050: Scenarios, Results, Policy Options. Intl Food Policy Res Inst.

Porter, J.R., Xie, L., Challinor, A.J., Cochrane, K., Howden, S.M., Iqbal, M.M., Lobell, D.B., Travasso, M.I., 2014. Food Security and Food Production Systems, in: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (Eds.)]. Cambridge University Press.

Rahmstorf, S., Coumou, D., 2011. Increase of extreme events in a warming world. Proc. Natl. Acad. Sci. 108, 17905–17909. https://doi.org/10.1073/pnas.1101766108

Rashid, S., Gulati, A., Cummings Jr, R.W., 2008. From parastatals to private trade: Lessons from Asian agriculture. Intl Food Policy Res Inst.

Rashid, S., Jayne, T.S., 2010. Risk Management in African Agriculture, in: A Review of Experiences. Paper Prepared for the Fourth African Agricultural Markets Program (AAMP) Policy Symposium, Agricultural Risks Management in Africa: Taking Stock of What Has and Hasn't Worked. pp. 6–10.

Schierhorn, F., Faramarzi, M., Prishchepov, A.V., Koch, F.J., Müller, D., 2014. Quantifying yield gaps in wheat production in Russia. Environ. Res. Lett. 9, 084017. https://doi.org/10.1088/1748-9326/9/8/084017

Schlenker, W., Roberts, M.J., 2009. Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. Proc. Natl. Acad. Sci. 106, 15594–15598. https://doi.org/10.1073/pnas.0906865106

Schlenker, W., Roberts, M.J., Lobell, D.B., 2013. US maize adaptability. Nat. Clim. Change 3, 690–691. https://doi.org/10.1038/nclimate1959

Serra, T., Zilberman, D., 2013. Biofuel-related price transmission literature: A review. Energy Econ. 37, 141–151.

Sternberg, T., 2012. Chinese drought, bread and the Arab Spring. Appl. Geogr. 34, 519–524. https://doi.org/10.1016/j.apgeog.2012.02.004

The World Bank, 2015. World Development Indicators | The World Bank [WWW Document]. URL http://wdi.worldbank.org/table/3.1# (accessed 9.26.15).

Tilman, D., Socolow, R., Foley, J.A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., 2009. Beneficial biofuels—the food, energy, and environment trilemma. Science 325, 270.

Urban, D., 2012. Projected temperature changes indicate significant increase in interannual variability of U.S. maize yields. Clim. Change 112, 525–533. https://doi.org/10.1007/s10584-012-0428-2

von Braun, J., Algieri, B., Kalkuhl, M., 2014. World food system disruptions in the early 2000s: causes, impacts and cures. World Food Policy 1.

Werrell, C.E., Femia, F., 2013. The Arab spring and climate change: A climate and security correlations series.

West, P.C., Gerber, J.S., Engstrom, P.M., Mueller, N.D., Brauman, K.A., Carlson, K.M., Cassidy, E.S., Johnston, M., MacDonald, G.K., Ray, D.K., Siebert, S., 2014. Leverage points for improving global food security and the environment. Science 345, 325–328. https://doi.org/10.1126/science.1246067

Wright, B., 2014. Global biofuels: key to the puzzle of grain market behavior. J. Econ. Perspect. 28, 73–97.

4.6. Supplementary Information

Table S1: List of all countries strongly depending on wheat imports ($IDR_{jc} \geq 1/4$ and $w_{jc} \geq 1/4$) and their three largest suppliers*.

Country	Largest supplier	2nd largest supplier	3rd largest supplier	Data Source	Annotations
Afghanistan	Kazakhstan (75%)	Pakistan (9%)	Tajikistan (5%)	FAO	
Albania	Russia (55%)	France (9%)	Hungary (6%)	FAO	
Algeria	France (57%)	Mexico (8%)	Canada (8%)	FAO	
Armenia	Russia (81.22%)	Georgia (10.16%)	Ukraine (3.65%)	GTAP	
Azerbaijan	Kazakhstan (53%)	Russia (37%)	Ukraine (6%)	FAO	
Chile	USA (52%)	Canada (23%)	Argentina (22%)	FAO	
Djibouti	Canada (78.33%)	Russia (13.96%)	Germany (2.18%)	GTAP	Agg.: Rest of Eastern Africa
Egypt	Russia (36%)	USA (22%)	France (9%)	FAO	
Georgia	Russia (54%)	Kazakhstan (28%)	Ukraine (8%)	FAO	
Iraq	USA (42.39%)	Russia (31.18%)	Canada (12.52%)	GTAP	Agg.: Rest of Western Africa
Israel	Switzerland (32%)	Netherlands (21%)	USA (19%)	FAO	
Italy	France (28%)	Canada (12%)	USA (8%)	FAO	
Jordan	Russia (39%)	Ukraine (21%)	Syria (19%)	FAO	
Kyrgyzstan	Kazakhstan (96%)	Uzbekistan (2%)	Russia (1%)	FAO	
Lebanon	Russia (44%)	Kazakhstan (14%)	Ukraine (13%)	FAO	
Malta	USA (37%)	Latvia (11%)	France (9%)	FAO	
Mauritania	France (63%)	Russia (6%)	Uruguay (6%)	FAO	
Mauritius	France (72.83%)	USA (25.54%)	Argentina (0.71%)	GTAP	
Mongolia	Kazakhstan (36%)	Russia (35%)	USA (27%)	FAO	
Montenegro	Serbia (43%)	France (20%)	Russia (15%)	FAO	
Morocco	France (40%)	Canada (14%)	USA (12%)	FAO	
Republic of Macedonia	Croatia (46.42%)	Hungary (25.51%)	Rest of Europe (15.43%)	GTAP	Agg.: Rest of Europe
Saint Lucia	Saint Vincent and the Grenadines (89%)	Grenada (11%)		FAO	
Saudi Arabia	Canada (24%)	Germany (18%)	Ukraine (13%)	FAO	
Tajikistan	Kazakhstan (96.56%)	Russia (3.32%)	Ukraine (0.05%)	GTAP	Agg.: Rest of Former Soviet Union
Tunisia	Ukraine (18%)	Russia (15%)	Italy (9%)	FAO	
United Arab Emirates	Canada (21%)	Germany (20%)	Argentina (13%)	FAO	
Yemen	USA (18%)	Australia (16%)	Russia (13%)	FAO	

Table S2: List of all countries strongly depending on maize imports ($IDR_{jc} \geq 1/4$ and $w_{jc} \geq 1/4$) and their three largest suppliers*.

Country	Largest supplier	2nd largest supplier	3rd largest supplier	Data source	Annotations
El Salvador	USA (89%)	Mexico (8%)	Nicaragua (1%)	FAO	
Guatemala	USA (99%)	Mexico (1%)		FAO	
Honduras	USA (99%)			FAO	
Lesotho	South Africa (97.43%)	Zambia (2.33%)	Kenya (0.03%)	GTAP	Agg.: Rest of South Africa Customs Union
Mexico	USA (97%)	South Africa (2%)		FAO	
Swaziland	South Africa (100%)			FAO	
Zimbabwe	South Africa (66%)	Zambia (26%)	Malawi (6%)	FAO	

Table S3: List of all countries strongly depending on rice imports ($IDR_{jc} \geq 1/4$ and $w_{jc} \geq 1/4$) and their three largest suppliers*.

Country	Largest supplier	2nd largest supplier	3rd largest supplier	Data source	Annotations
Brunei Darussalam	Thailand (93.47%)	Viet Nam (1.65%)	China (1.52%)	GTAP	Agg.: Rest of South-East Asia
Guinea-Bissau Liberia	China (20.69%)	Thailand (17.88)	Senegal (15.65%)	GTAP	Agg.: Rest of Western Africa
Malaysia	Vietnam (55%)	Thailand (35%)	Pakistan (7%)	FAO	
Senegal	Thailand (45%)	Vietnam (15%)	Brazil (10%)	FAO	

***** For some of the countries in question GTAP 8.1 provides export data only on an aggregate level (as e.g. Rest of Western Africa). Further, maize is not a separate sector but part of the sector group Other Grains that also comprises barley, rye, oats and other cereals. Further, GTAP holds data for the year 2007only whereas the information derived from FAO represents five-year averages (2007-2012). Source: FAOSTAT Food Balance Sheets and GTAP.

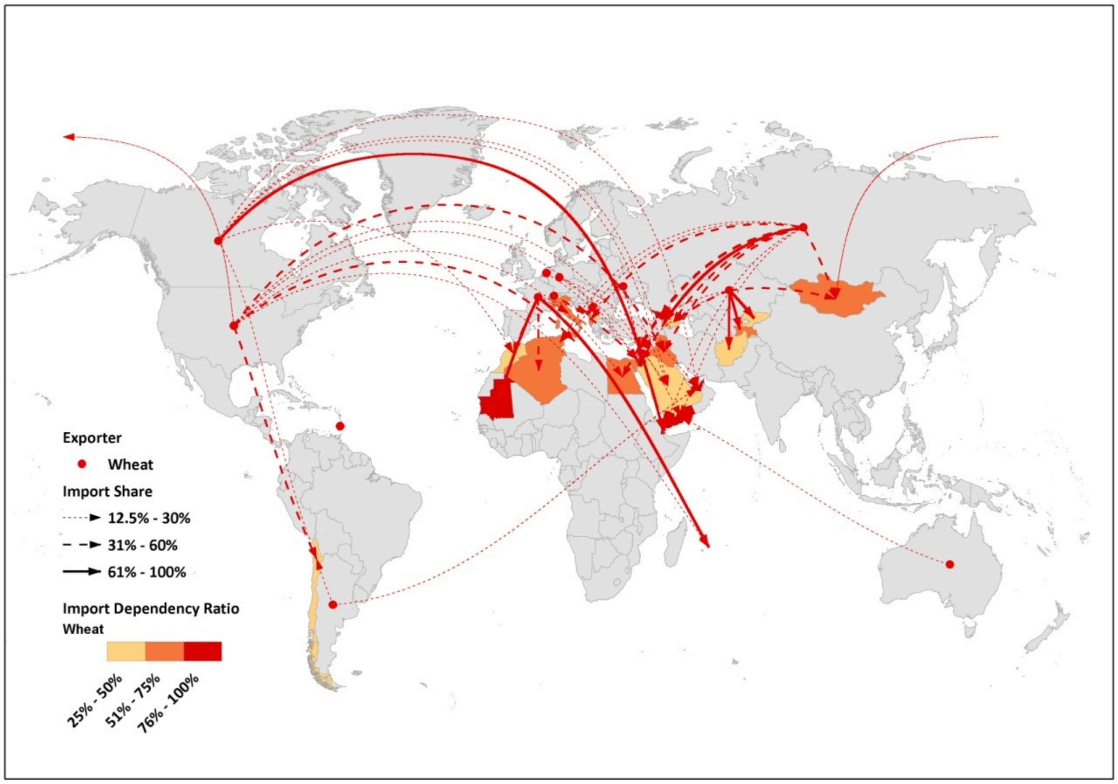

Figure S1: Major wheat import flows for most caloric trade dependent countries. The color intensification signifies the Import Dependency Ratio. Each country is linked to its three major suppliers given that the supplier holds a share of more than one fifth of the total wheat import volume. The thicker the arrow, the higher the share the exporting country has on the import volume of that country.

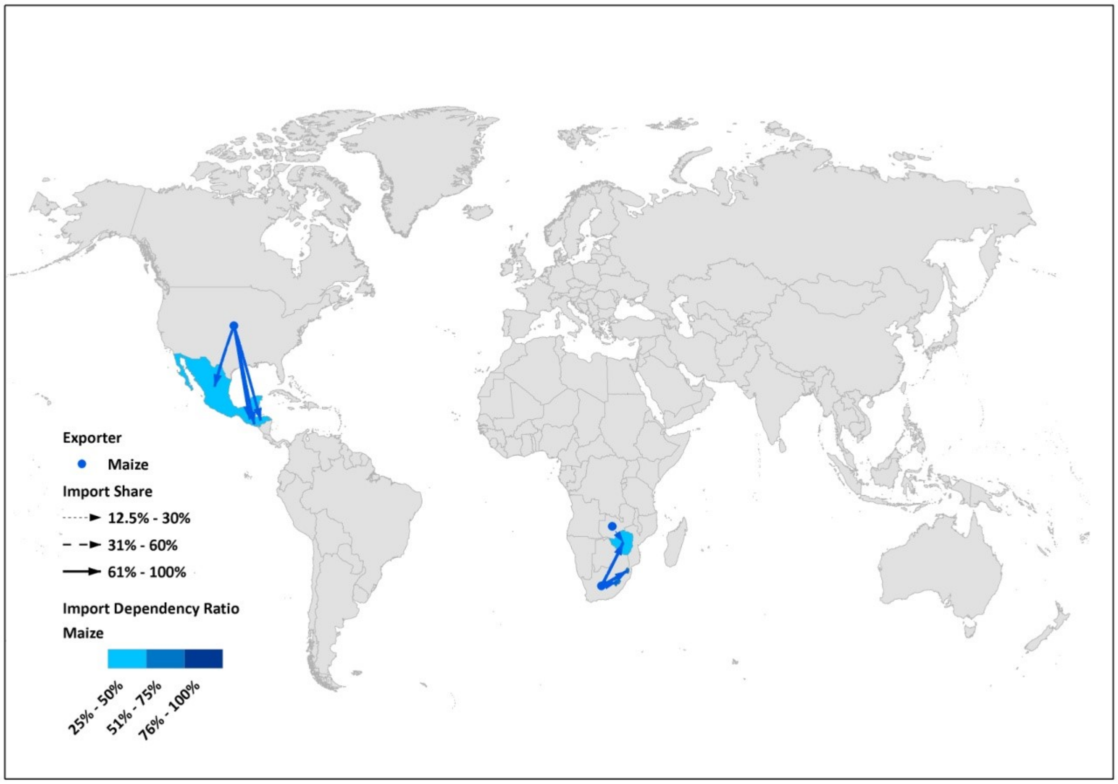

Figure S2: Major maize import flows for most caloric trade dependent countries. The color intensification signifies the Import Dependency Ratio. Each country is linked to its three major suppliers given that the supplier holds a share of more than one fifth of the total maize import volume. The thicker the arrow, the higher the share the exporting country has on the import volume of that country.

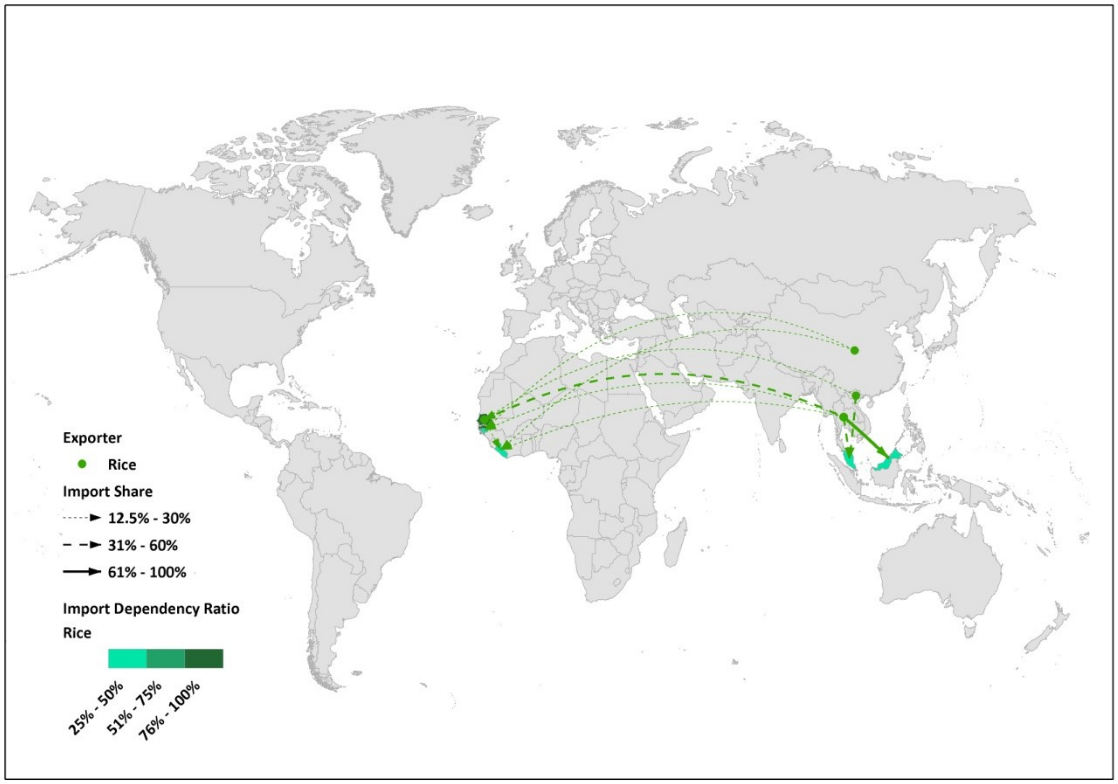

Figure S3: Major rice import flows for most caloric trade dependent countries. The color intensification signifies the Import Dependency Ratio. Each country is linked to its three major suppliers given that the supplier holds a share of more than one fifth of the total rice import volume. The thicker the arrow, the higher the share the exporting country has on the import volume of that country.

Technical Appendix

To derive the formula for the market adjustment θ, we develop a small analytical model which illustrates how production or trade shocks influence availability on international markets under the presence of price effects and market adjustment responses. We consider one importer who imports

$$M = \sum_{i \in \mathbf{X}} X_i \qquad \text{(S1)}$$

i.e. the sum of bilateral exports $\mathbf{X_i}$ from all exporting countries $i \in \mathbf{X}$, where $\mathbf{X}$ is the set of exporting countries. Import is determined by an iso-elastic demand function $M = M_0 p^{\eta}$ where $\eta < 0$ is the price elasticity of demand. We abstract from transportation and trade costs.

Country *i*'s export X_i is a function of world market prices p: $X_i = D_i p^{\varepsilon}$ with D_i a scaling parameter (typically related to country *i*'s population and production size) and $\varepsilon > 0$ is the price elasticity of supply. Large values of ε indicate that countries respond strongly to prices and expand their exports while $\varepsilon \to 0$ indicates inelastic supply. For simplicity and clarity of the argument, we assume that exporters only differ by the scaling parameter D_i but not by their supply elasticity. Assuming that all exporting countries have strictly positive exports, the export share of country *i* on global exports, s_i, is further given by $s_i = D_i / D$ with $D = \sum_{j \in \mathbf{X}} D_j$.

Substituting the demand functions in equation (S1) yields

$$M_0 p^{\eta} = \sum_{i \in \mathbf{X}} D_i p^{\varepsilon} = D p^{\varepsilon}.$$

Solving for $\ln p$ gives:

$$\ln p^* = \frac{\ln M_0 - \ln D}{\varepsilon - \eta}.$$

Log-transforming equation (1) and inserting $\ln p^*$ then gives:

$$\ln M = \ln M_0 + \frac{\eta}{\varepsilon - \eta} (\ln M_0 - \ln D)$$

From this, the elasticity of imports M with respect to a homogenous international supply shock D is given by:

$$\theta := \frac{\partial \ln M}{\partial \ln D} = \frac{-\eta}{\varepsilon - \eta}.$$

Note that $\eta < 0$ and $\varepsilon > 0$. If the supply shock originates from country *i* only, i.e. a relative change in D_i, the relative change in imports is

$$\frac{\partial \ln M}{\partial \ln D_i} = \frac{-\eta}{\varepsilon - \eta} s_i = \theta s_i.$$

Two implications follow immediately: (i) Shocks in countries with large export shares have a larger impact on total imports than shocks in countries with smaller shares. (ii) If global supply is inelastic, i.e. $\varepsilon \to 0$, the shock translates to a change in imports *proportional to the export share*; if supply elasticity is of the same magnitude as the absolute of the demand elasticity, i.e. $\varepsilon \approx |\eta|$, the shock in country i affects imports still by 50% of the export share. Thus, even considering the fact that other countries compensate for country *i*'s reduction in exports, reduces total imports substantially, in particular if s_i is large.

In the long run (i.e. annual period), supply elasticities for food crops range from 0.02 (rice) to 0.27 (corn) (Haile et al. 2016). Demand elasticities for staple food vary typically between -0.5 and -0.3 (Seale *et al* 2003), implying that θ_{jc} would range between 0.53 and 0.96. In the short run, supply elasticities are likely to be much lower as adjustment through higher production is not possible and shipping of grains takes several weeks. Supply elasticities on a monthly time period should therefore be close to zero, implying $\theta_{jc} \approx 1$. Thus, even with international trade equilibrium effects, we have still substantial impacts on domestic markets. Table S4 shows the endogenous market adjustment parameter for a large set of parameter combinations.

Table S4: Impact of relative supply shock in international market after trade adjustment effect. The values in the table are calculated with the formula $\frac{-\eta}{\varepsilon-\eta}$.

	demand elasticity -η										*Mean*
supply elasticity ε	**0.05**	**0.10**	**0.15**	**0.20**	**0.25**	**0.30**	**0.35**	**0.40**	**0.45**	**0.50**	
0.02	0.71	0.83	0.88	0.91	0.93	0.94	0.95	0.95	0.96	0.96	*0.90*
0.04	0.56	0.71	0.79	0.83	0.86	0.88	0.90	0.91	0.92	0.93	*0.83*
0.06	0.45	0.63	0.71	0.77	0.81	0.83	0.85	0.87	0.88	0.89	*0.77*
0.08	0.38	0.56	0.65	0.71	0.76	0.79	0.81	0.83	0.85	0.86	*0.72*
0.10	0.33	0.50	0.60	0.67	0.71	0.75	0.78	0.80	0.82	0.83	*0.68*
0.12	0.29	0.45	0.56	0.63	0.68	0.71	0.74	0.77	0.79	0.81	*0.64*
0.14	0.26	0.42	0.52	0.59	0.64	0.68	0.71	0.74	0.76	0.78	*0.61*
0.16	0.24	0.38	0.48	0.56	0.61	0.65	0.69	0.71	0.74	0.76	*0.58*
0.18	0.22	0.36	0.45	0.53	0.58	0.63	0.66	0.69	0.71	0.74	*0.56*
0.20	0.20	0.33	0.43	0.50	0.56	0.60	0.64	0.67	0.69	0.71	*0.53*
0.22	0.19	0.31	0.41	0.48	0.53	0.58	0.61	0.65	0.67	0.69	*0.51*
0.24	0.17	0.29	0.38	0.45	0.51	0.56	0.59	0.63	0.65	0.68	*0.49*
0.26	0.16	0.28	0.37	0.43	0.49	0.54	0.57	0.61	0.63	0.66	*0.47*
0.28	0.15	0.26	0.35	0.42	0.47	0.52	0.56	0.59	0.62	0.64	*0.46*
0.30	0.14	0.25	0.33	0.40	0.45	0.50	0.54	0.57	0.60	0.63	*0.44*
Mean	*0.30*	*0.44*	*0.53*	*0.59*	*0.64*	*0.68*	*0.71*	*0.73*	*0.75*	*0.77*	

References

Haile M G, Kalkuhl M, Von Braun J 2016 Worldwide Acreage and Yield Response to International Price Change and Volatility: A Dynamic Panel Data Analysis for Wheat, Rice, Corn, and Soybeans. American Journal of Agricultural Economics. 98(1) 172-190.

Seale J L, Regmi A and Bernstein J 2003 International evidence on food consumption patterns (Economic Research Service, US Department of Agriculture).

PART II

Chapter 5

5. Urban transitions and diets*

Christopher Bren d'Amour
Bhartendu Pandey
Meredith Reba
Sohail Ahmad
Felix Creutzig
Karen C. Seto

* Currently in preparation as C. Bren d'Amour, B. Pandey, M. Reba, S. Ahmad, F. Creutzig, K.C. Seto: Urban transitions and diets

Urban transitions and diets

Christopher Bren d'Amour[1,2], Bhartendu Pandey[3], Meredith Reba[3], Sohail Ahmad[1],

Felix Creutzig[1,2], Karen C. Seto[3]

Abstract

Approximately 6.5 billion people will be living in urban areas by 2050. Urbanites consume more diversified diets than their rural counterparts, including higher value food items such as processed foods. Yet, there is no clear understanding why urban dwellers consume differently. Most studies attribute the differences to rising incomes. However, cities can influence diets in multiple ways, depending upon the level of urban development and nature of economic activities. Here, we explore the empirical relationships between urbanization and packaged food, processed food, and food away from home consumption at different spatial scales, using country level data for a global analysis and household level data for India.

We find that urbanization affects the consumption of packaged foods at the country level. In addition, our findings suggest that this effect increases with the level of urban development, which we approximate by an urban development index at the global level and by different city classes for India. We also observe variations in processed food and food away from home consumption at different levels of urban development within India. These urban effects vary significantly between metropolitan and non-metropolitan urban areas. While income is still the most important driver for changing food consumption, our findings underline the importance of urbanization. As the effects vary across different urban contexts, our results highlight the need for a more nuanced understanding of how urban consumption patterns vary with different levels of urban development. Our findings have implications for general debates about food and nutrition security as well as public health and resource use.

Keywords: processed foods, packaged foods, urbanization, food away from home, dietary changes, urban transitions

[1] Mercator Research Institute on Global Commons and Climate Change, D-10829 Berlin, Germany
[2] Technische Universität Berlin, D-10623 Berlin, Germany
[3] Yale School of Forestry and Environmental Studies, Yale University, New Haven, CT 06511
[*] Author to whom any correspondence should be addressed.

5.1. Introduction

While significant attention has been devoted to understanding the role of food consumption in sustainably providing for 9 billion in 2050 (Alexandratos and Bruinsma, 2012), less consideration has been given to the fact that 6.3 billion of these people will be living in urban areas (United Nations, 2014). Compared to their rural counterparts, urbanites consume more diversified diets, mostly consisting of higher value food items (Popkin, 1999). These diets require higher resource inputs, such as land or water (Erb et al., 2016; Wirsenius et al., 2010), and can be expected to have wide-ranging implications, for example for public health (Popkin, 2001; Tilman and Clark, 2014). These dietary shifts are increasing the incidence of chronic non-communicable diseases.

The studies related to urban food consumption span across different disciplines (Kearney, 2010; Ma et al., 2006; Popkin, 1999; Reardon et al., 2014; Regmi and Dyck, 2001; Stage et al., 2010; Zhang and Wang, 2003). In general, urban diets are characterized by higher input grain consumption, more fat and animal products, more processed foods as well as more food away from home (FAFH), compared to rural diets (Gaiha et al., 2009; Popkin, 1999; Popkin and Bisgrove, 1988). There is agreement that people living in urban areas consume differently than their rural counterparts. Yet, there is no clear understanding of *why* people consume differently in urban areas (Seto and Ramankutty, 2016). Most of these studies attribute the distinctness of urban diets to rising incomes and conflate rising incomes, westernization, and urbanization, and offer only a comparison of urban diets to rural ones.

Here, we hypothesize that urbanization can influence diets in multiple ways, depending upon the level of urban development and economic activity. Better spatial and financial accessibility, for example, and higher availability of different food types, restaurants, and supermarkets are likely exposing urban consumers to new dietary options. Socio-economic factors such as employment and household structure in urban areas are also affecting consumption. As more women enter the labor market in urban areas, opportunity costs of cooking at home increase, leading to more consumption of processed foods and FAFH.

Urbanization has an effect on all of the above. We use the term '*urban effect'*, which we define as any kind of variation (of consumption/structure/…) between rural areas and urban areas that occurs with different levels of urban development. This is not only limited to food consumption patterns. For example, we observe an urban effect on employment in India, meaning that the structure of employment varies with urban development, usually towards more service sector employment in metropolitan cities.

Identifying and disentangling these urban influences on food consumption patterns is complex for a number of reasons. First, urbanization is linked to higher incomes and different employment structure, which in turn affect food consumption patterns. At the same time, urbanization in itself is directly influencing food consumption as well. Therefore, there are direct and indirect urban effects that need to be controlled for. Second, the magnitude of these effects is likely to vary within and between cities, depending on the development level of the individual city or country. Here, we use the term '*urban transition*', which we define as spectrum that captures the specificities and complexity of urbanization at different spatial scales. Some effects, such as the increased consumption of FAFH, are likely to be more pronounced in larger cities with higher incomes, better infrastructure, provision of services, and connectivity to world markets. However, the size of the city alone is hardly a suitable indicator to capture the complex nature of urban development (Bettencourt and West, 2010). Without adequate infrastructure and the provision of basic services, such as access to basic sanitation and electricity, people living in larger cities are likely to consume diets that are more similar to the ones of their rural counterparts. A formalized understanding of the relationship between urbanization and food consumption is missing, and, more specifically, between different levels of urban development and food consumption.

Our study is based on two hypotheses: (H1) urbanization has an effect on food consumption patterns that goes beyond an income effect; (H2) this urban effect varies with the complexity of urbanization. The latter can be assessed at different spatial scales, for example at the national level, but also at the city level.

In this study, we contribute to the understanding of the influence of urbanization by identifying this *urban effect*. We do so by focusing on selective food items at two different scales. First, we conduct a country level analysis on the empirical relationships between urbanization and packaged food consumption to test our basic hypothesis (H1) that urbanization has an effect on food consumption patterns. Second, having established our working hypothesis at the country level, we also test hypothesis (H1) and (H2), namely that there is variation with different levels of complexity of urbanization within a single country, using detailed household survey data for India. In particular, we assess variations in consumption patterns of (a) processed foods, and (b) FAFH, using a nationally representative consumer expenditure survey from the National Sample Survey Office (NSSO, 2010). Further, we determine which other variables are significant determinants of the consumption of these food items. The reason for the selection of these food items is grounded in the assumption that their consumption is less affected by cultural background or religious norms that might have an important effect on consumption patterns of other food items such as meat. Further, increasing consumption of these items is observable across the developing world (Baker and Friel, 2014; Euromonitor International, 2017; Monteiro et al., 2013; Pingali, 2007), often tied to trade liberalization (Thow and Hawkes, 2009).

5.2. Urbanization and packaged food consumption

In this part of the study, we focus on the empirical relationship between urbanization and packaged food consumption at country level. We use this section to test our first hypothesis (H1). To approximate the complexity and variation of urbanization of individual countries, we compute an *Urban Development Index* (UD index, see SI for a detailed description), based on the approach from Brelsford et al (2017), using World Bank data (The World Bank, 2015). There are two central notions: first, urbanization is a dynamic and multidimensional development process with different levels of complexity that goes beyond the share of the population living in urban areas and includes, for example, the expansion of urban areas and cultural change (Seto et al., 2014). The level and complexity of urbanization is unevenly distributed, especially in developing regions. Universal provision of basic services, such as access to electricity, clean water and sanitation as well as adequate housing, are essential determinants of sustainable urban development (Brelsford et al., 2017). Second, this urban development will affect food consumption patterns, especially for modern food types such as packaged foods.

We analyze the basic relationship between the UD index and different socio-economic indicators (Figure 1A) to get a better understanding of the index. We find that the UD index has a positive correlation with urban population share ($r = 0.51$), GDP per capita ($r = 0.54$), and service sector employment ($r = 0.59$, Figure 1A). This positive relationship is expected, as all of these measures are indicators of the broader economic and structural development of countries. We observe a strong correlation between UD index and per-capita packaged food consumption (0.73, Figure 1A&B), indicating that urban development is likely a significant predictor of packaged food consumption.

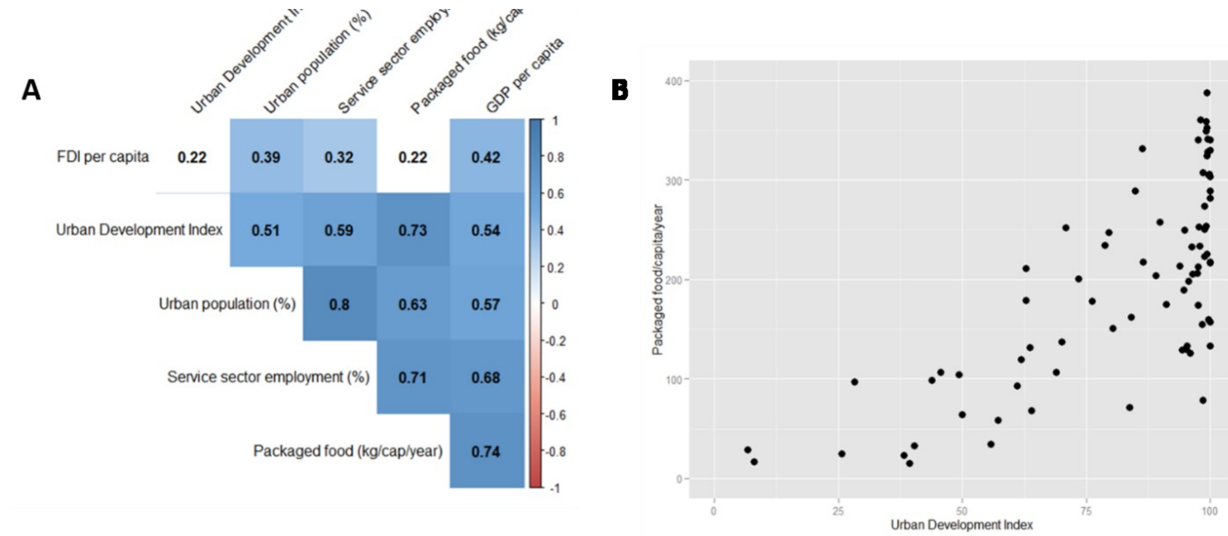

Figure 1 – Urban development and packaged food consumption. A) Correlation matrix between packaged food consumption (kg/per capita/year) and different indicators. B) Relation between the Urban Development Index and packaged food consumption. Color of correlation boxes indicated the correlation coefficient (blue indicates positive correlation, red negative). Boxes with significance level of at least 0.01 are filled, remaining boxes are not filled. Source: Euromonitor International (2017) and World Bank (2015).

We focus on packaged food consumption and explore how the per capita consumption relates to these same socio-economic indicators, including the UD index. We find the strongest coefficient of correlation with GDP per capita, followed by UD index and service sector employment, indicating increased consumption of packaged foods with higher levels of these variables. This is in line with findings from earlier studies as highlighted in the introduction. Additionally, the coefficient for UD index is 0.1 higher than the index for urban population share, meaning that the urban development index is stronger correlated with packaged food than urban population share.

Controlling for these indicators, we estimate package food consumption using ordinary least squared (OLS) regression models (Table 1). The models use GDP per capita, urban population share, UD index, service sector employment, and foreign direct investment as independent variables. We find that GDP per capita and UD index are strongly positively correlated (p<0.01) with packaged food consumption, but the share of urban population is weakly correlated (*p<0.1*)[1]. Moreover, these findings show that income is only partially explaining packaged food consumption. Our findings suggest that a 10% increase in GDP per capita would translate into an increase in packaged food consumption of 3% (nearly 5.9kg/capita/yr). Similarly, if the UD index increases by 10% (bound between 0-100), we would expect packaged food consumption to increase by 6.2% per capita annually. We did not find any significant relationship between service employment shares with packaged food consumption, against our intuition, may be due to larger spatial scale of analysis.

[1] We test for multicollinearity using the Variance Inflation Factor (VIF).

This country level analysis does not account for the huge variation, both in consumption patterns and complexity of urbanization (S1). However, these findings set the stage for a more detailed analysis involving household survey data, as detailed in the next section.

Table 1 – Correlates of packaged food consumption (kg/capita/year), selected countries, 2017

VARIABLES	Packaged Food PC per year (log)	
	b	β
GDP per capita (log)	0.303***	0.471
	(0.0698)	
Urban population share	0.00771*	0.179
	(0.00391)	
Urban Dev. Index (log)	0.622***	0.406
	(0.104)	
Service employment share	0.000494	0.00964
	(0.00559)	
FDI per capita	-4.16e-05**	-0.136
	(1.76e-05)	
Constant	-0.979**	
	(0.429)	
Observations	79	79
R-squared	0.803	0.803

Notes: Standard errors in parentheses; *** p<0.01, ** p<0.05, * p<0.1; β is a standardized coefficient for comparison in terms of magnitude; Data source: Euromonitor International (2017) and World Bank (2015)

5.3. Lessons from India

To account for subnational variation and to test both hypotheses at the subnational level, we focus on India in the main analysis of this paper. India is a very interesting case, not only due to its population size. India is a country that is still in the earlier stages of its urban transition, both in terms of their urban population, and in terms of the UD index (cf. figure S1). In particular, India's urban population is currently less than one-third of the total population and by 2050 will be just over half (United Nations, 2014). Furthermore, as Mitra et al. (2016) have shown, 79% of India's urban population resided in settlements of 100,000 or fewer in 2011. Overall, 52% of the country lived in towns and villages with populations fewer than 5,000. In this section, we analyze variation in consumption patterns of processed foods and FAFH within India at different urban development levels—metropolitan urban regions, non-metropolitan urban regions, and rural regions. We use a household level consumer expenditure survey from the National Sample Survey Office (NSSO) for the year 2010 (NSSO, 2010) to highlight urban consumption trends and to get an understanding of the structural composition of households of the different sectors.

Table 2 provides an overview of household characteristics by sector (sectors being either “rural”, “urban non-metropolitan”, “urban metropolitan”; the latter refers to metropolitan cities, which have a population of > 1 million, the former to all remaining cities). Here, we compare the two extremes, rural and metropolitan households (see Table 2 for detail on non-metropolitan households). The average rural household has a comparatively low monthly per capita expenditure (MPCE, ~1,200 rupees) and consists of five people. About 30% of these households report attainment of at least secondary education by any member of the household, while 41% of the households reported agricultural sector as their primary occupation. About 11% of households are either single or nuclear households without children. In contrast, the average MPCE of households in metropolitan cities is twice as high (~2400 rupees) and is slightly smaller, consisting of one fewer household member (four total). 54% of the households have at least one member with education levels at the secondary level or higher, including 34% with a graduate degree.

Table 2 – Summary statistics of household characteristics by sector. If not indicated otherwise, numbers reflect the share of households (in %) in the respective sector. Education level refers to highest education level in a household. Only the higher education levels are listed (min secondary). Primary occupation does not include those looking for a job or unclassified. Own calculations based on NSSO data for 2010 (NSSO, 2010).

	Rural	**Urban non-metro**	**Urban metro**
Avg. MPCE (in rupees)	1195.2	1732.0	2388.8
Avg. Size (# of people)	4.9	4.4	4.2
Avg. Age (years)	29.9	30.5	31.5
Highest education level			
Secondary & Higher Secondary	17.1	20.4	20.5
Graduate/PG/Diploma/Certificate	13.2	29.7	33.5
Primary occupation			
Agriculture	40.9	9.3	3.6
Industry	25.3	27.9	30.6
Services	26.2	48.6	49.7
Basic service sector occupations	2.1	4.6	6.0
Household structure			
Single	4.0	8.6	12.3
Nuclear Family no kids	7.3	7.3	7.3
Nuclear Family with unmarried child or only married child	47.0	47.3	43.9
Joint Family (Other combinations)	41.7	36.8	36.5

Higher education levels are reflected in the primary occupation of these households: only <4% of the households are employed in the agricultural sector, while the majority of households works in services (56%) or industry (31%). The share of households working in basic services, which include occupations such as street vendors, shoe cleaners, domestic helpers, triples to 6%. About 20% are single households or nuclear households without children. With urban and accompanying economic development, the structure of households is changing. Single nucleus households in which both parents work will consume differently than larger joint families in urban areas. It is hence important to understand these structural differences.

These structural differences also seem to affect consumption patterns. Expenditure on processed foods increases with urbanization, from 3.7% in rural to 5.2% in metropolitan cities (Table 3). FAFH is much more prevalent in urban contexts. The number of meals consumed away from home is ten times higher in households living in metropolitan cities than in rural areas (0.4 vs 4.0).

These urban effects are more visible in higher MPCE quartiles (Table 3). We observe homogenous expenditure across sectors on processed foods in the first and second quartiles, ranging from 3.3% in rural areas to 3.7% in metropolitan cities, and more variation in the higher quartiles (from 3.9% to 6.3%). In low-income groups, consumption patterns are similar across the three sectors. Generally, expenditure shares increase with MPCE within the same sector. The differences between MPCE quartiles become wider, with a notable gap between the third and fourth quartile. The findings for FAFH consumption confirm this pattern, in particular between the third and fourth expenditure quartile, exemplified by an increase of almost 4 meals per capita in metropolitan cities (per month, from 1.8 to 6.7).

Table 3 – Summary statistics of processed food and FAFH on payment consumption across sectors. Processed food expenditure is at household level, FAFH on payment on a per capita basis – per month. Data Source: (NSSO, 2010).

	Processed food expenditure share			**FAFH**		
	% of total food expenditure			Average number of meals per capita		
	Rural	Urban non metro	Urban metro	Rural	Urban non metro	Urban metro
Total	3.7	4.6	5.2	0.4	1.7	4.0
MPCE Quartiles						
Q1	3.3	3.4	3.4	0.1	0.2	0.4
Q2	3.5	3.7	3.7	0.2	0.5	0.5
Q3	3.9	4.3	4.4	0.4	1.1	1.8
Q4	4.8	5.8	6.3	1.8	3.7	6.7
Household structure						
Single	6.6	8.2	9.2	5.6	16.9	28.3
Nuclear Family no kids	4.1	4.9	5.2	0.3	0.5	1.0
Nuclear Family with unmarried child or only married child	3.6	4.3	4.8	0.2	0.3	0.5
Joint Family (Other Combinations)	3.6	4.2	4.5	0.2	0.4	0.7

Household structure is also an important determinant of processed food and FAFH consumption. Again, we see that urban, and especially metropolitan households, consume more than rural households across the respective household types (Table 3). Single households in particular consume significantly more, with single households in metropolitan cities standing out (9.2% on processed foods, 28.3 meals away from home). Nuclear families and joint families consume the least of the two items (<5% spending on processed foods, and <1 meals away from home in metropolitan cities).

To analyze the relative significance of these variables, we use OLS regression models, with processed food expenditure share and FAFH on payment as dependent variables. We include a range of socio-economic variables as independent variables, including the ones introduced in tables 1 and 2 but also variables such as access to modern cooking fuels. The data does not allow to compute the UD Index at the sub-district level. However, we approximate urban development by including a categorical variable "sector", which captures if a household lives in "rural", "urban non-metropolitan", or "urban metropolitan" areas. The underlying assumption is that the complexity and the degree of urbanization is substantially higher in metropolitan cites compared to non-metropolitan areas. With this independent variable, we control for an urban effect that goes beyond household structure, income, employment etc.

Table 4 presents the results of the various determinants of 'share of processed food consumption' and 'FAFH (number of meals per capita) on payment'. Our models explain about 10% of the observed variations in the consumption of these food items. The explanatory power further increases to up to 60% for the FAFH model after considering household cooking facility (see SI). Dwelling Unit's cooking facility and number of meals taken on payments are highly correlated. The model with cooking facility explains to a large extent on number of meals taken away (60% with cooking facility vs. 10% without cooking facility). Here we suspect that new (or seasonal) migrants might opt for dwelling units without cooking facility, e.g., youth hostel, paying guest accommodation, and preferably eat outside. We exclude this variable from our main models as it seems to distort the results (see table S2 for regression results including 'cooking facility').

Income, proxied by monthly per capita consumption expenditure (MPCE), is the most important explanatory variable in both models. A 10% increase in MPCE, the households' share of processed foods to total food expenditure expect to increase by 0.11 percentage points and number of meals FAFH increase by 0.25 (per capita, per month), ceteris paribus. The standardized coefficient β indicates that MPCE explains 19% of the variations in processed food expenditure and 23% of the variation in FAFH consumption. Essentially, MPCE is the most important explanatory variable for the consumption of both food items.

The 'sector' variable is essential to test both hypothesis of this study [(H1) there is an urban effect on diets and (H2) this effect varies with urban development]. After controlling for variables such as income, education, employment (cf. table 4), the estimates show that the sector variable is highly significant for both models. Compared to rural households, non-metropolitan urban and metropolitan-urban households spend a higher share of their food expenditure on processed foods and consume a larger number of meals away from home (FAFH). Again, compared to rural households, non-metropolitan urban and metropolitan-urban households consume 0.26 and 0.55 percentage points more, respectively. Similarly, compared to rural households, non-metropolitan urban and metropolitan-urban have 1.2 and 3.0 more meals per capita away from home, respectively. While the β is low for processed foods (3% for non-metropolitan urban areas and 5% for metropolitan urban areas), it is substantially higher for FAFH consumption (8% for non-metropolitan urban and 15% for metropolitan urban areas). This indicates that the urban effect explains substantially more variation for FAFH consumption than for processed food consumption.

Table 4 –Determinants of households' expenditure on processed foods (share of total expenditure) and consumption of FAFH (no of meals pc).

Dependent variable	Share of processed foods (of total food expenditure)		FAFH (number of meals per capita)	
	b	ß	*b*	ß
MPCE (log)	1.100***	0.185	2.489***	0.231
	(0.0271)		(0.0481)	
Urban-non metro (ref: rural)	0.265***	0.0328	1.182***	0.0803
	(0.0313)		(0.0556)	
Urban-metro (ref: rural)	0.548***	0.0475	3.060***	0.146
	(0.0435)		(0.0772)	
Ocu: Industry (ref: agriculture)	0.269***	0.0329	0.616***	0.0415
	(0.0340)		(0.0602)	
Ocu: Service (ref: agriculture)	0.375***	0.0498	0.450***	0.0329
	(0.0344)		(0.0612)	
Ocu: Basic service (ref: agriculture)	0.458***	0.0226	0.101	0.00277
	(0.0710)		(0.126)	
HH size	-0.179***	-0.112	-0.327***	-0.113
	(0.00604)		(0.0107)	
HH age - average	-0.0126***	-0.0356	-0.0159***	-0.0246
	(0.00128)		(0.00228)	
Have cooking aide	1.004***	0.0579	-1.483***	-0.0467
	(0.0615)		(0.110)	
Have electricity	0.145***	0.0149	0.0404	0.00228
	(0.0356)		(0.0630)	
Have modern cooking fuels	-0.312***	-0.0414	-3.264***	-0.238
	(0.0329)		(0.0583)	
Lit-informal (ref: illiterate)	-0.401	-0.00493	1.205**	0.00817
	(0.274)		(0.486)	
Lit-others (ref: illiterate)	-0.249***	-0.0160	0.0502	0.00180
	(0.0765)		(0.135)	
Primary-middle (ref: illiterate)	-0.266***	-0.0360	0.128	0.00954
	(0.0617)		(0.110)	
Secondary/HS (ref: illiterate)	-0.294***	-0.0311	0.312***	0.0182
	(0.0678)		(0.121)	
Graduate+ (ref: illiterate)	-0.0679	-0.00758	0.311**	0.0190
	(0.0702)		(0.125)	
Constant	-2.663***		-14.45***	
	(0.198)		(0.351)	
Observations	84,489		86,576	
R-squared	0.082		0.100	

Notes: Standard errors in parentheses. ***p<0.01, **p<0.05, *p<0.1. β is a standardized coefficient for comparison in terms of magnitude

In terms of occupation of the household head, our findings show that compared to those households with a primary occupation in agriculture, those with a primary occupation in either the industry or service sector consume more (Table 4). For instance, compared to agricultural households, service sector households consume 0.38 percentage points more processed food and 45 less meals per capita away from home, ceteris paribus.

With education attainment, on the one hand, the share of processed food decreases on the other hand number of meals taken away from home increases. These changes could be attributed to awareness and education-related occupational changes.

5.4. Discussion

Our study confirms the working hypotheses that (H1) urbanization has an effect on urban diets and that (H2) that effect varies depending on the development level and complexity of the urban area. We show that urbanization is an important determinant for the consumption of packaged foods, processed foods, and FAFH. Our results indicate that income is the most important determinant of uptake of processed foods and meals taken away from home. However, after controlling for a range of socioeconomic variables, we find that the location influences consumption of processed foods and FAFH in India. For instance, households living in metropolitan areas consume ten times more FAFH than those households living in rural areas.

Many factors that this study does not account for due to a lack of sufficient and available data influence food consumption patterns (reflected by the low R^2 of our household level analysis for India). Cultural influences are difficult to quantify but are likely to play a role when comparing consumption across different countries. To minimize the possible effect of cultural influences, we focus on packaged foods, processed foods and FAFH. These food items are on the rise across the developing world, seemingly regardless of cultural norms (Baker and Friel, 2014; Monteiro et al., 2013).

Further, at the country level, the UD index is only one representation of variations in urban development and does not capture the entire complexity of urban development transitions of countries. For example, it does not account for the different employment structures typical in urban areas. Still, the country level analysis is an important indication of the importance of urbanization and sets the stage for the detailed analysis of India. The detailed household survey used in this study does not allow computing the UD index for individual cities, let alone districts within a single city. To capture different stages of urban development, we use two separate urban classes, namely “urban non-metropolitan” and “urban metropolitan”. Hence, we do not account for intra-city variation in access to amenities (as we do in our country level analysis), which is very relevant in the Indian context (Das et al., 2015). Due to lacking data, we approximate urban development and complexity by the urban population, contrary to what we have done in the country level analysis. However, in our household level analysis in India, we control for items such as ‘access to electricity’, which are also part of the UD index. Nevertheless, more detailed information on the development level of individual cities or even inequalities within cities, as for example Brelsford et al (2017) have shown, would be a very significant contribution.

However, a better understanding of global consumption patterns is an essential factor to sustainable future food systems, especially to tackle all forms of malnutrition (Ingram, 2017). Food consumption in urban areas is a key component in this regard (IFPRI, 2017; Richards et al., 2016).

Our results indicate that urban transitions are a key component in that regard. The country level analysis conducted in this paper highlights that depending on how advanced countries rank on the spectrum of urban transitions (approximated by the UD Index), they will consume more packaged foods. In our analysis of Indian consumption pattern, we show that people not only consume differently in cities, but that people likely consume differently depending on the individual development level of cities. This urban development level and associated complexity also affects other important determinants of food consumption patterns, such as income level, education, and primary occupation. By controlling for these factors, we are able to single out an urban effect that captures the development stage, complexity of cities. This could include the spatial configuration of individual cities, but also the transport system etc. More importantly, this would also entail the accessibility and the exposure to different, modern food types.

Our findings for India are of particular importance to discussions on public health that have been dominant in international development corporation (FAO, IFAD, UNICEF, WFP and WHO, 2017). The observed tendencies to consume more processed foods and FAFH are linked to the prevalence of diseases such as obesity (Garnett, 2016). There is a range of possible options for consuming FAFH, including food stalls, full service, and fast-food restaurants. Of these, fast-food is likely to have the biggest health impact (Rosenheck, 2008). For example, consumption of fast-food in the US is directly linked to increasing risk of obesity and type 2 diabetes (Pereira et al., 2005). However, the NSSO data does not provide any information regarding the origin of the FAFH.

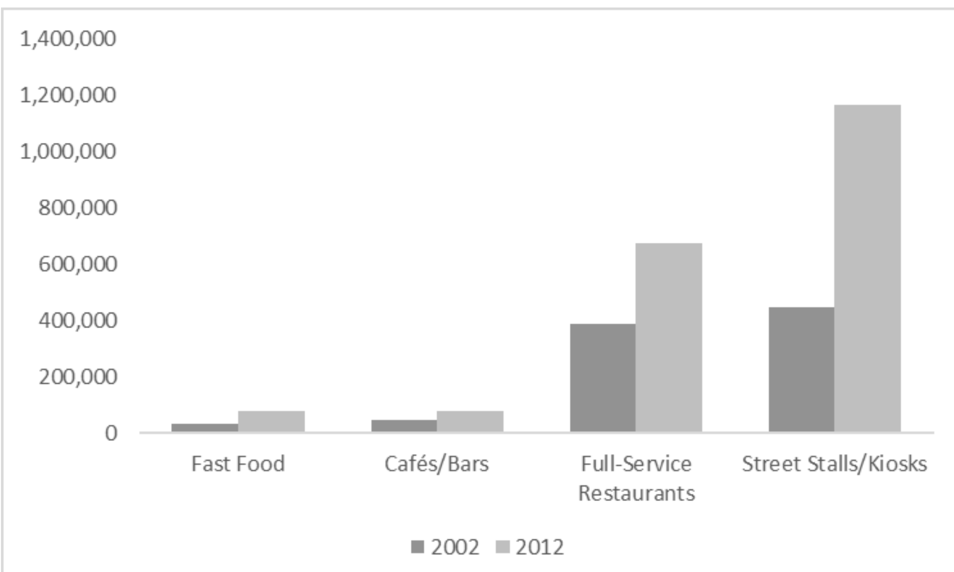

Figure 2 – Number and type of food service outlets in India, 2002 and 2012. Source: Euromonitor International (2017).

To illustrate some of the potential implications of this trend of increasing FAFH, we have compiled information on the number of food outlets (Figure 2) and how they have grown over a similar ten-year period (2002-2012). The number of full service restaurants increased from 390k to 680k. Remarkably, the number of street stalls and kiosks almost tripled from 440k to 1,165k. Arguably, some of that growth can be attributed to the increasing demand from an increasing population. But most of that increasing demand will be due to changes in consumption patterns in urban areas.

Similar observations for public health have been made for processed foods, which in developing countries are primarily being sold in supermarkets (Minot et al., 2015; Rischke et al., 2015). In Kenya, for example, Demmler et al. (2017) have shown that supermarkets have a direct effect on people's health, increasing the prevalence of obesity and other nutrition-related diseases.

Policy recommendations are discussed at the country level. However, the implications are transferable across other countries that face the same transitions. One obvious implication is for policy makers to account for the fact that much of the future demand will come from urban areas and that this demand is significantly different from the demand from rural areas. Any policies targeted at guaranteeing food and nutrition security should acknowledge the specificities of urban consumption.

Further, the findings of this study highlight a transition of diets in urban areas towards more processed foods and FAFH, with potentially far-reaching implications for public health. As changing diets are results of changes in environments, behavior and food systems, improving diets will require policies that can address all these drivers, especially in urban context (IFPRI, 2017). The potential implications that the increasing consumption of food items such as processed foods entail warrant specific policies targeted at tackling poor nutritional intake. In this context, policies at the national level are relevant, exemplified by mandatory nutrition labeling for packaged foods (Lobstein and Davies, 2009). Other options include economic incentives, for example taxing of particularly unhealthy ultra-processed foods (Mytton et al., 2012). In addition, educating about the importance of good nutrition promises long-lasting effects on consumption behavior. Other alternatives include prevention campaigns and banning of marketing directly aimed at children (IFPRI, 2017). Most of these policies aim to inform and educate the consumer about the potential health implications of unhealthy diets.

The findings for India on the increasing consumption of FAFH and the increasing number of options to eat outside indicate that it will be essential to monitor what is being consumed away from home in what sort of a restaurant. To monitor the nutritional health of the population, this information will be key.

5.5. Conclusion

As Ingram (2017) argues "*we need to manage food demand, not just meet it*" to tackle food security issues, most notably malnutrition. In order to do that, we need a detailed understanding of what is driving changes in food consumption across the developing world. In this study, we highlight the importance of urbanization and urban transitions. While income remains the most important driver for changes in consumption, we show that urban development, the complexity of urban areas, and associated urban living, are also affecting consumption of packaged foods, processed foods and FAFH. However, many open questions remain, especially in the Indian context. In metropolitan cities, for example, single households consume almost 30 meals away from home in a single month, yet we have no way of knowing what they consume; and in which type of restaurant they go. It will also be essential to understand inner city variations, not only in food demand but also in terms of development level, as the example of food deserts suggest (Walker et al., 2010). In food areas, the spatial access to healthy foods is limited.

The limited selection of food items covered in this study further begs the question if the urban effect is also observable for other food items, such as traditional staple grains for example (or if it reverses).

Further, now that we identify an urban effect, the logical next step would be to scrutinize what it potentially entails. Essentially, this would include answering the question of '*how exactly urban areas affect food consumption patterns (other than by socio-economic variables)*'. For example, how is the spatial configuration in a single city affecting consumption? What other, inherently urban factors could contribute to that effect? To the knowledge of the authors, a more formalized understanding of this is still missing.

A detailed understanding, for example by conducting a case study of a single city, would help to clarify many of these open questions, especially regarding the spatial configuration (such as urban form, land use, and urban farming) of a city and the inner city variation. This would entail qualitative and quantitative analyses of how households behave in their urban environment.

In general, the role of urban development in food systems research is still underexplored in many regards (Seto and Ramankutty, 2016), specifically in the context of urban food consumption. Understanding what is driving the consumption of 6.5 billion people in urban areas will help to alleviate concerns regarding food security and public health but also concerns related to the increasing consumption of resource intensive diets. By identifying an urban effect on diets, this study provides an important baseline for future research in this field.

References

Alexandratos, N., Bruinsma, J., 2012. World agriculture towards 2030/2050: the 2012 revision. ESA Working paper.

Baker, P., Friel, S., 2014. Processed foods and the nutrition transition: evidence from Asia. Obes. Rev. 15, 564–577.

Bettencourt, L., West, G., 2010. A unified theory of urban living. Nature 467, 912–913.

Brelsford, C., Lobo, J., Hand, J., Bettencourt, L.M.A., 2017. Heterogeneity and scale of sustainable development in cities. Proc. Natl. Acad. Sci. https://doi.org/10.1073/pnas.1606033114

Das, S., Ghate, C., Robertson, P.E., 2015. Remoteness, Urbanization, and India's Unbalanced Growth. World Dev. 66, 572–587. https://doi.org/10.1016/j.worlddev.2014.09.013

Demmler, K.M., Klasen, S., Nzuma, J.M., Qaim, M., 2017. Supermarket purchase contributes to nutrition-related non-communicable diseases in urban Kenya. PLOS ONE 12, e0185148. https://doi.org/10.1371/journal.pone.0185148

Erb, K.-H., Lauk, C., Kastner, T., Mayer, A., Theurl, M.C., Haberl, H., 2016. Exploring the biophysical option space for feeding the world without deforestation. Nat Commun 7.

Euromonitor International, 2017. Passport Global Market Information Database: EuroMonitor International.

FAO, IFAD, UNICEF, WFP and WHO, 2017. The State of Food Security and Nutrition in the World 2017. Building resilience for peace and food security. FAO, Rome.

Gaiha, R., Jha, R., Kulkarni, V.S., 2009. How Pervasive is Eating Out in India? The Australian National University, Australia South Asia Research Centre.

Garnett, T., 2016. Plating up solutions. Science 353, 1202. https://doi.org/10.1126/science.aah4765

IFPRI, 2017. 2017 Global Food Policy Report. International Food Policy Research Institute, Washington, DC. https://doi.org/10.2499/9780896292529

Ingram, J., 2017. Perspective: Look beyond production. Nature 544, S17–S17.

Kearney, J., 2010. Food consumption trends and drivers. Philos. Trans. R. Soc. Lond. B Biol. Sci. 365, 2793–2807. https://doi.org/10.1098/rstb.2010.0149

Lobstein, T., Davies, S., 2009. Defining and labelling 'healthy'and 'unhealthy'food. Public Health Nutr. 12, 331–340.

Ma, H., Huang, J., Fuller, F., Rozelle, S., 2006. Getting rich and eating out: consumption of food away from home in urban China. Can. J. Agric. Econ. Can. Agroeconomie 54, 101–119.

Minot, N., Stringer, R., Umberger, W.J., Maghraby, W., 2015. Urban shopping patterns in Indonesia and their implications for small farmers. Bull. Indones. Econ. Stud. 51, 375–388.

Mitra, C., Pandey, B., Allen, N.B., Seto, K.C., 2016. Contemporary Urbanization in India, in: The Routledge Handbook of Urbanization and Global Environmental Change. Routledge, pp. 64–76.

Monteiro, C.A., Moubarac, J.-C., Cannon, G., Ng, S.W., Popkin, B., 2013. Ultra-processed products are becoming dominant in the global food system. Obes. Rev. 14, 21–28. https://doi.org/10.1111/obr.12107

Mytton, O.T., Clarke, D., Rayner, M., 2012. Taxing unhealthy food and drinks to improve health. BMJ Br. Med. J. Online 344.

NSSO, 2010. Household Consumer Expenditure. Minist. Stat. Programme Implement. Gov. India.

Pereira, M.A., Kartashov, A.I., Ebbeling, C.B., Van Horn, L., Slattery, M.L., Jacobs, D.R., Ludwig, D.S., 2005. Fast-food habits, weight gain, and insulin resistance (the CARDIA study): 15-year prospective analysis. The lancet 365, 36–42.

Pingali, P., 2007. Westernization of Asian diets and the transformation of food systems: Implications for research and policy. Food Policy 32, 281–298. https://doi.org/10.1016/j.foodpol.2006.08.001

Popkin, B.M., 2001. The nutrition transition and obesity in the developing world. J. Nutr. 131, 871S–873S.

Popkin, B.M., 1999. Urbanization, Lifestyle Changes and the Nutrition Transition. World Dev. 27, 1905–1916. https://doi.org/10.1016/S0305-750X(99)00094-7
Popkin, B.M., Bisgrove, E.Z., 1988. Urbanization and nutrition in low-income countries. Food Nutr Bull 10, 3–23.
Reardon, T., Tschirley, D., Dolislager, M., Snyder, J., Hu, C., White, S., 2014. Urbanization, diet change, and transformation of food supply chains in Asia. Mich. Glob. Cent. Food Syst. Innov.
Regmi, A., Dyck, J., 2001. Effects of urbanization on global food demand. Chang. Struct. Glob. Food Consum. Trade 23–30.
Richards, P., Reardon, T., Tschirley, D., Jayne, T., Oehmke, J., Atwood, D., 2016. Cities and the future of agriculture and food security: a policy and programmatic roundtable. Food Secur. 8, 871–877. https://doi.org/10.1007/s12571-016-0597-3
Rischke, R., Kimenju, S.C., Klasen, S., Qaim, M., 2015. Supermarkets and food consumption patterns: The case of small towns in Kenya. Food Policy 52, 9–21.
Rosenheck, R., 2008. Fast food consumption and increased caloric intake: a systematic review of a trajectory towards weight gain and obesity risk. Obes. Rev. 9, 535–547.
Seto, K.C., Dhakal, S., Bigio, A., Blanco, H., Delgado, G.C., Dewar, D., Huang, L., Inaba, A., Kansal, A., Lwasa, S., McMahon, J., Müller, D.B., Murakami, J., Nagendra, H., Ramaswami, A., 2014. Human settlements, infrastructure and spatial planning, in: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
Seto, K.C., Ramankutty, N., 2016. Hidden linkages between urbanization and food systems. Science 352, 943–945. https://doi.org/10.1126/science.aaf7439
Stage, J., Stage, J., Mcgranahan, G., 2010. Is urbanization contributing to higher food prices? Environ. Urban. 22, 199–215.
The World Bank, 2015. World Development Indicators | The World Bank [WWW Document]. URL http://wdi.worldbank.org/table/3.1# (accessed 9.26.15).
Thow, A.M., Hawkes, C., 2009. The implications of trade liberalization for diet and health: a case study from Central America. Glob. Health 5, 5. https://doi.org/10.1186/1744-8603-5-5
Tilman, D., Clark, M., 2014. Global diets link environmental sustainability and human health. Nature 515, 518–522. https://doi.org/10.1038/nature13959
United Nations, 2014. World Urbanization Prospects: The 2014 Revision, Highlights. Department of Economic and Social Affairs. Popul. Div. U. N.
Walker, R.E., Keane, C.R., Burke, J.G., 2010. Disparities and access to healthy food in the United States: A review of food deserts literature. Health Place 16, 876–884.
Wirsenius, S., Azar, C., Berndes, G., 2010. How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agric. Syst. 103, 621–638. https://doi.org/10.1016/j.agsy.2010.07.005
Zhang, W., Wang, Q., 2003. Changes in China's urban food consumption and implications for trade. Presented at the American Agricultural Economics Association annual meeting, Montreal, Canada, July, pp. 27–30.

5.6. Supplementary Information

Urban Development Index

To capture the complexity and variations, we compute an Urban Development Index (UD index), based on the approach from Brelsford et al, using World Bank data (The World Bank, 2015). UD index of spatial unit *i* is defined as:

$$Xi = \left[X_i^{water} X_i^{electricity} X_i^{sanitation} \left(1 - X_i^{slums}\right)\right] \qquad \text{Eq.1}$$

where X_i^{water} is the share of the urban population with access to an improved water source. The other superscripts refer to access to improved sanitation facilities, electricity as well as the share of the urban population living in slums. The index is bound between $X_i = 0$ and $X_i = 1$, where a low value indicates low access or a lack of at least one of these services and a value of 1 universal access to all (see SI for more detail). Generally, developed countries have an UD index of 1, while there is a wider range of variation among emerging countries. India, for example, had an UD index of 0.27 in 2000, compared to China's of 0.46. However, both have seen remarkable increases: by 2010, the UD index for India had increased to 0.38 and from China to 0.57 (Figure S1), indicating increasing accessibility of basic amenities in urban areas.

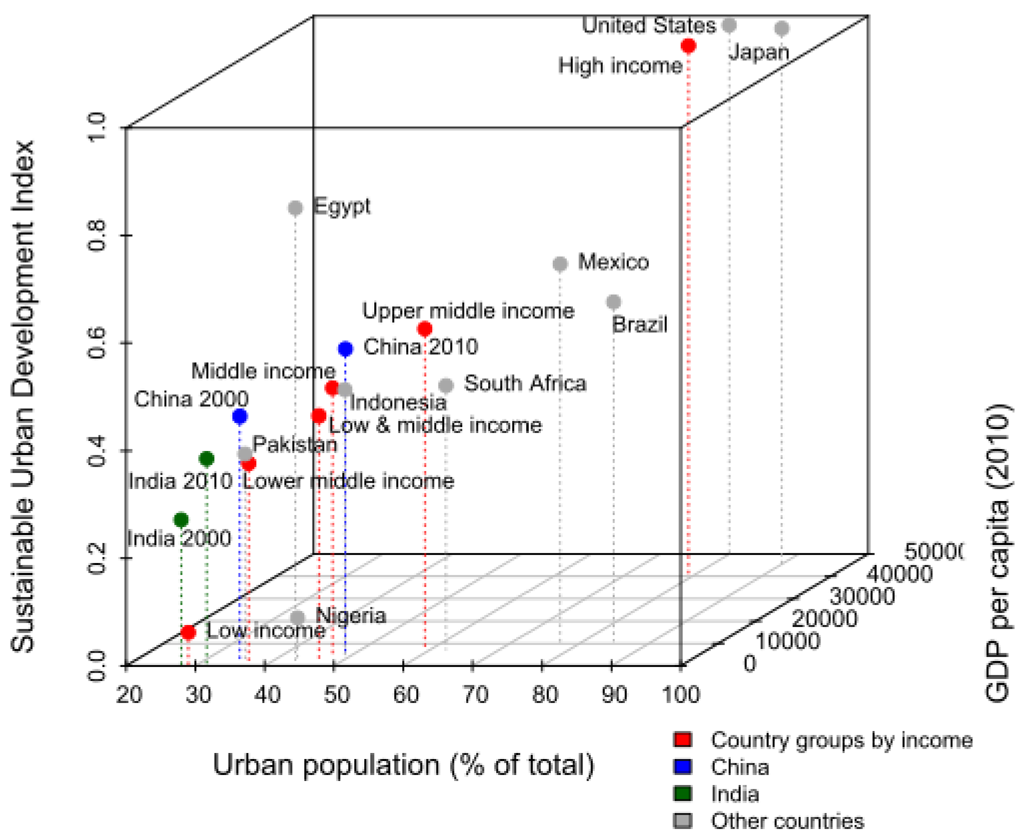

Figure S1 - Spectrum of urban transition: a multidimensional plot of the urban transition of a selection of countries and country groups. The share of the population living in urban areas is mapped against GDP per capita (in USD) and the SUD. Country selection is based on the absolute urban population in 2010 in Africa (n=3), Asia (n=6), and the Americas (n=2). To underline the individual transition pathways, China and India are mapped for 2000 and 2010. This figures is generated using World Bank data (The World Bank, 2015).

Table S1 Summary Statistics of packaged food consumption, selected countries.

Variable	Unit	Obs.	Mean	Std. Dev.	Min	Max
Processed Food PC	kg/capita / year	79	196.9	99.0	15.0	388.0
GDP per capita	USD	79	21692.1	22013.6	1012.9	101222.4
Urban population share	%	79	68.1	17.4	23.6	100.0
Urban Dev. Index	1-100, see text	79	82.0	23.6	6.7	100.0
Service employment share	%	79	60.0	14.7	20.0	80.3
FDI per capita	USD	79	938.2	2464.0	-2631.0	11775.0

Data source: Euromonitor International (2017), World Bank (2015)

Table S2 –Determinants of households' expenditure on processed foods (share of total expenditure) and consumption of FAFH (no of meals pc) including having access to cooking facility.

	(1)	(2)
Dependent Variable	Processed foods: share of total food expenditure PC	FAFH on payment: number of meals
MPCE (log)	0.932***	1.010***
	(0.0270)	(0.0322)
Ocu: Industry (ref: agriculture)	0.250***	0.475***
	(0.0336)	(0.0400)
Ocu: Service (ref: agriculture)	0.322***	-0.0814**
	(0.0340)	(0.0407)
Ocu: Basic service (ref: agriculture)	0.442***	0.00427
	(0.0701)	(0.0835)
HH size	-0.148***	-0.0340***
	(0.00600)	(0.00718)
HH age - average	-0.0102***	0.00435***
	(0.00127)	(0.00152)
Have cooking aide	1.137***	-0.255***
	(0.0607)	(0.0733)
Have electricity	0.128***	-0.0840**
	(0.0351)	(0.0418)
Have modern cooking fuels	-0.00599	-0.490***
	(0.0331)	(0.0396)
Have cooking facility	-5.945***	-45.13***
	(0.126)	(0.136)
Urban-non metro (ref: rural)	0.140***	0.0118
	(0.0310)	(0.0371)
Urban-metro (ref: rural)	0.259***	0.497***
	(0.0434)	(0.0519)
Lit-informal (ref: illiterate)	-0.505*	0.226
	(0.270)	(0.323)
Lit-others (ref: illiterate)	-0.245***	0.130
	(0.0755)	(0.0899)
Primary-middle (ref: illiterate)	-0.255***	0.238***
	(0.0609)	(0.0730)
Secondary/HS (ref: illiterate)	-0.289***	0.366***
	(0.0669)	(0.0802)
Graduate+ (ref: illiterate)	-0.0656	0.377***
	(0.0693)	(0.0830)
Constant	4.157***	38.29***
	(0.243)	(0.282)
Observations	84,489	86,576
R-squared	0.106	0.603

This table is similar to table 4 of the main text, except here we have included a new explanatory variable "have cooking facility" in household dwelling unit, as we mentioned in the main text. With this new variable, the explanatory power for the processed food is almost same, about 10%, whereas for FAFH the explanatory power has increased to 60%, almost six folds. A cooking facility is negatively associated with both processed food consumption and FAFH, after controlling other variables (Table S2). Compared to households without cooking facility, household with cooking facility we would expect to decrease share of processed food by 5.9 percentage points, and as much as 45 meals per capita per month, ceteris paribus. Remaining coefficients are more or less same in direction and magnitude. This initial finding indicates the role of micro built environment on discouraging uptake of the processed foods or FAFH. However, for extracting any policy relevant outcome, we must check for self-selection bias in the model, which is likely to be in this case.

Chapter 6

6. Synthesis and outlook

This dissertation is structured around the hypothesis that urbanization is affecting food systems in a multitude of ways, many of which remain to be explored. It contributes to the understanding of the role of urbanization by answering the two main questions outlined in the introduction:

- How is urban area expansion affecting food production activities?
- How is urbanization and associated urban living affecting food consumption patterns?

This concluding chapter (i) synthesizes the findings of the four core chapters of this dissertation, (ii) discusses these findings in light of the GECAFS framework, (iii) outlines its policy relevance and implications, and (iv) provides an outlook for future research.

6.1. The spatial dimension of urbanization

The first set of research questions are primarily concerned with urbanization as land use form. In particular, the implications of urban area expansion for food production are explored.

Chapter 2 sets the stage and examines multiple land-use drivers to assess the impacts of human activity. It seeks to answer the following questions:

- How are competing land-uses driven by human activities affecting the food production landscape?
- What are the geographical hotspots of land conversion?
- What is the direct and indirect impact of human activity?

The study reveals regionally diverging patterns of global land-use change, grounded in direct human pressures, telecoupled land demand by international trade, and varying climate change impacts. By incorporating data on the displacement of land-use, the study finds that regions can be associated with three crude types of land-use dynamics. The first dynamic can be categorized as a 'consumers' land use and consists of mostly developed countries from the Northern hemisphere. It features high land footprints, reduced direct human pressures, and increased reliance on imported goods. The 'producer' type consists of food exporting countries such as Argentina and Brazil in South America. Here, telecoupled land-use links, often originating in 'consumer' regions, drive expansion of agricultural production at the expense of biodiversity and carbon storage. In the 'mover' regions, the study finds strong direct pressures of human activities, with a wide variety of outcomes. These range from a concurrent expansion of population, livestock, and croplands in Sub-Saharan Africa to strong pressure on cropland by urbanization in Eastern Asia. As these regions are generally defined by rapid population growth, this group likely plays the most important role in future land-use change.

The study highlights the global dimension of land use, grounded on the one hand in the transboundary externalities of climate change mitigation and biodiversity conservation, but also other drivers such as trade in land-intensive agricultural commodities. Local land use changes should therefore be considered as part of a multilayered biophysical-socioeconomic system. The importance of telecoupled interactions between distant human and natural systems substantiates the need for international cooperation to manage global land resources, especially in the context of food production.

Chapter 3 builds on the findings of the previous chapter and provides a more detailed analysis of local land use changes and their global implications. It investigates the implications of urban area expansion on surrounding croplands. It is motivated by two observations: first, most cities are surrounded by fertile croplands; second, numerous case studies have identified the conversion of croplands due to urban area expansion as a problematic development. This chapter seeks to answer the following questions:

- Where are croplands most vulnerable to conversion due to future urban expansion?
- What is the magnitude of cropland loss, especially of prime cropland, due to future urban expansion?
- How will the loss of croplands affect total cropland area and relative economic importance of agriculture for different countries?

This study finds that projected urban area expansion will take place on some of the world's most productive croplands, in particular in Asia and Africa, where 80% of the losses are expected to occur. Globally, future urban expansion is expected to convert 27–35 Mha of croplands between 2000 and 2030. This amounts to 1.8–2.4% of global croplands and 3.4–4.2% of the yearly production capacities. While the losses can be compensated by global food systems, the effects will not be distributed equally. In particular, countries from rapidly urbanizing regions from Asia and Africa can be expected to urbanize a substantial share of their croplands.

In these regions, this dynamic potentially adds pressure to already strained food systems and threatens livelihoods. Efforts will need to compensate for cropland losses, whether by intensifying remaining production, by expanding agricultural production into new areas, or by increasing imports. The findings of this chapter suggest that strategies and policies to effectively steer patterns of urban expansion will be critical for preserving valuable cropland.

Chapter 4 deviates from the urban expansion narrative. It investigates the impacts of the limited capacities of individual countries to produce enough food to meet the domestic demand. It builds on findings from chapters 2 and 3: first, the importance of distal interactions, or teleconnections, in the global food system. Second, the decreasing food self-sufficiency of developing countries, mostly due to resource constraints. The underlying hypothesis of this chapter is that the increasing dependency on food imports is potentially problematic as developing countries expose their vulnerable populations to world market volatility, both in terms of prices and supply. The chapter aims at assessing the implications of this exposure for food import dependent developing countries. It seeks to answer the following set of questions:

- Which countries have a strong dietary reliance on specific crops that they also need to import?
- What happens in the case of supply shocks, for example if exporting countries introduce restrictive trade policies?
- What would be the effect on the calorie supply of the poorest people in these countries?

The findings reveal that many countries strongly rely on one of the key staple crops (maize, rice, wheat) as main sources of calories, and that a significant number of these countries have to import a substantial share of these staples. This strong reliance, both in terms of calorie intake and import dependency, makes these countries susceptible to food supply shocks. Regional differences in the vulnerability to food supply shocks are associated to different food consumption habits. Middle Eastern countries are for instance particularly vulnerable to wheat supply shocks, whereas Central American countries heavily rely on imported maize and Western African countries on imported rice. This chapter further shows that the market concentration of the export market for these staple is very high and usually dominated by a few exporters. This further enhances the vulnerability of the global food supply system, indicating the disruptive capacity of a supply shock in the most dominant producing regions. The modeled supply shocks further underline the working hypothesis that exposure to world markets comes at a risk, especially when it concerns staple crops that are essential for the diets of the poorest part of the population. The results show that supply shocks exemplified by export bans in major producing regions would put up to 200 million people below the poverty line at risk, 90% of which live in Sub-Saharan Africa.

This chapter reveals that the problematic confluence of strong and mostly bilateral import dependence and a high dietary reliance on specific crops is common and often regionally concentrated. Import dependent countries could mediate food import dependency by increasing domestic production if they have sufficient biophysical capacities. However, the potential to produce enough domestically is often limited by biophysical constraints. Strategies to stabilize food supply could include regional trade agreements combined with regional grain emergency reserves.

6.2. Urban living

The second set of research questions is concerned with urban areas and associated urban living. It seeks to answer how it is affecting food consumption patterns.

Chapter 5 explores the empirical relationship between urbanization and the consumption of food items on different spatial scales. It focuses on packaged foods at the country level, and processed foods and food away from home (FAFH) in India. In particular, it seeks to answer the following questions:

- What is driving urban food consumption patterns?
- Is there an urban effect on diets that is not income related?
- What are the consequences of this urban effect on diets?

The findings show that the level of urban development affects consumption of packaged foods at the country level. While controlling for income and other variables, the findings show that an increase in the urban development index leads to a statistically significant increase in packaged food consumption. These findings are verified by a more detailed analysis of household survey data in India. Here, the findings suggest variations in processed food and food away from home consumption at different levels of urban development, namely between non-metropolitan and metropolitan urban areas. Further, an urban effect on diets is identified that is not income related. The effect is particularly strong for FAFH consumption, less so for processed foods. The urban effects vary significantly between metropolitan cities and non-metropolitan urban areas.

While income is still the most important driver of changing food consumption, our findings underline the importance of urbanization and associated urban living. As the effects vary across different urban contexts, our results highlight the need for a more nuanced understanding of how urban consumption patterns vary with different levels of urban development.

6.3. Discussion

This section discusses how the findings of this dissertation contribute to the research on global change and food systems. In this context, I use elements of the GECAFS framework (Figure 1) to discuss (i) how the findings supplement the research on global change and food system activities, and (ii) what the potential inferences are regarding food system outcomes. This section differentiates between two types of inferences: First, direct inferences based on the findings of this dissertation (solid lines in Figure 1); Second, not yet quantifiable, indirect inferences, based on broader implications of the findings (dotted lines in Figure 1). This section discusses the two parts of this dissertation separately.

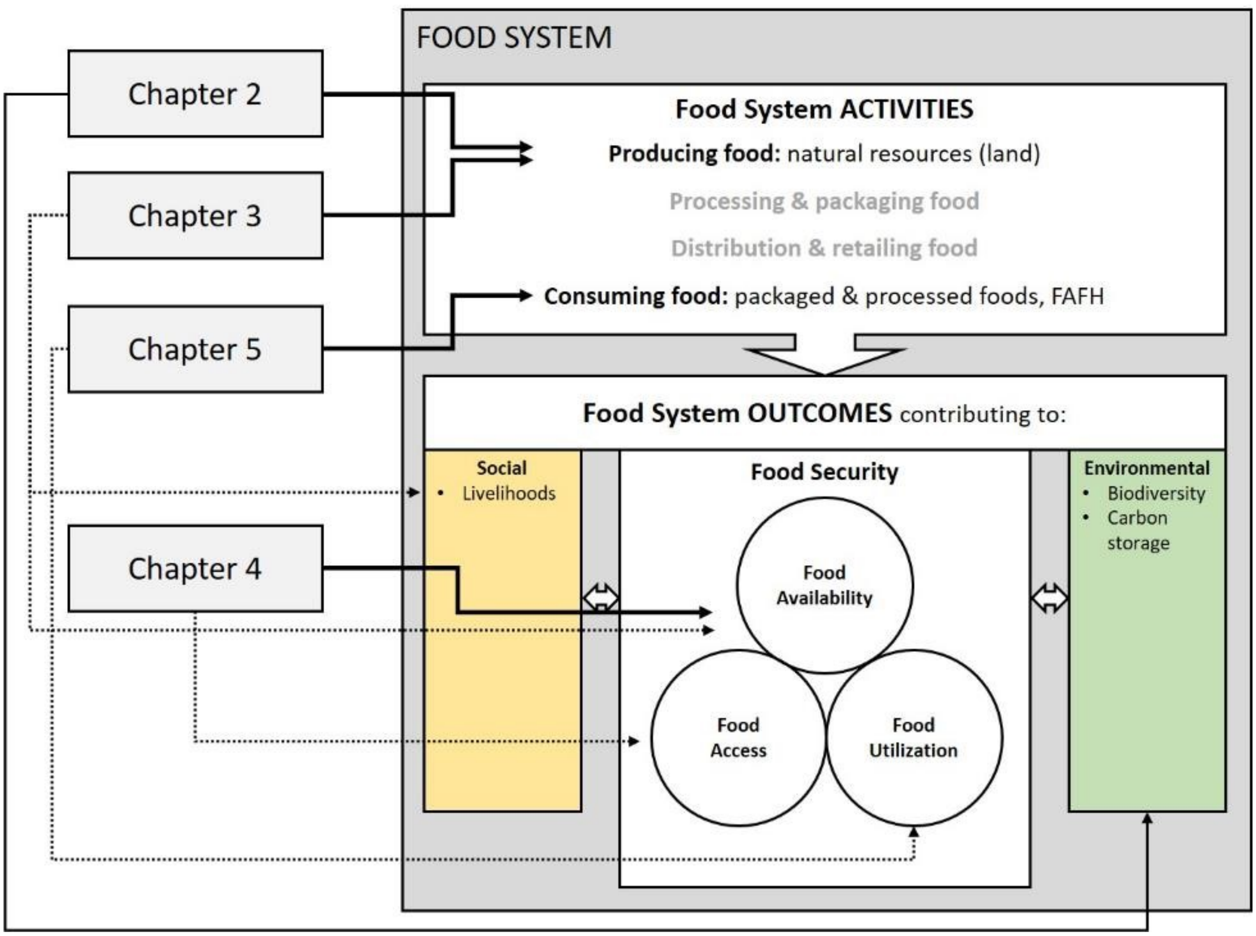

Figure 1 – Contribution of Chapters 2-5 to research on food systems under global change. Black lines indicate to which food system activity/outcome the chapters contribute directly. Dotted lines represent the most important indirect contributions (not exhaustive). Adjusted GECAFS framework (Figure 1 in the *Introduction*), based on Ericksen (2008) and Ingram (2011).

Part 1 mostly supplements the research on global change drivers and food production activities. As already indicated in the introduction, research on this topic spans across different disciplines and communities, and covers aspects such as climate change impacts (Lobell, 2011; Porter et al., 2014), and/or resource constraints (Lambin and Meyfroidt, 2011; Smith et al., 2010, 2014). The findings from chapters 2 and 3 are important contributions to the latter, in particular the literature on land-use change. Chapter 4 contributes to understanding potential consequences for food system outcomes by focusing on trade related aspects. All chapters add novel perspectives as detailed below.

Chapter 2 contributes to the literature on global land-use change, which has emerged as an important component of global environmental change and sustainability research (Turner et al., 2007). In their seminal contribution, Foley et al. (2005) highlight the need to account for the global consequences of land use, which previously had largely been considered a local issue. In this context, they also identified the trade-offs between immediate human needs, most notably land to produce food, and the limited capacity of the biosphere to provide enough goods and service in the long term. Subsequently, a range of papers have assessed the total area requirements to meet these human needs for a range of purposes under the narrative of competing land uses (Harvey and Pilgrim, 2011; Hurtt et al., 2011; Lambin and Meyfroidt, 2011; Smith et al., 2010; Wirsenius et al., 2010). Lambin and Meyfroidt (2011), for example, investigate how globalization impacts global land use transitions 2000-2030. They provide two aggregate estimates of projected land demand in 2030, essentially highlighting the trade-off between agricultural expansion and deforestation. They also observe an increasing separation between the location of the production and consumption, thus acknowledging the importance of distal environmental interactions in land systems (Meyfroidt et al., 2013), also known as 'teleconnected effects' (cf, for example, Friis et al., 2016). Another important contribution by Smith et al. (2010) reviews global land-use transition scenarios in models from 1990 until 2050. These studies generally focus on total area requirements to accommodate human needs while maintaining the biophysical capacities. They do not account for geographical patterns, the density, and productivity of land use. There is also a lack of a holistic analysis of geographical patterns of land system dynamics that investigates both location and density of land-use changes across spatial and temporal scales.

Chapter 2 addresses this research gap by combining and re-analyzing spatial data for human needs (shelter, food) and biophysical stability (biodiversity, climate stabilization). It further contributes by synthesizing the existing literature in an in-depth region-specific review, which also serves to validate the findings of the analysis. Further, the study incorporates telecoupled effects in its assessment. The concept of telecoupling expands that of teleconnections and captures not only distal environmental interactions (as teleconnections generally do) but also socio-economic interactions between coupled human and natural systems (cf. for example Liu et al., 2013 for a detailed description of these concepts). Essentially, the study underlines that local land-use changes are part of a multilayered biophysical-socioeconomic system that transcends spatial and temporal scales. Land use is increasingly displaced, from high-income to low-income countries, as for example Weinzettel et al. (2013) have shown. This is increasingly reflected in the land use literature. Notably, Friis et al. (2016) have observed that the frameworks of teleconnections and telecouplings are increasingly used to capture these effects, also in the context of urbanization (Seto et al., 2012).

Chapter 3 provides an analysis of local land-use competition and their global implications. The chapter focuses on urban area expansion at the expense of croplands. Specifically, it provides the land-use community with the first global estimate of the amount of croplands that is being lost to urban area expansion. Due to the relatively small land footprint (urban areas accounted for less than 0.5% of the global surface in 2000; Schneider et al., 2009) the implications of urban area expansion have not been sufficiently explored at the global level. Notable exceptions are the implications of urban area expansion for biodiversity and carbon pools (McDonald et al., 2008; McKinney, 2002; Seto et al., 2012). Earlier studies on the particular issue of the urbanization of croplands were conducted on a regional or city level (Ahmad et al., 2016; Bagan and Yamagata, 2014; Chen, 2007). The findings of chapter 3 close this research gap and reveal expected aggregate losses of about 30 Mha of prime croplands by 2030 compared to 2000. To put these results into perspective, Lambin and Meyfroidt (2011) predict a total land demand increase from 2000 to 2030 of 285 Mha (in their conservative estimate). The authors do not account for the losses associated with urban land expansion. According to their estimate, only 71 Mha of unused productive land would be left untouched in 2030, if no further deforestation would take place (Lambin and Meyfroidt, 2011). The findings from chapter 3 suggest that from 2000 to 2030, global available cropland is likely to be reduced by another 30 Mha, thus almost halving the number of available unused productive land in 2030. This would not even consider the fact that the urbanized cropland is almost twice as productive as the remaining croplands. This example serves to highlight the significance of these aggregate losses in a world where land, a key input for food production, is limited.

The expansion of urban areas and subsequent cropland losses need to be accounted for when assessing total land demand. However, beyond aggregated global cropland losses the findings also underline the importance of understanding the regional impacts. In some of the rapidly urbanizing developing countries, for example Egypt, the losses will substantially affect the food production capacities. The displacement of land-use, which had largely been observed from high-income countries to low(er)-income countries (Weinzettel et al., 2013), might also become more of an issue between low-income countries.

As food production is a function of croplands and the respective yields per unit area, chapters 2 and 3 have obvious implications for global food production activities of food systems, namely by affecting land as a key input for production (Figure 1). These implications are relatively clear, across scales. The findings are also likely to affect other food system activities, such as processing, packaging, and distribution. However, these implications are only discussed briefly to provide a more holistic assessment. Increasing trade of food products, as observed in numerous countries (Porkka et al., 2013), is likely to transform activities along the food value chain (Wilkinson, 2008). In exporting countries, processing activities are becoming more important (Athukorala and Sen, 1998), as raw products are often first processed and packaged, before they are shipped abroad. As the supply chains become longer, the distribution system also becomes more important, in both importing and exporting countries.

The implications for food system outcomes (*social*, *environmental*, *food security*, figure 1) are less clear-cut and more complex to assess. Chapter 2 allows for some direct inferences regarding environmental outcomes, as the analysis reveals that much of the expansion of human activity, especially for food production, co-occurs with significant biodiversity losses. While the concept of co-occurrence used in chapter 2 does not imply causality, there is a strand of literature linking expanding food production as major driver behind biodiversity loss (Reidsma et al., 2006; Searchinger et al., 2015). This framework considers biodiversity as well as carbon storage as environmental food system outcomes (cf. figure 1).

The findings of chapter 3 allow for more specific, albeit indirect, observations regarding food system outcomes. Thus far, the implications were mostly discussed at the global level. To discuss the implications for food security outcomes, the effects need to be understood at the local level. When croplands surrounding urban areas are lost, there is an obvious effect on local food *availability*. This will require some mitigating action to guarantee stable food *availability*, such as sourcing from further inland or increasing imports. Arguably, the more important effect will be on *social* food system outcomes, which in turn also affect the *accessibility* dimension of food security (cf. chapter 1.2 of this dissertation). Specifically, the expansion of urban areas coincides with the loss of income and the displacement of peri-urban households (Simon, 2008). Displaced subsistence farmers might lose the ability to feed themselves, becoming net buyers of food. And, as already indicated, for these households and the urban poor in general, food security becomes an issue of financial accessibility rather than availability (Cohen and Garrett, 2010). However, the findings of chapter 3 do not allow for direct inferences regarding the connection between the loss of productive croplands and food system outcomes.

Chapter 4 contributes to the understanding of the role of food trade, thus departing from the previous focus on land use, and complements the previous findings from another perspective. Trade is an important component for food systems (FAO, 2015), as it helps to counterbalance distributional imbalances between resource-poor and resource-rich regions. In terms of food security, trade will allow countries to increase the *availability* of food products (Porkka et al., 2013), which is one of the essential components. However, as Clapp (2015) notes there is a longstanding and to this date unresolved debate about whether trade is a threat or opportunity for food security. She states that "*the global trade in food is an economic activity, but it is also an activity deeply tied to food security, rural livelihoods, culture, ecology, and politics*". As this dissertation does not seek to position itself in this discourse, the opposing viewpoints are only briefly introduced. Proponents argue along the lines of classical trade theory that efficiency gains due to comparative advantages will increase food supplies at all scales and contribute to higher incomes (Lamy, 2013; Schumacher, 2013; World Bank, 2007). Opponents argue that rising food prices and increasing food price volatility in international markets have direct impacts on food security (Clapp, 2015). Trade will increase the exposure to world market volatility, creates dependencies, and potentially affects the financial and spatial *accessibility*.

Central to chapter 4 is one observation: some countries with limited biophysical capacities have or will have no options other than to import a more or less substantial share of their food supply (FAO, 2015). The earlier findings, especially from chapter 3, corroborate this observation. Chapter 4 seeks to contribute to the general understanding of food import dependencies in countries. Specifically, it is concerned with the implications of food supply shocks for food import dependent developing countries. In the analysis, the implications for the calorie supply of the poorest part of the population are modelled. In terms of food security outcomes, the study finds that supply shocks, for example due to an export ban, would decrease the domestic calorie supply in the short term, thus decreasing the *availability* (Figure 2). However, as these supply shocks would be mediated by price effects (Kalkuhl, 2014), they would also affect the *accessibility*. These effects would be especially pronounced in urban context, as urban areas tend to be better connected to world markets and hence more exposed (Cohen and Garrett, 2010).

Part 2 of this dissertation contributes to the understanding of food consumption patterns (Figure 1). Chapter 5 supplements research on consumption activities of food systems by arguing that there is an urban effect on diets. In general, changing food consumption patterns are mostly linked to rising incomes (Cirera and Masset, 2010; Du et al., 2004). Much of the research that is to some degree concerned with urban diets attributes the distinctness of urban diets also to rising incomes, or conflates rising incomes, westernization, and urbanization. However, the findings of chapter 5 suggest that there are multiple ways in which urbanization affects diets, regardless of higher incomes of urban residents. While there is agreement that people living in urban areas consume differently than people in rural areas, there is still no clear understanding why that is the case. Most studies offer only a comparison of urban diets to rural ones, based on descriptive statistics. By isolating on urban effect on diets, chapter 5 thus adds a novel perspective to the research on changing consumption patterns.

The findings of chapter 5 also have indirect implications for other food system activities. As for example Erb et al. (2016) have shown, diets will essentially determine if the currently available resources for food production will allow to cover the food demand of future populations (in that case without further deforestation). In this context, more meat-based diets in particular will put enormous pressure on resources. Currently observed trends on increasing consumption of animal based products across the developing world point in that direction (Kearney, 2010).

In terms of food system outcomes, the findings of chapter 5 allow for indirect inferences regarding the *utilization* dimension of food security (figure 1). This dimension essentially refers to the "*safe and nutritious food*" part of the definition of food security introduced in the introduction of this dissertation. The findings highlight a strong urban effect on FAFH, and similarly on consumption of processed foods in India. This can have important implications for public health. There is a range of possible options for consuming FAFH, including food stalls, full service, and fast-food restaurants. Of these, fast-food is likely to have the biggest health impact (Rosenheck, 2008). Depending on what is being consumed in these restaurants, increasing FAFH consumption poses substantial risks to public health. For example, fast-food consumption in the US is directly linked to increasing risk of obesity and type 2 diabetes (Pereira et al., 2005). Similar observations have been made for processed foods, which in developing countries are primarily being sold in supermarkets (Minot et al., 2015; Rischke et al., 2015). In Kenya, for example, supermarkets have a direct effect on people's health, increasing the prevalence of obesity and other nutrition-related diseases (Demmler et al., 2017).

6.4. Policy relevance and implications

Sustainable Development Goal number 2 puts eradicating hunger and all forms of malnutrition by 2030 at the top of the development agenda (United Nations, 2015). Food systems are responsible for ensuring that these goals are achieved. It will require providing (i) enough food that (ii) is healthy and nutritious, and (iii) accessible to everyone. In times of accelerating global change dynamics, such as demographic change, globalization, urbanization, and climate change, achieving these goals will require a detailed understanding of how exactly these drivers are affecting food systems. As detailed in the previous section, this dissertation contributes to that field of research in a number of ways. The individual chapters present various entry points for policy makers to intervene and counteract at different scales.

Chapter 2 offers multiple policy alternatives. On the macro level, the findings substantiate the need international cooperation to manage global land. In this regard, chapter 2 feeds into an ongoing discourse over appropriate governance regimes for land (Creutzig, 2017; Magalhães et al., 2016). Creutzig (2017) argues that land should be considered as global commons, both conceptually by the research community and legally by the international community. Necessary regulatory changes include the scaling up of international financing of conservations and carbon storage efforts and the harmonization of ambitious conservations standards. On the regional level, more targeted policies promise successful interventions. In 'consumer' regions, for example, sustainability certificates could foster a shift towards a more sustainable land use (Tayleur et al., 2016). These should be supplemented by policies targeted at changing food consumption behavior towards more sustainable diets. These will be discussed in more detail when the policy recommendations for chapter 5 are presented. In 'producer' regions, both domestic and international ecosystem protection and nature conversation measures are crucial components of protecting ecosystems. In particular, a harmonization of ecosystem protection measures and financing of nature conversation (Waroux et al., 2016), and an upscaling of international payment for ecosystem services schemes (Rands et al., 2010) would be crucial components. Further, as carbon stock movements are not always related to biodiversity, it is crucial for the design of environmental policies, such as REDD+, to differentiate between land carbon stock and biodiversity (Phelps et al., 2012). 'Mover' regions would profit from more efficient land-use. Specific measures to further improve efficient land use involve intensification that complies with the protection of important ecosystems, soil carbon, and water resources (Garnett et al., 2013) as well as multi-purpose systems that integrate several land uses, an approach called land sharing (Fischer et al., 2014; Lambin and Meyfroidt, 2011). Additional policies to preserve croplands from urbanization are detailed in the next section.

Chapter 3 allows for more targeted policy recommendations. Urban policy makers and planners play a crucial role in managing urban expansion and preventing the encroachment on productive croplands. Containing urban area expansion is an established planning approach to encourage compact, public transport-oriented urban forms, crucial for example for securing long-term climate mitigation goals (Creutzig et al., 2016). The same approach also preserves agricultural lands in peri-urban areas, as Daniels (1999) has shown. However, the effectiveness of these containment strategies around the world is mixed, and its success depends on many factors, including the willpower of policy makers and institutional contexts. An alternative approach could be the selective protection of open space from urban encroachment. The transfer of development rights could be used to effectively redirect new growth from areas to be protected (in this case productive croplands) to areas where more development is desired (Johnston and Madison, 1997). However, national policy makers can also contribute by designing crucial economic incentives. In particular, fuel taxes have been shown to induce more compact urban form and preserve open space (Creutzig, 2014).

A range of possible policy interventions can be deduced from chapter 4. Import dependent countries can implement measures to prevent extreme food shortages, and mediate food import dependency. One option would be to increase domestic production by more efficient land-use, for example by increasing agricultural productivity. For countries in Sub-Saharan Africa, this would include closing yield gaps (West et al., 2014). Another obvious alternative would be the diversification of trading partners but also of diets to reduce risks to sudden supply shocks. However, a range of countries will not be able to increase their domestic production or diversify fully. In these cases, regional trade agreements combined with regional grain emergency reserves are a promising tool to stabilize food supply at low costs (Kornher and Kalkuhl, 2016). In addition, policies targeting agricultural export restrictions should be implemented. Such measures would include modifying existing disciplinary actions against export taxes and restrictions by the World Trade Organization (WTO) and improving their enforceability (Anania, 2013).

The findings of chapter 5 essentially highlight a transition of diets in urban areas towards more processed foods and FAFH, with potentially far-reaching implications for public health. Multiple interventions exist to tackle poor nutritional intake. As changing diets are results of changes in environments, behavior and food systems, improving diets will require policies that can address all these drivers (IFPRI, 2017). Policies at the national level are relevant, for example mandatory nutrition labeling for packaged foods (Lobstein and Davies, 2009). Another option are economic incentives, for example taxing of particularly unhealthy ultra-processed foods (Mytton et al., 2012). In addition, educating about the importance of good nutrition promises long-lasting effects on consumption behavior. Other alternatives include prevention campaigns and banning of marketing directly aimed at children (IFPRI, 2017). Most of these policies aim to inform and educate the consumer about the potential health implications of unhealthy diets.

Recent changes in focus of international development corporation and research institutions further reflect the timeliness and broader significance of these contributions. The "Global Land Outlook" (GLO) report (United Nations and Convention to Combat Desertification, 2017) is one example of an emerging class of global land use assessments. Essentially a collaborative effort by a consortium of development agencies, it is also suitable example of the relevance of the first part of this dissertation. It reflects "*a growing sense of urgency*" (United Nations and Convention to Combat Desertification, 2017) for detailed assessments of land use dynamics. Further, by dedicating an entire chapter to urbanization, it underlines the increasing awareness of urban area expansion as relevant land-use form.

The relevance of the second part of this dissertation is also reflected in a recent report, again by a consortium of UN agencies. The first edition of the "State of Food Insecurity and Nutrition in the World 2017" (FAO, IFAD, UNICEF, WFP and WHO, 2017) elevates the importance of both food security and nutrition. Nutrition had of course been considered in earlier reports – as part of food security assessments. By definition, the nutritional component was always included (cf. *Introduction*). But the explicit mention also indicates increasing awareness of the acuteness of the issue of nutrition, which is also reflected in the declaration of the "*decade of nutrition*" in 2016 (FAO, 2016). One key aspect in tackling the issue of malnutrition is a detailed understanding of what is driving changes in food consumption patterns (Ingram, 2017). Chapter 5 contributes to that debate in a novel way, by highlighting the urban effect on diets.

Finally, the underlying hypothesis of this dissertation, namely that urbanization is significantly affecting food systems, is also reflected in an important publication. The International Food Policy Research Institute publishes a Global Food Policy Report every year. In order to be included in the report "*a topic must represent a new development in food policy or a new way of looking at an important food issue*" (IFPRI, 2017). The 2017 edition (IFPRI, 2017) is explicitly concerned with the implications of urbanization on food systems and the ties between rural and urban areas. It states that "*rapid urbanization, particularly in developing countries, is a critical ongoing trend shaping food security and nutrition that will continue 2017 and beyond*" (IFPRI, 2017).

6.5. Outlook and future research

The findings of this dissertation present important contributions to the understanding of the role of urbanization in food system transitions but also suggest several avenues for future research.

As the discussion has shown, many open questions remain both regarding food system activities and food system outcomes. A more detailed understanding of the implications of urbanization on packaging and processing activities as well as on retail and distribution would provide valuable insights. Rapid urbanization is driving change in these activities, essentially transforming agricultural value chains (IFPRI, 2017). This raises important questions. What will be the effect on employment and food prices for both the rural and the urban population? What is the role of urban markets and how are they shaping agricultural value chains? What are the consequences for small-scale producers? How can governments intervene, for example by providing infrastructure?

More specifically, chapter 3 raises questions regarding the consequences for livelihoods in peri-urban settings. Who will be impacted? In particular, what will be the effect on smallholders? Will impacted and displaced households be able to enter urban or other non-farm labor markets? Will they move to cities? In this context, it will be essential to understand what exactly is being produced near urban areas, and who is producing it. Ideally, this would be supplemented with information where these products are sold. An analysis of this should also include a time dimension to capture how peri-urban households react to encroaching urban areas and changes in consumption patterns in cities. These findings would allow for clearer inferences regarding food system outcomes.

Monitoring the transition of developing countries as they urbanize could provide valuable insights in that regard. This would require combining high-resolution spatial data on urban extent, croplands, and farm size with subnational census data, ideally at the city-level.

Chapter 5 has already contributed to the understanding of urban diets. However, many open questions remain. How else are urban environments shaping the food choice of urban residents, for example by the spatial structure or modes of transportation? How can the variation between urban areas explained? A reasonable starting point would be to formalize the understanding of urban diets and consumption patterns by introducing a conceptual framework. This framework should answer how the specificities of urban areas and associated urban living are potentially affecting diets and should be empirically verifiable.

Additional questions would concern the retail structure and restaurant chains. How are super markets and fast-food chains affecting food choice? Are they essentially catering demand or creating demand? Some of these effects have been studied, but only locally, for example in Kenya (Rischke et al., 2015). It would be interesting to see if these results are transferable across the developing world and if the lessons learnt in one country can help other countries. Since it is likely that supermarkets and fast-food restaurants are affecting public health, it would also help to understand how they could contribute to create an enabling environment for a healthy and balanced nutrition.

Assessing the implications on multiple dimensions of the food system will require considerable efforts, bridging different disciplines. Assessment-style reports such as FAO's "State of Food Security and Nutrition of the World" are essential in this context. Another approach are transdisciplinary studies such as Herrero et al. (2017), who provide a breakdown of global agricultural and nutrient production by farm size. Further, they study the associations between farm size, agricultural diversity, and nutrient production. This particular contribution will allow designing policies to promote healthy, nutritious diets. Essentially, tackling food and nutrition security will require substantially more research on a range of topics. An urban perspective provides a promising way forward.

References

Ahmad, S., Avtar, R., Sethi, M., Surjan, A., 2016. Delhi's land cover change in post transit era. Cities 50, 111–118. https://doi.org/10.1016/j.cities.2015.09.003

Anania, G., 2013. Agricultural Export Restrictions and the WTO. Geneva, Switzerland.

Athukorala, P., Sen, K., 1998. Processed food exports from developing countries: patterns and determinants. Food Policy 23, 41–54.

Bagan, H., Yamagata, Y., 2014. Land-cover change analysis in 50 global cities by using a combination of Landsat data and analysis of grid cells. Environ. Res. Lett. 9, 064015. https://doi.org/10.1088/1748-9326/9/6/064015

Chen, J., 2007. Rapid urbanization in China: A real challenge to soil protection and food security. CATENA, Influences of rapid urbanization and industrialization on soil resource and its quality in China 69, 1–15. https://doi.org/10.1016/j.catena.2006.04.019

Cirera, X., Masset, E., 2010. Income distribution trends and future food demand. Philos. Trans. R. Soc. B Biol. Sci. 365, 2821–2834.

Clapp, J., 2015. Food security and international trade: unpacking disputed narratives. Background paper prepared for The State of Agricultural Commodity Markets 2015–16. FAO Rome.

Cohen, M.J., Garrett, J.L., 2010. The food price crisis and urban food (in)security. Environ. Urban. 22, 467–482. https://doi.org/10.1177/0956247810380375

Creutzig, F., 2017. Govern land as a global commons. Nature 546, 28.

Creutzig, F., 2014. How fuel prices determine public transport infrastructure, modal shares and urban form. Urban Clim. 10, 63–76.

Creutzig, F., Agoston, P., Minx, J.C., Canadell, J.G., Andrew, R.M., Le Quéré, C., Peters, G.P., Sharifi, A., Yamagata, Y., Dhakal, S., 2016. Urban infrastructure choices structure climate solutions. Nat. Clim. Change 6, 1054–1056.

Daniels, T., 1999. When city and country collide: Managing growth in the metropolitan fringe. Island Press.

Demmler, K.M., Klasen, S., Nzuma, J.M., Qaim, M., 2017. Supermarket purchase contributes to nutrition-related non-communicable diseases in urban Kenya. PLOS ONE 12, e0185148. https://doi.org/10.1371/journal.pone.0185148

Du, S., Mroz, T.A., Zhai, F., Popkin, B.M., 2004. Rapid income growth adversely affects diet quality in China—particularly for the poor! Soc. Sci. Med. 59, 1505–1515.

Erb, K.-H., Lauk, C., Kastner, T., Mayer, A., Theurl, M.C., Haberl, H., 2016. Exploring the biophysical option space for feeding the world without deforestation. Nat Commun 7.

Ericksen, P.J., 2008. Conceptualizing food systems for global environmental change research. Glob. Environ. Change 18, 234–245.

FAO, 2016. News Article: UN General Assembly proclaims Decade of Action on Nutrition [WWW Document]. URL http://www.fao.org/news/story/en/item/408970/icode/ (accessed 10.14.17).

FAO, 2015. The State of Agricultural Commodity Markets 2015-2016: Trade and food security: achieving a better balance between national priorities and the collective good. FAO, Rome.

FAO, IFAD, UNICEF, WFP and WHO, 2017. The State of Food Security and Nutrition in the World 2017. Building resilience for peace and food security. FAO, Rome.

Fischer, J., Abson, D.J., Butsic, V., Chappell, M.J., Ekroos, J., Hanspach, J., Kuemmerle, T., Smith, H.G., von Wehrden, H., 2014. Land Sparing Versus Land Sharing: Moving Forward. Conserv. Lett. 7, 149–157. https://doi.org/10.1111/conl.12084

Foley, J.A., 2005. Global Consequences of Land Use. Science 309, 570–574. https://doi.org/10.1126/science.1111772

Friis, C., Nielsen, J.Ø., Otero, I., Haberl, H., Niewöhner, J., Hostert, P., 2016. From teleconnection to telecoupling: taking stock of an emerging framework in land system science. J. Land Use Sci. 11, 131–153. https://doi.org/10.1080/1747423X.2015.1096423
Garnett, T., Appleby, M.C., Balmford, A., Bateman, I.J., Benton, T.G., Bloomer, P., Burlingame, B., Dawkins, M., Dolan, L., Fraser, D., Herrero, M., Hoffmann, I., Smith, P., Thornton, P.K., Toulmin, C., Vermeulen, S.J., Godfray, H.C.J., 2013. Sustainable Intensifi cation in Agriculture: Premises and Policies. Science 341, 33–34.
Harvey, M., Pilgrim, S., 2011. The new competition for land: food, energy, and climate change. Food Policy 36, S40–S51.
Herrero, M., Thornton, P.K., Power, B., Bogard, J.R., Remans, R., Fritz, S., Gerber, J.S., Nelson, G., See, L., Waha, K., Watson, R.A., West, P.C., Samberg, L.H., van de Steeg, J., Stephenson, E., van Wijk, M., Havlík, P., 2017. Farming and the geography of nutrient production for human use: a transdisciplinary analysis. Lancet Planet. Health 1, e33–e42. https://doi.org/10.1016/S2542-5196(17)30007-4
Hurtt, G.C., Chini, L.P., Frolking, S., Betts, R.A., Feddema, J., Fischer, G., Fisk, J.P., Hibbard, K., Houghton, R.A., Janetos, A., Jones, C.D., Kindermann, G., Kinoshita, T., Klein Goldewijk, K., Riahi, K., Shevliakova, E., Smith, S., Stehfest, E., Thomson, A., Thornton, P., van Vuuren, D.P., Wang, Y.P., 2011. Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. Clim. Change 109, 117–161. https://doi.org/10.1007/s10584-011-0153-2
IFPRI, 2017. 2017 Global Food Policy Report. International Food Policy Research Institute, Washington, DC. https://doi.org/10.2499/9780896292529
Ingram, J., 2017. Perspective: Look beyond production. Nature 544, S17–S17.
Ingram, J., 2011. A food systems approach to researching food security and its interactions with global environmental change. Food Secur. 3, 417–431.
Johnston, R.A., Madison, M.E., 1997. From land marks to landscapes: a review of current practices in the transfer of development rights. J. Am. Plann. Assoc. 63, 365–378.
Kalkuhl, M., 2014. How Strong Do Global Commodity Prices Influence Domestic Food Prices in Developing Countries? A Global Price Transmission and Vulnerability Mapping Analysis. Glob. Price Transm. Vulnerability Mapp. Anal. May 2014 ZEF-Discuss. Pap. Dev. Policy.
Kearney, J., 2010. Food consumption trends and drivers. Philos. Trans. R. Soc. Lond. B Biol. Sci. 365, 2793–2807. https://doi.org/10.1098/rstb.2010.0149
Kornher, L., Kalkuhl, M., 2016. The costs and benefits of regional cooperation on grain reserves: the case of ECOWAS, in: Food Price Volatility and Its Implications for Food Security and Policy. Springer, pp. 353–384.
Lambin, E.F., Meyfroidt, P., 2011. Global land use change, economic globalization, and the looming land scarcity. Proc. Natl. Acad. Sci. 108, 3465–3472. https://doi.org/10.1073/pnas.1100480108
Lamy, P., 2013. The Geneva Consensus: making trade work for all. Cambridge University Press.
Liu, J., Hull, V., Batistella, M., DeFries, R., Dietz, T., Fu, F., Hertel, T., Izaurralde, R.C., Lambin, E., Li, S., Martinelli, L., McConnell, W., Moran, E., Naylor, R., Ouyang, Z., Polenske, K., Reenberg, A., de Miranda Rocha, G., Simmons, C., Verburg, P., Vitousek, P., Zhang, F., Zhu, C., 2013. Framing Sustainability in a Telecoupled World. Ecol. Soc. 18. https://doi.org/10.5751/ES-05873-180226
Lobell, D.B., 2011. Climate trends and global crop production since 1980. Science 333, 616–620. https://doi.org/10.1126/science.1204531
Lobstein, T., Davies, S., 2009. Defining and labelling 'healthy'and 'unhealthy'food. Public Health Nutr. 12, 331–340.

Magalhães, P., Steffen, W., Bosselmann, K., Aragão, A., Soromenho-Marques, V., 2016. Cambridge Scholars Publishing. The Safe Operating Space Treaty. Cambridge Scholars Publishing, Cambridge UK.
McDonald, R.I., Kareiva, P., Forman, R.T., 2008. The implications of current and future urbanization for global protected areas and biodiversity conservation. Biol. Conserv. 141, 1695–1703.
McKinney, M.L., 2002. Urbanization, biodiversity, and conservation: the impacts of urbanization on native species are poorly studied, but educating a highly urbanized human population about these impacts can greatly improve species conservation in all ecosystems. Bioscience 52, 883–890.
Meyfroidt, P., Lambin, E.F., Erb, K.-H., Hertel, T.W., 2013. Globalization of land use: distant drivers of land change and geographic displacement of land use. Hum. Settl. Ind. Syst. 5, 438–444. https://doi.org/10.1016/j.cosust.2013.04.003
Minot, N., Stringer, R., Umberger, W.J., Maghraby, W., 2015. Urban shopping patterns in Indonesia and their implications for small farmers. Bull. Indones. Econ. Stud. 51, 375–388.
Mytton, O.T., Clarke, D., Rayner, M., 2012. Taxing unhealthy food and drinks to improve health. BMJ Br. Med. J. Online 344.
Pereira, M.A., Kartashov, A.I., Ebbeling, C.B., Van Horn, L., Slattery, M.L., Jacobs, D.R., Ludwig, D.S., 2005. Fast-food habits, weight gain, and insulin resistance (the CARDIA study): 15-year prospective analysis. The lancet 365, 36–42.
Phelps, J., Webb, E.L., Adams, W.M., 2012. Biodiversity co-benefits of policies to reduce forest-carbon emissions. Nat. Clim. Change 2, 497–503. https://doi.org/doi:10.1038/nclimate1462
Porkka, M., Kummu, M., Siebert, S., Varis, O., 2013. From Food Insufficiency towards Trade Dependency: A Historical Analysis of Global Food Availability. PLOS ONE 8, e82714. https://doi.org/10.1371/journal.pone.0082714
Porter, J.R., Xie, L., Challinor, A.J., Cochrane, K., Howden, S.M., Iqbal, M.M., Lobell, D.B., Travasso, M.I., 2014. Food Security and Food Production Systems, in: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (Eds.)]. Cambridge University Press.
Rands, M.R., Adams, W.M., Bennun, L., Butchart, S.H., Clements, A., Coomes, D., Entwistle, A., Hodge, I., Kapos, V., Scharlemann, J.P., others, 2010. Biodiversity conservation: challenges beyond 2010. Science 329, 1298–1303.
Reidsma, P., Tekelenburg, T., Van den Berg, M., Alkemade, R., 2006. Impacts of land-use change on biodiversity: an assessment of agricultural biodiversity in the European Union. Agric. Ecosyst. Environ. 114, 86–102.
Rischke, R., Kimenju, S.C., Klasen, S., Qaim, M., 2015. Supermarkets and food consumption patterns: The case of small towns in Kenya. Food Policy 52, 9–21.
Rosenheck, R., 2008. Fast food consumption and increased caloric intake: a systematic review of a trajectory towards weight gain and obesity risk. Obes. Rev. 9, 535–547.
Schneider, A., Friedl, M.A., Potere, D., 2009. A new map of global urban extent from MODIS satellite data. Environ. Res. Lett. 4, 044003.
Schumacher, R., 2013. Deconstructing the theory of comparative advantage. World Soc. Econ. Rev. 2013, 83.
Searchinger, T.D., Estes, L., Thornton, P.K., Beringer, T., Notenbaert, A., Rubenstein, D., Heimlich, R., Licker, R., Herrero, M., 2015. High carbon and biodiversity costs from converting Africa/'s wet savannahs to cropland. Nat. Clim. Change 5, 481–486.

Seto, K., Reenberg, A., Boone, C.G., Fragkias, M., Haase, D., Langanke, T., Marcotullio, P., Munroe, D.K., Olah, B., Simon, D., 2012. Urban land teleconnections and sustainability. Proc. Natl. Acad. Sci. 109, 7687–7692. https://doi.org/10.1073/pnas.1117622109

Simon, D., 2008. Urban Environments: Issues on the Peri-Urban Fringe. Annu. Rev. Environ. Resour. 33, 167–185. https://doi.org/10.1146/annurev.environ.33.021407.093240

Smith, P., Bustamante, M., Ahammad, H., Clark, H., Dong, H., Elsiddig, E.A., Haberl, H., Harper, R., House, J.I., Jafari, M., Masera, O., Mbow, C., Ravindranath, N.H., Rice, C.W., Robledo Abad, C., Romanovskaya, A., Sperling, F., Tubiello, F.N., 2014. Agriculture, Forestry and Other Land Use (AFOLU), in: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Smith, P., Gregory, P.J., Vuuren, D. van, Obersteiner, M., Havlík, P., Rounsevell, M., Woods, J., Stehfest, E., Bellarby, J., 2010. Competition for land. Philos. Trans. R. Soc. B Biol. Sci. 365, 2941–2957. https://doi.org/10.1098/rstb.2010.0127

Tayleur, C., Balmford, A., Buchanan, G.M., Butchart, S.H., Ducharme, H., Green, R.E., Milder, J.C., Sanderson, F.J., Thomas, D.H., Vickery, J., others, 2016. Global Coverage of Agricultural Sustainability Standards, and Their Role in Conserving Biodiversity. Conserv. Lett.

Turner, B.L., Lambin, E.F., Reenberg, A., 2007. The emergence of land change science for global environmental change and sustainability. Proc. Natl. Acad. Sci. 104, 20666–20671. https://doi.org/10.1073/pnas.0704119104

United Nations, 2015. RES/70/1. Transforming our world: the 2030 agenda for sustainable development. Seventieth U. N. Gen. Assem. N. Y. 25.

United Nations, Convention to Combat Desertification, 2017. The Global Land Outlook, first edition. Bonn.

Waroux, Y. le P. de, Garrett, R.D., Heilmayr, R., Lambin, E.F., 2016. Land-use policies and corporate investments in agriculture in the Gran Chaco and Chiquitano. Proc. Natl. Acad. Sci. 113, 4021–4026. https://doi.org/10.1073/pnas.1602646113

Weinzettel, J., Hertwich, E.G., Peters, G.P., Steen-Olsen, K., Galli, A., 2013. Affluence drives the global displacement of land use. Glob. Environ. Change 23, 433–438. https://doi.org/10.1016/j.gloenvcha.2012.12.010

West, P.C., Gerber, J.S., Engstrom, P.M., Mueller, N.D., Brauman, K.A., Carlson, K.M., Cassidy, E.S., Johnston, M., MacDonald, G.K., Ray, D.K., Siebert, S., 2014. Leverage points for improving global food security and the environment. Science 345, 325–328. https://doi.org/10.1126/science.1246067

Wilkinson, J., 2008. The food processing industry, globalization and developing countries. Transform. Agri-Food Syst. Glob. Supply Chains Smallhold. Farmers 87–108.

Wirsenius, S., Azar, C., Berndes, G., 2010. How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agric. Syst. 103, 621–638. https://doi.org/10.1016/j.agsy.2010.07.005

World Bank, 2007. World development report 2008: Agriculture for development. World Bank, Washington, D.C., USA.

Acknowledgements

This dissertation also marks the end of an important and certainly life-changing journey for me. Ending it provides a great opportunity to express gratitude to everyone who has supported, inspired, and helped along the way.

First, I want to thank Prof. Dr. Ottmar Edenhofer and Prof. Dr. Felix Creutzig for their supervision. I would like to thank Prof. Edenhofer for his thoughtful guidance and valuable feedback, and for giving me the opportunity of being part of this uniquely stimulating institute. He was a constant source of inspiration during my time at MCC. I am deeply indebted to Prof. Creutzig for a number of reasons. First, for taking a chance on a pragmatic business school graduate with limited knowledge of “real” academia and a questionable methodological skillset. Second, for creating a thriving working group environment with a high degree of flexibility. Third, for fostering the exchange with other institutes that eventually materialized in very successful collaborations that proved very valuable for my development. Fourth, for supporting me in any way I needed it. I never felt that I could not do something (admittedly, only as long as it was reasonable and I could clearly state why I wanted to do it). Fifth, for stressing the importance of good academic writing (and reviewing). Sixth, for pushing me when I needed it. His depiction of a PhD, which he described (I am paraphrasing!) as “*90% hard work, endurance, and tolerance of frustration*”, proved to be very accurate.

I would also like to thank a range of other scholars who have supported and guided me along the way, especially Prof. Karen Seto, who invited me to visit her lab. Her way of developing students by encouraging them to come up with their own solutions for all sorts of problems helped me to mature as a researcher. Further, I am grateful to Prof. Dr. Helmut Haberl and Prof. Dr. Karlheinz Erb, who I was able to visit early on in my PhD. The fruitful discussions and brainstorming sessions were an important milestone for my personal development. I would also like to thank all my co-authors for their amazing work and input.

More generally, I am highly indebted to everybody at MCC who made my time as a PhD student such a fruitful experience. Without the good organization and administration, this would certainly not be possible. Therefore, I would like to thank Susann, Annelie, Martin, Liane, and Elisabeth for putting up with an armada of overcommitted and (dis)organized researchers! I would further like to thank all my fellow PhD students, here and abroad, who sat right next to me on this rollercoaster ride. Blanca, Steffen, Christoph, Leonie, Marcel, Jenn, Alex, Barbora, Hauke, Johanna, Sebi, Max, Ira, Andri, Peter (and whomever I forgot to mention): it has been my pleasure. The same holds true for Bhartendu, Kellie, Ken, Chris, Meredith, Alex, and Paige in the US.

I am very grateful to everyone in our working group. Especially Blanca, Ulf, and Sohail. Blanca, for making this office a better place. Ulf, for doing just that but also for providing me with a crash course in everything there is to know about GIS, which was a turning point for me. Sohail for conquering my reservations towards any sort of econometric analysis by being a very patient teacher, and further for spreading inexhaustible amounts of optimism.

Further, I would like to thank Johanna and Blanca for their valuable feedback on this dissertation and Dorothe Ilskens for helping in the challenging administrative process. I would also like to thank Linus for his advice and support. I would further like to thank my friends for not annoying me with too many silly and unqualified questions, and for accepting that a PhD is a “real job”.

Finally, I am deeply indebted to my family. I would like to thank my parents and siblings for their patience and unconditional support. I dedicated this dissertation to them.

Statement of contribution

Chapters 2 to 5 are the result of collaborations between the author of this dissertation and a range of collaborators. The author of this dissertation has made extensive contributions to all four chapters, ranging from conceptual design to analyses and composition of the manuscripts. This section details the contribution of the author to the four core chapters and further acknowledges major contributions of collaborators.

Chapter 2: as second author in this extensive collaborative project, the author was involved in the research design. Together with Ulf Weddige and Tim Beringer, he conducted the lion's share of the analysis of the geospatial datasets. Specifically, he was responsible for the modelling of biodiversity losses, and the mapping and visualization of the results. Further, together with all other authors, the author contributed to the region-specific literature review, covering the Middle East and Norther Africa. He was responsible for the composition of the supplementary materials, and was involved in the composition of the manuscript. As lead author, Felix Creutzig was responsible for the development of the research question and in charge of the research design as well as the main manuscript, with input from all co-authors.

Chapter 3: as lead author, the author was involved in all aspects of this study, starting from the development of the research question. Together with Femke Reitsma, Felix Creutzig, and Karen Seto, the study design was developed. The author was the main responsible for the different analyses conducted in this study, namely the geospatial analysis of cropland and cropland productivity datasets, as well as a dataset on projected urban area expansion, with the support from the co-authors. Further, he was responsible for the visualization of the results. The author was in charge of the composition of all parts of the manuscript, with significant input and contributions from all co-authors.

Chapter 4: as lead author, the author was involved in all aspects of this study, starting from the development of the research question to the research design. All co-authors contributed to the research design. The author was responsible for the main analysis, namely the vulnerability analysis, the empirical modelling of food supply shocks, and the vulnerability mapping. Leonie Wenz provided supplementary analysis, and Matthias Kalkuhl provided the formalization of the empirical and analytical model. The author was in charge of the composition of all parts of the manuscript, with significant input and contributions from all co-authors.

Chapter 5: as lead author, the author was involved in all aspects of this study, starting from the development of the research question to the research design. Together with Bhartendu Pandey and Meredith Reba, and with further input from Karen Seto, the author set up the research design. The author conducted the country level analysis and the largest part of the analysis of the household survey data for India. In this context, Bhartendu Pandey was responsible for the data processing and additional analysis, and Sohail Ahmad contributed significantly to the regressions analyses. The author was in charge of the composition of all parts of the manuscript, with significant input and contributions from all co-authors.

Tools and resources

All chapters of this dissertation were written in Microsoft Office Word (Versions 2013 and 2016). Zotero products ('Zotero Standalone', 'Zotero for Firefox', 'Zotero plug-in for Microsoft Office Word') were used as reference management system. In some chapters, additional resources and tools have been used for modelling, data analysis, and visualization of results, as indicated in the following:

Introduction:

- The adjusted GEFACS framework (Figure 1) was produced in Microsoft Office PowerPoint (Version 2016).

Chapter 2:

- The geospatial analysis was conducted using ArcGIS 10.5.1. Subsequent analyses were conducted in Microsoft Office Excel (Version 2013) and R (RStudio v1.1.3).
- Maps were generated in ArcMap 10.5.1.
- Figures 2 and 4 were modified externally by a graphic designer
- Figure 3 was generated in Microsoft Office Excel (Version 2013)
- Figure 5 was generated using Python 2.7 (using *matplotlib*)

Chapter 3:

- The geospatial analysis was conducted using ArcGIS 10.5.1.
- Figures 1-2 were compiled and generated in ArcMap 10.5.1.
- Further analyses were made using Microsoft Office Excel (Version 2013)

Chapter 4:

- Analysis was conducted using Microsoft Office Excel (Version 2013)
- Figure 1 was generated using Microsoft Office Excel and PowerPoint (Version 2013)
- Figure 4 was generated using R (RStudio v1.1.3)
- Maps were generated using ArcMap 10.5.1.

Chapter 5:

- Main analyses were conducted using R (RStudio v1.1.3) and Stata 14.
- Additional analysis were conducted in Microsoft Office Excel (Version 2013)
- Figure were generated in R (RStudio v1.1.3) and Microsoft Office Excel (Version 2013).

Chapter 6:

- Figure 1 was produced in Microsoft Office PowerPoint (Version 2016).

List of publications

The chapters of this dissertation correspond to individual articles, some of which are already published as peer-reviewed journal articles. The following list provides an overview over the status of these articles and, if they have been published, the publication details.

List of publications

Chapter 2	F. Creutzig, **C. Bren d'Amour**, U. Weddige, S. Fuss, T. Beringer, A. Gläser, M. Kalkuhl, J.C. Steckel, A. Radebach, O. Edenhofer **Assessing human and environmental pressures of global land-use change 2000-2010** Preprint, currently under review
Chapter 3	**C. Bren d'Amour**, F. Reitsma, G. Baiocchi, S. Barthel, B. Güneralp, K.H. Erb, H. Haberl, F. Creutzig, K.C. Seto **Future urban land expansion and implications for global croplands** Accepted manuscript, final version available under: *Proc. Natl. Acad. Sci.,* (2017), 114 (34) 8939-8944 https://doi.org/10.1073/pnas.1606036114
Chapter 4	**C. Bren d'Amour**, L. Wenz, M. Kalkuhl, J.C. Steckel, F. Creutzig **Teleconnected food supply shocks** Accepted manuscript, final version available under: *Environ. Res. Lett.*, 11 (2016), p. 035007 http://dx.doi.org/10.1088/1748-9326/11/3/035007
Chapter 5	**C. Bren d'Amour**, B. Pandey, M. Reba, S. Ahmad, F. Creutzig, K.C. Seto **Urban transitions and diets** In preparation