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Food Demand and Supply under Global Change

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Abstract

Anthropogenic activities have transformed the Earth's environment, not only on local level, but on the planetary-scale causing global change. Besides industrialization, agriculture is a major driver of global change. This change in turn impairs the agriculture sector, reducing crop yields namely due to soil degradation, water scarcity, and climate change. However, this is a more complex issue than it appears. Crop yields can be increased by use of agrochemicals and fertilizers which are mainly produced by fossil energy. This is important to meet the increasing food demand driven by global demographic change, which is further accelerated by changes in regional lifestyles. In this dissertation, we attempt to address this complex problem exploring agricultural potential globally but on a local scale. For this, we considered the influence of lifestyle changes (dietary patterns) as well as technological progress and their effects on climate change, mainly greenhouse gas (GHG) emissions. Furthermore, we examined options for optimizing crop yields in the current cultivated land with the current cropping patterns by closing yield gaps. Using this, we investigated in a five arc-minute spatial resolution the extent to which food demand can be met locally and regionally, and/or by global trade. Globally, food consumption habits are shifting towards calorie rich diets. Due to dietary shifts combined with population growth, the global food demand is expected to increase by 60–110% between 2005 and 2050. Hence, one of the global sustainability challenges is to meet the growing food demand, while at the same time, reducing agricultural inputs and environmental consequences. In order to address the above problem, we used several freely available datasets and applied multiple interconnected analytical approaches. This includes artificial neural network, scenario analysis, data aggregation and harmonization, downscaling algorithm, and cross-scale analysis.

Globally, we identified sixteen dietary patterns between 1961 and 2007 with food intakes ranging from 1,870 to 3,400 kcal/cap/day. These dietary patterns also reflected changing dietary habits to meat rich diets worldwide. Due to the large share of animal products, very high calorie diets that are common in the developed world, exhibit high total per capita emissions of 3.7–6.1 kg $CO_{2eq.}$/day. This is higher than total per capita emissions of 1.4–4.5 kg $CO_{2eq.}$/day associated with low and moderate calorie diets that are common in developing countries. Currently, 40% of the global crop calories are fed to livestock and the feed calorie use is four times the produced animal calories. However, these values vary from less than 1 kcal to greater 10 kcal around the world. On the local and national scale, we found that the local and national food production could meet demand of 1.9 and 4.4 billion people in 2000, respectively. However, 1 billion people from Asia and Africa require intercontinental agricultural trade to meet their food demand. Nevertheless, these regions can become food self-sufficient by closing yield gaps that require location specific inputs and agricultural management strategies. Such strategies include: fertilizers, pesticides, soil and land improvement, management targeted on mitigating climate induced yield variability, and improving market accessibility. However, closing yield gaps in particular requires global N-fertilizer application to increase by 45–73%, P_2O_5-fertilizer by 22–46%, and K_2O-fertilizer by 2–3 times compare to 2010. Considering population growth, we found that the global agricultural GHG emissions will approach 7 Gt $CO_{2eq.}$/yr by 2050, while the global livestock feed demand will remain similar to 2000. This changes tremendously when diet shifts are also taken into account, resulting in GHG emissions of 20 Gt $CO_{2eq.}$/yr and an increase of 1.3 times in the

crop-based feed demand between 2000 and 2050. However, when population growth, diet shifts, and technological progress by 2050 were considered, GHG emissions can be reduced to 14 Gt $CO_{2eq.}$/yr and the feed demand to nearly 1.8 times compare to that in 2000. Additionally, our findings shows that based on the progress made in closing yield gaps, the number of people depending on international trade can vary between 1.5 and 6 billion by 2050. In medium term, this requires additional fossil energy. Furthermore, climate change, affecting crop yields, will increase the need for international agricultural trade by 4% to 16%.

In summary, three general conclusions are drawn from this dissertation. First, changing dietary patterns will significantly increase crop demand, agricultural GHG emissions, and international food trade in the future when compared to population growth only. Second, such increments can be reduced by technology transfer and technological progress that will enhance crop yields, decrease agricultural emission intensities, and increase livestock feed conversion efficiencies. Moreover, international trade dependency can be lowered by consuming local and regional food products, by producing diverse types of food, and by closing yield gaps. Third, location specific inputs and management options are required to close yield gaps. Sustainability of such inputs and management largely depends on which options are chosen and how they are implemented. However, while every cultivated land may not need to attain its potential yields to enable food security, closing yield gaps only may not be enough to achieve food self-sufficiency in some regions. Hence, a combination of sustainable implementations of agricultural intensification, expansion, and trade as well as shifting dietary habits towards a lower share of animal products is required to feed the growing population.

Zusammenfassung

Anthropogene Aktivitäten auf lokaler, regionaler und auch auf globaler Ebene sind zunehmend eine der relevanten Treiber für den globalen Wandel. Als betroffener Sektor ist die Landwirtschaft eine wichtige Komponente, denn Bodenerosion, Wasserknappheit und Klimawandel beeinflussen landwirtschaftliche Erträge unmittelbar. Damit schließt sich ein Kreis, denn der Mensch ist nicht nur Verursacher des Umweltwandels, sondern wird beispielsweise durch zurückgehende Erträge in der Landwirtschaft, direkt betroffen sein. Allerdings stellt sich die Situation in der Landwirtschaft komplexer dar, als es vordergründig scheint. Durch den Einsatz von Agrochemikalien und durch fossile Energienutzung erzeugte Dünger steigen Erträge. Zudem kommt es durch einen globalen demographischen Wandel zu einer vermehrten Nahrungsmittelnachfrage, die zusätzlich durch Veränderungen der regionalen Lebensstile beschleunigt wird. Diese Arbeit stellt sich genau diesem Problemkomplex, indem sie versucht, die Potentiale der globalen Landwirtschaft auf kleinräumiger Skala auszuloten. Hierbei werden Prognosen hinsichtlich des Einflusses von Lebensstiländerungen (Ernährungsmuster) gleichermaßen berücksichtigt, wie Veränderungen der landwirtschaftlichen Produktionsmethoden und deren Einfluss auf den Klimawandel. Zudem wird untersucht wie die Erträge auf derzeitig kultiviertem Land und unter Beibehaltung der Anbaufolge weiter optimiert werden können. Mithilfe dieses Ansatzes ist es möglich, auf einer hohen räumlichen Auflösung (5′-Grid) Projektionen zu liefern, die eine Aussage darüber treffen, inwieweit die Nahrungsmittelproduktion lokal sichergestellt werden kann und falls nicht, wie dies durch regionalen und/oder globalen Handel erfolgen kann. Global betrachtet verschiebt sich der Lebensmittelkonsum hin zu kalorienreichen Ernährungsweisen. Ein zusätzliches Bevölkerungswachstum bedingt, dass es zwischen 2005 und 2050 zu einem Anstieg der Lebensmittelnachfrage von 60–110% kommen wird. Es ist daher eine zentrale Herausforderung auf dem Weg zur globalen Nachhaltigkeit, die wachsende Nachfrage nach Lebensmitteln zu befriedigen und gleichzeitig den landwirtschaftlichen Ressourcenverbrauch sowie die Belastungen für die Umwelt zu reduzieren. Um den oben umrissenen Problemkomplex bearbeiten zu können, werden verschiedene frei verfügbare Datensätze sowie eine Vielzahl ineinandergreifender analytischer Ansätze, darunter künstliche neuronale Netze, Szenarioanalysen, Downscaling und skalenübergreifende Methoden zur Anwendung gebracht.

Auf diese Weise konnten, global gesehen, für den Zeitraum 1961 bis 2007 sechzehn Ernährungstypologien mit einem täglichen Kalorienkonsum zwischen 1,870 und 3,400 kcal pro Kopf identifiziert werden. Diese Muster spiegeln global veränderte Ernährungsgewohnheiten wie z.B. eine Tendenz hin zu fleischhaltiger Kost wider. Durch den hohen Anteil tierischer Produkte verursachen sehr kalorienreiche Ernährungsweisen, wie sie in entwickelten Ländern üblich sind, hohe pro Kopf Emissionen von 3,7–6,1 kg $CO_{2eq.}$/Tag. Diese übersteigen die pro Kopf Emissionen von 1,4–4,5 kg $CO_{2eq.}$/Tag einer in Entwicklungsländern üblichen kalorienarmen Ernährungsweise. Zusätzlich werden weltweit 40% aller landwirtschaftlichen Erzeugnisse als Futtermittel genutzt und somit aus jeweils durchschnittlich 4 kcal Getreide, jedoch regional variierend von weniger als 1 kcal bis über 10 kcal Getreide, 1 kcal tierische Produkte erzeugt. Bei der Betrachtung auf lokaler sowie nationaler Skala wird deutlich, dass die entsprechende lokale und nationale Nahrungsmittelproduktion im Jahr 2000 im Prinzip die Nachfrage von 1,9 Milliarden Menschen, beziehungsweise 4,4 Milliarden Menschen, erfüllen konnte. Nichtsdestotrotz sind ca. 1 Milliarde Menschen in Asien und Afrika auf interkontinentalen Handel angewiesen um ihre Lebensmittelnachfrage zu decken. Allerdings könnten regionale Produktionslücken vielfach geschlossen werden, wenn lokal angepasste Maßnahmen ergriffen würden. Solche

Maßnahmen umfassen die nachhaltige Verwendung von Düngemitteln und Pestiziden, Bodenverbesserung, Maßnahmen zur Abschwächung klimabedingter Ernteschwankungen sowie ein verbesserter Marktzugang. Dennoch bedingt die Schließung von Ertragslücken insbesondere eine Erhöhung der Stickstoffdüngung um 45–73%, der Phosphatdüngung um 22–46% und der Kaliumdüngung um das 2- bis 3-fache im Vergleich zum Jahr 2010. Bei ausschließlicher Berücksichtigung des Bevölkerungswachstums werden zudem die globalen Treibhausgasemissionen durch die Landwirtschaft bis zum Jahr 2050 auf jährlich 7 Gt $CO_{2eq.}$ ansteigen, während die Nachfrage nach angebauten Futtermitteln gegenüber 2000 annähernd gleich bleiben wird. Dies ändert sich erheblich, wenn veränderte Ernährungsgewohnheiten einbezogen werden. In diesem Fall ist ein Anstieg der Treibhausgasemissionen auf 20 Gt $CO_{2eq.}$ pro Jahr möglich und eine Steigerung der landwirtschaftlichen Futtermittelnachfrage um das 1,3-fache im Zeitraum von 2000 bis 2050 augenscheinlich. Beides kann jedoch durch die zusätzliche Einbeziehung technologischen Fortschritts reduziert werden: die Emissionen auf jährlich 14 Gt $CO_{2eq.}$ und die Futtermittelnachfrage auf das 1,8-fache des Werts aus dem Jahr 2000. Ein wesentliches Resultat der Arbeit ist, dass je nachdem, wie erfolgreich Ertragslücken geschlossen werden, die Zahl der von internationalem Handel abhängigen Menschen zwischen 1,5 und 6 Milliarden variiert. Dieser wird zumindest mittelfristig zusätzliche fossile Energie benötigen. Zudem wird der Einfluss des Klimawandels auf Ernteerträge den Bedarf an internationalem Handel mit landwirtschaftlichen Produkten um 4% bis 16% erhöhen.

Zusammenfassend zieht diese Dissertation drei wesentliche Schlüsse. Erstens werden veränderte Ernährungsgewohnheiten im Vergleich zur ausschließlichen Berücksichtigung von Bevölkerungswachstum, die Nachfrage nach Getreide, die landwirtschaftlichen Treibhausgasemissionen sowie den internationalen Handel mit Nahrungsmitteln siginifikant erhöhen. Zweitens könnten ein adäquater Technologietransfer und ein technologischer Fortschritt diese Veränderungen abmildern, indem Ernteerträge angehoben, landwirtschaftliche Emissionen gesenkt und die Effizienz der Umwandlung von Futtermittel in tierische Produkte gesteigert werden. Zudem könnten Abhängigkeiten vom internationalen Handel durch den Konsum lokaler und regionaler Produkte und durch Diversifizierung von Erzeugnissen deutlich verringert werden. Drittens sind zur Schließung von Ertragslücken ortsspezifische Maßnahmen erforderlich, wobei die Nachhaltigkeit einer solchen Intensivierung stark von der Auswahl und Umsetzung dieser Maßnahmen abhängt. Zur Ernährung einer wachsenden Weltbevölkerung wird daher eine Kombination aus nachhaltiger Intensivierung und Ausweitung der Landwirtschaft, des Handels sowie eine Verschiebung von Ernährungsgewohnheiten hin zu geringeren Anteilen tierischer Produkte benötigt.

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Contents

List of Figures

List of Tables

Abbreviations and Symbols

Admin-1	First Level Administrative Unit
Admin-2	Second Level Administrative Unit
Admin-3	Third Level Administrative Unit
Admin-4	Fourth Level Administrative Unit
ANN	Artificial Neural Network
cap	Capita
CH_4	Methane
CIAT	International Center for Tropical Agriculture
CIESIN	Center for International Earth Science Information Network
CIS	Crop Insufficient
CO_2	Carbon Dioxide
$CO_{2\text{eq.}}$	Carbon Dioxide Equivalent
CS	Current Status
DFT-UK	Department for Transport, United Kingdom
EJ	Exajoule
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	FAO Statistical Databases
FG	Food Group
FSS	Food Self-Sufficiency
FW	Food Waste
g	Gram
GAEZv3.0	Global Agro-ecological Zones version 3.0
GADM	Global Administrative Areas
GDP	Gross Domestic Product
GHG	Greenhouse Gas
Gt	Gigatonne
ha	Hectare
HDI	Human Development Index
HI	High-Input Agriculture

HI_x	Closing Yield Gaps to Attain x% of HI Yields
ICP	Increase Crop Production
IEA	International Energy Agency
IFPRI	International Food Policy Research Institute
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
IPNI	International Plant Names Index
K_2O-fertilizer	Potash fertilizer
kcal	Kilo-calorie
kg	Kilogram
LI	Low-Input Agriculture
LPS	Livestock Production System
MAE	Mean Absolute Error
MDS	Multidimensional Scaling
MSU	Michigan State University
Mt	Megatonne
N-fertilizer	Nitrogen fertilizer
NA	Not Available
O/I	Output/Input
P_2O_5-fertilizer	Phosphate fertilizer
PCA	Principal Component Analysis
PJ	Petajoule
RQ	Research Question
SOM	Self-Organizing Map
SOMTOP	SOM with Measure of Topological Distortions (-TOP)
Subconti.	Subcontinent
t	Tonne
UN	United Nations
UNDP	United Nations Development Programme
UNHCR	United Nations High Commissioner for Refugees
UNICEF	United Nations Children's Fund
UNU	United Nations University
USDA	United States Department of Agriculture
US-EPA	United States Environmental Protection Agency
WFP	World Food Programme
WHO	World Health Organization
yr	Year

Chapter 1

Introduction and Overview

Humanity's Capacity to feed a growing population has been a matter of scientific debate for centuries (Boserup, 2005, Malthus, 1798). Although doubts have been raised on possibilities to produce enough food to sustain increasing global population (Malthus, 1798), innovations and technological progress mostly enabled humankind to subsist on planet Earth (Boserup, 2005). Nevertheless, there are people currently suffering from hunger and undernourishment (FAO, 2010). This is often considered as a distribution problem rather than a production one (Sen, 1983). However, concerns regarding the ability of mankind to feed the future population are being raised again. On demand side, this is due to expected lifestyle shifts and population growth that will subsequently increase the global food demand (Godfray et al., 2010). On supply side, climate change and shrinking cultivable land will place limitations on the potentials of future food production (Kastner et al., 2012, Lobell et al., 2008). For example, global warming will very likely reduce mean biophysical crop yields without CO_2 fertilization effect (Nelson et al., 2014).

Beginning with industrial revolution in the 18^{th} century, mankind has continuously transformed the Earth's environment from local levels to planetary-scale (Steffen et al., 2006). This has propelled the planet into a new geological epoch, the Anthropocene (Crutzen, 2002, Steffen et al., 2011), mainly through changing climate, transforming global land use and land cover, altering global water and nutrient cycles, and driving a large fraction of species to extinction (Vitousek et al., 1997). Besides industrialization, agriculture is one of the major drivers of global environmental change. For example, the agriculture sector directly and indirectly contributes around one third of global anthropogenic greenhouse gas (GHG) emissions (Vermeulen et al., 2012). Moreover, agricultural trade requires fossil energy and thus, contributes to additional transport related emissions. Currently, local and regional food availability has increasingly been international trade dependent (Fader et al., 2013, Porkka et al., 2013).

Hence, this thesis contributes to ongoing debate on how to feed a growing population, while limiting human alteration of the Earth's environment including climate change. Our analysis is on a global scale, but with a local and regional focus. In the following pages, we briefly elaborate on the relevant issues to food demand and supply with its associated anthropogenic inputs and environmental impacts. Subsequently, we present the research questions and our research approach with the thesis overview.

1.1 Food Demand

Globally, food demand is increasing and will continue to increase in the future with the changes in dietary patterns and population growth. Previously, dietary changes occurred in Western Europe with lifestyle shifts due to the long-term rise in incomes following industrialization. In the early-nineteenth century, the total calorie intake in Western Europe was the same as in developing countries in the 1960s (Grigg, 1995a). These European diets were mainly composed of starchy staples that provided more than two thirds of the total calorie intake of around 2,200 kcal/cap/day. By the mid-twentieth century, they were transformed into affluent diets with a total calorie intake of more than 3,000 kcal/cap/day (FAO, 2011a, Grigg, 1995a). These diets consisted of a large share of animal products, sugar, fruits, vegetables, and oils. Recently, such increase in average food intake and shift in food composition has been occurring in developing and emerging countries (Gerbens-Leenes et al., 2010, Pingali, 2007).

Between 1970 and 2000, the average food intake in developing countries has increased from 2,100 to 2,600 kcal/cap/day (Alexandratos, 2006), and animal product intake by more than 100% (Kearney, 2010). However, the average food intake in some regions, e.g., East Africa, Middle Africa, and South Asia, is still lower than 2,500 kcal/cap/day (FAO, 2011a). Globally, around 900 million people are suffering from hunger and undernourishment (FAO, 2010). Moreover, income inequality within a region may result subnational variation in food consumption (Dasgupta & Ray, 1986). Nevertheless, expected income increase, urbanization, lifestyle changes, and poverty reduction will drive global dietary shifts toward more affluent diets in the future as past tends continue.

Currently, the sources of calories and protein vary between developing and developed countries (FAO, 2011a, Grigg, 1995b, 1996). Starchy staples are the major source of calories for developing countries and animal products are important sources of protein for developed ones. Additionally, amounts of animal fat and vegetable oil intake are significantly higher in developed countries compared to developing ones (Grigg, 1999). Although several studies investigated such geographic variation of food composition, systematic identification of global dietary patterns and diet shifts is still missing. Existing studies look at either temporal or spatial patterns, but not both, which is crucial for understanding global diet shifts over time and space.

Diet shifts toward affluent diets demand additional crops for livestock feed besides other resources (e.g., water and land). Presently, 36% of globally produced crop calories is used as livestock feed, converting around 4 kcal of crop products into 1 kcal of animal product (Cassidy et al., 2013). This results the global feed conversion efficiency of around 25%. Such data on current crop-based feed use and its efficiency are available on the country scale (FAO, 2011a) but are missing on subnational level. This is important because of variation in spatial distribution of livestock types (e.g., poultry, pigs, cattle, sheep and goats) depending on social, cultural, and economic factors (Wint & Robinson, 2007). Additionally, such subnational data is essential for a holistic assessment of food security and self-sufficiency at local and regional scales.

1.2 Food Supply

Agriculture, consisting of crop production and livestock rearing, is the major source of human food supply. The total amount of crop production depends on the area of cropland and crop productivity/yield. In a broader sense, agro-ecological features consisting of edaphic and climatic conditions, and levels of human inputs and management are governing factors for crop yields (IIASA/FAO, 2012, Licker et al., 2010, Neumann et al., 2010). Similarly, livestock production systems that convert forage, fodder and feed into animal products, are influenced by climatic factors and the mode of agricultural practices (Eggleston et al., 2006, Robinson et al., 2011).

Historically on the global scale, growing food demand was met mainly by cropland expansion. The global cropland is estimated to have increased by approximately 4.5 times between 1700 and 1990 from 270 to 1,470 million ha (Goldewijk, 2001, Meyer & Turner, 1992). During this period, regions in Former Soviet Union, North America, South America, and South East Asia experienced larger cropland expansion than the global average (Meyer & Turner, 1992). At the same time, the global pasture-land increased by more than six fold from 520 to 3,450 million ha (Goldewijk, 2001). Currently, cropland and pasture-land cover around 11% and 24% of the global ice-free land area, respectively (FAO, 2011a). However, available agriculture land per person has decreased in the recent decades (Kastner et al., 2012). Moreover, the further expansion of cultivated land is not feasible in every country. Land suitable for conversion for agriculture is a limited resource, which is unevenly distributed across the globe (Bruinsma, 2011, Fischer et al., 2001).

Besides cropland expansion, land use intensification, driven by green revolution, has increased global crop production over the last 50 years (Matson et al., 1997). Such agricultural intensification has increased land use efficiency, increasing crop yields, through the application of high-yield crop varieties, fertilizers, irrigation, and pesticides. During the last two decades (1985–2005), the global crop production has increased by 28%, of which 8% came from expansion of cropland and harvested area, and 20% from increased crop productivity (Foley et al., 2011). However, crop productivity improvement varies geographically. For example, globally, yields of the four major crops (maize, rice, wheat, and soybean) have either stagnated or decreased across 24–39% of their harvested areas over the last 50 years (1961–2008) (Ray et al., 2012). Moreover, crop yields currently differ even across regions with similar agro-ecological features, mainly due to variation in human inputs and land management (Licker et al., 2010). The current crop yields in most regions are lower than their biophysical potentials, depicting crop yield gaps (IIASA/FAO, 2012).

On local and regional scales, the international food trade is playing crucial role in increasing the current food supply (Fader et al., 2013, Porkka et al., 2013). Contrary, consumers are becoming more attracted to local and regional agricultural products (Kneafsey et al., 2013). However, overall environmental and health benefits of local food compared to non-local food is a matter of scientific debate (DeLind, 2011, Edwards-Jones, 2010, Kneafsey et al., 2013). Local food can occasionally be inferior to non-local food depending on production and storage practices. Nevertheless, the potential of local food to meet the local demand has only been explored by a few studies (e.g., Morrison et al. (2011)), and a global study on such potentials is still missing. This is important to explore options to decrease the distance between field and fork, also known as food-miles, reducing international trade dependency and emissions, while enabling local and regional food security.

By 2050, the global mean biophysical crop yield is likely to be reduced by 17% due to climate change with no CO_2 fertilization effect compared to a scenario with unchanging climate (Nelson et al., 2014). Although increased atmospheric CO_2 concentration may have positive fertilization effects on some crop yields, its overall effect is highly uncertain (Lobell & Field, 2008, Long et al., 2006). In some regions, crop production may benefit from moderate global warming, for example, European crop yields are expected to increase with climate change and increased atmospheric CO_2 (Ewert et al., 2005). Nevertheless, agriculture is one of the sectors that is highly vulnerable to climate change (i.e., rising temperature and changing precipitation patterns) and climate extremes (e.g., droughts and floods). The effects of climate change will be significant on low-input subsistence agricultural systems due to traditional management approaches (Easterling et al., 2007, Lal et al., 2011, Morton, 2007). Additionally, productivity of high-input agricultural systems (e.g., irrigated farming) may also reduce because of decreased water availability, and increased crop water demand with rising temperatures regionally.

1.3 Inputs and Environmental Impacts

Agriculture expansion and intensification are two options implemented so far to increase global food producing for meeting the growing demand. Such land-use changes and land intensification have had local, regional, and global environmental consequences (Klein Goldewijk et al., 2011, Matson et al., 1997). Additionally, modern agriculture requires direct and indirect inputs (Conforti & Giampietro, 1997, Molden et al., 2007, Schneider & Smith, 2009). Fertilizers, pesticides, irrigation water, and fossil fuels for farm machineries are examples of some direct inputs. Indirect inputs mainly consist of energy to produce fertilizers and pesticides, and to operate irrigation pumps.

During the last 50 years, global fertilizer and pesticide use has substantially increased (Matson et al., 1997, Tilman et al., 2001). Use of nitrogen fertilizer grew by around 8.5 times from 12 to 110 Mt/yr between 1961 and 2010, and phosphate fertilizer use by 3 times from 10 to 40 Mt/yr over the same period (FAO, 2011a). Similarly, global expenditures on pesticide imports increased by around 10 times and irrigated cropland area by about 70% between 1960 and 2000 (Tilman et al., 2001). However, 80% of current cultivated land is in rain-fed condition, where 60–70% of the global crop production takes place (Falkenmark & Rockström, 2004). Additionally, energy use for agriculture has increased by 40% globally between 1973 and 2011 from 5,300 to 7,400 PJ/yr (IEA, 2014). Moreover, meeting the future food demand will increase such input use. For example, nitrogen fertilizer use is expected to increase up to 225–250 Mt/yr by 2050 (Tilman et al., 2011). However, the increased input demand may be lowered by enhancing resource use efficiency. For example, about half of the reactive nitrogen applied in cropland was estimated to be lost to the biosphere in 1995 (Bodirsky et al., 2012). When inefficiently applied, fertilizers are lost to water bodies and the atmosphere enriching the biosphere with reactive nitrogen and phosphate (Smil, 1999). Hence, efficient resource use also reduces such environmental consequences.

Looking at others environmental impacts, agriculture is directly and indirectly responsible for around 22–24% of the total anthropogenic GHG emissions. Directly, agriculture contributes about 10–12% of the total emissions and is accountable for 56% of the total non-CO_2 GHG emissions (Smith et al., 2014). Within agriculture, livestock is a major emitter of GHGs (Herrero et al., 2013). For example, methane emissions from enteric fermentation accounts for 32% of the total agricultural non-CO_2 emissions in 2005 (Metz et al., 2007). Indirectly, land conversion causing deforestation mostly for agricultural use, contributes to 12% of the total emissions (Houghton et al., 2012, Smith et al., 2014). Such agricultural expansion also has negative impacts on biodiversity and ecosystem services (Nelson et al., 2010). Furthermore, food trade contributes to additional transport related emissions (Weber & Matthews, 2008). Although such agricultural emission inventories are available for all countries (USEPA, 2006), data on emissions related to individual dietary patterns are still missing. Moreover, there is a need to investigate environmental impacts and input use related with dietary patterns for giving a comprehensive assessment of implications of food consumption habits.

Both strategies, agriculture expansion and intensification, for meeting the future food demand will have further environmental consequences. Land conversion for agricultural use contributes to anthropogenic emissions and has negative impacts on ecosystems (Canadell et al., 2007, Nelson et al., 2010). In contrast, agricultural intensification increases crop yields and may reduce GHG emissions per unit of crop production due to avoided land conversion (Burney et al., 2010). However, the traditional ways of intensification also have negative externalities, e.g., nitrogen and phosphorus losses to ecosystems and ecosystem deterioration (Liu et al., 2010, MacDonald et al., 2011). Hence, there is a need to identify methods for sustainable agricultural intensification (Godfray et al., 2010) that closes yield gaps with efficient use of inputs and reduces associated environmental consequences. Besides nutrient and water management (Mueller et al., 2012), this requires location specific input and management strategies that tackle biophysical and socioeconomic factors causing yield gaps. However, information on such location specific agricultural strategies for closing crop yield gaps is still missing.

1.4 Research Questions

Motivated by the above discussion on the current knowledge on food demand and supply, and associated inputs and environmental impacts, the overarching and guiding research question of this thesis is as follows:

How can current and future food security be ensured on local, regional, and global scales, and environmental impacts of agriculture be reduced considering the major drivers for growing food and feed demand, and socio-ecological constraints that limit local food production?

In general, the aim of this thesis is to provide a global overview of current and future agriculture considering various factors that includes climate change, demographic growth, and lifestyle changes. In these regards, we have defined four major research questions (RQs):

RQ 1 How is it possible to identify global dietary patterns systematically and in an objective way, and how can these patterns be used to identify diet shifts and to explore the future emissions from agriculture?

RQ 2 Which role does livestock play in global food production, and how are crop and livestock production interrelated on local and regional scales?

RQ 3 How sufficiently is food produced on local and regional scales, and how is this influenced by agricultural potentials, lifestyles, demographic growth, and climate change?

RQ 4 How essential is it to close local yield gaps, and how can these gaps be closed in a sustainable manner?

1.5 Research Approach and Thesis Overview

For answering the above research questions, we used a set of interconnected analytical approaches (Figure 1.1). First, we applied a self-organizing neural network approach on food supply data (FAO, 2011a) covering 1961–2007 to systematically identify global dietary patterns and diet shifts. Based on these dietary patterns, we estimated GHG emissions embodied in diet types. Using identified relations between dietary patterns and the human development index (HDI) of countries, we estimated the future food consumption and composition. Furthermore, three scenarios were analyzed to estimate the future food demand and associated GHG emissions. These scenarios considered population growth, diet shifts, and technological progress. The analytical approaches, detailedly explained in Appendix A, were applied to answer RQ 1 in Chapter 2. The obtained diet shift projection was also used for answering subsequent research questions in the following chapters (Figure 1.2).

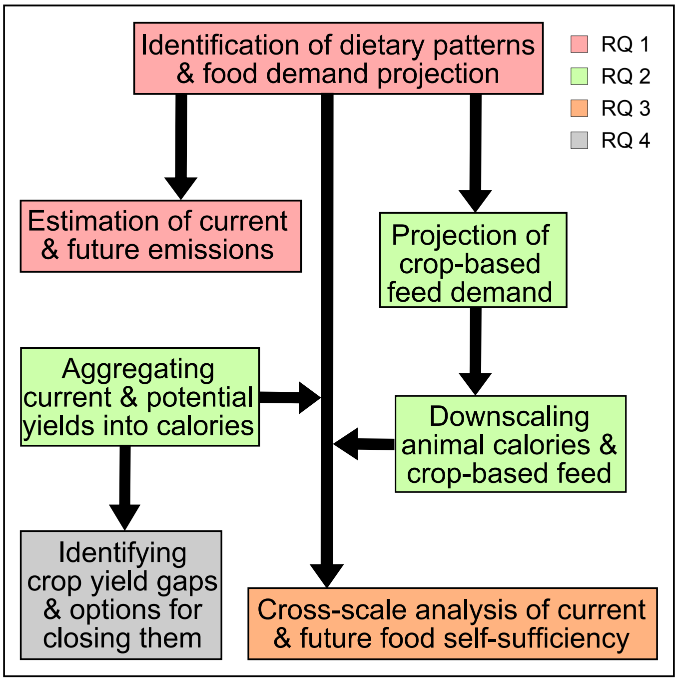

FIGURE 1.1: Schematic diagram presenting multiple interconnected analytical approaches used in this thesis for answering the research questions (RQs) posed in Section 1.4. Different approaches used for addressing the research question are represented by different colors. Arrows represent interconnection among the approaches, where results are used as input for subsequent approaches.

Second, RQ 2 was addressed in Chapter 3 using three different approaches: i) the aggregation of crop yields into calories, ii) the projection of crop-based livestock feed demand, and iii) the downscaling of current and projected animal calories and feed demand (Figure 1.1). Crop yield data for different crops, provided in mass units, were converted into calorific values using nutritive factors (FAO, 2001), and then aggregated to obtain data on total crop calorie production. This approach was used for current and potential crop yield data provided on a 5 arc-minute grid resolution by IIASA/FAO (2012). A similar conversion and aggregation approach was also carried out for data on crop-based feed use and animal product production. The future feed demand on a country scale was estimated based on relations between countrywide animal calorie production and feed calorie use. For this, three scenarios were developed accounting for population growth, diet shifts and feed conversion efficiency. Furthermore, current and projected animal calorie production and feed calorie demand on a country scale were downscaled to a 5 arc-minute grid. Our downscaling algorithm considered gridded data on livestock production system and livestock density (Robinson et al., 2011, Wint & Robinson, 2007) in addition to other factors. Such aggregated and downscaled data enabled us to identify role of livestock in global food production on local and regional scales. Details on these approaches are provided in Appendix B. Additionally, resulting aggregated and downscaled data was also used for addressing subsequent research questions in the next chapters (Figure 1.2).

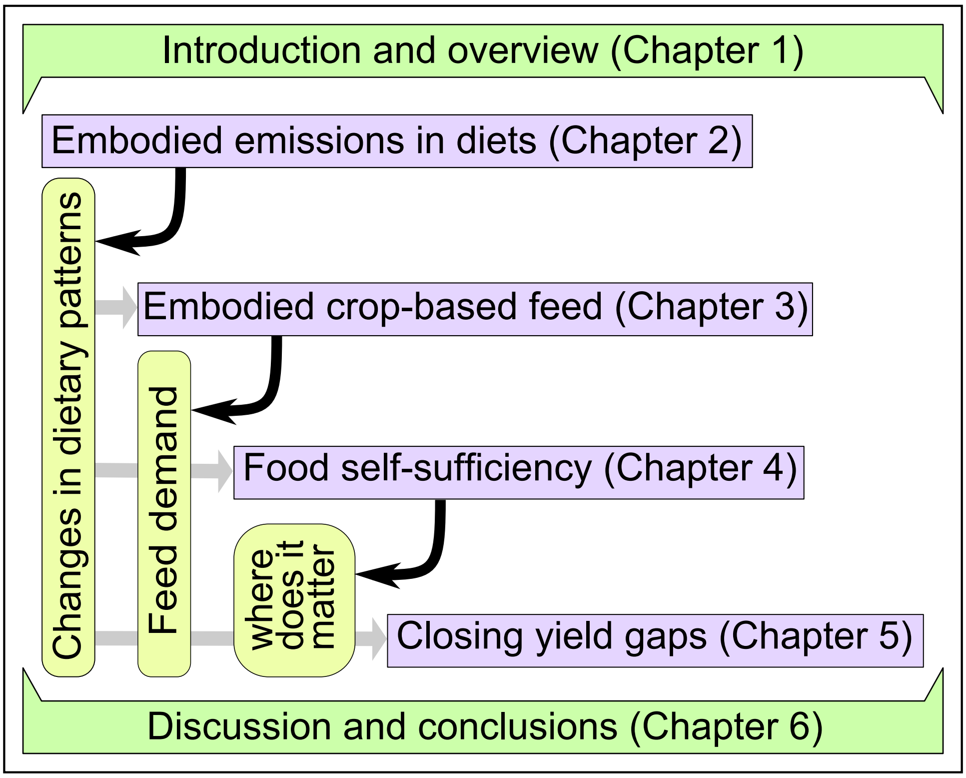

FIGURE 1.2: A schematic diagram presenting the overview and the structure of the thesis. It additionally shows how the six chapters (horizontal boxes) of the thesis are interlinked and interrelated. Chapter 1 and 6 embrace the other four chapters to build up this thesis. The black arrows represent outcomes of the different chapters (vertical boxes) that are used as inputs for subsequent chapters demonstrated by gray arrows.

Third, we carried out cross-scale food self-sufficiency (FSS) analysis in Chapter 4 for providing answers to RQ 3 (Figure 1.1). We considered a region as food self-sufficient if the total crop and animal calorie produced in the region is enough to meet its food and feed consumption. Starting at a 5 arc-minute grid resolution, FSS analysis was done at four different administrative levels, as well as country and continental scales. Such analysis enabled us not only to identify local and regional capacities to meet the food and feed demand but also to estimate unavoidable national and international agricultural trade. Besides analyzing the current FSS status for the year 2000, we conducted various analyses accounting for factors that can influence local and regional FSS, and subsequent agricultural trade. These factors were: i) closing crop yield gaps, ii) low-input subsistence agriculture, iii) food groups composing dietary pattens, and iv) reduction of food waste. Similarly, the future scenarios of FSS were analyzed considering the five dimensions that drive food and feed supply (climate change and closing yield gaps), and demand (population growth, diet shifts, and feed conversion efficiency). Appendix C provides the details on this approach.

Fourth, we identified local and regional crop yield gaps to answer RQ 4 in Chapter 5 (Figure 1.1). For this, we used data on the current and potential crop calorie production from Chapter 3. Additionally, we applied FSS analysis developed in Chapter 4 to understand in which regions closing yield gaps would enable food security and self-sufficiency (Figure 1.2). Next, we analyzed biophysical and socioeconomic constraints that can be overcome by shifting from low-input to high-input agriculture. Data on such constraints were obtained from GAEZv3.0 (IIASA/FAO, 2012), which were: soil related constraints, climate induced yield variability, agro-climate related pests, diseases, and weeds constraints as well as market accessibility. Afterwards, we determined regions with similar constraint compositions for identifying the strategies to tackle prevailing single or multiple constraints to close yield gaps. We additionally estimated amount of fertilizers (N, P_2O_5 and K_2O) required to sustain high-input crop yields. For this, we calculated differences between crop nutrient uptakes by low-input and high-input agriculture. Details on this approach is provided in Appendix D.

Finally, we discussed specific answers to the research questions (RQs 1–4) obtained from Chapters 2–5 in Chapter 6. This is how all the six chapters of this thesis are interlinked and interrelated (Figure 1.2). Furthermore, Chapter 6 also provides discussion on main findings of this thesis and states its conclusions, addressing the overarching and guiding research question.

Chapter 2

Embodied Greenhouse Gas Emissions in Diets[1]

Abstract

Changing food consumption patterns and associated greenhouse gas (GHG) emissions have been a matter of scientific debate for decades. The agricultural sector is one of the major GHG emitters and thus, holds a large potential for climate change mitigation through optimal management and dietary changes. We assess this potential, project emissions, and investigate dietary patterns and their changes globally on a per country basis between 1961 and 2007. Sixteen representative and spatially differentiated patterns with a per capita calorie intake ranging from 1,870 to >3,400 kcal/day were derived. Detailed analyses show that low calorie diets are decreasing worldwide, while in parallel diet composition is changing as well: a discernable shift toward more balanced diets in developing countries can be observed and steps toward more meat rich diets as a typical characteristics in developed countries. Low calorie diets which are mainly observable in developing countries show a similar emission burden than moderate and high calorie diets. This can be explained by a less efficient calorie production per unit of GHG emissions in developing countries. Very high calorie diets are common in the developed world and exhibit high total per capita emissions of 3.7–6.1 kg $CO_{2\text{eq.}}$/day due to high carbon intensity and high intake of animal products. In case of an unbridled demographic growth and changing dietary patterns the projected emissions from agriculture will approach 20 Gt $CO_{2\text{eq.}}$/yr by 2050.

2.1 Introduction

Globally, food consumption patterns are changing both in terms of total amount and composition (Alexandratos, 2006, Kearney, 2010). Population growth and poverty reduction are commonly mentioned as major driving forces for this development which is expected to continue (Bruinsma, 2003, Kearney, 2010). Moreover, because of lifestyle

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related changes in diet compositions food demand will increase significantly, even with no further growth of global population (Alexandratos, 2006, Kastner et al., 2012). Food production usually requires inputs, like fuel and fertilizer (Conforti & Giampietro, 1997, Schneider & Smith, 2009), and accounts for approx. 70% of global water withdrawal (Molden et al., 2007). Current agricultural practices induce high environmental stress and in particular contribute 10–14% to the total anthropogenic greenhouse gas (GHG) emissions (Metz et al., 2007, USEPA, 2006). Today agriculturally managed land covers about 38% of global land area (FAO, 2011a), but inadequate agricultural practices have led to soil degradation in many regions in the past (Lüdeke et al., 1999). Concerning the fact that in some regions worldwide human attribution of net primary production approaches approx. 90%, an array of additional problems in agriculture is foreseeable in the future (Haberl et al., 2007, Imhoff et al., 2004). Consequently, during the last 50 years it has been observed that the agricultural land available to feed one person has been decreasing (Kastner et al., 2012). As a result of constraints on agricultural land availability, the energy requirements for food production have increased (Conforti & Giampietro, 1997). Therefore, it is likely that the necessary increase in food production will exacerbate environmental stress and increase demand for external inputs (Tilman et al., 2001).

A dietary shift toward a reduction in meat consumption has the potential to significantly decrease GHG emissions (Carlsson-Kanyama & González, 2009, Eshel & Martin, 2006, González et al., 2011, Popp et al., 2010, Reay et al., 2012, Stehfest et al., 2009). However, current trends are pointing in the opposite direction. Lifestyle related changes in diet with increased intake of animal products, vegetable oils, and sugar-sweeteners had occurred mainly in Western Europe over the past few decades (Grigg, 1995a). More recently, a westernization of diets has also been occurring in developing countries (Gerbens-Leenes et al., 2010, Pingali, 2007). Still, animal protein, animal fat, and vegetable oil intake is significantly higher in developed countries compared to developing countries (Grigg, 1995b, 1999).

To better understand diet related emissions, we identified typical dietary patterns on food consumption and composition per country by means of a self-organizing neural network approach for a database covering 1961–2007 (FAO, 2011a, Kohonen, 2001). Based on these patterns we estimate GHG emissions embodied in the diets considering both agricultural non-CO_2 emissions and emissions related to fossil fuel use. To project future dietary patterns and associated total agricultural GHG emissions we use the relationships between diet and the development level of countries. Following the call to go beyond GDP (Fleurbaey, 2009), we measured development in terms of the human development index (HDI) values, while previous studies used per capita income (Gerbens-Leenes et al., 2010, Grigg, 1995b, 1999, Popp et al., 2010). We estimate emissions for three scenarios: a) population growth only, b) population growth and changes in dietary patterns, and c) change in population, diet as well as technology and management.

2.2 Results

2.2.1 Typical Patterns of Food Consumption

Global food consumption patterns can be represented by sixteen systematically derived dietary patterns. The patterns differ in regard to the food composition and energy content (Figure 2.1). For a plausible and brief discussion, we group the patterns into four groups related to the energy content, i.e., low (pattern #1–#3), moderate (pattern #4–#8), high (pattern #9–#11), and very high (pattern #12–#16) calorie diets (for a more encompassing description cf. Appendix Text A.1).

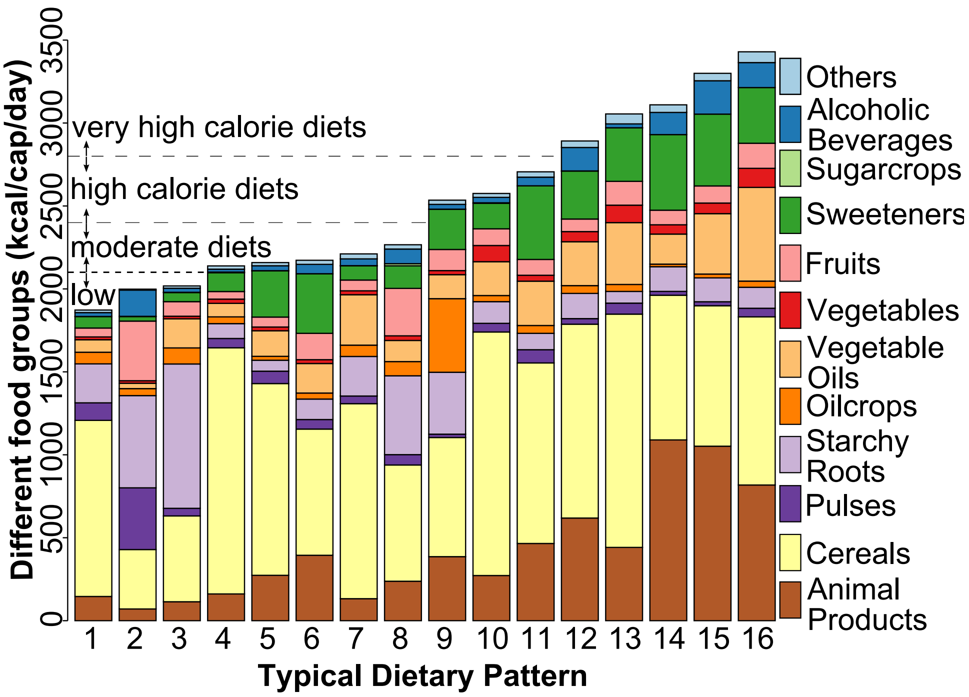

FIGURE 2.1: The sixteen dietary patterns observed world-wide for the analyzed period 1961-2007. “Others” represents the difference between the sum of all food groups and the total calorie intake. The sixteen identified patterns are categorized into low (< 2,100 kcal/cap/day), moderate (2,100–2,400 kcal/cap/day), high (2,400–2,800 kcal/cap/day), and very high calorie diets (> 2,800 kcal/cap/day).

The diets with low energy content provide less than 2,100 kcal/cap/day and are composed by more than 50% cereals (pattern #1) or more than 70% starchy roots, cereals, and pulses (pattern #3). Animal products play a minor role in this group (<10%). All countries exhibiting low calorie diets are developing countries, mainly located in Africa and Asia. China was also a member of this group until 1977. Diets with a moderate energy content are characterized by 2,100–2,400 kcal/cap/day. One prominent example, namely pattern #4, is characterized by the fact that more than 70% of the energy is supplied by cereals. This prototype which was mostly observed in Africa and Asia represents the cultural habit of the usage of rice based diets. Countries belonging to the group of high calorie diets (2,400–2,800 kcal/cap/day) show particular regional characteristics, i.e., with a high fraction of fruits and oil crops (e.g., pattern #9). This archetype was mainly observed in Caribbean and Pacific island states. Very high calorie diets provide more than 2,800 kcal/cap/day. For these diets a high amount of meat and alcoholic beverages is representative (e.g., pattern #14 and #15). A Mediterranean style diet (pattern #16) is composed by a high fraction of vegetable oil, vegetables, and fruits. This pattern is also prominent in Canada (since 1995) and the United States (since 2000) implying that a transition in food consumption may occur. Nevertheless, even among the very high calorie diets we found a pattern (#13) which is based on a high fraction of cereals combined with a very low consumption of alcoholic beverages, as it is culturally forced for certain African and Asian countries.

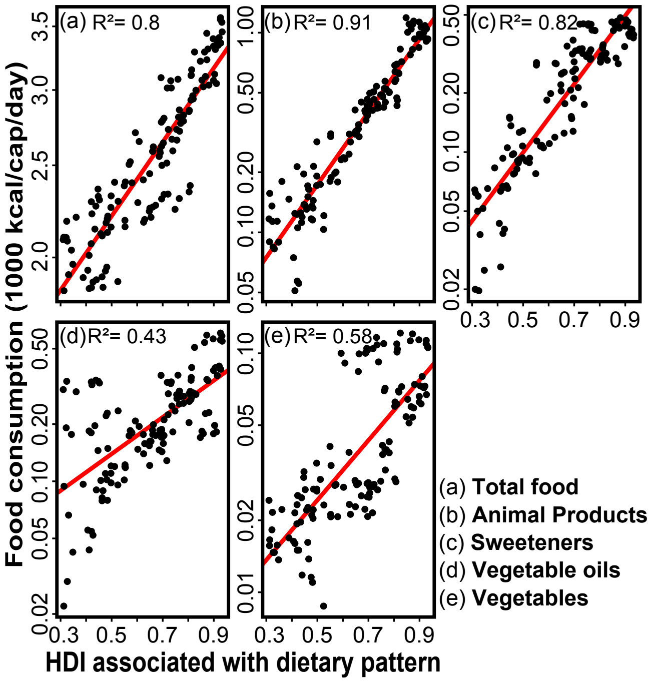

FIGURE 2.2: Relation between development (HDI) and consumption of total food (a), animal products (b), sweeteners (c), vegetable oils (d), and vegetables (e). Average values for each dietary pattern and year are shown. Note that the y-axis is in logarithmic scale, implying that a linear shape corresponds to an exponential relation.

Our examinations regarding the relation between dietary patterns and certain development levels show that the amount of total calories, animal products, sugar-sweeteners, vegetable oils and vegetables have a clear exponential relationship with the HDI (Figure 2.2).

2.2.2 Transitions of Dietary Patterns

In agreement with the fact that the long-term nutrition state is improving, food consumption patterns move from low toward higher calorie diets. Accordingly, the number of people living on low calorie diets is decreasing, while the number of people that are consuming high calorie diets is increasing (Figure 2.3). In particular, the situation in the nourishment status of China changed from 1977 to 1978 (Figure 2.3, #1 → #4). After the end of the cultural revolution, China started with drastic economic reforms leading to a much better food supply. Other fluctuations are related to a changing membership for India (#4 → #5) (e.g., on 1982, 1985, 1995, etc.). In addition, the applied neural network approach also detected a newly emerging pattern in the middle of the 1960ties revealing that lifestyles are changing. This diet archetype (#16) is comparatively healthy, i.e., it is composed of a good share of vegetable oils, vegetables, and fruits. At the end of the analyzed period this consumption style comprised approx. 500 million people. Maps for different years showing the spatial distribution of the patterns are presented in Appendix Figure A.1.

More detailed examinations identify typical transitions pathways (cf. Figure 2.4 and Appendix Table A.1). The figure makes clear that globally a clear tendency exists for shifts from low toward high calorie diets, while in parallel the needed energy input is also increasing. All the shifts represent certain lifestyles which are expressed in the diet composition. One of the most prominent shifts is that from pattern #1 to #4 which represents an increase in the total calorie intake, but retains cereals as the major energy source. A subsequent transition is that from #10 to #13. Overall this pathway corresponds to an increase in the calorie content associated with a fairly constant food

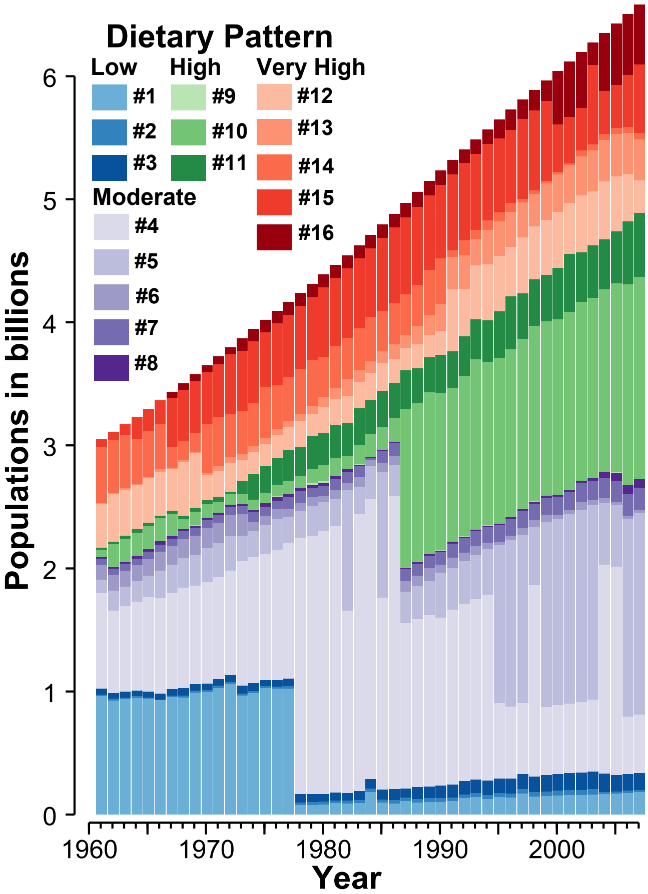

FIGURE 2.3: Number of people living on a certain dietary pattern for each year (1961–2007). The color codes represent the sixteen dietary patterns. The huge changes in the number of people consuming low calorie diets from 1977 to 1978 and on moderate calorie diets from 1986 to 1987 are due to dietary transitions in China. The huge fluctuation in the number of people consuming pattern #4 and pattern #5 diets (e.g., on 1982, 1985, 1995, etc.) is mainly because of shifting membership of India between pattern #4 and pattern #5. Note that pattern #16 newly emerged in the middle of the 1960ties.

composition. Countries who showed this change were mainly located in Asia and North Africa. A possible explanation is the limited affordability of animal products combined with local environmental conditions and religious taboos influencing meat and alcohol consumption (Grigg, 1995b). Other frequent transitions are those from #6 to #11, #14 to #15, and #4 to #5, which are all characterized by changing food composition to an increased share of animal products, vegetable oils, and sugar-sweeteners. This mostly occurred in European, American, and some African countries. Examples are Brazil (#6 → #11) in 1974, Germany (#14 → #15) in 1964 and for the United States in 1967, and Kenya (#4 → #5) in 1980. Further often observed pattern shifts, i.e., #5 to #11, represent an increase in mainly animal products, sweeteners, and fruits, while retaining a relatively high fraction of pulses. This shift held for Mexico in 1973 and for Thailand in 2006. A trend which is mainly observable in industrialized countries is reflected by the shift from pattern #15 (high amount of animal products, sugar sweeteners, and alcoholic beverages) to pattern #16 (comparatively more vegetables and fruits). This obviously represents a shift in the mind-set of the consumers, i.e., that reports on research findings on negative health consequences associated with a meat rich diet (Willett, 1994).

In face of the overarching trend toward higher calorie diets some exceptions exist. On the one hand, dietary patterns #2, #3, #7, and #8 remain constant over time and are largely disconnected from other trends. As a major reason, no significant changes in the development status of some states in Middle, Central, West, and East African states were identified. On the other hand, the applied approach is able to reconstruct changes toward diets with a lower calorie content. Such a development can be often associated

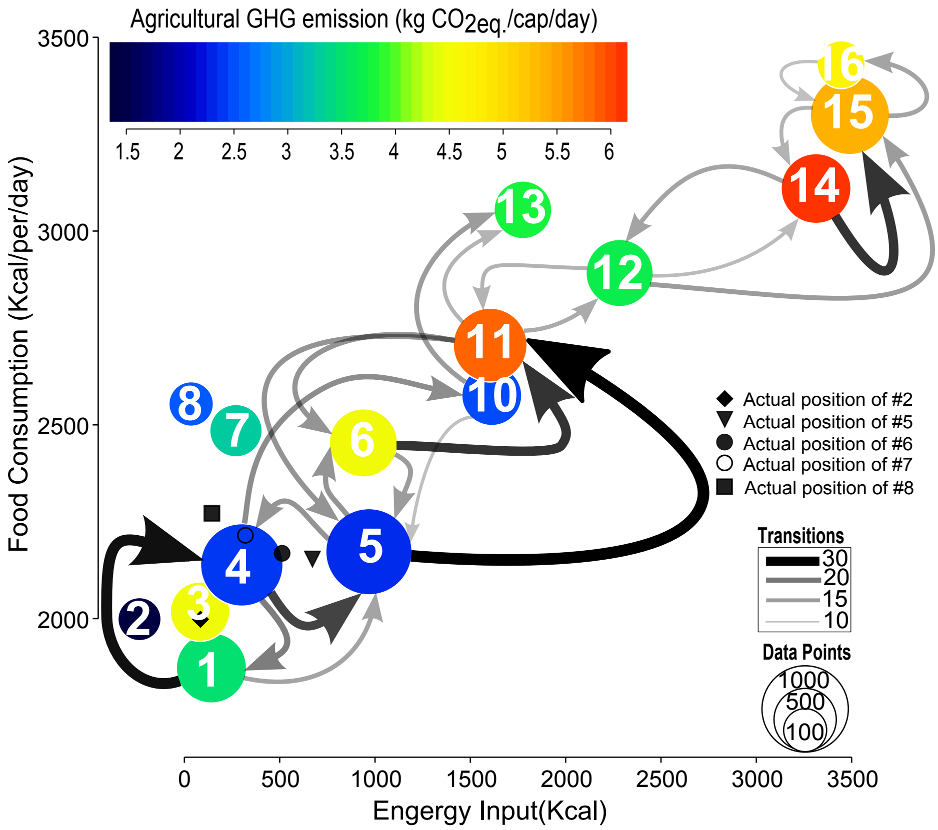

FIGURE 2.4: Graphical representation of the most characteristic transitions pathways. Arrows of varying thickness show the number of changes occurring for all countries over the entire period. Changes occurring fewer than ten times are omitted; for a tabular representation and further details cf. also Appendix Table A.1. Note, that pattern #9 is not shown due to missing data about energy input. The diagram shows fossil energy input (x-axis), total food consumption (y-axis), total GHG emissions (color codes), pattern importance (as total number of country and year represented by the point size). For the description of diet typologies refer to Figure 2.1.

with conflicts and other societal disruptions. For example, during the civil war in Angola (1980–1987) the diet changed from diet typology #3 to #1. Similarly, during the collapse of the former Soviet Union and Yugoslavia in most of the succession states the calorie intake decreased and moved from #14 to #12 or even #12 to #10, respectively.

2.2.3 Embodied Fossil Energy and GHG Emissions

Countries characterized by high calorie diets exhibit a production mode which needs high fossil energy inputs (1,800–3,500 kcal/cap/day). In other words, almost 1 kcal of fossil energy per kcal food consumed is required. In countries with low calorie diets, the energy input can be as low as 80–150 kcal/cap/day (Figure 2.4 and Table 2.1). Converting this to fossil fuel related GHG emissions, we found emissions ranging between 0.64 and 1.35 kg $CO_{2eq.}$/cap/day for very high calorie diets and between 0.03 and 0.05 kg $CO_{2eq.}$/cap/day for low calorie diets. For consideration of the overall GHG emissions, one needs to include non-CO_2 GHG emissions from enteric fermentation, rice cultivation, manure management, and agricultural soils. These non-CO_2 GHG emission intensities are in general relatively high for low and the moderate calorie diets (e.g., pattern #1, #3, #6, and #7) and result in high total emissions for these patterns (> 3 kg $CO_{2eq.}$/cap/day). In contrast, the non-CO_2 GHG emission intensities for crop and livestock are smaller for the very high and the high calorie diets group (Table 2.1). Thus, the high energy input and management strategies make agriculture more productive in developed as in developing countries (Licker et al., 2010, Neumann et al., 2010). Thus, more agricultural goods can be harvested for the same amount of non-CO_2 GHG emissions. At the same time, dietary shifts toward diets that include less animal products would have a great potential for climate change mitigation (Carlsson-Kanyama & González, 2009, Eshel & Martin, 2006, Eshel et al., 2010, González et al., 2011, Popp et al., 2010, Stehfest et al., 2009), which is reflected in the higher non-CO_2 GHG emission intensity for livestock (1.44 to 13.06 g $CO_{2eq.}$/kcal) compared to crop production (0.31 to 1.81 g $CO_{2eq.}$/kcal). Consequently, the total GHG emissions are only slightly higher for high and very high calorie diets (2.48–6.10 kg $CO_{2eq.}$/cap/day) compared to low and moderate calorie diets (1.43–4.48 kg $CO_{2eq.}$/cap/day; Figure 2.4 and Table 2.1). Thus, in regard to the attribution of emissions to the agricultural sector, our approach provides a step forward by associating fossil fuel input and non-CO_2 GHG emissions explicitly to different food consumption patterns.

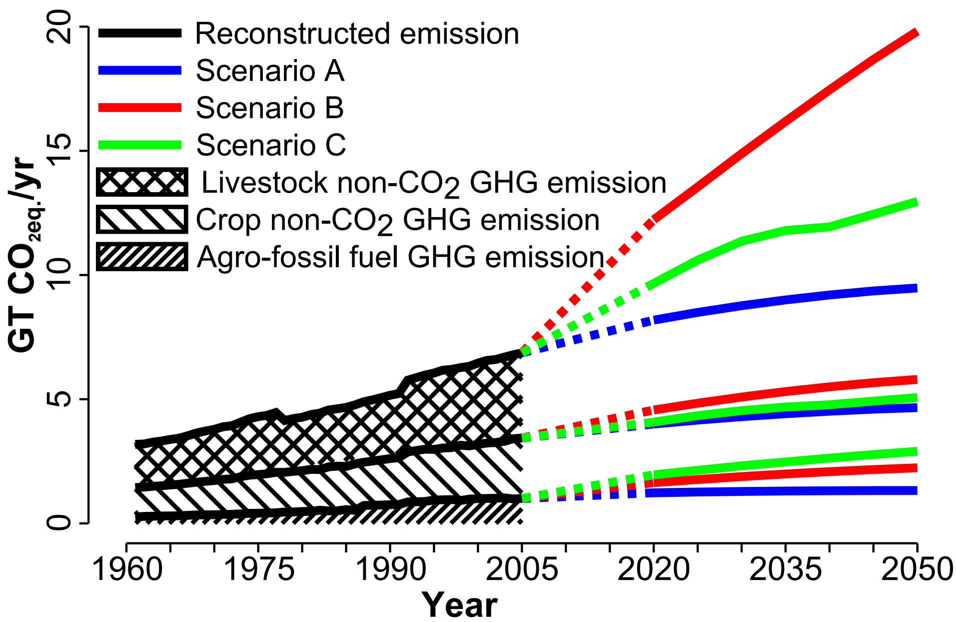

FIGURE 2.5: Reconstructed and projected global total agricultural GHG emissions for three scenarios. A: population growth only, B: population growth and changes in dietary patterns, C: change in population, diets as well as technology and management. Total GHG emissions are decomposed into non-CO_2 GHG emissions from livestock and crop, and GHG emissions from use of fossil fuel in agriculture. The depression in 1978 is mainly due to change in dietary pattern of China from pattern #1 to pattern #4 and the related lower non-CO_2 GHG emissions from livestock. The sharp rise in emissions in 1992 is caused by inclusion of the countries from the former Soviet Union in the analysis from 1992 onwards.

For future development Figure 2.5 shows that the agriculture related GHG emissions will increase by about 40% in 2050 compared to that in 2005 (Metz et al., 2007) due to population growth and hence, increased food demand (scenario A) (Appendix Figure A.2). When changes in dietary patterns, i.e., lifestyle evolutions, are considered emissions will more than double to about 19.8 Gt $CO_{2eq.}$/yr in 2050 (scenario B). Taking into account

TABLE 2.1: Environmental impact data for the different dietary patterns. Values are calculated based on equations 2.2–2.5 (Section 2.4 and Appendix Text A.2). No information on energy O/I ratio and agricultural GHG emissions was available for countries belonging to cluster 9. The table also reflects different agricultural practices. For example, for pattern #1 the high emissions are obviously related to an inefficient livestock management (cmp. column 6 and 10).

Pattern	Crop Products PC_z (kcal/cap/day)	Animal Products PA_z (kcal/cap/day)	Feed F_z	Non-CO_2 GHG Emissions Intensity (g $CO_{2eq.}$ /kcal) Crop ec_z	Livestock ea_z	Energy O/I Ratio $R_{O/Iz}$	Total Fossil Energy FE_z (kcal/cap/day)	Emissions from Fossil Energy (kg $CO_{2eq.}$ /cap/day)	Total GHG Emissions ET_z (kg $CO_{2eq.}$ /cap/day)
1	1,727	146	268	0.82	12.48	14.1	141.8	0.05	3.51
2	1,928	71	297	0.42	6.58	26.2	85.0	0.03	1.43
3	1,904	114	278	1.81	4.30	26.6	82.0	0.03	4.46
4	1,977	161	408	0.64	4.75	7.9	301.2	0.11	2.39
5	1,885	273	511	0.50	3.25	3.6	675.5	0.24	2.34
6	1,778	394	820	1.07	3.83	5.0	521.2	0.19	4.48
7	2,078	133	445	0.57	13.06	8.1	312.3	0.11	3.29
8	2,028	238	665	0.44	5.59	20.3	133.0	0.05	2.56
9	2,149	386	138	N/A	N/A	N/A	N/A	N/A	N/A
10	2,303	272	1,061	0.37	2.37	2.1	1,612.4	0.58	2.48
11	2,240	465	1,364	0.91	4.25	2.3	1,603.8	0.58	5.85
12	2,273	619	2,681	0.32	2.02	2.2	2,282.0	0.83	3.68
13	2,613	442	1,762	0.52	1.96	2.5	1,775.5	0.64	3.78
14	2,020	1,090	3,662	0.51	1.84	1.7	3,313.2	1.20	6.10
15	2,248	1,052	5,037	0.32	1.70	2.1	3,490.9	1.26	5.37
16	2,611	818	4,701	0.31	1.44	2.1	3,445.1	1.35	4.66

that for not transgressing the 2°C global warming target (25% probability of overshooting) an annual emission budget should be kept below 30 Gt $CO_{2eq.}$/yr (Meinshausen et al., 2009). This highlights the tremendous potential the food sector can play in regard to ambitious climate protection goals, while on the opposite the increase in food demand can be an essential component in future climate disruptions (Alexandratos, 2006, Kastner et al., 2012). If one consider improved agricultural practices (scenario C), about 65% of non-CO_2 GHG emissions can be avoided through higher productivity. However, such modified agricultural practices in 2050 require about 33.6 EJ/yr energy input through fossil fuels, which is about 30% more than the fuel energy needed if the agricultural practices remain similar to 2007 (Appendix Figure A.3), indicating that also this part can contribute considerably to emission reduction. The reduction potential of the livestock sector is shown in Figure 2.5. This sector is the major contributor of the agricultural non-CO_2 GHG emissions sharing more than 50%, 70% and 60% of the total GHG emissions in scenarios A, B, and C, respectively. In contrast, differences between the three scenarios are small for CO_2 emissions from fossil fuels and non-CO_2 emissions from crops.

2.3 Discussion

We present important changes of food consumption styles over the last 50 years for all countries with 16 distinct dietary patterns. We found that these patterns are typical for certain regions. They changed over time in regard to the composition of diets as well as to the total calorie consumption. Environmental impacts in terms of fossil fuel requirements and the total GHG emissions generally increased as diets become more calorie rich.

With our approach we provide several innovations for the assessment of food consumption patterns. The advantage of the SOMTOP method (see Section 2.4) used for pattern recognition enables a non-linear dimensionality reduction and feature clustering. As an outcome, a systematic data-driven archetypical model can be built, which supplies valuable and systematic insights into the relations of features of the certain food patterns in comparison to empirical approaches implemented by others (Kariel, 1966). The SOMTOP is robust in the presence of non-linearities and assures that the topological structure of the data is maintained when mapping data from a high-dimensional onto a low-dimensional space in order to detect the degrees of freedom.

The spatial distribution of the patterns supports findings of previous studies, such as a high amount of consumed animal products in diets for North America, Europe, and developed states in the Pacific (Grigg, 1995b). This holds as well for developing countries in which a high proportion of cereals and starchy roots are important for the nourishment of the people. Nevertheless, such a comprehensive global analysis of existing dietary patterns has not been undertaken before. It was feasible to assess dietary patterns consistently for such long-term data and to derive a comprehensive understanding of changes in diets from these patterns. It was one advantage of the used method that it could detect newly emerging patterns during the course of time. Finally, the estimation of GHG emissions (fossil fuel based and non-CO_2) associated with these dietary patterns adds a further uniqueness to our study.

The findings contribute to the on-going discussion of the need for sustainable agricultural intensification (Foley et al., 2011, Godfray et al., 2010, Tilman et al., 2011). It was shown that the non-CO_2 GHG emission intensities of developing countries are larger compared to developed countries (Table 2.1) and therefore, have great potential to contribute to emission reductions. Our scenarios suggest that optimized management may contribute to emission reductions of up to 7 Gt $CO_{2eq.}$/yr in 2050. Our approach also highlights the importance of the livestock sector for diet related GHG emissions. Emissions from this sector are increasing rapidly according to our estimations and about 14 Gt $CO_{2eq.}$/yr by 2050 (scenario B) will be related to the consumption of animal products. Summing-up, agricultural intensification should focus on an optimization of emission intensities, while at the same time keeping other environmental stresses and anthropogenic inputs as low as possible. This will be addressed in a following study which will deal with the compatibility of our projections with current and future land-use demands.

2.4 Materials and Methods

2.4.1 Food Consumption Patterns

We characterized dietary patterns using global time series data on total food consumption and food composition per country from 1961 to 2007 from FAOSTAT (FAO, 2011a). The data cover 11 food categories, which contribute to more than 90% of the global food supply and the total food consumption in kcal/capita/day. The 11 food groups comprise animal products, cereals, pulses, starchy roots, oilcrops, vegetable oils, vegetables, fruits, sugar-sweeteners, sugarcrops, and alcoholic beverages. The food data cover 217 countries and country groups, e.g., Asia, Europe, World. The data comprise of 9,145 items (pairs of countries and years) made up of 12 input variables. A number of conventional multivariate statistical methods can be used to identify patterns from the data, but they have some common limitations (e.g., the data is often considered normally distributed (T.W. Andreson, 2003); the variables are usually assumed to be correlated (Jolliffe, 2002); and the data is commonly expected to exhibit stationarity (Yan & Thil, 2008)). It was found that the food data set is not normally distributed and exhibits non-linearities between the variables. Additionally, due to changing food consumption patterns (Alexandratos, 2006, Kearney, 2010), it is hard to expect stationarity in the data. Therefore, we used a self-organizing map (SOM) (Kohonen, 2001) to cluster the data, which is a robust method for non-linear and noisy data.

A SOM is a neural network that can be interpreted as a self-supervised clustering and non-linear dimensionality reduction technique. It also tries to preserve the topological ordering of the input data in the low-dimensional network space. Compared to other clustering (e.g., hierarchical and k-means) and linear dimension reduction approaches (e.g., PCA and MDS), the SOM creates a topologically ordered segmentation of the data space (Skupin & Agarwal, 2008) and conceptualizes input vectors as representative samples from an n-dimensional information continuum instead of discrete objects (Skupin, 2002). The self-organizing map was coupled with a neighborhood distortion measurement approach (-TOP) (Bauer & Pawelzik, 1992). This part provides a quantitative measure P to estimate topological distortions during the classification process (Bauer & Pawelzik, 1992). An optimal dimension is found when $P \approx 0$, while $P > 0$ indicates a too large and $P < 0$ (Appendix Table A.2) a too small dimension. Thus, the dietary patterns we identified are motivated by the structure in the data (Appendix Text A.2 and Appendix Figure A.5). The source code of the SOMTOP model was developed in C and successfully validated and applied to several other studies (Kropp, 1998, Kropp & Schellnhuber, 2008). We determined a network with 16 representative nodes and a three-dimensional configuration ($4 \times 2 \times 2$) as optimal to describe the observed variation in the data sufficiently (about 72% of the variance explained, topographic product $P = 0.002 \pm 0.001$, cf. Appendix Table A.2). Each of the sixteen nodes represents a set of countries for different years having a certain food composition and total food supply. To derive diet transitions, the changes in dietary pattern of a country in consecutive years were considered.

2.4.2 Relating Food Consumption to the HDI

Data on the human development index from the HDI trend 1980–2007 (UNDP, 2009) were used to determine the relationship between the HDI and food consumption associated with the dietary patterns. Based on this relation and the HDI projection taken from Costa et al. (2011), we estimated future food consumption (Appendix Text A.3).

2.4.3 Assessing Fossil Energy and GHG Emissions

For estimating fossil energy and GHG emissions associated with the dietary patterns, we combined data on agricultural energy output/input (O/I) ratio ($R_{I/O}$) (Conforti & Giampietro, 1997), agricultural non-CO_2 GHG emissions (USEPA, 2006), feed supply (FAO, 2011a), nutritive factors (FAO, 2001) and food production (FAO, 2011a). First, we calculated the feed supply in kcal/cap/day (F) and the non-CO_2 GHG emission intensity per kcal of crop products (ec) and animal products (ea) for each country from the FAOSTAT and agricultural non-CO_2 GHG emissions data (Appendix Text A.2). To aggregate the impact data to the sixteen dietary patterns, we consider the sixteen sets (Z) of pairs of countries (C) and years (Y), making up a certain dietary pattern, and related subsets Z' as the elements for which data on X ($R_{I/O}$, ec, ea, and F) is available. Then the average value (X_z) for a dietary pattern was calculated as the average from the set Z' (equation 2.1). Subsequently, we will denote these dietary pattern specific averages as $R_{I/Oz}$ (energy O/I ratio), ec_z and ea_z (non-CO_2 GHG emission intensities), and F_z (feed use). From these values, we calculated GHG emissions from crop products (EC_z), animal products (EA_z), and total food consumption (ET_z) with equations 2.2, 2.3 and 2.4, respectively. PC_z and PA_z are the consumption of crop products (total food consumption minus animal products consumption) and animal products, respectively, while eD is the emission intensity of diesel (0.36 g $CO_{2\text{eq.}}$/kcal) (DFT-UK, 2008), which was used to estimate GHG emissions from fossil energy. The required fossil energy input (FE_z) was estimated with equation 2.5. Note that equations 2.3 and 2.5 include a term to estimate environmental impacts from animal feed.

$$X_z = \frac{1}{\#(Z')} \sum_{(C,Y) \in Z'} X(C,Y) \tag{2.1}$$

$$EC_z = ec_z \times PC_z + R_{O/Iz} \times PC_z \times eD \tag{2.2}$$

$$EA_z = ea_z \times PA_z + R_{O/Iz} \times F_z \times eD + ec_z \times F_z \tag{2.3}$$

$$ET_z = EC_z + EA_z \tag{2.4}$$

$$FE_z = R_{O/Iz} \times PC_z + R_{O/Iz} \times F_z \tag{2.5}$$

For future development, three scenarios were analyzed (Appendix Text A.3): scenario A considered population growth only; scenario B represented population growth and changes in dietary patterns; and scenario C contained changes in population, diets as well as technology and management. In order to project dietary patterns and estimate related GHG emissions from agriculture, we made use of the exponential relation between diet components and the HDI (Figure 2.2) and combined it with the HDI projections (cf. above).

Chapter 3

Embodied Crop Calories in Animal Products[1]

Abstract

Increases in animal products consumption and the associated environmental consequences have been a matter of scientific debate for decades. Consequences of such increases include rises in greenhouse gas emissions, growth of consumptive water use, and perturbation of global nutrients cycles. These consequences vary spatially depending on livestock types, their densities, and their production system. In this paper, we investigate the spatial distribution of embodied crop calories in animal products. On a global scale, about 40% of the global crop calories are used as livestock feed (we refer to this ratio as *crop balance for livestock*), and about 4 kcal of crop products are used to generate 1 kcal of animal products (*embodied crop calories* of around 4). However, these values vary greatly around the world. In some regions, more than 100% of the crops produced is required to feed livestock requiring national or international trade to meet the deficit in livestock feed. Embodied crop calories vary between less than 1 for 20% of the livestock raising areas worldwide and greater than 10 for another 20% of the regions. Low values of embodied crop calories are related to production systems for ruminants based on fodder and forage, while large values are usually associated with production systems for non-ruminants fed on crop products. Additionally, we project the future feed demand considering three scenarios: a) population growth, b) population growth and changes in human dietary patterns, and c) changes in population, dietary patterns, and feed conversion efficiency. When considering dietary changes, we project the global feed demand to be almost doubled (1.8–2.3 times) by 2050 compared to 2000, which would force us to produce almost equal or even more crops to raise our livestock than to directly nourish ourselves in the future. Feed demand is expected to increase over proportionally in Africa, South East Asia, and South Asia, putting additional stress on these regions.

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3.1 Introduction

Globally, human diets are changing in terms of the amount and composition of food (Alexandratos, 2006, Kearney, 2010). Most of the changes are toward higher calorie dietary patterns consisting of a larger share of animal products, vegetable oils, and sugar and sweeteners (Pradhan et al., 2013b). Dietary patterns play an important role in shaping various aspects of the agricultural sector. An increase in intake of animal products exacerbates environmental consequences induced by agriculture (Steinfeld et al., 2006). For example, it leads to increases in agricultural greenhouse gas (GHG) emissions (Eshel & Martin, 2006, Reay et al., 2012) and growth in demand for anthropogenic inputs like fertilizer (Metson et al., 2012). The livestock sector uses about 26% of global land area directly as pastures and meadows (FAO, 2011a). Livestock is a major emitter of GHGs, e.g., CH_4 emission from enteric fermentation accounts for 32% of the total agricultural non-CO_2 GHG emissions in 2005 (Metz et al., 2007). However, the livestock sector plays an important role in global food security (Wint & Robinson, 2007) and livelihood conditions as animal products provide high-quality protein to consumers. Livestock generates regular income, draft animal power, and manure for producers and plays critical role as an asset depending on the livestock production system (FAO, 2011c).

The total global crop calorie demand, including the demand for humans and livestock, is projected to double by 2050 compared to 2005 as per capita crop calorie demands will likely increase with per capita income (Tilman et al., 2011). Meeting this projected dietary change would aggravate agriculture induced environmental impacts. For example, expected higher calorie dietary patterns by 2050 would increase agricultural GHG emissions by more than 60% compared to 1995 (Popp et al., 2010) and demand more than 1.8 times the present agricultural water use (Hanjra & Qureshi, 2010). This also leads to a large increase in major fluxes of the nitrogen cycle (Bodirsky et al., 2012, Smil, 2002), for which we have already transgressed the planetary boundary (Rockström et al., 2009). The livestock sector will increasingly play a major role in contributing agricultural GHG emissions (Pradhan et al., 2013b) and in perturbation of global nutrients cycles (Bouwman et al., 2013). However, the crop demand and the environmental impacts vary spatially. Although human attribution of net primary production is 22% on a global scale, it exceeds 90% in some regions worldwide (Haberl et al., 2007, Imhoff et al., 2004). Similarly, spatial distribution of different types of livestock vary based on various social, cultural, and economic factors (Wint & Robinson, 2007). Climatic factors and the mode of agricultural practices influence the geography of livestock production systems (Eggleston et al., 2006, Robinson et al., 2011). Subsequently, we observe geographical variation in animal product production (FAO, 2011b) and livestock influences on local nutrient fluxes (Potter et al., 2010).

Hence, the overarching goal of this study is to investigate the spatial distribution of embodied crop calories in animal products and to project the future feed demand. This involves three main steps. First, we downscale country scale feed data (FAO, 2011a) into a raster grid of five arc-minute ($5'$) resolution using data on livestock densities and their production systems (Robinson et al., 2011, Wint & Robinson, 2007). For this study, we defined feed explicitly as the crop products supplied to raise livestock, however, the total feed mix might consist of crop products, crop residues, fodder, and forage (non-crop feed). Second, we compare derived gridded feed data with gridded data on the production of crop and animal calories to understand the spatial distribution of crop balance for livestock and embodied crop calories in animal products. We define the crop balance for livestock as the ratio between feed calories used and crop calories produced, and the embodied crop calories as the ratio between feed calories used and animal calories produced. Finally, we estimate the future feed demand considering three scenarios: a) assuming diets would remain as they were in the year 2000 but the population growth according to UN (2011), b) dietary changes as projected by Pradhan et al. (2013b), with the same population growth considerations, and c) changes in population, dietary patterns, and feed conversion efficiency.

3.2 Materials and Methods

3.2.1 Data Harmonization and Aggregation

Table 3.1 presents the overview of data used for this study. Data for feed, crop production, and animal production are normally provided in mass units. Using nutritive factors from FAO (2001), we converted the data from mass units into calorie units to be able to compare and aggregate these values (Appendix Text B.1 and Appendix Table B.1). We derived the countrywide crop calories and crop mass used as feed based on the FAOSTAT Commodity Balances (FAO, 2011a). Similarly, we calculated livestock-wise animal calories produced on a country using the FAOSTAT Livestock Primary Production (FAO, 2011a). Since the data on livestock densities adjusted for the year 2000 is available for six livestock types (Wint & Robinson, 2007), we only considered animal calories provided by these livestock types. The six livestock types, with their associated animal products are: cattle, buffaloes, goats, and sheep, which all provide both milk and meat; pigs which provide meat only, and poultry which provide meat and eggs.

TABLE 3.1: List of data used for the study

Data	Resolution	Unit	Source
food supply	country	kcal/cap/day	FAO (2011a)
feed use	country	t/yr	FAO (2011a)
animal product	country	t/yr	FAO (2011a)
population projection	country	count	UN (2011)
dietary patterns projection	country	kcal/cap/day	Pradhan et al. (2013b)
livestock feed requirement	region	kg/head/day	Haberl et al. (2007)
crop productivity	$5'$	t/ha	IIASA/FAO (2012)
crop harvest area	$5'$	ha	IIASA/FAO (2012)
fodder productivity	$5'$	t/ha	Monfreda et al. (2008)
fodder harvest area	$5'$	ha	Monfreda et al. (2008)
livestock density	$3'$	count/km^2	Wint & Robinson (2007)
livestock production system	$3'$	–	Robinson et al. (2011)
nutritive factor	item	kcal/100 g	FAO (2001)

Gridded total crop calorie production was calculated using downscaled data on crop yields and area harvested from the GAEZv3.0 (IIASA/FAO, 2012) for the year 2000 (see Appendix Text B.1). We considered 19 crop types provided by the GAEZv3.0 excluding non-food crop (e.g., cotton and fodder), stimulant cash crops (e.g., tea, coffee, and cacao) and crop commodities under residual section. These 19 crop types account for more than 90% of the global crop calories produced in 2000 (FAO, 2011a). Gridded livestock density data (Wint & Robinson, 2007) and gridded livestock production system data (Robinson et al., 2011) on $3'$ resolution were harmonized to the $5'$ resolution of the crop data with the *Bilinear Resampling Technique* in ArcMap 10.

3.2.2 Downscaling Country Data to the $5'$ Grid

We obtained the total animal calorie production for the year 2000 to a grid by adapting methodology reported in FAO (2011b) (see Appendix Text B.2.1). We proportionally distributed livestock-wise calorie production based on gridded livestock density data.

Downscaling of countrywide feed calories for the year 2000 to a grid was done in three steps (see Appendix Text B.2.2). First, we estimated countrywide feed requirements. We calculated feed required per grid cell for each livestock types in tonne per year multiplying regional and livestock-wise daily feed requirements (Haberl et al., 2007) with the gridded livestock counts. Then, we aggregated the gridded feed requirements into two categories: ruminant feed requirements for cattle, buffaloes, goats, and sheep, and non-ruminant feed requirements for pigs and poultry. Depending on the livestock production system (LPS), the feed requirements are met by a mix of fodder, forage, crop residues, and crop products. To simplify the analysis, we grouped the 14 LPSs provided by Robinson et al. (2011) into two categories: rangeland consists of rangeland-based LPSs and non-rangeland consists of mixed rain-fed and irrigated LPSs including classes urban and other. Adapting the methods of European Commission (2009), we considered that non-ruminants are provided with feed whereas ruminants graze in pastures in addition to consuming non-crop feed (e.g., fodder, forage, and/or crop residues) for rangeland LPS. For non-rangeland, crop products were assumed to be fed to ruminants only when the produced non-crop feed on the grid was not enough to meet their feed requirements. However for non-ruminants, crop products were used as feed regardless of the LPSs.

In the second step, we distributed the derived data on country feed calories from FAOSTAT (FAO, 2011a) to ruminants and non-ruminants. Since FAOSTAT does not distinguish feed share for ruminants and non-ruminants, we used two approaches (I and II) for this (see Appendix Text B.2.2). In approach I, we prioritized non-ruminants for obtaining feed calories because globally around 80% of the total livestock feed is supplied to non-ruminants (Erb et al., 2012). This is a close to reality approach that provides a low bound for ruminant feed calories but a high bound for non-ruminants. For this, we first allocated the country feed calories to non-ruminants based on the crop mass used as feed and the non-ruminant feed requirement. Then the remaining feed calories were assigned to ruminants if the crop mass used as feed is larger than the non-ruminant feed requirement. But if that is not the case, we assumed that ruminants are supplied only with non-crop feed. However, farming systems exist around the world where similar amount of feed is used for ruminants and non-ruminants, e.g., in Denmark (Dalgaard et al., 2006). Taking this into account, we assumed a second approach. In approach II, we proportionally distributed country feed calories to non-ruminants and ruminants based on their respective feed requirements. We considered this as an extreme case that provides a high bound for ruminant feed calories but a low bound for non-ruminants.

In the third and final step, we disaggregated the country scale ruminant and non-ruminant feed calories into grids to obtain gridded feed calories (Appendix Text B.2.2). For this, we proportionally distributed the country scale non-ruminant feed calories across the country grids based on the grid and the country scale non-ruminant feed requirements. In case of ruminants, we estimated the crop products required as feed on a grid based on the difference between the ruminant feed requirement and the production of non-crop feed. Afterwards, we proportionally distributed the ruminant feed calories based on the difference, assuming that ruminants are fed only on non-crop feed in rangeland and in the grids where enough non-crop feed are produced to meet the requirements. Finally, we obtained the grid feed by summing up ruminants and non-ruminants feed calories.

3.2.3 Projection of Feed Demand

We assumed that the demand for animal calories drives their production and that the production drives feed demand. Countrywide total animal calorie production (AP) and animal calories consumed by humans (AC) demonstrate a linear relation in a log–log plot (Figure 3.1a). Additionally, country scale animal calorie production (AP') from the six livestock types and feed calories (FC) demonstrate a similar relation (Figure 3.1b). We derived AP, AP', AC, and FC from the FAOSTAT (FAO, 2011a) (Appendix Text B.3). The parameters, slope (m) and intercept (n), of these relations changed across time showing a complex behavior (Figure 3.1a$'$ and 3.1b$'$). We simplified the complex behavior to linear trends in the parameters overtime based on observation over the last decades showing a linear increase in n and decrease in m. Biases for these fits are discussed in Appendix Text B.3 and Section 3.4. Applying linear extrapolation, we estimated the future values of n^y (y: the year) and m^y. The extrapolated values of n^y and m^y across time implicitly represent changes in the future role of international trade to meet countrywide animal product demand (Figure 3.1a$'$) and changes in feed conversion efficiencies (Figure 3.1b$'$). We then projected the future total animal calorie production AP_c and feed calorie demand FC_c by country based on their relationships with AC_c and AP'_c, respectively (see Appendix Text B.3).

We defined three scenarios to project the feed demand. The first one (scenario A) is a baseline scenario where the dietary pattern of a country stays the same as in the year 2000 and hence, per capita animal product consumption. Scenario A only considers population change for countries based on the midrange population scenario from UN (2011) that estimates around 9 billion people globally by 2050. We considered this scenario as a low bound. In addition to population change, the second one (scenario B) takes into account country specific changes in dietary patterns as provided by Pradhan et al. (2013b). Pradhan et al. (2013b) estimated the future per capita animal product demand by country till 2050 based on observed exponential relationship between per capita animal product intake and the Human Development Index (HDI), using the HDI extrapolation from Costa et al. (2011) based on logistic regression. The data for per capita animal product demand cover 148 countries. We considered this scenario as an upper bound based on changes in animal products demand and population. Additional to changes in population and dietary patterns, the third one (scenario C) considers changes in feed conversion efficiency based on the extrapolated values of n_2^y and m_2^y (see Appendix Text B.3). This is a midrange scenario.

3.3 Results

3.3.1 Spatial Patterns of Feed Calories

Figure 3.2 presents a gridded map of feed calories for the year 2000 based on approach I (see Appendix Figure B.1 for approach II). The map presents embodied feed used for livestock in billions of kilo-calories per 5 arc-minute grid. For about 60% cells with the feed value larger than 0.2 billion kcal/yr, grid feed estimation based on approach I is

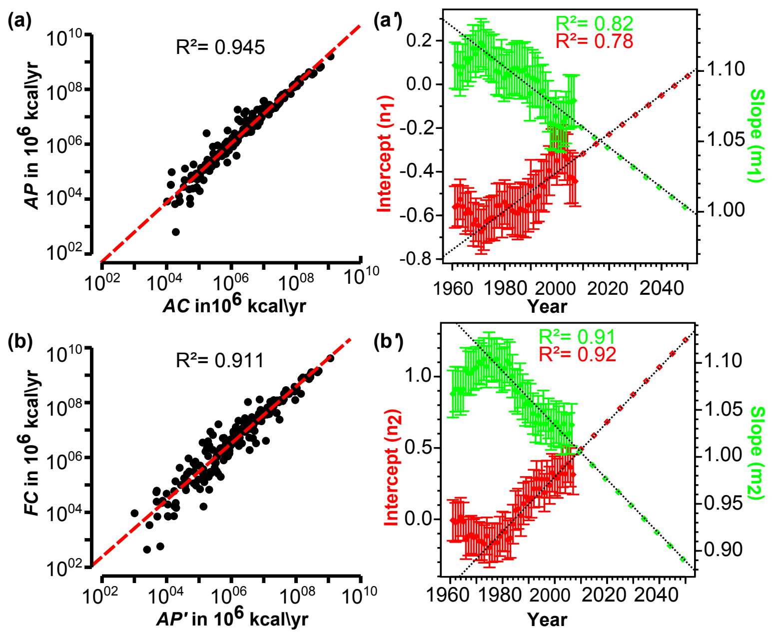

FIGURE 3.1: Relations among animal calorie consumed, animal calorie produced, and feed used, and trends of slope (m) and intercept (n) observed between 1961–2007. (a) Correlation between countrywide animal calorie consumed (AC) and produced (AP, total animal calories) for 2007 on a log–log plot. (b) Correlation between countrywide animal calorie produced (AP', animal calories obtained from the six livestock species) and crop calories used as feed (FC) for 2007 on a log–log plot. The red dashed lines show their linear relations. Trends of slope (m) and intercept (n) observed between 1961–2007 for (a′) correlation between AC & AP, and (b′) correlation between AP' and FC. The error bars represent the standard errors. We observe linear increase in n and linear decrease in m over the last decades for both relationships, shown by dotted lines.

within ±30% range of the result obtained from approach II (Appendix Figure B.1). We observed more than double overestimation or underestimation for around 20% of the cell while comparing results from approach I and II. That means the 'close to reality' approach I represents the 'extreme case' approach II in about 60% of the cells within ±30% range. The underestimation is due to ruminants getting equal priority as non-ruminants for crop-based feed in approach II (see Brazil and India in Appendix Figure B.1), whereas the overestimation is due to non-ruminants getting the first priority in approach I.

On continental scale, North America, Europe (excluding North Europe and Russia), and East Asia are regions that use a very high amount of crop-based feed. Table 3.2 displays information on continental scale and highlights that in these regions (all Europe excluding North Europe) feed consumption is larger than 800×10^{12} (or eight hundreds thousands billions) kcal/yr. One billion kilo-calories of food is enough to sustain about 1,000 persons for a year with a daily diet of 2,800 kcal/cap/day. Thus, the crop calories used as feed in these regions is enough to nourish ≈ 800 million people, which is about the number of people (≈ 900 million) estimated to be undernourished in 2010 (FAO, 2010). Central America, South and South East Asia, and South America also use a high amount of crop-based feed. Overall, on a continental scale, feed calorie consumed is the lowest in Africa (≈ 200×10^{12} kcal/yr). However, some regions in Africa, e.g., Nigeria, Nile valley, and South Africa, the values are comparatively high.

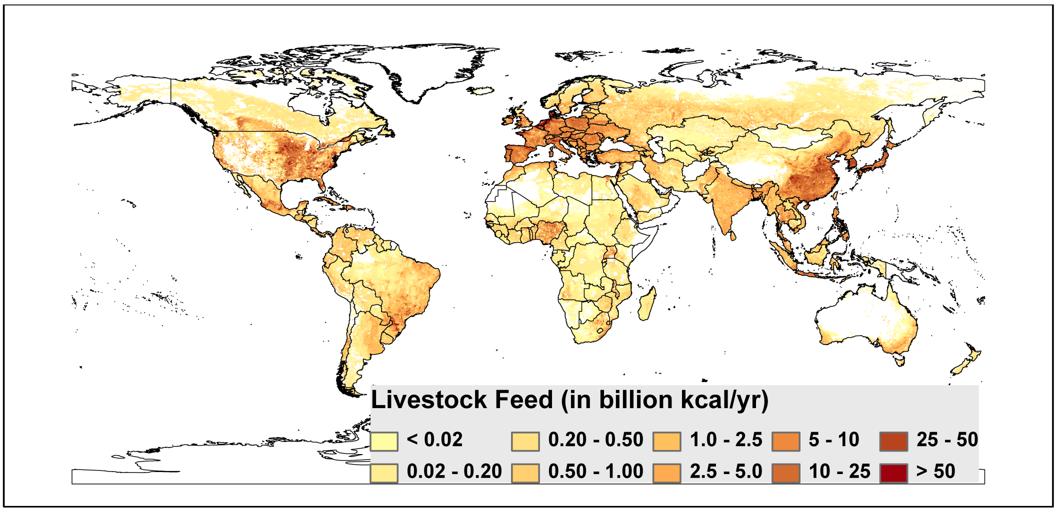

FIGURE 3.2: Gridded map showing crop production consumed as livestock feed (FC_k) in billions kcal/yr based on approach I. Livestock in these grid cells are fed on crops regardless of where the crops were produced. Cattle, buffaloes, goats, sheep, pigs, and poultry are livestock considered in this investigation. Missing and zero values are represented by white color in the map.

3.3.2 Feed, Crops and Livestock Calories

Figure 3.3a shows a gridded map of the crop balance for livestock. Similarly, Figure 3.3b presents a gridded map of the embodied crop calories in animal products. Maps of crop calorie production and livestock calorie production are presented in Appendix Figure B.2 and B.3.

Looking at the first indicator used in our study, the crop balance for livestock, we see it is around 0.40 on a global scale (Table 3.2). That means 40% of the global crop calories is fed to livestock. The balance is greater than 1 for around 30% of grid cells for the both approaches I and II (Figure 3.3a–inset), i.e., the feed used in these areas is greater than the crop calories produced. Accordingly, these areas need national or international trade to meet their feed consumption. Identifying the regions where trade is a necessity is an important result of our analysis. This result also highlights the role of livestock production systems in spatial flow of biomass and nutrient (Billen et al., 2010, Erb et al., 2009). For around 30 to 35% of grid cells, we observed a crop balance of less that 10%. These are regions producing a high amount of crop calories (Appendix Figure B.2) and/or using a low amount of feed (Figure 3.2). However, the lower values of crop balance do not rule out the possible use of crop calorie produced on the cell as feed on other cells worldwide. In addition to the feed, crop products are also needed to meet the dietary demand of people living in those regions. Spatially, we observed a high number of cells with values exceeding the global average of 0.4 or the threshold of self sufficiency of 1 across the Americas, Europe, North Africa, West Asia, and East Asia (Figure 3.3a). These regions consist of areas producing a comparatively high amount of animal calories (Appendix Figure B.3) with high densities of pigs and poultry (Wint & Robinson, 2007). Moreover, the crop balance is also higher in regions producing a lower amount of crop calories (Appendix Figure B.2), but raising non-ruminants (pigs and poultry), e.g., high values appearing as a band in Russia (Figure 3.3a). The balance is comparatively low (below the global average) in regions producing a lower amount of

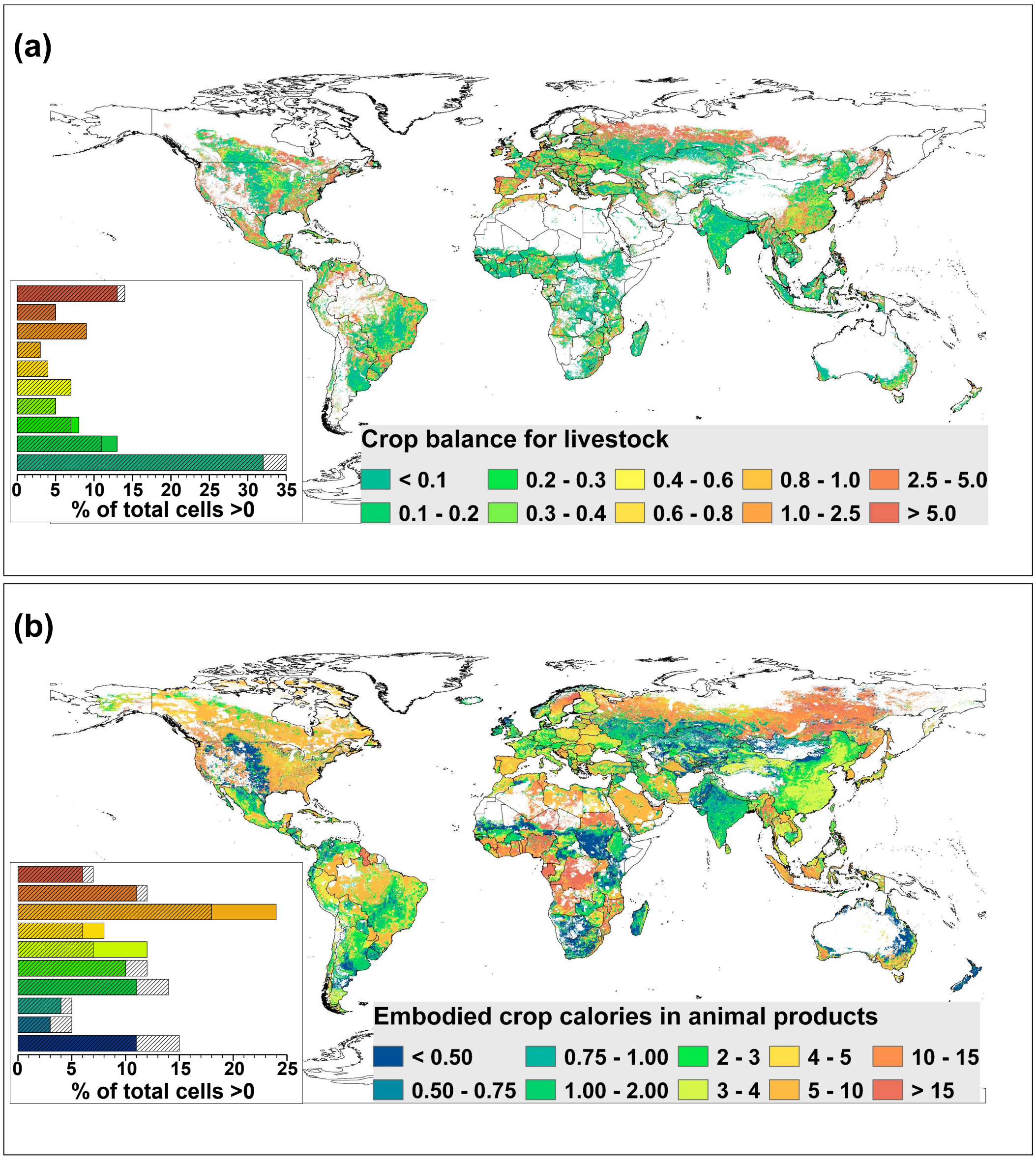

FIGURE 3.3: Maps showing the ratios among crop calories produced, animal calories produced, and feed consumed for year 2000 based on approach I. (a) crop balance for livestock and (b) embodied crop calories in animal products. Insets present statistics for both maps with hatched bar showing statistics for the results based on approach II. The estimated global average values of the crop balance and the embodied crop calories are ≈ 0.4 and ≈ 4 respectively for the year 2000.

Table 3.2: Regional overview on crop calories, animal calories, and feed. The columns present regional breakdown of crop calorie production (CP), animal calorie production (AP), feed calories for 2000 (FC), and feed demand for 2050 without dietary changes (FC_5), with dietary changes (FC_5^d), and also including changes in feed conversion efficiency ($FC_5^{d,f}$) in 10^{12} kcal/yr. Additionally, they provide regional values of crop balance for livestock (FC/CP) and embodied crop calories (FC/AP) along with the ratios between projected feed demand for 2050 and feed consumed in 2000 without dietary changes (FC_5/FC), with dietary changes (FC_5^d/FC), and also including changes in feed conversion efficiency ($FC_5^{d,f}/FC$).

Regions	CP	AP	FC	FC_5	FC_5^d	$FC_5^{d,f}$	$\frac{FC}{CP}$	$\frac{FC}{AP}$	$\frac{FC_5}{FC}$	$\frac{FC_5^d}{FC}$	$\frac{FC_5^{d,f}}{FC}$
	10^{12} kcal/yr										
Africa											
East Africa	165	9	29	88	467	422	0.18	3.21	3.00	15.98	14.44
Middle Africa	58	2	10	74	272	271	0.17	6.53	7.57	27.73	27.68
North Africa	126	16	65	92	335	243	0.52	4.21	1.41	5.13	3.73
South Africa	57	6	21	23	25	25	0.37	3.76	1.10	1.22	1.21
West Africa	271	6	79	245	1,121	931	0.29	14.05	3.11	14.24	11.83
America											
Caribbean	23	3	11	13	40	42	0.48	3.47	1.14	3.60	3.78
Central America	149	22	88	117	272	220	0.59	4.05	1.33	3.10	2.51
North America	1,704	146	816	692	953	593	0.48	5.57	0.85	1.17	0.73
South America	771	81	252	290	527	408	0.33	3.12	1.15	2.09	1.62
Asia											
Central Asia	78	9	24	38	66	65	0.31	2.77	1.59	2.76	2.72
East Asia	1,774	236	803	551	1,203	695	0.45	3.40	0.69	1.50	0.87
South Asia	1,264	111	166	202	867	550	0.13	1.50	1.22	5.23	3.32
South East Asia	756	28	150	180	819	629	0.20	5.32	1.20	5.46	4.19
West Asia	173	21	101	150	408	360	0.59	4.90	1.48	4.02	3.55
Europe											
East Europe	731	84	374	240	327	287	0.51	4.46	0.64	0.87	0.77
North Europe	192	42	129	129	164	149	0.67	3.12	0.99	1.27	1.15
South Europe	264	49	226	228	333	280	0.86	4.62	1.01	1.47	1.24
West Europe	532	98	303	260	300	239	0.57	3.10	0.86	0.99	0.79
Oceania											
Australia & New Zealand	149	22	38	42	61	49	0.26	1.69	1.11	1.61	1.29
World	9,235	988	3,685	3,653	8,558	6,457	0.40	3.73	0.99	2.32	1.75

animal calories (Appendix Figure B.3), but a higher amount of crop calories (Appendix Figure B.2), as in Australia, New Zealand, South Asia, South East Asia, Middle Africa, and East Africa.

The second indicator, the embodied crop calories in animal products, is 3.7 on a global scale (Table 3.2). That means global average crop-based feed consumed to produce one kcal of animal products is $\approx$ 4 kcal. We found that the value of embodied crop calories is smaller than the global average for about 40 to 50% of the cells including about 20 to 25% of the cells with values less than 1 (Figure 3.3b–inset). The lower embodied calories mostly refer to either rangeland livestock production systems or other production systems mainly raising ruminants (cattle, buffaloes, goats, and sheep) fed on non-crop feed. Although these livestock production systems have lower embodied crop calories, the amount of non-crop calories is normally higher and other environmental stress generated by these livestock systems may be of a higher value, e.g., use of land and energy, and emission of greenhouse gases (De Vries & De Boer, 2010, Zervas & Tsiplakou, 2012). We observed the cells with the embodied crop calories of less than 1 widely across these regions including East and South Africa, the United States, and Argentina (Table 3.2). Additionally, we figured out that more than 5 kcal of crop products are used to generate

1 kcal of animal products in about 40% of the cells for the both approaches I and II, including about 20% of the cells with values greater than 10. A high number of cells with embodied crop calories greater than 5 are mostly distributed across South East Asia, North America, Middle Africa, and West Africa (Figure 3.3b). Additionally, countries like Russia, Suriname, and Guyana also consist of a larger number of cells with high values. The high values are associated with livestock production systems other than rangeland, mainly involving non-ruminants fed on crop products. Additionally, the values are higher for less intensive production systems than for intensive ones. For example, non-ruminants have shares of more than 60% of animal calorie produced in China and Nigeria (FAO, 2011a), however, the embodied crop calories is lower for China than for Nigeria. One explanation for this is the less intensive production system in Nigeria compared to that of China (Robinson et al., 2011).

3.3.3 Feed Demand for 2050

Figure 3.4 presents a trend and projection of the global feed and food demand until 2050. On a global scale, we can see a trend of increased use of crop-based feed. In 1961, $\approx 1.3 \times 10^{15}$ kcal of feed were used, which has increased by ≈ 1.9 times to $\approx 3.7 \times 10^{15}$ kcal in 2000. However, the ratio of crop calories used as feed and consumed directly by human remained between 0.7 and 0.8 from 1961 to 2000.

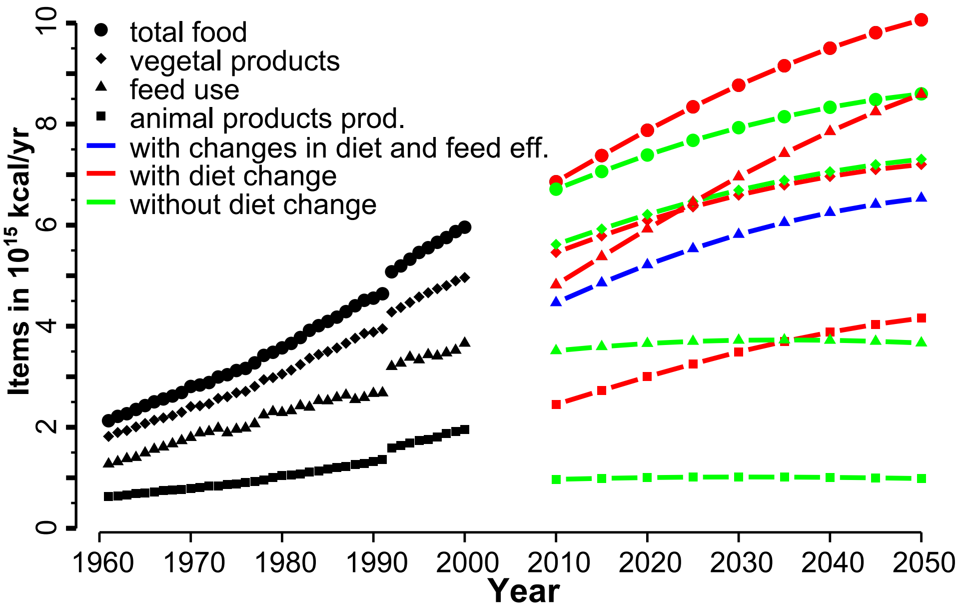

FIGURE 3.4: Global feed use projection until 2050. The figure also shows total supply of food calories, vegetal calories, and animal calories for human consumption and crop calories used as feed on the global scale from 1961 to 2000. The sharp rise in the values for 1992 is caused by inclusion of the countries from the former Soviet Union in the analysis from 1992 onwards. Projection of the demand of food calories, vegetal calories, and animal calories for human consumption and the feed demand until 2050 are presented for three scenarios: (a) without dietary pattern changes but with population changes (scenario A), (b) with dietary pattern and population changes (scenario B), and (c) with dietary pattern, population, and feed conversion efficiency changes (scenario C). Since feed conversion efficiency do not affect food demand, Scenario B & C overlap for food calories, vegetal calories and animal calories for human consumption.

We found that the global feed demand would more than double (2.3 times) in 2050 compared to 2000 while considering the changes in dietary patterns and population (scenario B), and 1.8 times if changes in feed efficiency are also considered (scenario C) (Table 3.2). The changes in dietary patterns consist of a high intake of total calories, animal products, sugar-sweeteners, oils, and vegetables with increased in countries' HDI (Pradhan et al., 2013b). Therefore, the high feed demand we estimated, is related to increase in animal product consumption and an expected global population of 9 billion by 2050. We figured out that the ratio of crop calories demand for feeding livestock and for direct human consumption will increase between 0.9 and 1.2 by 2050 due to dietary pattern changes, in contrast to the ratio varying between 0.7 and 0.8 for the last 5 decades. This results increases in the share of the global crop calories used as feed from 40% in 2000 between 48% and 55% by 2050. Thus, changes in population, animal product consumption, and feed demand lead society to produce equal or even more crops to raise livestock than to nourish mankind directly in the future. Overall, we calculated a need of 60% to 80% increases in crop calorie production by 2050 compared to 2000.

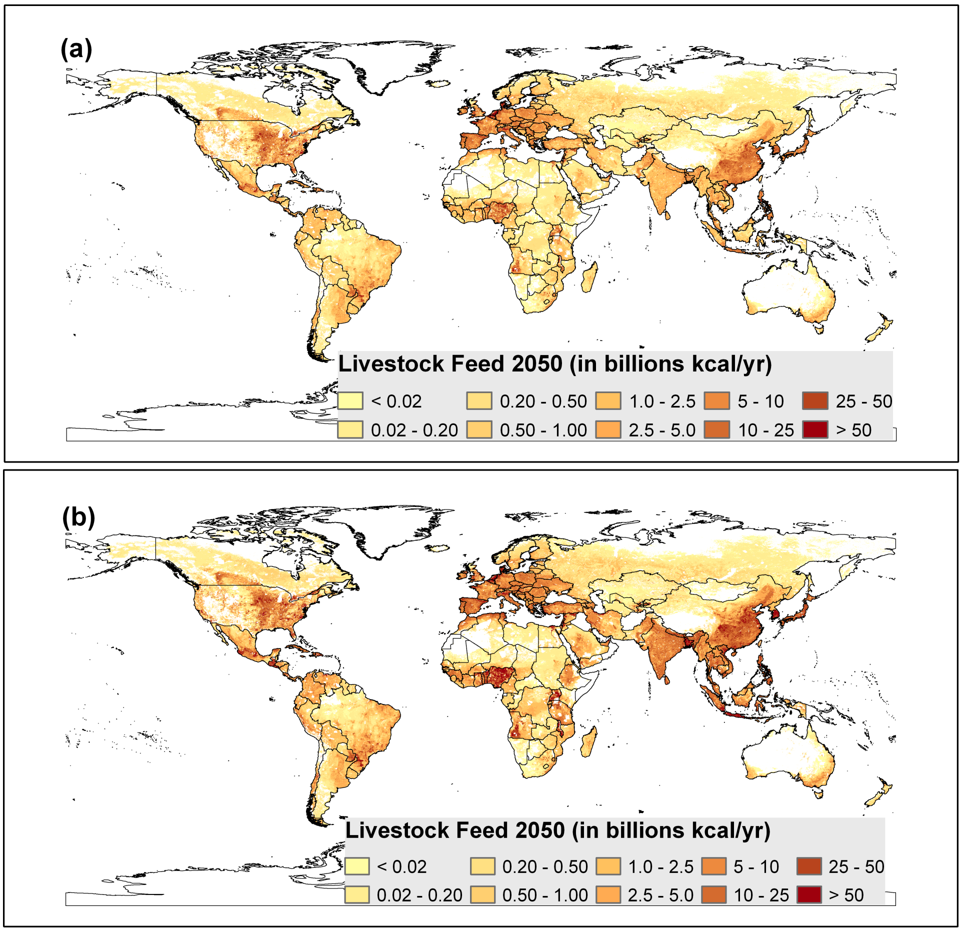

FIGURE 3.5: Gridded map of projected feed calorie demand presented in billions kcal/yr for year 2050 for two scenarios. (a) low bound scenario A without dietary pattern changes but with population changes and (b) upper bound scenario B with dietary pattern and population changes. Both maps are based on the results from approach I.

The ratio between feed used in 2000 and feed demand in 2050 varies across regions and in the three scenarios (Figure 3.5 and Appendix Figure B.4). In scenario A, we see the feed demand increases by more than 50% for most African countries and less than 25% for most South East and South Asian countries (Figure 3.5a and Appendix

Figure B.4a). This is due to an expected increase in population in these regions (UN, 2011). For regions like Europe and East Asia, and countries like the United States, Brazil, and South Africa, feed demand decreases under scenario A, because of the projected decrease in population in these regions by 2050 (UN, 2011). Additionally, this decrease in feed demand might also be due to changes in feed conversion efficiency in these regions between 2000 and 2007 (deduced from decrease in slope across time in Figure 3.1b′). Overall feed demand is nonetheless comparatively larger in these regions for all scenarios (Figure 3.5). In scenario B, we see increases in the feed demand for most of the regions. We estimated that the feed demand will be more than tripled by 2050 for most of African, and South East and South Asian countries (Appendix Figure B.4b). Additionally, we found that regions in Africa (besides South Africa), South East Asia, and West Asia will not be able to meet their feed demand by 2050 based on their present total crop production (Table 3.2). This indicates that these continents are potential feed-limited regions, and thus, they need to increase their crop production and/or be dependent on international trade even to feed their livestock in the future. Presently, these countries' dietary patterns have a small share of animal products (FAO, 2011a) that is projected to increase in the future with development (Pradhan et al., 2013b). In scenario C, we observe increases in the feed demand for most countries as in scenario B. However, the increases in demand are lower than that for scenario B in most of the regions due to changes in feed conversion efficiency. Overall, changes in dietary pattern toward more animal product consumption increase crop-based feed demand. This demand could be reduced by increasing feed conversion efficiency.

3.4 Discussion

In this study, we present global maps with crop calories used as feed and their interrelations with crop and animal calorie production, and project the feed demand until 2050. In the past, crop products have been increasingly used to feed livestock with an growth of ≈ 1.9 times from 1961 to 2000. This trend will continue more rapidly in the future resulting in around double (1.8–2.3 times) the feed demand by 2050 compared to 2000 due to an increase in population and dietary pattern shifts toward higher intake of animal products, mainly in developing countries. However, the increase in feed demand varies geographically. Compared to the developed world, the feed demand growth rate will be larger in developing countries.

With our approach we present several innovations for assessing roles of dietary patterns in shaping various aspects of the agricultural sector. The first novelty lies in aggregating information on crop and animal products in a single comparable calorific unit. A limited number of studies try to present this information in units other than mass units (Cassidy et al., 2013, Foley et al., 2011). This is important because human dietary requirements are generally measured in calorific values (FAO/WHO/UNU, 2004). Moreover, our analysis presenting 40% of crop calories used as feed is similar to that of 36% provided by Cassidy et al. (2013).

Second, information we uniquely deduced on gridded feed calories is a consumption rather than production perspective. This gridded feed data complements existing gridded livestock data sets, such as livestock density (Wint & Robinson, 2007), livestock production systems (Robinson et al., 2011), animal products (FAO, 2011b), and livestock manure (Potter et al., 2010). Such information can be used for a holistic assessment of food security and food self-sufficiency on local, regional, and global scales, considering both crop and animal calorie production, and crop calories use for direct human consumption and for livestock feed. Additionally, our study highlights variability between global and gridded analysis presenting that $\approx$ 4 kcal of crop products are embodied in 1 kcal of animal products on a global scale, however, there are regions even within a country with values less than 1 or more than 10. Similarly, we identified regions using more crop calories to feed their livestock than crop calories they produced, showing a necessity of within-country transfers and/or international trade to meet the shortfalls. This is more important when larger regions/countries become more trade dependent. For example, regions in Africa (besides South Africa), South East Asia, and West Asia would not be able even to meet their feed demand by 2050 without increasing their present crop production.

Third, we are able to project the future crop-based feed demand making use of existing relationships between animal calorie production, animal calorie consumption, and feed consumption at a national scale. This adds to existing studies that focus on projections of crop demand (Alexandratos, 2006). Our results project 60% to 80% increases in global crop calorie demand by 2050 compared to 2000, differ from the projected $\approx$ 100% increases in the demand by 2050 compared to 2005 (Tilman et al., 2011). However, our results are closer to the projected 60% higher food demand than that of 2005 (Alexandratos & Bruinsma, 2012). The discrepancy might be due to the explicit consideration of livestock feed demand which other studies (e.g., Tilman et al. (2011)) consider only implicitly.

Although this study produced clear findings as mentioned above, interpretation of the results also require an understanding of its limitations. One of the limitations lies in our assumption that non-crop feed is not explicitly transferred among grid cells. This overestimates country scale ruminant crop-based feed by more than 20% for about 30% of the countries. However, we distributed feed calorie used in a country to ruminants only after fulfilling non-ruminant feed requirements in approach I, which reduces the overestimation. Moreover, on a global scale only around 12% of cells produces more non-crop feed than needed to meet ruminants' requirements. Additionally, our assumption that crop-based feed is supplied to ruminants only if produced non-crop feed is not enough, slightly underestimates crop-based feed used for ruminants. However, we used this simple approach due to underlying complexity in identifying cells where crop-based feed might be supplied to ruminants although enough non-crop feed could be produced. Moreover, globally only around 20% of the total feed is supplied to ruminants (Erb et al., 2012).

The second limitation is that the actual feed composition affects the mass of required feed. Here, we used a single value for feed requirement regional and livestock-wise due to data constraints. This might be a reason for observing few cases of greater countrywide feed mass requirement for non-ruminants than countrywide feed mass used. Due to data unavailability, we did not take into account intensive and/or landless livestock production system while downscaling feed calorie used, which is another limitation of this study. Additionally, our future projection is based on global relations instead of country trends which may exhibit some limitations due to variations between global and country trends. However, we tried to represent this by considering country specific residuals during the projections. Moreover, our models are able to reconstruct the past country animal calorie production trends for more than 85% of the countries within the mean absolute error (MAE) as fraction of actual value of 20% (Appendix Figure B.5) and the past country feed trends for more than 60% of the countries within a MAE as fraction of actual value of 30%.

Our study highlights an important implication of the ongoing dietary pattern changes toward a large share of animal products. The study explicitly indicates a need to grow equal or even more crops to feed livestock than for direct human consumption by 2050. However, whether the feed demand could be met or not will depend on the future crop price volatility (Wright, 2011) and the future increases in crop yields (Edgerton, 2009). Moreover, the current crop yield trends are insufficient to double crop production by 2050 (Ray et al., 2013) showing a need to explore ways for sustainable agricultural intensification (Mueller et al., 2012) and/or to expand cultivated land. Biofuel as a climate change mitigation option is also a competitor for limited suitable land for cultivation (Fargione et al., 2008). Moreover, the feed demand will increase by more than 2 times mainly in developing countries in Asia and Africa, where people are presently suffering from undernourishment (FAO, 2010). Additionally, crop production in these regions will very likely suffer from the negative impacts of climate change if sufficient adaptation measures are not implemented (Lobell et al., 2008). Summing up, we ask an important question regarding the approach to meeting future animal product demand: Is it possible to make livestock production systems more efficient, therefore enabling these systems to meet the animal product demand in a sustainable way taking into account the environmental impacts of different kinds of livestock-rearing systems (Pretty et al., 2010) or do we need a shift to dietary composition with small share of animal products, reversing current trends?

Chapter 4

Food Self-Sufficiency across Scales: How Local Can We Go?[1]

Abstract

This study explores the potential for regions to shift to a local food supply using food self-sufficiency (FSS) as an indicator. We considered a region food self-sufficient when its total calorie production is enough to meet its demand. For future scenarios, we considered population growth, dietary changes, improved feed conversion efficiency, climate change, and crop yield increments. Starting at the 5′ resolution, we investigated FSS from the lowest administrative levels to continents. Globally, about 1.9 billion people are self-sufficient within their 5′ grid, while about 1 billion people from Asia and Africa require cross-continental agricultural trade in 2000. By closing yield gaps, these regions can achieve FSS, which also reduces international trade and increases a self-sufficient population in a 5′ grid to 2.9 billion. The number of people depending on international trade will vary between 1.5 and 6 billion by 2050. Climate change may increase the need for international agricultural trade by 4% to 16%.

4.1 Introduction

Globally, food and feed demand is increasing and will continue to increase due to population growth and dietary pattern changes (Godfray et al., 2010). Most of the changes are toward more affluent diets consisting of a large share of animal products with high embodied greenhouse gas (GHG) emissions (Pradhan et al., 2013b) and crop-based feed (Pradhan et al., 2013a). Additionally, food production and consumption are becoming more spatially disconnected with growing dependency on international trade (Fader et al., 2013). Trade requires fossil energy and contributes to transport related GHG emissions in order to supply food from field to fork (Weber & Matthews, 2008). In 2004, the transport sector was responsible for 13% of the global emissions (Metz et al., 2007).

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Recently, consumers have become increasingly attracted to local and regional agricultural products (Kneafsey et al., 2013). Studies have reported on the social benefits of local food such as building community relationships between consumers and producers, and often creating economic benefits for producers via rural development (Kneafsey et al., 2013). The environmental and health benefits of local food compared to nonlocal food is of scientific debate (DeLind, 2011, Edwards-Jones, 2010, Kneafsey et al., 2013) because local food can occasionally be inferior (Edwards-Jones, 2010). Depending on the production efficiency, agricultural trade may even save water and land area (Fader et al., 2011). Moreover, few studies explore the potential of local food to meet local demand (Morrison et al., 2011). Nevertheless, a global study on this potential over spatial scales for the present and in the future is still missing. To date, studies have focused on food availability, trade, and self-sufficiency mainly on country scales, showing improved food availability over the past decades mostly due to increased food trade (Porkka et al., 2013).

In the future, global crop calorie demand is expected to increase by 60% to 110% between 2005 and 2050 (Alexandratos & Bruinsma, 2012, Tilman et al., 2011). This increased crop demand will be slightly reduced by progress in feed conversion efficiency, the amount of feed needed to produce a unit of animal product (Pradhan et al., 2013a). However, the current crop yield trends will not meet the future crop demand (Ray et al., 2013). Presently, crop yields vary even across regions with similar growing conditions (Licker et al., 2010) and in most regions are lower than their biophysical potentials (IIASA/FAO, 2012), suggesting potential crop yield gaps. Closing these gaps could potentially meet the expected crop demand, but requires nutrient and water management (Mueller et al., 2012). Moreover, a reduction in mean biophysical crop yields is more likely according to climate change scenarios (Nelson et al., 2014). Climate change will significantly impact low-input subsistence agricultural systems (Lal et al., 2011, Morton, 2007) that exhibit large yield gaps.

The goal of this study was to investigate the potential of regions to shift to a local food supply, minimizing food-miles using food self-sufficiency (FSS) as an indicator. We consider a region as food self-sufficient when the total calorie produced in the region is enough to meet its total calorie consumption, and define the FSS status as the lowest possible spatial scale on which the region could obtain FSS. FSS here reflects local and regional food availability aspects of food security that also considers food accessibility and acceptability (Pinstrup-Andersen, 2009). More precisely, this study has three main objectives. The first is to identify how local a region can be in meeting its food and feed demand based on the present and potential crop yields. The second is to estimate number of food self-sufficient people at different spatial scales, and required amount of food and feed transfer/trade across these scales. The third is to assess the future FSS status considering the five dimensions that drive food and feed production (climate change and crop yields) and consumption (population, dietary patterns, and feed conversion efficiency).

4.2 Materials and Methods

4.2.1 Data Harmonization

We conducted the FSS analysis based on the demand and supply of agricultural products in calorific values on a five arc-minute (5′) grid, the lowest spatial scale that data on global crop yields are available. The demand side consists of human food consumption and crop calories fed to livestock. Human food consumption comprised of crop and animal calories. The supply side includes crop and animal calorie production. Table 4.1 presents the overview of data used for this study. We calculated food calorie consumption on a raster grid of 5′ resolution using gridded population data (CIESIN/IFPRI/CIAT, 2011a) and the average countrywide food calorie intake per cap/day (FAO, 2011a) for the year 2000. Since the gridded population data is in 2.5′ resolution, we aggregated it to 5′ by summing up the population counts. We used gridded data on feed calorie consumption, and crop and animal calorie production for 2000 (Pradhan et al., 2013a). Pradhan et al. (2013a) downscaled data on countrywide feed calorie consumption and animal calorie production from FAO (2011a) to 5′ grid using data on gridded livestock density and livestock production system from Wint & Robinson (2007) and Robinson et al. (2011), respectively. To investigate FSS under different crop yields, we estimated potential crop calorie production on current cultivated land with current cropping patterns for low-input and high-input agriculture (Appendix Text C.1). For this, we used data on potential crop yields and area harvested in 2000 for 19 crop types provided by the GAEZv3.0 (IIASA/FAO, 2012) and nutritive factors from FAO (2001) (Appendix Table C.1). These 19 crops account for more than 90% of the global crop calories produced in 2000 (FAO, 2011a).

Table 4.1: List of data used for the study

Data	Resolution	Unit	Source
food supply	country	kcal/cap/day	FAO (2011a)
food trade	country	t/yr	FAO (2011a)
population projection	country	count	UN (2011)
dietary patterns projection	country	kcal/cap/day	Pradhan et al. (2013b)
crop yield	5′	t/ha	IIASA/FAO (2012)
crop harvest area	5′	ha	IIASA/FAO (2012)
land cover types	5′	percentage	IIASA/FAO (2012)
gridded feed calories	5′	kcal	Pradhan et al. (2013a)
gridded animal calories	5′	kcal	Pradhan et al. (2013a)
gridded crop calories	5′	kcal	Pradhan et al. (2013a)
gridded population	2.5′	count	CIESIN/IFPRI/CIAT (2011a)
urban rural extents	0.5′	–	CIESIN/IFPRI/CIAT (2011b)
nutritive factor	items	kcal/100 g	FAO (2001)

4.2.2 Cross-scale Food Self-Sufficiency

We used a novel approach to evaluate FSS across scales. Starting from the 5′ grid, we compared total calories produced and consumed on a grid cell considering the grid as food self-sufficient when its total calorie production was equal to or larger than its total calorie consumption. Then we analyzed FSS at different administrative levels (Admin-4 to Admin-1) from the lowest administrative unit to the country level. The first administrative level (Admin-1) corresponds to state or province and the fourth one (Admin-4) to municipality or county in some countries. We added and then analyzed the total calorie produced and consumed in an administrative unit to identify whether the administrative unit is food self-sufficient or not. We used the GADM database (GADM, 2012) to delimit the administrative units. The GADM provides data on the administrative boundaries for all countries, at all levels, which we converted into 5′ raster using the *Polygon to Raster* tool in ArcMap 10. Further, we assessed FSS on subcontinental and continental scales based on the UN classification of geographical region and composition.

Initially, we investigated the current FSS status (CS) using gridded data on food and feed calorie consumption, and crop and animal calorie production for 2000. Since a quarter of the produced food is currently lost/wasted (Kummu et al., 2012), our second analysis examined how reducing food waste (FW) may enhance FSS. For this, we assumed food waste was food consumption greater than 2,550 kcal/cap/day, the global average human energy requirement (Walpole et al., 2012), and limited the maximum food consumption in the above CS analysis to 2,550 kcal/cap/day. Third, we replaced crop production in the CS analysis by crop production under low-input agriculture (LI). As present day agriculture usually demands huge inputs (Tilman et al., 2001), this analysis focused on understanding how far the current consumption levels could be sustained by low-input agriculture. Moreover, some regions and some crops are under-performing with lower yields than their estimated potentials (IIASA/FAO, 2012). Closing such yield gaps will increase the global food availability (Mueller et al., 2012). To explore how closing yield gaps may enhance FSS, we replaced crop production in the CS analysis by crop production under high-input agriculture (HI) as our fourth analysis. We defined crop yield gaps as differences between the simulated high-input potential crop yields and the downscaled current crop yields for 2000 (IIASA/FAO, 2012).

The above four analyses considered production and consumption of total calories but not dietary composition. Our fifth and sixth analyses accounted for this using the production and consumption of six food groups including livestock feed, which reflects the food acceptability aspect of the food security. The five (cereals, starchy roots, vegetable oils and oil-crops, sugar-sweeteners and sugar-crops, and total animal products) of the six food groups provided around 90% of the global average calorie intake per cap/day in 2007 (FAO, 2011a). Moreover, the other food group (total vegetal products) consisted of fruits and vegetables besides other crops. For these analyses, we defined a region being as food self-sufficient if it is able to produce as many calories in each of the food groups as it consumes. The fifth analysis (FG) considers crop production in 2000, while the sixth (FG_{HI}), the high-input potential crop production.

Considering current crop yield trends (Ray et al., 2013), closing yield gaps by 100% sounds ambitious. Hence, we divided our fourth analysis (HI) into four subanalyses to understand how closing yield gaps at different levels (HI_{50}, HI_{75}, HI_{90}, and HI_{100}) would enhance FSS. HI_{50} represents closing yield gaps to attain 50% of the high-input potential crop calorie production and HI_{100} to attain 100%.

4.2.3 Scenarios 2050

The future food and feed demand will mainly be driven by changes in population, dietary patterns, and feed conversion efficiency (Alexandratos & Bruinsma, 2012, Pradhan et al., 2013a, Tilman et al., 2011), whereas progress on closing yield gaps and climate change will influence the future food and feed supply (Mueller et al., 2012, Nelson et al., 2014). We defined 36 scenarios considering these five dimensions (population, dietary patterns, feed conversion efficiency, yield gaps, and climate change) to assess FSS for 2050 (Appendix Figure C.1). We classified the scenarios into three groups (I–III) based on changes in population (pop), dietary patterns (dp), and feed conversion efficiency (fce) (Appendix Text C.2). In these three groups, the scenarios differ based on three climate variations (constant climate (no cc), IPCC's A2 scenario and B2 scenario) as well as closing yield gaps to attain the four levels of the high-input potential crop calorie production (HI_{50}, HI_{75}, HI_{90}, and HI_{100}) resulting in 36 ($3 \times 3 \times 4$) scenarios. Scenario group I provides baseline scenarios that consider changes in population size using the year 2000 dietary pattern, whereas, group II takes into account changes in dietary patterns and population size. Scenario group III considers changes in feed conversion efficiency, dietary patterns, and population size. An example of these scenarios is a scenario assuming population growth (pop), constant climate (no cc), and closing yield gaps to attain 90% of the high-input potential (HI_{90}), which is also represented by "pop, no cc, and HI_{90}".

For scenario analyses, we used data on projected feed calorie demand and animal calorie production on 5′ grid (Pradhan et al., 2013a); countrywide dietary pattern changes (Pradhan et al., 2013b); the midrange population scenario from UN (2011); and crop yields under climate change from the GAEZv3.0 (IIASA/FAO, 2012). The feed calorie demand and the animal calorie production data provided by Pradhan et al. (2013a) for 2050 considered changes in population size, dietary patterns, and feed conversion efficiency. On the basis of the high-input crop yields for IPCC's A2 and B2 scenarios with and without CO_2 fertilization effect (IIASA/FAO, 2012), we calculated the high-input crop calorie production under climate change using the methodology described in Appendix Text C.1. UN (2011) midrange population scenario forecasts the global population to be approximately 9 billion by 2050 and distinguishes between countrywide urban and rural populations. We proportionally distributed the countrywide urban and rural population across the country grids based on the gridded population data (CIESIN/IFPRI/CIAT, 2011a) and the urban-rural extents (CIESIN/IFPRI/CIAT, 2011b) for 2000 (Appendix Text C.3). Additionally, we estimated the potential increase in build-up areas (i.e., land for infrastructure and settlement) based on linear relationships between countrywide urban-rural build-up areas and population in a log–log plot (Appendix Text C.3 and Appendix Figure C.2). Using this estimation of build-up area changes, we derived associated loss of cultivated land and reduction in crop calorie production showing around a 5% decrease in the cultivated area with a 6% to 7% reduction in crop calorie production (Appendix Figure C.3). We considered this loss of crop calorie production in a grid cell during FSS analysis for 2050.

4.3 Results

4.3.1 Current FSS

Figure 4.1 presents the lowest spatial scale at which a region would be food self-sufficient in 2000. Here, we found that around 1.9 billion people live within a 5′ grid area where enough crop and animal calories were produced to sustain their food and feed consumption (Figure 4.2–CS). Such regions are widely distributed across the globe (Figure 4.1a). Moving to larger scales, we found regions with FSS on subnational scales (Admin-4 to Admin-1) in both food self-sufficient and insufficient countries. We observed that additional regions with 1.5 billion people could achieve FSS at their first level administrative units (Admin-1). India, Brazil, Argentina, Nigeria, the United States, Germany, and Australia are a few of the countries that are capable of producing enough food and feed to meet their demands. At the country level, about 4.4 billion people subsist in regions that could sustain their food and feed demand without international trade. This includes regions with a population of around 1 billion requiring with-in country food and feed transfer to meet their shortfalls beyond their first level administrative units. Regions like South Asia, South America, and West Europe could be self-sufficient at the subcontinental level. On the continental scale, FSS is achievable on all continents besides Africa and Asia (Figure 4.1a). This shows that there is a need for cross-continental trade for about 1 billion people living in Asia and Africa (Figure 4.2). However, these continents consist of countries with low purchasing power and hence, a high number of people suffering from malnourishment and hunger, facing challenges to ensure their food security (FAO, 2010). Furthermore, we found that reducing food waste would increase the numbers of food self-sufficient people across the scales (Figure 4.2–FW).

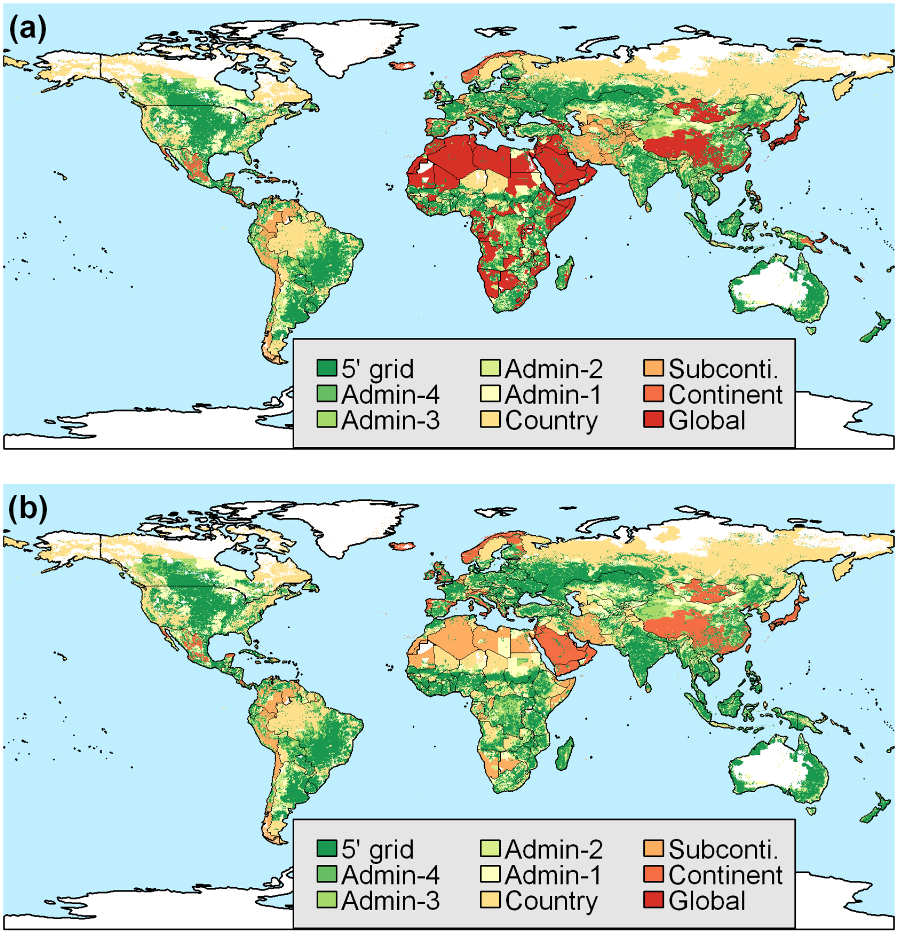

FIGURE 4.1: Maps depicting the lowest possible spatial scale on which a region could obtain FSS for 2000: (a) based on current total calorie production and consumption (CS), and (b) considering closing yield gaps to attain 50% of the high-input potential (HI_{50}). The color coding represents the spatial scales that include 5′ grid, the fourth to the first level administrative unit (Admin-4 to Admin-1), country, subcontinent (subconti.), and continent.

4.3.1.1 Crop Yields

Considering crop yields, we found that it would be possible to achieve FSS for all the continents by closing yield gaps to attain 50% of the high-input potential (HI_{50}) (Figure 4.1b and 4.2). In this analysis, the FSS status mainly of Asia and Africa improves (Appendix Figure C.4b and C.4b′), which would also enhance their food security. This is because of the high potential in these regions to increase food availability by closing yield gaps (Mueller et al., 2012). While considering closing yield gaps to attain HI_{90}, we found that FSS can be obtained at the subcontinental level globally. In this case, regions with a population of around 410 million will be dependent on international food and feed trade within their subcontinent. Moreover, this results in 2.9 billion people living in 5′ grid areas that produce enough crop and animal calories to meet their food and feed demand (Figure 4.2–HI_{90}). Globally, closing yield gaps to attain HI_{100} could almost double crop calorie production of which many opportunities lie in developing and transitional regions such as Asia, Africa, East Europe, and South America (Appendix Table C.2).

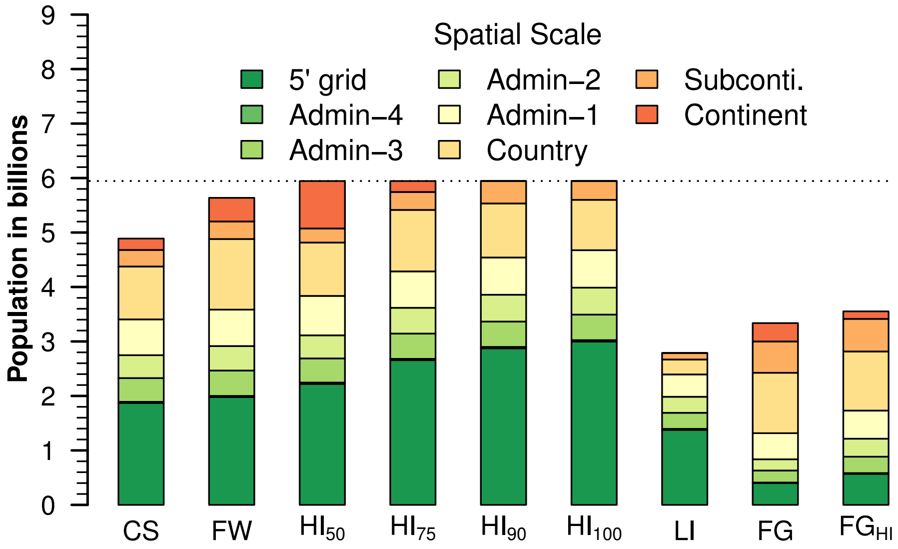

Figure 4.2: Food self-sufficient population estimated for 2000 based on: current total calorie production and consumption (CS), reducing food waste (FW), closing yield gaps to attain 50%–100% of the high-input potential (HI_{50}–HI_{100}), the low-input crop production (LI), and consumption of the six food groups (FG) under current crop production and under high-input potential (FG_{HI}). The color coding represents the spatial scales that include 5′ grid, the fourth to the first level administrative unit (Admin-4 to Admin-1), country, subcontinent (subconti.), and continent. The dotted line represents the global population in 2000. The number of people requiring intercontinental food trade was estimated by the differences between the dotted line and the heights of the bars.

Concerning trade in terms of countrywide required imports (Appendix Text C.4), our estimations suggest that global food and feed trade of around 1,000 trillion kcal/yr in 2000 could be reduced to 400 trillion kcal/yr by closing yield gaps to attain HI_{100}. This means that closing yield gaps does not only increase food availability and ensure food security but can also help reduce international trade and minimize food-miles (Weber & Matthews, 2008), lowering associated GHG emissions from transportation. However, achieving the high-input potential based on traditional intensified agriculture could exacerbate environmental stress and increase demand for external inputs (Tilman et al., 2001). Furthermore, agricultural trade may even be environmentally beneficial saving water and land if the trade is from resource abundant regions with efficient agricultural systems to resource scarce regions (Fader et al., 2011).

For low-input crop production (LI), we found that even the net food exporting regions, such as North and South America, cannot be food self-sufficient (Appendix Figure C.4c). This mode of labor intensive subsistence agriculture using traditional management techniques (IIASA/FAO, 2012) may be unable to meet the present global food and feed demand, and to ensure regional and global food security (Appendix Table C.2). However, the FSS status of some regions in Africa and Asia can be improved because of their lower current crop production compared to their low-input potential (Appendix Figure C.4c′).

4.3.1.2 Food Groups

Considering food composition based on production and consumption of the six food groups (FG), the FSS status differs for all the regions requiring food produced in higher spatial scales (Appendix Figure C.4d). This is because current agricultural practices specialize some regions in the intensive production of few crops. Only about 400 million people live in a 5′ grid area where enough varieties of the food groups are produced to sustain their existing dietary compositions (Figure 4.2–FG). For approximately 2.4 billion people, all of the food groups are currently produced within their countries, such as Australia, Brazil, France, Germany, India, and the United States. At a continental scale, the number of food self-sufficient people increases only to around 3.3 billion. This shows the present day importance of the international trade in meeting our food and feed demands, and in ensuring the global food security. Globally, around 2,000 trillion kcal of food were imported in 2000 (FAO, 2011a), which is double the required imports estimated based on the difference between total calories produced and consumed at the country scales. Moreover, the above numbers of food self-sufficient people at all the scales do not change much when considering the food groups and closing yield gaps to attain HI_{100} (Figure 4.2–FG_{HI}). From this, we can infer that there is a need to change current cropping patterns by diversifying crop production to meet the dietary composition in addition to closing yield gaps, which would enhance local and regional FSS.

4.3.2 FSS by 2050

Our FSS analysis for 2050 was based on three scenario groups that consider changes in population, dietary patterns, and feed conversion efficiency. Each scenario group consists of three climate variations and closing yield gaps to attain the four different levels of the high-input potential, resulting in 36 scenarios. Among these scenarios, Figure 4.3 presents a representative FSS status by 2050 for the two extreme scenario groups considering population growth only (scenario group I) as a lower bound, and changes in population and dietary patterns (scenario group II) as an upper bound.

4.3.2.1 Scenario Group I

Looking at scenario group I with a constant climate, we found that closing yield gaps to attain 50% of the high-input potential (HI_{50}) will be insufficient for Asia and Africa to be food self-sufficient by 2050 (Appendix Figure C.5a) due to population growth. However, there is the potential to achieve FSS on a continental scale for all the continents with closing yield gaps to attain HI_{90} (Figure 4.3a). Comparing this with similar yield gap closing for 2000, we see a decrease in global food self-sufficient people in the 5′ grid from

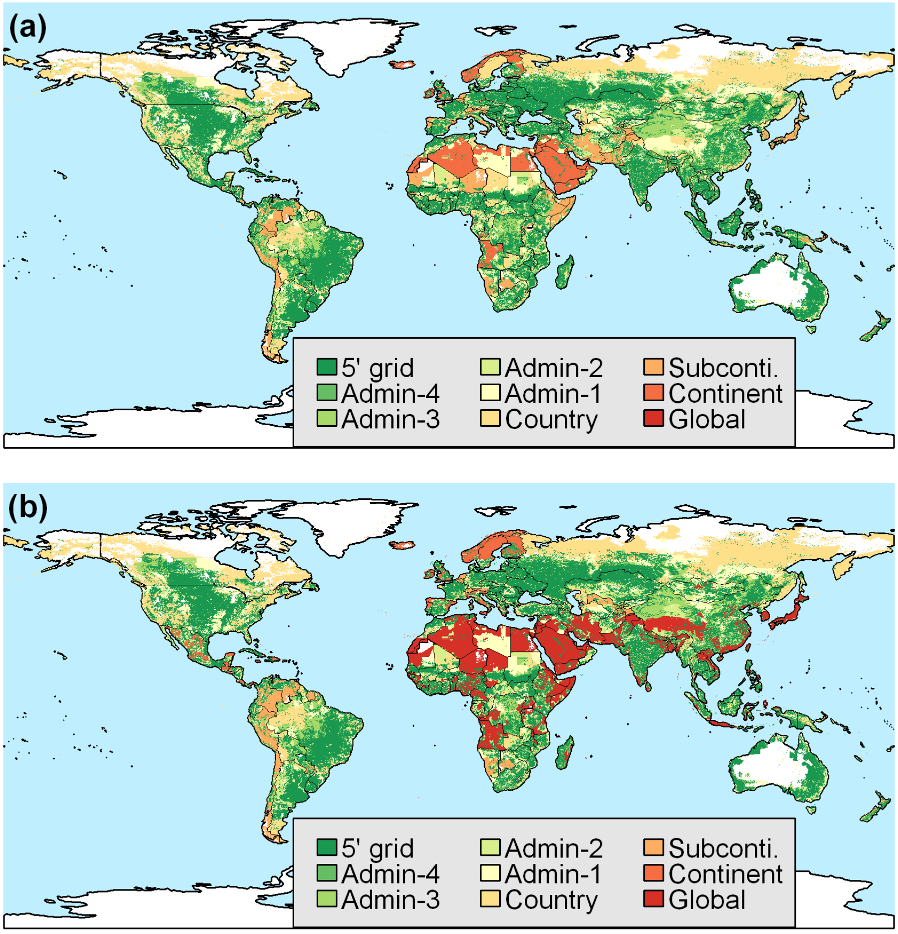

FIGURE 4.3: Maps depicting the lowest possible spatial scale on which a region could obtain FSS for 2050 for two different scenarios: (a) population growth with no climate change and closing yield gaps to attain 90% of the high-input potential (pop, no cc, and HI_{90}), and (b) changes in population and dietary patterns with no climate change and closing yield gaps to attain 90% of the high-input potential (pop+dp, no cc, and HI_{90}). The color coding represents the spatial scales that include 5′ grid, the fourth to the first level administrative unit (Admin-4 to Admin-1), country, subcontinent (subconti.), and continent.

2.9 billion to 2.4 billion between 2000 and 2050 (Figures 4.2 and 4.4). Hence, in the future a growing number of people will depend on food produced in larger regions. This may increase required global food and feed trade to around 1,000 trillion kcal/yr by 2050 from 400 trillion kcal/yr in 2000 with closing yield gaps to attain HI_{100}. Moreover, due to urbanization causing an increase in urban population and a decrease in rural population for some regions (UN, 2011), many rural areas could achieve FSS at a lower spatial scale (Mongolia and China in Appendix Figure C.5). Nevertheless, this would also result in urban regions requiring a larger area to sustain their food and feed demand.

4.3.2.2 Scenario Group II

Outcomes for scenario group II with constant climate show that the number of people living in food self-sufficient regions decreases across all the scales (5′ grid to continent)

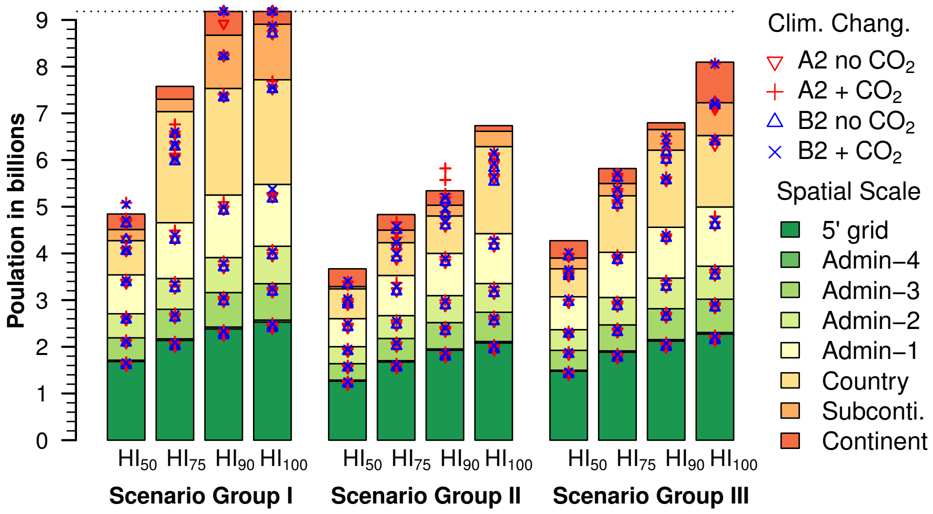

FIGURE 4.4: Food self-sufficient population estimated for 2050. Within scenario groups, the scenarios differ in climate and closing yield gaps to attain 50%–100% of the high-input potential (HI_{50}–HI_{100}). Bars represent the food self-sufficient population considering no climate change, whereas, symbols present the population under IPCC's A2 climate scenario without and with CO_2 fertilization (A2 no CO_2, and A2 + CO_2), and respective B2 climate scenario (B2 no CO_2, and B2 + CO_2). The color coding represents the spatial scales that include 5′ grid, the fourth to the first level administrative unit (Admin-4 to Admin-1), country, subcontinent (subconti.), and continent. The dotted line represents the midrange global population by 2050 (UN, 2011).

when the changes in population and dietary patterns are considered compared to those for scenario group I (Figure 4.4). This is due to changing dietary patterns resulting in an overall increase in food and feed demand (Appendix Table C.2). For example, in this scenario group the food self-sufficient populations in the 5′ grid would decrease to 1.9 billion taking into account closing yield gaps to attain HI_{90}. Figure 4.3b shows that Asia and Africa might not be self-sufficient in this case resulting in previously self-sufficient countries for scenario group I like Bangladesh, China, India, and Pakistan requiring food produced beyond their continent to meet their calorie demands (Appendix Figure C.6a′). This might increase global food and feed trade by about 2.5 times (up to 3,500 trillion kcal/yr) compared to that under scenario I with closing yield gaps to attain HI_{100}. Therefore, looking at future scenarios of changing dietary patterns toward a high calorie diet with a large share of animal products, we found that closing yield gaps only may be insufficient to ensure FSS for all continents by 2050. This implies a need for agricultural expansion in some regions to achieve FSS and (or) a need for substantially increased international trade to meet the food and feed demands to ensure food security. However, expansion of cultivated land is not feasible everywhere because of limited availability of suitable land resources for conversion into agricultural land, which is unevenly distributed across the globe (Bruinsma, 2011, Fischer et al., 2001).

4.3.2.3 Scenario Group III

Looking at scenario group III with a constant climate, we find that the number of people living in food self-sufficient regions increases across all the scales compared to that of scenario group II (Figure 4.4). Changes in feed conversion efficiency considered in this scenario group enables countries, such as China and India that would require food and feed produced beyond their continent in scenario group II–HI_{90}, to achieve FFS at the national scale (Appendix Figure C.6b and C.6b′). However, Africa, a region for which a large increase in feed demand is projected (Pradhan et al., 2013a), will still require food and feed produced beyond the continent. Moreover, changes in feed conversion efficiency lower the overall food and feed demand (Appendix Table C.2) that may limit an increase in global food and feed trade to 2,800 trillion kcal/yr by 2050.

4.3.2.4 Climate Change

Considering the impacts of climate change on crop production, we find that in almost all cases a higher number of people would be food self-sufficient under the IPCC's optimistic B2 scenario compared to that under pessimistic A2 scenario (Figure 4.4). This is mainly due to a lower projected temperature rise for B2 scenario than for A2 scenario. Moreover, a slight increase in the number of food self-sufficient people is observed while taking into account positive fertilization effects of increased atmospheric CO_2 concentration on some crop yields. Some developed countries in the north may gain from increased crop production due to warmer temperatures under both climate scenarios (Appendix Figure C.6c′ and C.6d′). In contrast, changing climate in Asian and African developing countries may jeopardize FSS. Overall, climate change may increase global food and feed trade by 4% to 8% under A2 scenario with CO_2 fertilization, and by 10% to 16% without CO_2 fertilization considering our scenario groups (I–III) with yield gaps closing to attain HI_{100}. Under the B2 scenario, this increment will range between 5% and 9% with CO_2 fertilization, and between 9% and 15% without CO_2 fertilization. Moreover, the effects of shifts in dietary patterns and closing yield gaps appear more sensitive than that of climate change in our analysis. In summary, changes in dietary patterns will make local, regional, and global food security and self-sufficiency more dependent on international trade in the future which would further be exacerbated due to climate change.

4.4 Discussion

Presently, all continents excluding Africa and Asia can achieve FSS. However, closing yield gaps would also enable Africa and Asia to be food self-sufficient. This would enhance local FSS by increasing the number of self-sufficient people in the 5′ grid from 1.9 billion to between 2.2 and 2.9 billion depending on closing yield gaps between 50% and 100% of high-input potential. However, closing yield gaps requires nutrient and water management (e.g., a 25% increases in current irrigated area is required to close yield gaps to 75%) (Mueller et al., 2012), and traditional intensified agriculture may exacerbate environmental stress (Tilman et al., 2001). Therefore, modern strategies to close yield gaps should be directed toward sustainable agricultural intensification (Tilman et al., 2011), increasing food production while simultaneously reducing its contribution to environmental stress (Pretty et al., 2010). However, looking at the future scenarios with dietary pattern changes and population growth, only bridging yield gaps may not be enough to achieve FSS for Africa and Asia by 2050.

With our approach, we developed several innovations for assessing FSS at the global, regional, and local scales. The first novelty lies in the cross-scale analysis we conducted that enabled us to show FSS at different spatial scales on one global map. To our knowledge, these maps are the first of their kind showing that actions at local levels are plausible to attain FSS in many regions. However, this requires producers to grow diverse crops and consumers to rely more on local products. We can infer this from the reduction in the self-sufficient population from 1.9 billion to 400 million when considering production and consumption of the six food groups instead of the total calories. Nevertheless, some regions may not be able to rely on the local supply because of their low potential yields due their agro-climatic features (IIASA/FAO, 2012) limiting required resources, e.g., water availability (Kummu et al., 2014). Moreover, our estimation of about 1.6 billion people relying on international agricultural trade in 2000 is higher than estimated by Fader et al. (2013), who calculated about 1 billion people. This discrepancy on the number of trade dependent people may be due to explicit consideration of feed in our analysis, which Fader et al. (2013) do not take into account. Similarly, our scenario analysis estimating the need for international trade for 1.5 to 6 billion by 2050 differs from scenarios provided by Fader et al. (2013) projecting the need for 0.8 to 5.2 billion without cropland expansion. These differences are due to variations in the scenarios of both studies. Scenarios from Fader et al. (2013) mainly account for climate change, crop yield, and population growth while our scenarios additionally consider changes in dietary patterns and feed demand. Although these two studies provide different estimates, both emphasize the present and the future role of international trade in meeting food and feed demand, and in ensuring global food security.

The second innovation of our study is to highlight different aspects of food and feed transfer/trade across scales. For example, globally, regions with about 2.5 billion people could be sustained by with-in country food and feed transfer, whereas regions with about only 1 billion people would require intercontinental trade mainly due to existing crop yield gaps. Moreover, our estimation of required global agricultural trade of around 1,000 trillion kcal/yr in 2000 is half of the global gross calorie trade calculated based on FAO (2011a). However, the global net calorie trade of about 900 trillion kcal/yr, obtained from the difference between countrywide calorie import and export, is near to our estimation (Appendix Text C.4). This reflects present trade dynamics where a country may import and export agricultural goods at the same time. Additionally, the results we obtained agree with the derived net calorie trade across country, subcontinental, and continental scales based on FAO (2011a) (Appendix Figure C.7). Further, we showed that the global agricultural trade could be reduced by closing yield gaps which would minimize food-miles, lowering associated GHG emissions from transportation. However, food production efficiencies are important when estimating the overall agricultural emissions besides food-miles (Edwards-Jones et al., 2008). Moreover, agricultural trade is also linked with virtual land, water, and nutrient flows (Konar et al., 2013, Lassaletta et al., 2014, Qiang et al., 2013) that would be environmentally beneficial if the flows are from resource abundant regions to resource scarce regions and may be problematic if the flows are in the opposite direction.

Third, this study considers spatially explicit production and consumption of crop and animal calories including livestock feed. A limited number of studies take into account food and feed explicitly during such analysis (Haberl et al., 2007, Tilman et al., 2011). In the future, feed will play an increasing role in FSS which is shown by a growing use of crop-based feed (Pradhan et al., 2013a). Changing dietary patterns toward affluent diets with a large share of animal products increases feed demand. This in return would lower FSS of regions requiring food and feed produced in larger areas. Thus, shifting diets to lower total calorie intake with a lower share of animal products, reversing current trends, could enhance FSS at a local scale and would increase food availability globally in addition to the reduction of agricultural emissions (Pradhan et al., 2013b, Reusser et al., 2013).

Although this study provides clear findings, interpretation of our results also requires an understanding of its limitations. Since our FSS analysis based on the total calorie production and consumption, a food self-sufficient region according to our analysis may depend on agricultural trade to meet its diet and feed compositions. Nevertheless, our study presents the potential of a region to be self-sufficient, which could be achieved by focusing agricultural practices to meet local and regional demands, and shifting dietary choices toward local and regional products. Moreover, two of our analyses considered dietary compositions based on production and consumption of the six food groups. Additionally, total calorie consumption in some regions may be insufficient to meet regions' dietary energy requirements and hence, may be food insecure though appeared self-sufficient in our analysis. However, most countries total calorie intake in 2000 was greater than the minimum dietary energy recommended by the FAO. Currently, 13% of all the food produced is lost during harvesting, postharvesting, and processing (Kummu et al., 2012), which our analysis did not considered. This may overestimate our FSS results for some regions. Nevertheless, we analyzed how FSS would be enhanced by reducing food waste.

The other limitation is the simplistic approach we used to estimate crop calorie loss due to urbanization that ignores the possibility of build-up land expansion without population growth. Therefore, our result can be considered as a lower bound. However, this is our first attempt to capture the possible reduction in a cultivated area, which most agriculture modeling exercises ignore (Bodirsky et al., 2012, Lotze-Campen et al., 2008). One reason for this is the relatively small reduction in the total cultivated area due to urbanization; nevertheless, the resulting crop calorie loss is enough to feed around 1 billion people. Moreover, we did not consider variation in subnational population growth during our scenarios analysis, which is another limitation of this study. However, we took into account differentiated urban and rural population growth per country (UN, 2011). Additionally, our analysis was based on the average countrywide calorie intake that ignored subnational dietary variation (e.g., differences in calorie intake between urban and rural regions) mainly due to data limitations.

Our study demonstrates a possible implementation of "think global, act local" in the context of sustainable food production and consumption. The study explicitly shows that closing yield gaps will improve local, regional, and global food security and self-sufficiency. However, the current crop yield trends are insufficient to close these gaps by 2050 (Ray et al., 2013). This suggests a need to explore ways for sustainable agricultural intensification (Mueller et al., 2012, Tilman et al., 2011). Furthermore, closing yield gaps will not be enough for some regions to achieve FSS in the future, which implies a need for cropland expansion and/or international agricultural trade. Cropland expansion increases GHG emissions and has negative impacts on biodiversity and ecosystem services (Nelson et al., 2010), whereas agricultural intensification increases crop yields sometimes with a net emission reduction effect (Burney et al., 2010) mainly due to avoiding land conversion. Additionally, biofuel, a climate change mitigation option, also competes for the limited cultivated land (Fargione et al., 2008, Fischer, 2011). Moreover, not all locations need to close yield gaps to ensure FSS. This suggests a need to roll back some cultivated land for extensive agriculture that lowers agricultural related environmental stress. Nevertheless, changing dietary patterns will play a crucial role in the future food and feed demand (Pradhan et al., 2013a). Additionally, food demand could be reduced and food availability could be increased by lowering food waste and losses (Kummu et al., 2012, Liu et al., 2013) that would further enhance FSS. Therefore, an underlying question to ensure local, regional, and global food security and self-sufficiency is how to change consumer behavior toward sustainable consumption based on local and regional food with a lower share of animal products and producer practices to grow diverse crop and animal calories that meet local and regional demands.

Chapter 5

Closing Yield Gaps: How Sustainable Can We Be?[1]

Abstract

Global food production needs to be increased by 60–110% between 2005 and 2050 to meet growing food and feed demand. Intensification and/or expansion of agriculture are the two main options available to meet the growing crop demands. Land conversion to expand cultivated land increases GHG emissions, and impacts biodiversity and ecosystem services. Closing yield gaps to attain potential yields may be a viable option to increase the global crop production. Traditional methods of agricultural intensification often have negative externalities. Therefore, there is a need to explore location specific methods of sustainable agricultural intensification. We identified regions where the achievement of potential crop calorie production on currently cultivated land will meet the present and future food demand based on scenario analyses considering population growth and changes in dietary habits. By closing yield gaps in the current irrigated and rain-fed cultivated land, about 24% and 80% more crop calories can respectively be produced compared to 2000. Most countries will reach food self-sufficiency or improve their current food self-sufficiency levels if potential crop production levels are achieved. As a novel approach, we defined specific input and agricultural management strategies required to achieve the potential production by overcoming biophysical and socioeconomic constraints causing yield gaps. The management strategies include: fertilizers, pesticides, advanced soil management, land improvement, management strategies coping with weather induced yield variability, and improving market accessibility. Finally, we estimated the required fertilizers (N, P_2O_5, and K_2O) to attain the potential yields. Globally, N-fertilizer application needs to increase by 45–73%, P_2O_5-fertilizer by 22–46%, and K_2O-fertilizer by 2–3 times compared to the year 2010 to attain potential crop production. The sustainability of such agricultural intensification largely depends on the way management strategies for closing yield gaps are chosen and implemented.

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5.1 Introduction

The global crop demand for human consumption and livestock feed is expected to increase by 60–110% between 2005 and 2050 (Alexandratos & Bruinsma, 2012, Tilman et al., 2011). Changing dietary habits towards more affluent diets consisting of a larger share of animal products, vegetable oils, and sugar-sweeteners (Pradhan et al., 2013b) as well as the growing world population are the main drivers of the global crop demand (Godfray et al., 2010). Increasing crop demand can be fulfilled either by expanding cropland and harvested area, and/or by increasing crop yields. Between 1985 and 2005, the global crop production has increased by 28% of which only 8% came from the expansion of cropland and harvested area, and 20% from increased crop yields (Foley et al., 2011). However, yields of the four major crops (maize, rice, wheat, and soybean) have either stagnated or collapsed over the period of 1961–2008 across 24% to 39% of their cultivated areas globally (Ray et al., 2012). Yield growths per year of these crops over the same period is substantially less than the annual growth rate of 2.4% that will be required for doubling crop production by 2050 (Ray et al., 2013). Presently, crop yields vary across regions even within the same climatic zones (Licker et al., 2010). These variations in crop yields are related to market accessibility, purchasing power/income, agricultural work force, and terrain factors (Neumann et al., 2010), besides water and fertilizer management (Mueller et al., 2012). However, closing yield gaps will enhance food self-sufficiency (FSS) and enable food security at local, regional, and global scales (Pradhan et al., 2014).

In the future, the global mean biophysical potential crop yield is likely to be reduced due to climate change compared to an unchanging climate scenario (Nelson et al., 2014). Agriculture is one of the sectors, which is highly vulnerable to climate change and climate extremes which will increase the prevalence of agricultural production constraints, e.g., heat and water stress, and changes in pest and disease ranges. The effects of climate change will be significant on low-input agricultural systems characterized by large yield gaps due to traditional management approaches (Easterling et al., 2007, Morton, 2007). Furthermore, productivity of high-input agricultural systems (e.g., irrigated farming) may also be affected because of decreased water availability and increased crop water demand due to rise in temperature. Nevertheless, in some regions, crop production may benefit from moderate global warming (Fischer, 2011), for example, North European crop production could benefit from climate change and increased atmospheric CO_2 (Ewert et al., 2005, Kovats et al., 2014, Porter et al., 2014).

Crop production requires various inputs, of which nutrients (e.g., nitrogen, phosphorus, and potassium) and water are crucial. At the same time, associated water management and application of fertilizers and other agrochemicals may cause environmental stress and loss of biodiversity (Tilman et al., 2001). The agricultural sector consumes approximately 70% of the global water withdrawal (Molden et al., 2007). Globally, about 24% of the total cultivated land is irrigated (around 310 million hectares), which in return produces about 33% of the global crop production (Portmann et al., 2010). The agricultural sector directly contributes about 10% to 12% of the total anthropogenic greenhouse gas (GHG) emissions (Smith et al., 2014). Indirectly, agriculture additionally shares emissions related to land conversion that is responsible for 12% of the total GHG emissions (Smith et al., 2014). Cropland expansion has negative impacts on biodiversity and ecosystem services (Nelson et al., 2010) and hence, may not be a sustainable option to increase crop production. Agricultural intensification increases crop yields, but may reduce GHG emissions by unit of production due to avoided land conversion (Burney et al., 2010).

Nevertheless, the traditional way of intensifying agriculture also has negative effects, e.g., nutrient loss and ecosystem deterioration (Liu et al., 2010). Therefore, we need to explore ways to sustainably intensify current agriculture systems considering a broad range of potential management interventions that have been accessed in a more focused way (Mueller et al., 2012, Neumann et al., 2010). These management interventions should address the future food demand, closing crop yield gaps, and the minimization of environmental stress (Godfray et al., 2010, Pradhan et al., 2014, Tilman et al., 2011).

Consequently, the general objective of this study is to conceive location specific agricultural management and input options required for closing yield gaps to increase the crop production, meeting the present and future food demand. Here, crop yield gaps are defined as differences between the modeled potential attainable yields under high-input and advanced management assumptions and the downscaled achieved crop yields in 2000. More precisely, this study has the three specific objectives. Since every location may not need to attain potential yields to meet its food demand if export is excluded, our first objective is to identify regions where the closure of yield gaps matters in terms of reducing food deficits and improving food self-sufficiency (FSS). The second objective is to figure out agricultural inputs and management interventions that are needed to close yield gaps across various regions through exploring spatially explicit factors causing yield gaps. The third objective is to quantify required nutrients to attain potential yields in different locations.

5.2 Materials and Methods

Data used for this study is obtained from the Global Agro-ecological Zones (GAEZv3.0), the detailed methodology of which is presented in the GAEZv3.0 model documentation (IIASA/FAO, 2012). In short, based on principles of land evaluation, GAEZv3.0 estimates crop production potential described as the agronomically possible upper limit of crop yields for individual crops under given agro-climatic, soil, and terrain conditions for a specific level of agricultural inputs and management conditions. For crop production potential, GAEZv3.0 defines three generic input levels (low, intermediate, and high input levels). Under a low-input level, the farming system is considered largely subsistence and labor intensive based on traditional management, using local crop varieties. Under an intermediate-input level, the farming system is considered partly market oriented with a mixture of subsistence based and commercial scale production. Under a high-input level, the farming system is assumed to be mainly commercial agriculture with mechanized management, using adequate nutrients, agro-chemicals, and high yielding crop varieties. Additionally, to supplement potential yield information, GAEZv3.0 also provides downscaled crop yields and area harvested for the year 2000.

5.2.1 Production Gaps and Calorie Deficits

We defined crop production gaps as a ratio between the potential and the current crop calorie production. To estimate the calorie productions, we used data on current and potential crop yields, and area harvested in 2000 for 19 crop types from GAEZv3.0 (IIASA/FAO, 2012) and nutritive factors for converting crop mass into calories from FAO (FAO, 2001) (Appendix Table D.1). GAEZv3.0 provides in a global raster grid of 5 arc minute resolution information on both current and potential crop yields for two types of water supply (irrigated and rain-fed), and potential crop yields for the three input levels. We estimated the potential crop calorie production using crop yield data under high-input levels (Appendix Text D.1.1).

We analyzed crop calorie deficits based on the demand and supply of crop calories. The demand side consists of human vegetal product consumption and crop-based feed provided to livestock, which were calculated from gridded feed data (Pradhan et al., 2013a), countrywide per capita vegetal product intake (FAO, 2011a), and gridded population data (CIESIN/IFPRI/CIAT, 2011a) for the year 2000. The supply side includes crop calorie production that was derived from GAEZv3.0 (IIASA/FAO, 2012) (Appendix Text D.1.1). Since agricultural production constraints and management vary with agro-climatic conditions, crop calorie deficits and production gap analysis was conducted in sub-national moisture regime units (IIASA/FAO, 2012). The seven moisture regime categories used here are: hyper-arid, arid, dry semi-arid, moist semi-arid, sub-humid, humid, and per-humid. We identified regions with crop calorie deficits considering the current and the potential crop calorie production (Appendix Text D.1.2). Afterwards, we classified these regions into six groups based on prevalence and depth of crop production gaps and crop calorie deficits (Appendix Text D.1.3). By doing so, we located regions where closing production gaps results in FSS or significantly reduces calorie deficit status in a single global map.

Scenario analysis for two scenarios (scenario A and B) were used to identify regions where closing the production gaps matters and ensures future FSS by 2050 applying the above described method. Scenario A in which population changes but dietary patterns remain constant at in the year 2000 level, is a baseline scenario. Scenario B accounts for country specific changes in dietary patterns in addition to the population growth; maintaining a minimum calorie intake of 2,535 kcal/cap/day, representing the average for high calorie diets (Pradhan et al., 2013b). In this way, we accounted for changes in population (UN, 2011) and dietary patterns (Pradhan et al., 2013b) that drive future food and feed demand (Alexandratos & Bruinsma, 2012, Pradhan et al., 2013a, Tilman et al., 2011), and progress on closing crop yield gaps that influence future food and feed supply (Mueller et al., 2012, Nelson et al., 2014) (Appendix Text D.1.4).

5.2.2 Yield Gap Factors

We observed substantially larger yield gaps for rain-fed farming than for irrigated farming (Appendix Figure D.1). Globally, rain-fed farming covers 74% of cultivated land. So far it produces only 44% of the potential calorie production while irrigated farming has attained 60% of the potential calorie production. Hence, we focus this analysis on rain-fed cultivated land as it has a larger potential of additional crop production by closing yield gaps than irrigated land.

A number of biophysical and socioeconomic factors puts constraints on crop yields (Fischer et al., 2011, Lobell et al., 2009), resulting in yield gaps that can be tackled with adequate agricultural input and management (Figure 5.1). Initially, we analyzed the biophysical factors that can be overcome by shifting farming practices from traditional low-input to high-input advanced management. We started the analysis looking at agro-climatic constraints related to yield losses due to pests, diseases, weeds, and workability. The first three of the constraints can be reduced by improved pest management. However, the workability constraint related to weather conditions affecting the efficiency of farming

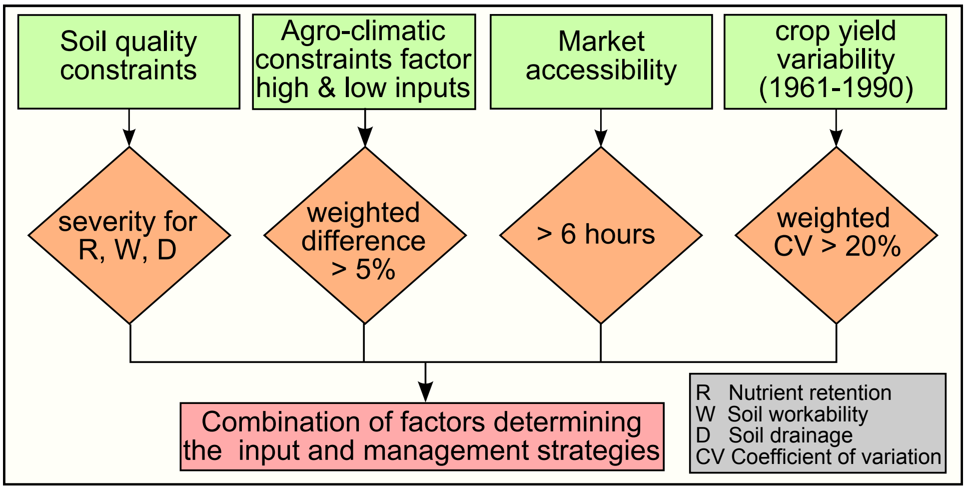

FIGURE 5.1: Flow chart showing the procedure used to design agricultural input and management strategies required to close yield gaps. The light green boxes represent the input data obtained from GAEZv3.0 (IIASA/FAO, 2012). The applied procedures are symbolized by the light orange diamonds, which are explained in Text D.2. The light red box shows the obtained result.

operation (e.g., excessive wetness causing problems in harvesting and handling of crop products) is hard to tackle.

We obtained data on crop specific agro-climatic constraints for low and high input levels at a 5′ resolution from GAEZv3.0. The constraints are characterized through the attainable percentage of the crop yields. Crop yields are determined by radiation and temperature regimes and water availability for a specific input level. The attainable percentage of crop yields is higher for high-input level, closing crop yield gaps, compare to that for low-input level. This is because improved pest management can reduce agro-climatic constraints related to yield losses due to pests, diseases, and weeds. We estimated the difference between the agro-climatic constraints for low and high input levels. The differences were calculated for crops in the two major crop groups (cereals and roots-tubers) and averaged with weights based on harvested area. In the year 2000, these two crop groups combined contributed around 80% of the total crop calorie production. By this, we identified regions where agro-climatic constraints could be attenuated by shifting from low to high input farming based on the weighted difference between agro-climatic constraints larger than 5% (Figure 5.1 and Appendix Text D.2).

As the second factor, we identified regions where crop production is hampered by soil quality constraints. GAEZv3.0 differentiates seven soil qualities and classifies them into four spatially explicit categories: no or slight, moderate, severe, and very severe constraints. Among them, constraints related to three soil qualities (rooting conditions, excess salt, and toxicity) are difficult to overcome using high inputs. Moreover, nutrient availability is an essential soil quality to attain high yields and is assessed separately as described in Section 5.2.3. Hence, we identified regions where constraints related to one or more of the remaining three soil qualities (nutrient retention capacity, soil drainage, and soil workability) are moderate to very severe. These are the regions where crop yields can be increased by soil and land management that improves the soil qualities.

Next, we attempted to capture socioeconomic factors playing important roles in closing yield gaps based on two indicators: yield variability and travel time to the nearest market.

The yield variability due to weather conditions may make farmers reluctant to take risks in terms of input applications without which crop yield increments are difficult (Swindale et al., 1981). GAEZv3.0 provides data on the coefficient of variation of agro-climatically attainable yields for the baseline period of 1961–1990 (IIASA/FAO, 2012). We used this data for crops in two crop groups (cereals and roots-tubers) to estimate the weighted yield variations based on irrigated and rain-fed harvested area, and identified regions with overall year-to-year yield variations larger than 20% (Appendix Text D.2).

Travel time to the nearest market is an important factor in enhancing agricultural productivity as it determines farmers' accessibility to inputs and influences market approachability for selling agricultural products. Consequently, we used spatially explicit accessibility data presenting travel time to the nearest market with a population of around 50,000 (IIASA/FAO, 2012) to identify regions with connecting time longer than 6 hours to markets. We used the traveling time of 6 hours as threshold because the numbers of smaller cities and towns decreases subsequently with increase in the travel time beyond 6 hours (Verburg et al., 2011).

We integrated the information from the four constraints (agro-climate constraints, soil quantity constraints, weather induced yield variability, and market accessibility) by identifying regions with similar dominant constraints. For each combination of dominant constraints, we identified management strategies needed to tackle the prevailing single or multiple constraints (Figure 5.1 and Appendix Text D.2). These management strategies are a novel approach to overcome and reduce yield gaps considering the biophysical and socioeconomic factors that have an impact on crop yields. For attaining high-input yields, implementation of these strategies is needed in addition to application of adequate nutrients and use of high yielding crop varieties. Moreover, we estimated additional crop calories that can be produced by implementing these strategies based on the differences between the current and the high-input potential crop calorie production.

5.2.3 Required Nutrients

Nutrient management plays a crucial role in closing yield gaps (Mueller et al., 2012). To obtain crop yields constantly above the low-input levels, fertilizer application is needed in addition to natural nutrient regeneration. Hence, we quantified the amount of fertilizers required to attain high-input potential crop yields considering differences in crop production under low and high input levels. As nutrients absorbed by crops are stored in crop products (e.g., grain) and residues (e.g., straw), we considered differences between yields and residues of the 16 crop types from GAEZv3.0 for high and low input levels, also accounting for fallow period requirements[2]. A low-input farming system requires a longer fallow period for natural nutrient regeneration that is substituted by fertilizer application in high-input agriculture, shortening the fallow period requirement. We calculated residue for a crop type based on its yield and harvest index (IIASA/FAO, 2012). Afterwards, we estimated the amount of additional crop nutrient uptake in crop yields and residues while attaining high-input potential yields. For this, we multiplied the crop harvested area by the differences in crop yields and residues between low and high input levels, and by the crop specific nutrients uptake in yield and in residue, respectively (Appendix Table D.1). We assumed that both crop products and residues

[2]GAEZv3.0 provides crop specific fallow period requirements for high and low input levels by crop group, by soil type and by climatic condition.

are removed from the fields. Hence, nutrient removal that has to be replenished by fertilizers (organic or chemical), is equal to the total nutrient uptake in yields and residues. Since fertilizers applied to crops may get lost due to leaching and volatilization, the total fertilizers required also varies depending on fertilizer application efficiencies. By this, we estimated the quantities of three macro-nutrients required (N, P_2O_5, and K_2O) to achieve the potential high-input yields (see Appendix Text D.3) assuming that micro nutrient constraints are tackled in fertilizer specific nutrient compositions.

5.3 Results

5.3.1 Focus Regions for Closing Yield Gaps

We found that modern agriculture practices have enabled us to produce globally about 50% more crop calories than can potentially be produced by farming under low-input levels. However, this achievement varies spatially and is mainly concentrated in the parts of Oceania, West Europe, North Europe, North America, South America, and South-East Asia (Appendix Figure D.2). The current global crop calorie production can be doubled by adapting available high-input agriculture practices in the present cultivated land with the present cropping patterns. So far only North and West European countries have almost met their high-input potential crop calorie production (Figure 5.2). Countries in North America, South-East Asia, and Oceania have mostly achieved more than 60% of their potential production. Countries in Africa and East Europe are at the lower end with the achievement of less than 40%.

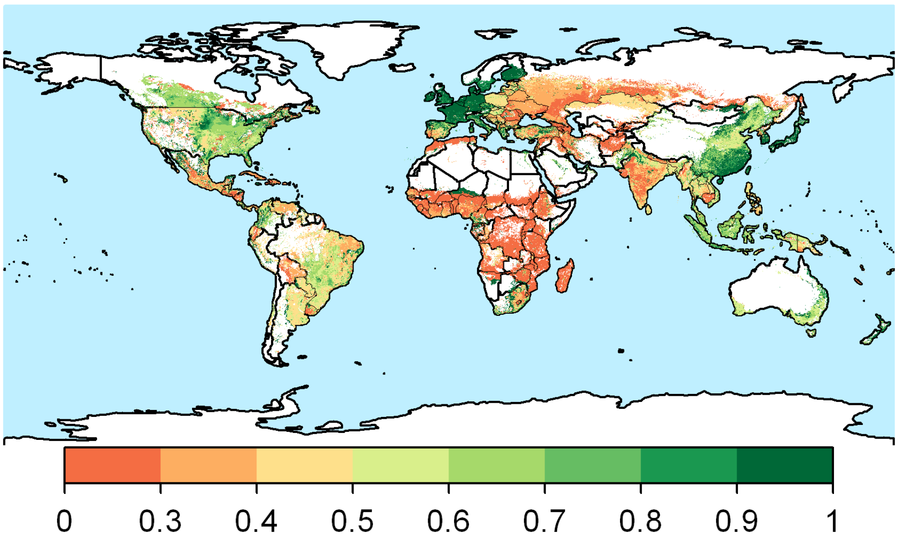

FIGURE 5.2: Location specific ratio of high-input crop calorie production attained in 2000. A ratio of 1 represents regions that have achieved their high-input crop calorie production.

Most African countries could produce enough food to meet their consumption requirements by achieving their potential yields (Figure 5.3). In many North and South American, European, and Asia-Pacific countries, the current food production meets their calorie requirements (Appendix Figure D.3). However, for some countries even achieving potentials would be insufficient to meet their food demand due to poor agricultural land resource conditions. For example, although countries in arid regions, such as the Middle East, may increase crop production and close yield gaps, these countries cannot become food self-sufficient. Some countries (e.g., Japan) have approximately achieved high-input potential yields, but are not food self-sufficient. This is also related to limited cultivable land availability and population. Other countries (such as the United States, India, and Brazil) are food self-sufficient at the national level but not in all climate zones.

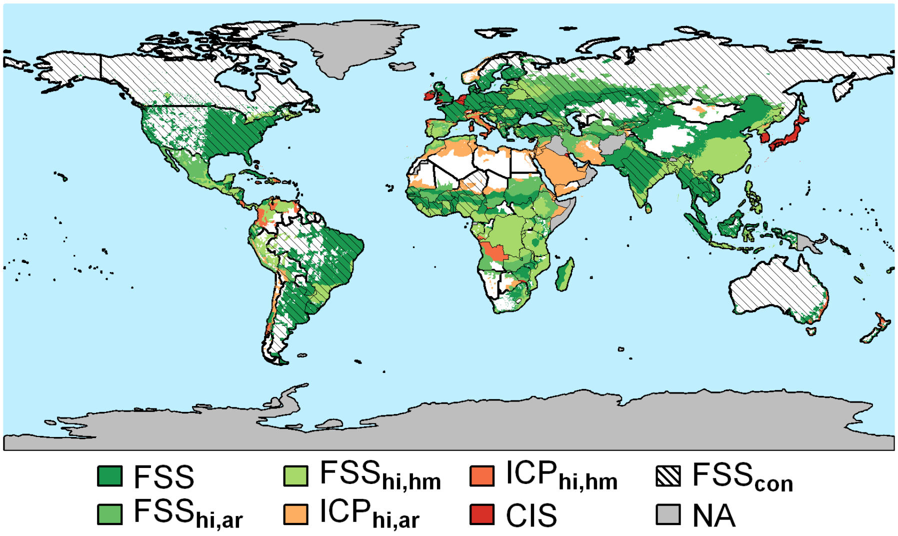

FIGURE 5.3: Regions that can achieve food self-sufficiency (FSS) based on their current crop production, have the potential to be food self-sufficient by attaining high-input (hi) yields, can only increase crop production (ICP) or almost attained high-input yields but are crop insufficient (CIS) by country (con) and by moisture regime (arid (ar) and humid (hm)) for 2000. Since agricultural production constraints and agricultural management vary with agro-climatic conditions, the results are presented by country moisture regime going beyond national scales. NA represents regions with missing data.

By 2050, some countries (such as the United States, Canada, Brazil, France, and Germany) can be food self-sufficient even based on their current crop production, provided their dietary patterns remain unchanged (scenario A, Figure 5.4a), whereas many African and Asian countries can be food self-sufficient when realizing high-input potentials. In contrast, some countries like Pakistan and Bangladesh cannot chieve FSS by closing yield gaps due to high population growth projected by 2050. In Africa, we find only a few countries that can produce sufficient food to feed a growing population by closing yield gaps under the assumptions of shifting dietary habits by 2050 by closing yield gaps (scenario B, Figure 5.4b). This implies yield gap closure can only decrease food insecurity and cannot reach FSS in the majority of African countries. Changes in dietary habits may not cause large differences in most developed countries which already have high consumption levels which are not likely to increase significantly by 2050. Countries in transition like India and China may see regional variations in FSS as a result of changing dietary habits on top of population growth. Nevertheless, closing yield gaps can enable food security in most countries globally. This requires the application of inputs as well as sound management for tackling the constraints causing such yield gaps, which may vary spatially. We will elaborate on this in Section 5.3.2.

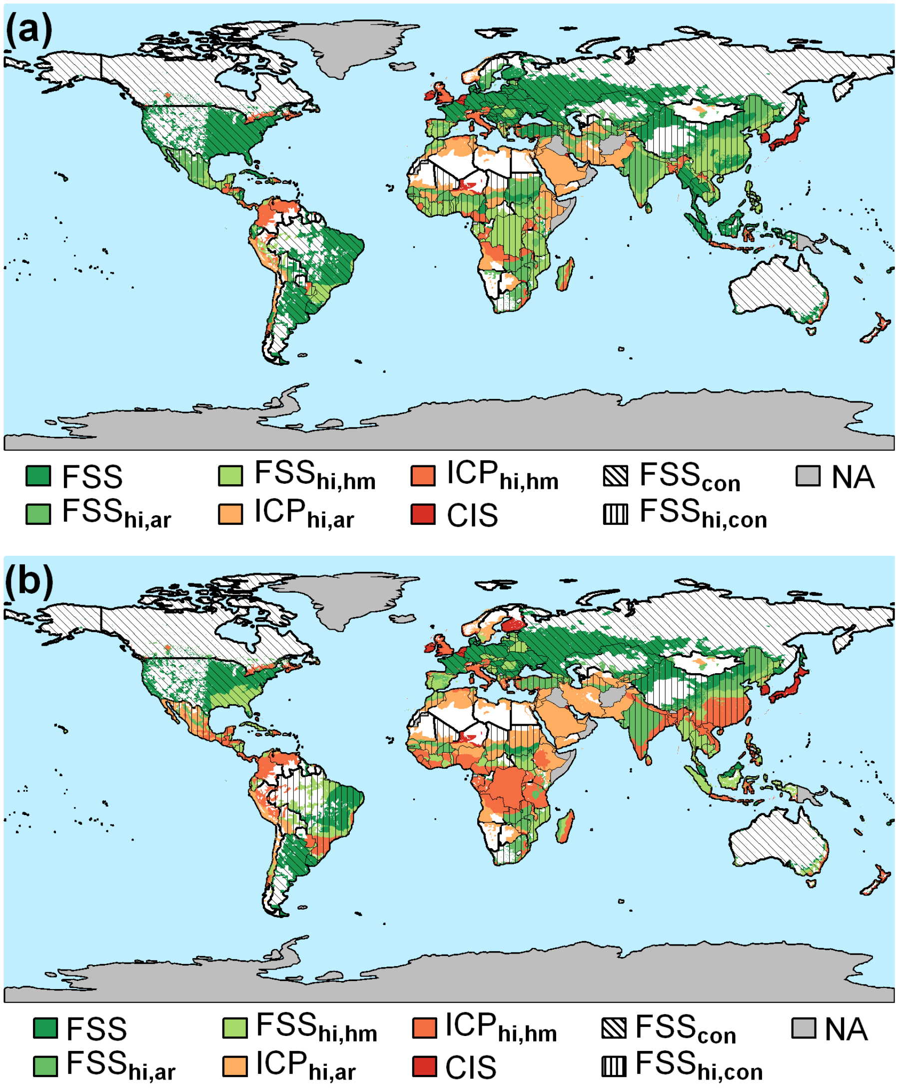

FIGURE 5.4: Regions that can achieve food self-sufficiency (FSS) based on their current crop production have the potential to be food self-sufficient by attaining high-input (hi) yields, can only increase crop production (ICP) or almost attained high-input yields but are crop insufficient (CIS) by country (con) and by moisture regime (arid (ar) and humid (hm)) considering two scenarios for 2050: (a) changes in population only, and (b) changes in population and dietary patterns. Since agricultural production constraints and agricultural management vary with agro-climatic conditions, the results are presented by country moisture regime going beyond national scales. NA represents regions with missing data.

5.3.2 Input and Management Strategies

5.3.2.1 Biophysical and Socioeconomic Constraints

Constraints that must be dealt to design the input and management strategies for closing yield gaps are: agro-climate related pest, disease, and weed constraints, soil related constraints, weather induced yield variability as well as market accessibility. Climate related pest, disease, and weed constraints are prevalent in both, humid regions, e.g., parts of Indonesia, China, and South America, and arid regions, e.g., parts of India, Sahel, and South Africa (Appendix Figure D.4a). In these regions, agro-climatic pest, disease, and weed constraints are responsible for up to 30% of the weighted differences between high and low input crop yields (Appendix Text D.2). Apart from poor nutrition status, soil constraints that must be overcome to achieve potential yields are nutrient retention capacity, soil drainage, and soil workability. Nutrient retention problems are widespread in Sub-Saharan Africa, East Europe, and the eastern part of the United States (Appendix Figure D.4b). Poor soil drainage generally affects dryland crop (e.g., wheat) production and is particularly prevalent in the Baltic States (e.g., Estonia, Latvia, and Lithuania), in some regions in North and South America, and some coastal countries such as Bangladesh. Soil workability will be a prevalent constraint in, for example, parts of India, Ethiopia, and Mexico. In some regions multiple soil constraints need to be dealt with, e.g., parts of Nepal, Myanmar, Thailand, Cambodia, Vietnam, and Laos (Appendix Figure D.4b).

Apart from above biophysical factors, socioeconomic constraints also need to be tackled to close yield gaps. The first indicator we analyzed, yield variability shows a higher yield variation in semi-arid zones worldwide, e.g., within the United States, Argentina, Angola, Namibia, South-Africa, Russia, Kazakhstan, India, China, and Australia (Appendix Figure D.4c). The observed yield variability is mainly due to year by year fluctuations in weather conditions (e.g., precipitation). A second socioeconomic indicator analyzed, travel time to the nearest market, shows that it takes more than six hours to reach the nearest market with a population of around 50,000 from a large portion of presently cultivated land in Africa, South-East Asia, and Central Asia (Appendix Table D.2). This means that farmers of these lands have limited access to the market for buying agricultural inputs (e.g., fertilizers, good quality seeds, etc.) and to sell their production surplus. This is frequently coupled with poor access to agricultural extension services providing up-to-date knowledge on agricultural practices to farmers.

5.3.2.2 Need for Intervention

To achieve potential crop yields, specific input and management interventions are needed that tackle the constraints described above (Figure 5.5 and Table 5.1). Regions with prevailing agro-climatic pest, disease, and weed constraints require integrated pest management using agro-chemicals and/or biological controls. So far integrated pest management has been poorly adopted in many developing countries (Parsa et al., 2014) resulting in a tremendous yield losses (Oerke, 2006).

Soil constraints that can be partly overcome include poor nutrient status. The poor nutrient status of soils can be cured by applying an adequate type and amount of organic and/or chemical fertilizers, but a prerequisite is that soil nutrient retention capacity is sufficient. On large scales, it is hard to improve nutrition retention capacity. On local levels, appropriate soil management that helps to increase soil carbon content may improve the retention capacity. Poor soil drainage can be tackled by artificial drainage, however, this method is costly. Nevertheless, in countries producing mainly wetland crops like rice (e.g., Bangladesh) poor soil drainage is not necessarily a constraint. Another soil constraint, soil workability, when associated with soil type and soil texture (i.e., cracking clay soil) which cannot be handled with the traditional farming based on manual labor and animal power. Only machine utilization and careful timing of field operations can overcome this constraint. This is observable, e.g., in parts of South Asia, West Asia, and Europe. Moreover, North and West Europe have almost met their potential crop calorie production adopting high-input mechanized farming systems. Multiple soil constraints existing in various regions will best be addressed via high-input precision farming that can tackle more than one constraint at the same time (Mueller et al., 2010).

Due to weather induced yield variability, farmers may be reluctant to take risks in terms of optimal application of inputs (e.g., fertilizers) resulting in lower yields. Measures to reduce risk of crop failure due to low precipitation (e.g., supplementary irrigation) and/or measures that encourage farmers to take risks (e.g., insurance schemes) may help to handle such sub-optimal farming to close yield gaps. In many regions the option of supplementary irrigation is not relevant due to lack of existing irrigation infrastructure or lack of accessible water resources. With climate change, measures to address such weather induced yield variability will increasingly be of relevance (Thornton et al., 2014). In regions with low market access, constructing and maintaining transport infrastructure may enable farmers to start closing parts of the yield gaps by using available inputs from the nearest market and benefit additional income from increased crop production and sales. For subsistence farming, access to market may be less relevant; for commercial farming it is a prerequisite.

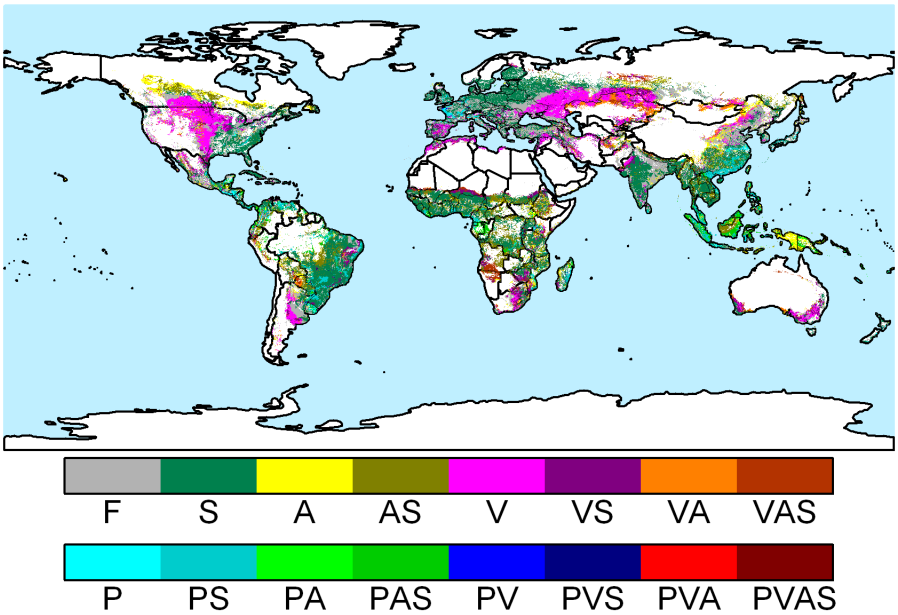

FIGURE 5.5: Location specific agricultural input and management strategies as required in different parts of the world to achieve high-input potential yields in addition to adequate fertilizer application (F). The strategies consist of soil quality management (S), managing accessibility to markets (A), weather induced yield variability management (V), and management of pests, diseases, and weeds (P). The different management strategies can have combinations of the individual elements (F, S, A, V, and P).

5.3.2.3 Description of Derived Strategies and Their impacts

Biophysical and socioeconomic factors causing yield gaps vary spatially and multiple constraints may persist locally. This indicates the need for multiple input and management interventions to help overcome yield reducing constraints. We defined location specific input and management strategies as multiple required interventions in a location to tackle

TABLE 5.1: Regional overview of additional crop calories that can be produced on rain-fed cultivated land by closing yield gaps with various management strategies in addition to adequate fertilizer application (F). The strategies consist of soil quality management (S), managing accessibility to markets (A), weather induced yield variability management (V), and management of pests, diseases, and weeds (P). The different management strategies can have combinations of the individual elements (F, S, A, V, and P). These values were estimated by summing up the differences between the current and the high-input potential crop calorie production by region and by the required management strategy.

Regions	**F**	**S**	**A**	**AS**	**V**	**VS**	**VA**	**VAS**	**P**	**PS**	**PA**	**PAS**	**PV**	**PVS**	**PVA**	**PVAS**
	10^{12} kcal/yr															
Africa																
East Africa	71.6	280.9	37.0	114.3	9.9	43.0	6.6	18.4	8.5	27.7	2.0	5.0	1.4	1.4	0.2	0.3
Middle Africa	4.6	81.1	2.5	65.6	0.2	9.0	0.1	14.0	0.4	7.7	0.1	6.3	0.0	0.1	0.0	0.0
North Africa	40.5	79.7	7.7	37.2	32.8	59.2	0.8	4.5	0.2	0.3	0.6	0.8	0.0	0.0	0.0	0.0
South Africa	4.2	15.1	0.9	2.9	11.5	21.2	1.3	2.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
West Africa	94.7	560.0	18.4	91.5	0.1	10.9	0.1	5.4	1.9	25.9	0.2	3.9	0.0	0.0	0.0	0.0
America																
Caribbean	20.8	20.2	0.6	0.4	1.0	0.7	0.0	0.1	0.7	1.1	0.0	0.0	0.0	0.0	0.0	0.0
Central America	39.7	43.7	5.6	6.6	3.8	4.8	0.3	0.7	28.3	24.0	2.5	4.3	0.4	0.2	0.0	0.0
North America	164.8	190.9	7.0	6.2	247.6	78.4	9.4	1.5	0.7	7.3	0.0	0.2	0.0	0.1	0.0	0.0
South America	138.4	277.4	10.4	44.9	43.3	30.8	4.0	4.5	5.8	71.6	1.4	10.4	0.1	2.1	0.0	0.3
Asia																
Central Asia	3.5	1.1	0.5	0.2	29.9	5.5	18.4	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
East Asia	140.8	130.7	18.9	19.2	23.2	9.5	2.9	0.9	5.5	31.2	0.9	1.5	0.1	0.1	0.0	0.0
South Asia	322.1	527.8	13.4	32.6	30.1	42.8	4.2	6.3	3.3	8.3	0.1	0.7	0.0	0.1	0.0	0.1
S.-East Asia	52.3	213.4	24.6	58.3	0.5	0.8	0.2	1.1	34.1	125.0	11.5	76.3	0.1	0.3	0.1	0.7
West Asia	75.3	52.8	2.0	2.4	29.1	16.2	0.8	0.6	0.2	0.5	0.0	0.0	0.0	0.0	0.0	0.0
Europe																
East Europe	472.4	415.9	5.2	5.1	434.6	42.4	9.5	3.5	0.4	0.6	0.0	0.0	0.0	0.0	0.0	0.0
North Europe	10.7	45.2	0.0	0.3	0.0	0.0	0.0	0.0	0.7	1.9	0.0	0.0	0.0	0.0	0.0	0.0
South Europe	48.2	55.4	0.7	0.6	26.0	23.4	0.4	0.2	3.6	5.6	0.1	0.1	0.0	0.0	0.0	0.0
West Europe	13.5	13.3	0.0	0.1	0.1	0.2	0.0	0.0	2.8	2.0	0.0	0.0	0.1	0.0	0.0	0.0
Oceania																
Australia & New Zealand	5.6	8.3	0.4	1.7	21.7	20.8	3.6	5.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
World	**1,724**	**3,013**	**156**	**490**	**945**	**419**	**62**	**75**	**97**	**341**	**19**	**110**	**2.3**	**4.3**	**0.4**	**1.4**

prevailing constraints for achieving potential yields. Figure 5.5 presents 16 different strategies required worldwide, which includes one or more of the following: pest, disease, and weed management (P), advanced soil management and land improvement (S), improving market accessibility (A), and management targeted on mitigating weather induced yield variability (V). Moreover, nutrient (fertilizer) management (F) and use of improved cultivars will go far in the regions without above-mentioned described constraints. Applying adequate nutrient management in currently available rain-fed cropland alone will produce an additional 1,700 trillion ($1,700 \times 10^{12}$) kcal/yr or an increase of around 20% globally compared to the year 2000 (Table 5.1). This amount will be sufficient to feed about 1.7 billion people with a daily diet of 2,800 kcal/cap/day. Parts of East Africa, West Africa, East Asia, West Asia, South Asia, North America, South America, and East Europe are among the regions having such potential (Figure 5.5). In these regions, a large amount of good and prime soil exist with none or little biophysical constraints (Appendix Table D.2). This lands can be rapidly used to increase crop yields with the sole investment of nutrient application. Another, additional 3,000 trillion kcal/yr of crops can be produced globally by overcoming prominent soil constraints (e.g., soil nutrition retention capacity, soil workability, and soil drainage) which prevail in South America, East Europe, South Asia, and West Africa. However, tackling these soil constraints requires large investments, e.g., building drainage infrastructure, general land improvement, and introducing farm mechanization. In Sub-Saharan Africa and South-East Asia, management strategies targeting multiple factors, e.g., a combination of advanced soil management with improved accessibility to the market, would potentially put an additional 500 trillion kcal/yr of crops in the world food market.

5.3.3 Required Fertilizers

Assuming that all other management options will result in achieving potential yields, sufficient nutrients need to be available. Globally, we estimated a net need of about 91.8 million tonnes of nitrogen fertilizers (N total nutrients) per year to replenish additional crop nutrient uptake while attaining the potential yields in the present cultivated land with the present cropping patterns (Figure 5.6). This nutrient need consists of uptake in crop yields and crop residues with respective values of 70.5 and 21.3 million tonnes/year. A substantial amount of fertilizer is consumed in the form of nutrient uptake in crop residues. Furthermore, a net amount of 33 million tonnes of phosphate fertilizers (P_2O_5 total nutrients) per year and 63 million tonnes of potash fertilizers (K_2O total nutrients) per year is needed in addition. In comparison, 106, 45, and 27 million tonnes/year of N, P_2O_5, and K_2O were applied in the year 2010 globally, respectively (FAO, 2011a). When considering a global fertilizer application efficiency of 50% to 60%, application of N fertilizers needs to be increased by 45% to 73%, P_2O_5 by 22% to 46%, and K_2O by more than 2 to 3 times for attaining the potential yields compared to that of the year 2010. These required nutrients can be of organic and/or chemical origin, of which phosphorus and potassium are finite resources. Hence, closing the nutrient loop related to human sanitation is an option for providing parts of the required nutrients (Mihelcic et al., 2011), which also reduces nutrient mining. Additionally, a high dependency on inorganic fertilizer may be problematic for achieving the potential yields as industrial fertilizer production is energy and GHG emission intensive.

Apart from increasing the amount of fertilizer application, enhancing its application efficiency, a ratio between required and applied fertilizer amount, is needed not only to

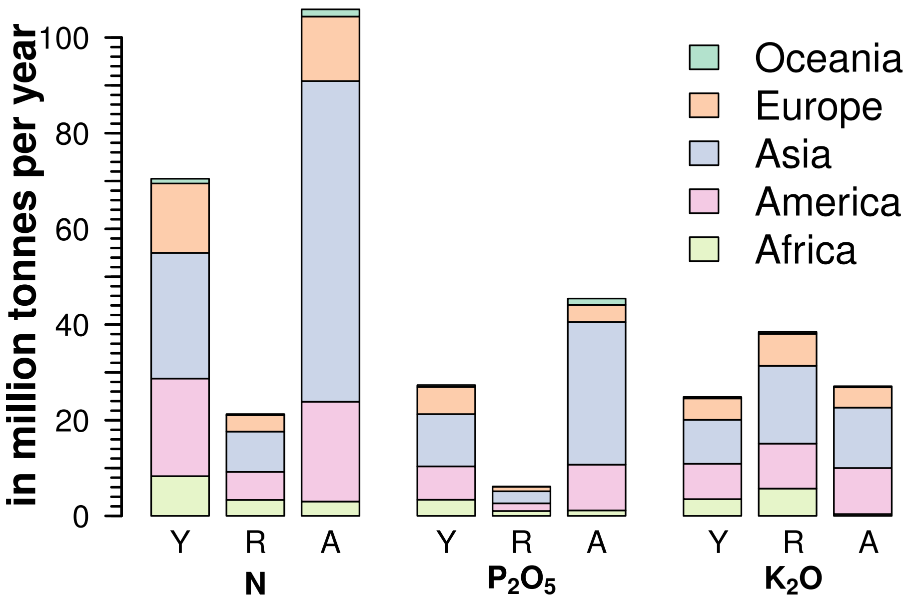

FIGURE 5.6: Additional amounts of macro-nutrients (N, P_2O_5, and K_2O) uptake by crop yields (Y) and crop residues (R) by attaining high-input potential yields compared to that with low-input yields, and the amount of fertilizers applied (A) in the year 2010 on a continental scale.

attain the potential yields but also to reduce total fertilizer demand. This is important because access and inefficient use of chemical fertilizers increases major fluxes of the nutrient cycles for which we have already transgressed the planetary boundary (Rockström et al., 2009). Moreover, we find variation in fertilizer requirements and fertilizer application efficiencies globally (Figure 5.6 and Appendix Figure D.5). East Asia, South Asia, South East Asia, North Europe, South Europe, West Europe, and Oceania are the regions with a higher amount of fertilizer application, mainly N and P_2O_5, than the amount of crop nutrient uptake by attaining the high-input potential yields (Appendix Table D.3). Among these regions, North and West Europe have almost attained their potential yields with fertilizer application efficiency of about 60% and can be considered a frontier in this regard. In East Asia, the application efficiency is limited to 40%.

5.4 Discussion

Globally, about 24% ($2,200 \times 10^{12}$ kcal/yr) and 80% ($7,350 \times 10^{12}$ kcal/yr) more crop calories can be produced compared to the total crop calorie produced in 2000 by closing yield gaps in current irrigated and rain-fed cultivated land, respectively. For some countries worldwide, closing their yield gaps is sufficient to meet their crop demand by 2050 considering population growth and dietary pattern changes. However, closing yield gaps is insufficient to meet the future crop demand for many African countries mainly when dietary changes are accounted for. For closing yield gaps, we need to implement various location specific agricultural input and management strategies. Adequate application of nutrients alone can increase crop calorie production by almost 20% whereas improvement of soil quality alone with adequate fertilizer application can generate an additional 30%. Moreover, application of N, P_2O_5, and K_2O fertilizers needs to be increased by up to

70%, 50%, and 300% respectively, for attaining the potential yields compared to that of the year 2010.

With our approach we introduce several innovations in identifying required input and management options to close yield gaps. The first innovation is the use of calorie unit aggregating crop productions based on GAEZv3.0 model outputs to determine the potential crop calorie production and the yield gaps. Although a limited number of studies have presented crop production in units other than mass units (Cassidy et al., 2013, Foley et al., 2011), estimation of yield gaps in calories is still missing. This is important as human dietary requirements are generally measured in calorific values. In addition, our estimation of the possibility to double the present global crop calories by closing yield gaps is higher (approx. 40%) than the estimates by other studies (Foley et al., 2011, Mueller et al., 2012). This is because our study presents the upper bounds of crop production under optimal high-input agriculture. So far few regions have achieved these high-input crop yields (IIASA/FAO, 2012). However, other studies use observed yield variations across similar agro-climatic zones to determine the yield gaps (Foley et al., 2011, Licker et al., 2010, Mueller et al., 2012).

The second innovation of this study concerns the combining of crop calorie production gaps with crop calorie deficits to identify the regions where closing yield gaps matter in terms of reduction or elimination of crop calorie deficits. For several countries e.g., the United States, Russia, Brazil, Australia, and countries in West Europe closing the present yield gaps is not required to ensure their present and future food self-sufficiency. This may in return suggest rolling back some cultivated land in these regions for extensive low-input agriculture to lower impacts associated with intensified agricultural practices. However, these countries are presently net food exporters (FAO, 2011a). If economically profitable and environmentally efficient, these countries may increase crop production for export and thereby further close their yield gaps. In most developing countries in Asia and Africa, achieving high-input potential yields will substantially reduce the present and future food deficits, improving national food self-sufficiency levels. Nevertheless, closing yield gaps is insufficient for many African countries, implying the need for cropland expansion and/or international agricultural trade to provide their future crop demand.

Third, we present a global picture as to what agricultural management strategies are required in different parts of the world to achieve the potential yields. A wide range of bio-physical and socioeconomic factors are to be tackled through the implementation of these management strategies that include soil quality management, management of pests, diseases, and weeds, yield variability management, and management of accessibility to markets. So far studies have either explained yield gaps using global biophysical and socio-economic data but not identified required strategies to close yield gaps (Neumann et al., 2010) or focused only on nutrient and water management to close yield gaps not looking at other required strategies (Mueller et al., 2012). Application of adequate nutrients is a basis to increase crop productivity. However, this alone may not be enough to achieve potential crop production on a global scale. For example, we found that 980 million hectares of current rain-fed cultivated land, contributing a crop calorie growth of around 60%, requires the above mentioned additional inputs and management beyond extra nutrients. Hence, we present packages of the required management strategies instead of focusing on one or two measures for closing yield gaps. Furthermore, we quantified additional nutrient uptake by crops while attaining the high-input potential yields compared to the low-input yields, enabling us to estimate the amount of required fertilizers. This adds further uniqueness to our study. The amount of required fertilizers also depends on their application efficiencies and the ways in which crop residues are handled.

Although our study provides clear findings, as mentioned above, interpretation of the results requires an understanding of its limitations. First, our crop calorie deficit analysis is based on total crop production and consumption, which does not account for dietary compositions. Nevertheless, our study identifies regions where closing the yield gaps matters for self-sufficiency. This can be achieved by shifting dietary choices towards regional products and/or by focusing agricultural practices to meet regional demands.

Second, our yield gap analysis for the year 2000 may not reflect the current yield gaps, but most data on downscaled crop yields is available only for circa 2000. Additionally, we did not account for possible technological progress, shifting the potential yields ceiling in the future. Nevertheless, yield gaps exist even while considering potential yields under currently available technology. Furthermore, climate heterogeneity within length of growing period (LGP) used in GAEZv3.0 is relatively large, rising concern regarding use of GAEZv3.0 to estimate yield gaps (van Wart et al., 2013). However, GAEZv3.0 takes into account this heterogeneity by applying thermal suitability screening procedure while simulating crop yields. The screening procedure makes use of other agro-ecological zone schemes (e.g., thermal climatic conditions, permafrost conditions, temperature profiles, vernalization conditions, etc.) including LGP for testing the match of prevailing conditions with crops' temperature requirements (IIASA/FAO, 2012). Therefore, LGP is only one out of a number of agro-ecological zone schemes used to simulate crop yields.

Third, we used a simplistic approach to design the agricultural management strategies looking at constraints that can be overcome by high-input farming as compared to traditional low-input agriculture. Since the present crop calorie production in most regions is between low and high input levels, it would be valuable to know the current management conditions for specifying management strategies more precisely. However, availability of such information in sub-national levels is limited mainly to fertilizer application (Potter et al., 2010).

Fourth, our study did not include one of the most relevant forces that will influence future agricultural production namely, climate change. In the future, climate change can increase crop yield variability and shift pest and disease ranges. This is a matter of ongoing studies. However, the approach used in this study can also be applied to investigate required input and management strategies for closing yield gaps under changing climatic conditions.

Summing up, our study provides an important contribution to the debate on agricultural intensification, presenting a global map of required management and input interventions to achieve the potential crop yields. Agricultural intensification, resulting in higher yields and more frequent harvests, not only demands massive inputs but also causes environmental stresses (Tilman et al., 2001). However, intensification and/or expansion of cultivated land are two main options available for increasing food production to meet growing demands. Cropland expansion is not feasible in all parts of the world because of uneven distribution of the limited suitable land for agriculture (Bruinsma, 2011). Moreover, agricultural expansion leading to deforestation and land-use change is a major source of GHG emissions (Smith et al., 2014). Therefore, agricultural intensification paired with the reduction of environmental consequences may be a preferred option to increase world food production. The sustainability of intensified agriculture highly depends on measures and methods with which required agricultural management strategies are chosen and implemented. In the future, these management strategies will also need to focus on adapting and building resilience to climate change, advancing towards climate smart agriculture (FAO, 2013). Hence, there is an urgent need to explore synergies between closing yield gaps and minimizing the agricultural production induced environmental stresses.

Chapter 6

Discussion and Conclusions

In this thesis, we investigated emerging questions to understand the future food demand and associated environmental impacts, mainly GHG emissions. More precisely, this thesis was guided by the following overarching research question: "How can current and future food security be ensured on local, regional, and global scales, and environmental impacts of agriculture be reduced considering the major drivers for growing food and feed demand, and socio-ecological constraints that limit local food production?" Diving deeper into this question, our thesis provided novel insights and a deeper understanding of the dynamics in agriculture as briefly enlisted below. The agricultural dynamics is mainly governed by anthropogenic activities and their impacts, namely: demographic growth, lifestyle shifts, technological progress, and climate change.

1. By applying an advanced nonlinear neural network approach to global food supply data, it was possible to identify sixteen typical dietary patterns. The patterns change over time for certain countries, reflecting shifts in lifestyles and eating habits. Further, we estimated the future food demand by correlating the dietary patterns with the HDI and using the HDI projections until 2050.

2. Proceeding with systematic analysis, it was feasible to associate agricultural emissions and energy use with each dietary pattern. Consequently, we estimated future emissions under plausible demographic and dietary changes. By 2050, agricultural emissions will triple compared to 2000 when agricultural productivity will not change.

3. Since diets are increasingly becoming richer in animal calories, we thoroughly analyzed crop demand for livestock. To produce one animal calorie, less than one to greater than ten crop calories were fed to livestock locally. Under plausible demographic and dietary changes, global feed demand may double between 2000 and 2050.

4. Due to the fact that cultivable land is limited and crop yield gaps exist in various regions across the world, we holistically investigated the extent food and feed demand can be satisfied locally and regionally by agricultural intensification. Closing yield gaps can enable current and future food self-sufficiency at local, regional, and global scales, reducing international trade and related emissions.

5. Apart from fertilizer application, we systematically identified strategies required for closing yield gaps in environmentally friendly ways. This requires location specific agricultural input and management strategies that can overcome yield limiting biophysical and socio-economic constraints. Sustainability of such intensification depends on how these strategies will be chosen and implemented.

Thus, with above methodological framework it was feasible to show that agricultural has potential to meet sustainability targets, but this implies suitable management and strict control measures. Each of the articles (Chapters 2–5, Pradhan et al., 2015, 2013a, 2014, 2013b) constituting this thesis discusses insights it provided on the future food demand and supply, and associated environmental impacts (Section 2.3, 3.4, 4.4, and 5.4). Here, we provide specific answers to the research questions posed in Section 1.4. Furthermore, this chapter elaborates key contributions of this thesis to ongoing debates on how to feed the growing population in a sustainable way, and synthesizes its most important conclusions.

6.1 Dietary Patterns and GHG Emissions

Globally, dietary patterns are becoming increasingly calorie rich diets, resulting in global food demand growth and increased GHG emissions from agriculture. The first research question (RQ 1) aims to enhance our understanding of this. The first research question is: "How is it possible to identify global dietary patterns systematically and in an objective way, and how can these patterns be used to identify diet shifts and to explore the future emissions from agriculture?"

For the first time, it was possible to identify the sixteen global dietary patterns systematically by applying a self-organizing neural network approach on the food supply data (FAO, 2011a). These dietary patterns represent the global food consumption habits and their shifts over the last 50 years (Figure 2.1 and Section 2.2.1). With improving development status, food consumption habits have changed toward affluent diets composed of a large share of animal products, sugar-sweeteners, and vegetable oils. Additionally, we estimated GHG emissions and fossil energy embodied in these sixteen dietary patterns (Section 2.2.3). The embodied emissions in the calorie rich diets (>2,800 kcal/cap/day) ranged between 1.3 and 2.2 t $CO_{2eq.}$/yr. Such diets required almost one kcal of fossil energy per kcal food consumed. This is mainly due to a substantial share of animal products in the calorie rich diets, and energy intensive agriculture system in developed countries where these diets are mostly consumed. Producing a unit of animal calorie currently emits more than three times the amount of GHGs than a unit of crop calorie (Table 2.1). Going beyond other studies considering only agricultural non-CO_2 emissions (Eshel & Martin, 2006, Reay et al., 2012, Stehfest et al., 2009), we estimated both CO_2 and non-CO_2 emissions by additionally considering emissions from fossil energy use.

In addition to the amount and composition of food intake, agricultural emission intensities play an important role in determining embodied emissions. The required GHG emissions to produce a unit of crop and animal calorie vary between developed and developing countries (Section 2.2.3 and Table 2.1). Although developed countries consuming calorie rich diets have overall high embodied emissions, emission intensities of both crop and animal products are larger in developing countries. For example, developed countries emission intensities of crop products are 0.3–0.5 g $CO_{2eq.}$/kcal whereas emission intensities for developing countries are 0.4–1.8 g $CO_{2eq.}$/kcal. This is mainly due to higher land and labor productivity in developed countries. Therefore, an intervention point is to reduce emission intensities in developing countries with technological progress and technology transfer. Identifying these sixteen dietary patterns, and their embodied emissions and emission intensities are a prerequisite to estimate the future food demand and related emissions.

We carried out a scenario analysis considering population growth, diet shifts, and technological change to estimate the future food demand and related emissions from agriculture. In the future, the global food demand will largely be driven by changes in food consumption habits toward affluent diets compared to population growth (Appendix Figure A.2). Such diet shifts will also heavily determine the future agricultural GHG emissions and fossil energy needs (Figure 2.5 and Appendix Figure A.3). By 2050, the agricultural emissions will be more than double, and the fossil energy demand will be 70% more in the scenario considering population growth and diet shifts compared to the one accounting only for population growth. Thus, diet shifts toward a lower share of animal products, reversing current trends, can be a highly relevant climate change mitigation option. Additionally, technological progress and technology transfer will limit global agricultural non-CO_2 GHG emissions to 60% of the emissions in the scenario considering only population growth and diet shifts (Appendix Figure A.4). Nevertheless, this will cost 30% more fossil energy (Appendix Figure A.3). Additionally, agricultural energy intensities are also related to GHG emissions and thus, the future technological progress and technology transfer also need to focus on efficient use of resources (e.g., land, fertilizers, pesticides, and water) along with increasing agricultural productivity. Moreover, the outcomes of this scenario analysis also enable us to answer the other research questions (RQ 2–4).

The self-organizing neural network approach applied here, is a self-supervised clustering and non-linear dimensionality reduction technique. This approach can be used for analyzing and interpreting large amounts of data from different fields. Additionally, we considered the HDI as an indicator for development to project the future dietary patterns. Such approach, to go beyond GDP, can also be relevant in other studies to represent the development status of a country. Moreover, an additional step forward in understanding the future food demand will be to explore different projection approaches. Depending on differences in demand systems specifications, income, and price elasticities, the food demand projections can vary (Valin et al., 2014).

6.2 Relation between Crop and Livestock Production

Shifting dietary habits toward affluent diets also demands additional crop-based feed to increase livestock production. Hence, we attempt to understand the interrelation between crop and livestock production by answering the second research question (RQ 2): “Which role does livestock play in global food production, and how are crop and livestock production interrelated on local and regional scales?”

For answering RQ 2, we analyzed global data on crop supply as livestock feed (FAO, 2011a) and found that the global crop calories fed to livestock has increased by almost 2 times between 1961 and 2000 (Figure 3.4 and Section 3.3.3). Such growing crop-based feed use also reflects ongoing changes toward intensive livestock production systems for meeting the growing animal calorie demand. Currently, about 40% of global crop calories is fed to livestock. We systematically downscaled country scale data on crop-based feed use and animal calorie production to a 5 arc-minute grid. Such downscaled data shows that the share of crop calories used as livestock feed varies geographically. Some regions require more than 100% of their crop production to feed their livestock (Figure 3.3a), inferring the need for trade to meet food and feed demand. Globally, about 4 kcal of crop-based feed is used to generate 1 kcal of animal product. Such crop-based feed use varies between less than 1 kcal to greater than 10 kcal on local level (Figure 3.3b). Low values are mostly related to ruminant production systems based on fodder and forage, whereas large values are usually related to crop-based non-ruminant production systems. North American, European, and East Asian regions use a large quantity of crop-based feed as their diets have a substantial share of animal products (Section 3.3.1 and 3.3.2, and Table 3.2). Presentation of such global raster maps on crop-based feed use, embodied crop calories in animal products, and the share of crop production required as livestock feed is a novel contribution of this thesis. These downscaled data on feed use and animal calorie production are also used to answer the remaining research questions.

We applied scenario analysis to understand the future role of livestock in global food production. The scenarios take into account population growth, diet shifts, and progress in feed conversion efficiency. The global crop-based feed demand will be more than double (1.8–2.3 times) by 2050 compared to 2000 mainly due to diet shifts. This will result in a need for more crops to feed livestock than for direct human consumption, requiring up to 55% of the total crop calorie demand. Moreover, a higher feed demand growth is expected in Africa, America (excluding North America), and Asia (excluding East Asia). The current levels of crop production in some of these regions are insufficient to meet their future feed demand (Appendix Figure B.4). This will be concern for food security. However, reduction of crop-based feed could significantly increase global food availability and would enable global food security from the production side. This can be achieved by more efficient conversions of crop calories into animal products and with dietary shifts toward a lower share of animal products.

Crop-based feed demand largely depends on the type of livestock production system. For example, a higher amount of crop-based feed is used in an intensive livestock production system than that in a mixed crop/livestock system or a rangeland system. With increasing demand for animal products, the livestock production system is anticipated to shift from traditional to more crop intensive feeding technologies (Keyzer et al., 2005). This demands a large volume of crop-based feed depending on livestock feed conversion efficiencies. Currently, livestock productivity varies across regions worldwide, e.g., parts of Europe and North America have higher feed conversion efficiencies compared to that of India and parts of South America. Hence, technological progress and technology transfer will play an essential role for more efficient conversion of crop calories to animal products in the future. Our scenario analysis showed that advancement in feed conversion efficiencies will limit the global crop-based feed demand to 75% of the demand in the scenario considering population growth and diet shifts but not technology progress by 2050 (Section 3.3.3 and Table 3.2). Moreover, we also downscaled these projected feed demand to a 5 arc-minute grid, and used them for addressing the research questions RQ 3 and 4.

Here, we aggregated information on crop and animal products into a single comparable calorific unit using nutritive factors (FAO, 2001). Such an approach can also be relevant to compare the different crop and animal products in terms of calorie content as human dietary requirements are generally measured in calorific units (FAO/WHO/UNU, 2004).

Moreover, our downscaling approach only considered the livestock production system and livestock density. This can be improved with data availability on subnational variation in livestock productivity, and spatial distribution of intensive livestock production systems. Similarly, an estimate of the future feed demand could be more holistic, when the demand for non-crop-based feed was also considered (Havlík et al., 2014, Herrero et al., 2013). Nevertheless, the focus of this thesis was to investigate the current and future food security also accounting for crop-based feed demand rather than a complete assessment of the livestock sector.

6.3 Local and Regional Food Self-Sufficiency

One of the current challenges is to ensure food security at local, regional, and global scales. Besides food trade, enhancement of local and regional food self-sufficiency (FSS) is an option to enable such food security. This will additionally reduce international trade dependency, subsequent fossil energy needs, and GHG emissions. Our third research question (RQ 3) aims to investigate such local and regional potentials, which is: "How sufficiently is food produced on local and regional scales, and how is this influenced by agricultural potentials, lifestyles, demographic growth, and climate change?"

For answering RQ 3, we conducted cross scale FSS analysis from a 5 arc-minute grid to a continental scale, defining a region food self-sufficient when total calorie produced (crop and animal products) in the region is enough to meet its food and feed demand. Globally, 1.9 billion people could be sustained by food produced within their 5 arc-minute grid areas, and 4.4 billion people, within their countries in the year 2000. This results in 1.2 billion people relying on international trade for food and feed supply (Section 4.3.1 and Figure 4.2). Such a degree of FSS could only be achieved when farmers grow diverse crops and consumers rely more on local products. Global import and export data (FAO, 2011a) also reflects this as about 900 trillion kcal/yr of food and feed was net imported on the global scale in 2000, whereas the gross import was twice the net value. This shows the current trade characteristic where a country imports and exports agricultural goods at the same time. By closing crop yield gaps, the number of food self-sufficient people can be increased at local and regional scales (Section 4.3.1, and 4.3.2). This will also reduce international trade dependency. Globally, 60% to 100% additional crop calories can be produced by closing yield gaps compared to the year 2000 (Foley et al., 2011, IIASA/FAO, 2012). Considering food and feed consumption in 2000, closing yield gaps would reduce the international agricultural trade by more than 50%. Nevertheless, there are regions that cannot be solely dependent on local and regional supply because of their limited agro-ecological potentials. In such situation, international agricultural trade plays a crucial role in enabling local and regional food security.

In the future, a growing number of people will depend on food and feed produced in larger regions compared to 2000. The number of food self-sufficient people will decrease at all the scales for the scenarios considering population growth and diet shifts compared to the ones accounting only for population growth (Section 4.3.2 and Figure 4.4). This results in an additional 1 to 2.8 billion people depending on international trade by 2050. Diets rich in calories and animal products not only require extra food, but also crop-based feed to raise additional livestock. Hence, international trade dependency can be decreased by changing dietary patterns toward fewer animal products, growing diverse types of crops, and consuming more local products. This also shows the importance of the results obtained in Chapters 2–3 for answering RQ 3. Additionally, our analysis for 2050 shows that effects of diet shifts and closing yield gaps will be stronger than that of climate change. By 2050, 1.5 to 6 billion people will rely on international trade depending on various crop production scenarios. Moreover, climate change may increase the need for international agricultural trade by 4% to 16%. Such a large range in the numbers of trade dependent people is significantly influenced by closing yield gaps to attain different levels of high-input potential crop production. Closing yield gaps to attain 50% of high-input potential results in the higher values while the lower values are related to closing yield gaps to attain 100% (Figure 4.4 and Appendix Figure C.5).

The cross-scale analysis applied here is a novel approach and an important contribution of this thesis for evaluating the scale at which food demand can be met. Such an approach can further be used to determine local and regional self-sufficiency of other resources. An example of this would be to investigate the potential of regions to supply nutrients to crops by closing the nutrient loop related to human sanitation. Moreover, an additional dimension to FSS research would be considering crop used for biofuel production. Nevertheless, biofuel is more environmentally beneficial if its feedstock comes from waste and non-crop biomass rather than from human edible crop products (Fargione et al., 2008). The share of crop calories used for producing biofuel was limited to 4% in 2010 (Cassidy et al., 2013). Additionally, it is very likely that the future crop production will suffer from the negative impacts of climate change without sufficient adaptation measures (Challinor et al., 2014, Lobell et al., 2008). This thesis attempts to account for this by considering crop yields based on IPCC's A2 and B2 scenarios. However, further studies can be carried out using the new set of IPCC's scenarios called the representative concentration pathways (Moss et al., 2010) which have replaced the previous ones (Rogelj et al., 2012). Recently, crop yield simulations based on these scenarios are becoming available (Deryng et al., 2014, Nelson et al., 2014). Similarly, cropping patterns may change across time, which are not considered in this thesis because of its complexity. Even for planning the future cropping pattern in a small area, a large number of factors need to be considered (Liu et al., 2014). However, the future reduction in cultivated land due to urbanization has been captured here, which most of agriculture modeling exercises so far ignore (Bodirsky et al., 2012, Lotze-Campen et al., 2008).

6.4 Measures to Close Yield Gaps

As mentioned above, closing crop yield gaps enables local, regional, and global food security and self-sufficiency. However, this requires various inputs and management strategies which are investigated to answer the last and fourth research questions (RQ 4) of this thesis: "How essential is it to close local yield gaps, and how can these gaps be closed in a sustainable manner?"

Addressing RQ 4, we found that closing yield gaps is essential to substantially reduce the present and future food deficits, and to improve food self-sufficiency for most developing countries in Asia and Africa (Section 5.3, and Figure 5.2 and 5.3). However, the current crop production of some countries (e.g., the United States, Russia, Brazil, and Australia) is sufficient to sustain their present and even future food demand. Such countries have the possibility to roll back some cultivated land for nature and/or for extensive agriculture. Nevertheless, these countries can also produce more food for export by closing yield gaps if this is economically profitable and environmentally efficient. Furthermore, closing yield gaps will not be enough to meet food and feed demand in some African and Asian regions by 2050. This implies additional needs of agricultural expansion and/or of substantial international trade. Identifying such regions that need agricultural intensification or with potential for extensive agriculture is a novel contribution of this thesis.

This thesis also presents location specific agricultural inputs and management strategies that are required for closing yield gaps including the needed amount of fertilizers (Section 5.3.2, Figure 5.4 and 5.5, Appendix Figure D.4 and D.5). Closing yield gaps requires to increased the global N and P_2O_5 fertilizers application by 70% and 50%, respectively, compared to 2010. Additionally, a wide range of biophysical and socioeconomic factors need to be tackled for this. Such factors, explored here, include soil quality management, management of pests, weeds, and diseases, yield variability management, and management of accessibility to markets. Soil quality plays an essential role in sustaining plant productivity and ecosystem functioning. However, agricultural mismanagement in the past has led to soil degradation in many regions worldwide (Lüdeke et al., 1999). Moreover, management of pests, weeds, and diseases plays a crucial role for obtaining optimum crop yields. Nonetheless, integrated pest management has been so far poorly adopted in many developing countries (Parsa et al., 2014). Similarly, fluctuation in climatic conditions, largely temperature and precipitation, results in significant temporal variation in crop yields (Cabas et al., 2010) which could partially be addressed by alternative management options (Smith et al., 2007). Furthermore, available transport infrastructure also influences crop yields as it determines farmers' accessibility to markets for buying agricultural inputs and to sell their production surplus. These factors vary spatially and more than one factor may persist locally indicating the need for multiple inputs and management strategies for closing yield gaps (Appendix Figure D.4). Thus, we stress that the current and future technological change needs to address these issues with management interventions including socioeconomic development, mainly in developing countries, instead of focusing on only one or two measures. Hence, the contribution of this thesis is to present for the first time, a global picture of the required location specific agricultural inputs and management strategies to close yield gaps.

Conventional intensified agricultural does not only result in higher yields closing yield gaps, but also causes tremendous effects on ecosystem and biodiversity (Tilman et al., 2001). Such agriculture is a net source of GHG emissions (Robertson et al., 2000) although it may reduce emissions per unit of crop production due to avoided land conversion (Burney et al., 2010). Moreover, excess and inefficient input use is associated with land, soil, and water pollution, loss of biodiversity, and soil and landscape degradation (Giller et al., 1997, Sutton & Bleeker, 2013). Therefore, continuing the traditional ways of intensive agriculture to close yield gaps will not sustain the planet within its safe operating space (Rockström et al., 2009). Nevertheless, subsistence low-input agriculture is insufficient to meet the current global food and feed demand (Appendix Table C.2 and Appendix Figure C.4c). Additionally, agricultural expansion is not feasible in all parts of the world due to the uneven distribution of limited cultivable land resources across the globe (Bruinsma, 2011). Land conversion for agricultural use is an additional source of GHG emissions (Canadell et al., 2007) and a major driver of biodiversity loss (Chapin III et al., 2000). Hence, sustainable agricultural intensification that closes yield gaps is a way forward to feed growing population and to lower environmental consequences associated with agriculture.

Agriculture intensification when implemented in sustainable ways will have environmental benefits and will reduce negative consequences. For example, proper agricultural practices in degraded land with integrated nutrient management based on use of compost and crop rotations that return large quantities of biomass to soil will enhance soil carbon sequestration (Lal, 2002). Agriculture management on a landscape level can contribute to biodiversity conservation and may provide important ecosystem services, e.g., pollination and biological control (Tscharntke et al., 2005). Therefore, agricultural intensification should be considered as a part of a complete system that also considers ecosystem services and biodiversity instead of focusing on crop yields only (Matson & Vitousek, 2006). Moreover, the sustainability of agricultural intensification highly depends on the way the required inputs and management strategies will be chosen and implemented.

Here, we identified the agricultural inputs and management strategies based on biophysical and socioeconomic constraints that can be overcome by shifting from low-input to high-input agriculture. These recommendations are more general and are presented on a global scale. However, such an approach investigating the constraints that cause yield gaps can also be adopted to narrow down these strategies into specific concrete measures. Moreover, there are needs for detailed analysis of the cost, benefits, and trade-offs associated with different measures to close the yield gap. Nevertheless, this is an initial approach, presenting such required inputs and management options on a global scale beyond quantification of needed fertilizers.

6.5 Conclusions

In our thesis, we paved the road towards a more detailed methodology for investigating factors that governs agricultural dynamics. We showed that with an adequate methodological framework insights can be gathered. Consequently, we were able, for example, to provide a projection of the future food and feed demand based on sixteen globally abstracted dietary patterns. Similarly, the future CO_2 emissions from the global agriculture was estimated using more scientifically sound approach. So far, studies focused on the non-CO_2 emissions from agriculture. We believe that our results provide an important contribution on agriculture and food security research. For example, we found that a combination of sustainable implementations of agricultural intensification, expansion, and trade as well as shifting dietary habits towards a lower share of animal products is required to feed the growing population. Additionally, consumption of local and regional food and production of diverse types of food can lower dependency on international food trade. However, we are also aware that there is still further research to be done. Although, we put forward effort to show the agricultural impact on climate via GHG emissions, a detailed analysis on how climate change will affect agriculture and food security is still missing. Nevertheless, a statement can be made that apart from climate change, demography growth, and lifestyle shifts will have major effects on the global agriculture. In the future, we will continue with this work.

Appendix A

Supporting Information: Embodied Greenhouse Gas Emissions in Diets[1]

A.1 Characteristics of Identified Dietary Patterns

The observed sixteen dietary patterns are distinguished by their energy content and food composition. The diets are broadly categorized into low (<2,100 kcal/cap/day), moderate (2,100–2,400 kcal/cap/day), high (2,400–2,800 kcal/cap/day), and very high calorie diets (>2,800 kcal/cap/day) based on average energy requirements. An average of 2,100 kcal/cap/day is recommended as the minimum energy requirement for a typical population in a developing country, assuming a standard population distribution and body size, for survival and light physical activity (UNHCR/UNICEF/WFP/WHO, 2002). For a moderately active lifestyle of a female population between age 18 to 30 with a mean height of 1.70 m, a mean energy intake of 2,400 kcal/cap/day is recommended (FAO/WHO/UNU, 2004). For a male population with similar features the energy requirement is of 2,800 kcal/cap/day (FAO/WHO/UNU, 2004).

The characteristics of the dietary patterns are as follows:

A.1.1 Low Calorie Diets

Pattern #1 (1,870 kcal/cap/day) characterizes food composition with cereals contributing to more than 50% of total energy supply. Developing countries in small Islands, Africa, and East Asia are members of this diet pattern, e.g., Haiti (1984–1997), Madagascar (1988–2007), Timor-Leste (1961–2007), Botswana (1961–1978), Zambia (1993, 1998–2007), Burkina Faso (1961–1985), Chad (1965–2007), Eritrea (1993–2007), Ethiopia (1993–2007), Tanzania (1961–1967, 1969–2007), China (1961–1977), Indonesia (1961–1972).

Pattern #2 (2,000 kcal/cap/day) demonstrate a diet with a high fraction of pulses, fruits, starchy roots, and alcoholic beverages as a basis for the food consumption pattern.

[1] This appendix and Chapter 2 have been published as: Pradhan, P., Reusser, D. E., & Kropp, J. P. (2013). Embodied Greenhouse Gas Emissions in Diets. PLoS ONE, 8(5), e62228. http://dx.doi.org/10.1371/journal.pone.0062228

It is also characterized by a low fraction of vegetables and vegetable oil in comparison to other patterns. Landlocked countries in East Africa, e.g., as Rwanda, Uganda, and Burundi were members of this dietary pattern for almost the entire period of the analysis.

Pattern #3 (2,018 kcal/cap/day) is characterized by the highest amount of starchy roots. Starchy roots, cereals, and pulses contribute more than 70% of the total food supply. Mainly Middle African and West African countries like Angola, Benin, Congo, Cote d'Ivoire, Democratic Republic of Congo, and Ghana belong to this class for the majority of years during 1961–2007.

A.1.2 Moderate Calorie Diets

Pattern #4 (2,140 kcal/cap/day) is a diet where cereals provide about 70% of the food energy supply. It prevailed mainly in Asian countries during their development phases, e.g., Azerbaijan (1992–2000), Saudi Arabia (1963–1970), Bangladesh (1961–2007), Cambodia (1961–2007), Indonesia (1973–2007), Vietnam (1961–2005), China (1978–1986), Republic of Korea (1961–1968), Tajikistan (1994–1995, 1998–2003). In addition, some developing African countries were also members, e.g., Kenya (1965–1979), Sudan (1992–1997), Burkina Faso (1986–2007), Mali (1970, 1985–2007), Chad (1961–1964), Lesotho (1961–2007), Zimbabwe (1961–1981).

For **pattern #5** (2,160 kcal/cap/day), the diet is composed of a very high amount of pulses, vegetable oil, and sugar-sweetener, and a very low amount of starchy roots. Pattern #5 diet is widely distributed among developing countries in Africa, South America, Central America, Asia, and Small Island Nations. Some countries which belong to this pattern were: Morocco (1961–1982), Botswana (1979–2007), Namibia (1961–2007), Kenya (1980–1996, 1998–2007), Djibouti (1961–2005, 2007), Mauritania (1961–1974, 1976–1994), Suriname (1961–1979, 1981–1983, 1985–1990), Guatemala (1961–2007), Honduras (1961–1994), Mexico (1961–1972), Maldives (1961–1988, 1990), Pakistan (1962–2007), Iran (1961–1979), Malaysia (1961–1976), Philippines (1966–2007), Mongolia (1963–1991, 1995–2007), Haiti (1998–2007), Seychelles (1961–1993, 2003–2006).

Pattern #6 (2,173 kcal/cap/day) exhibits the highest fraction of animal products and sugar-sweeteners. It was observed mainly in Central American, South American, and Small Island countries, but for different time periods. Member countries of this pattern were: Brazil (1961–1973), Colombia (1961–1993), Costa Rica (1961–1972), Ecuador (1961–2007), Paraguay (1979–1984, 1986–1993), Dominica (1961–1978, 1980–1985), Saint Kitts and Nevis (1961–1973), Saint Lucia (1961–1998, 2001).

Pattern #7 (2,210 kcal/cap/day) is a diet that offers the highest amount of vegetable oils and the lowest fraction of animal products in the current group. Mainly West African countries like Gambia, Guinea-Bissau, Liberia, Nigeria, Senegal, and Sierra Leone were members of this pattern for almost the entire period (1961–2007).

The dietary **pattern #8** (2,270 kcal/cap/day) shows the highest value of sugar crops, a high value of fruits with cereal and starchy roots contributing 30% and 20% of total food energy supply, respectively. Two Central African countries, namely Cameroon and Gabon, belonged to the pattern for almost the entire period of 1961–2007, while two West African countries, Cote d'Ivoire and Ghana, were members for only a couple of years (1964–1972, 1975–1982, and 1975–1976, 2005–2007).

A.1.3 High Calorie Diets

Pattern #9 (2,540 kcal/cap/day) represents a diet with the highest consumption of starchy roots and fruits in this group and the overall highest supply of oil crops. Some of the Island states, Fiji (1961–1970), Kiribati (1961–2007), Samoa (1961–2007), Sao Tome and Principe (1961–1980, 1982–2007), Sri Lanka (1979–1980), and Vanuatu (1961–2007) are included in the pattern #9 diet.

Pattern #10 (2,580 kcal/cap/day) features the highest amount of cereals in the current group contributing more than 55% of total food supply. This pattern was found in some countries belonging to West Asia, North Africa, Former Soviet Union, and in transition economies. Characteristic countries were: Iran (1980–1989, 1993), Turkey (1961–1970), Egypt (1962–1981, 1983–2007), Tunisia (1971–1973, 1976–1978), Turkmenistan (1992–2007), Uzbekistan (1992–2007), China (1987–2007), Vietnam (2006–2007).

Pattern #11 (2,710 kcal/cap/day) shows the highest portion of animal products, pulses, vegetable oils, sugar-sweetener, and alcoholic beverages among the high calorie diets. Some of the Small Island Nations were included in the pattern #11 diet for different time periods, e.g., Dominica (1986–1990, 1994), French Polynesia (1962–1964), Saint Kitts and Nevis (1974–2007), Seychelles (1998–2001). After 1970 many countries in Central America and South America became members of this type, e.g., Belize (2005–2007), Costa Rica (1973–2007), Mexico (1973–2007), Brazil (1974–2007), Colombia (1994–2007), Uruguay (2007).

A.1.4 Very High Calorie Diets

For **pattern #12** (2,890 kcal/cap/day) animal products, cereals, vegetable oils, and sugar-sweetener contributes around 20%, 40%, 10%, and 10% of the total energy supply, respectively. Countries in Central, South East, and South Europe, some in South America and Former Soviet Union are characteristic for this pattern. Countries which belonged to this pattern are: Slovakia (1993–1997, 1999–2007), Slovenia (1992–2007), Albania (1995–1996, 2007), Bosnia and Herzegovina (2005–2007), Romania (1967–2002, 2004, 2007), Italy (1961–1966), Portugal (1961–1986), Spain (1961–1972), Chile (1961–1985, 1988, 2004–2007), Guyana (1998–2003, 2005–2006), Paraguay (1985, 1994–2007), Belarus (1999–2005), Kazakhstan (1992–1997, 2000–2007), Russian Federation (1992–2006).

Pattern #13 (3,060 kcal/cap/day) exhibits the highest fraction of cereals pulses and vegetables, and the lowest fraction of alcoholic beverages among this group. Vegetal products contribute to more than 85% of the total food supply. It was mainly present in most of the countries in West Asia and the Arab League during time periods after 1970. Characteristic countries of this pattern are: Algeria (1988–1997, 1999–2007), Iran (1990–1992, 1994–2007), Jordan (1994–1996, 2002–2007), Morocco (1986, 1988–2007), Saudi Arabia (1980–2007), Syria (1978–2005), Tunisia (1974–1975, 1979–2007), Turkey (1971–2007), United Arab Emirates (1975–1979, 1982–2007).

Pattern #14 (3,110 kcal/cap/day) is a diet characterized by the overall highest amount of animal products and sugar-sweeteners, e.g., 35% of the energy supply comes from animal products. Mainly developed countries in North Europe, North America, and Asia Pacific belonged to this pattern, such as Australia (1961–1979, 1981, 1984), Canada

(1961–1979), Denmark (1961–1970, 1993–2007), Finland (1961–2000), Iceland (1961–2007), Ireland (1961–1984), New Zealand (1961–2007), Norway (1961–1994), the United States (1961–1966).

Pattern #15 (3,300 kcal/cap/day) is qualified by the overall highest consumption of alcoholic beverages and exhibits the second highest amount of animal products and sugar-sweeteners. It is also mainly observed in developed countries in North Europe, North America, and Asia Pacific, for example: Australia (1980, 1982–1983, 1985-2007), Austria (1963–2007), Canada (1980–1994), Finland (2001–2007), France (1961–2007), Germany (1964–2007), Ireland (1985–2007), Netherlands (1961–2007), Norway (1995–2007), Sweden (1966–2007), Switzerland (1961–2007), the United States (1967–1999, 2003).

Finally **pattern #16** (3,430 kcal/cap/day) defines the class of countries with the highest total calorie intake. It is also associated with the highest consumption of vegetable oils, vegetables, and fruits. The consumption of animal products is comparatively low in comparison to pattern #14 and #15, but higher than for pattern #12 and #13 diets. Developed countries in the Mediterranean region like Greece, Italy, and Spain were members of this pattern mostly during the period from 1967 to 2007, whereas other developed countries shifted to this pattern later, e.g., like Canada (1995–2007), Belgium (2002–2005), the United States (2000, 2002, 2004–2007).

A.2 Methods and Data

A.2.1 The SOMTOP Approach

Analysis and interpretation of large amounts of data has become one of the most important research tasks in earth systems science. Machine learning techniques such as artificial neural networks (ANNs) have several advantages in this regard. They are not only able to replicate the computational power of their biological examples but also are able to represent nonlinear relations, are capable of incorporating new information that is fed in, and are robust in handling noisy data. However, ANNs need large amounts of homogeneous data and the operator has to provide plausible explanations about why they approximate a solution. For the particular food data used in this study, the features of the ANN approach were explicitly wanted, i.e., certain patterns for diets should be derived and an optimal embedding, which allows the assessment of food transition pathways. For our analysis we implemented a neural network approach consisting of: i) a self-organizing map (SOM-) (Kohonen, 2001) and ii) an algorithm providing a quantitative measure P of topological distortions (-TOP) during the mapping of data on the neural network (Bauer & Pawelzik, 1992). The employed model approach has been used for several other studies and has shown its effective performance in complex data analysis (Ambroise et al., 2000, Crane & Hewitson, 2003, Hanewinkel et al., 2004, Kropp & Schellnhuber, 2008). A SOM in particular can be interpreted as a clustering and non-linear dimensionality reduction technique. The SOM in addition tries to preserve the topological ordering of the input data in the low-dimensional network space. We provide below a brief description of the applied approach. For a more detailed description of the algorithm, we refer to Kohonen (2001) and Bauer & Pawelzik (1992).

A.2.1.1 Self-Organizing Maps

Kohonen's SOM is inspired by biological examples of neural networks: the brains of mammals. The neurons are organized in areas of the neocortex such that they reflect some physical characteristics of the signals stimulating them (Bauer et al., 1996a,b). In a similar manner, a SOM extracts structural information from numerical data with an unsupervised learning process instead of memorizing all of it. During this process, an m-dimensional information continuum V is mapped onto an n-dimensional discrete space A, illustrating the structural information of the input data with a number of cells (or neurons) corresponding to the dimension of the map, where normally $n < m$. Geometry of the discrete space can be either rectangular or hexagonal. Each cell (i) is associated with a weight vector (ω) with the same dimension as of the input numerical data. In brief, Kohonen's algorithm can be formulated as follows:

1. Initialize the weight vectors (ω) for all cells with random values
2. Iteratively, present a randomly chosen input vector (v) to the map, where all cells compete to represent the input data with the following steps:
   (a) Compute the Euclidean distance between the input vector (ν) and all cells, and select the output cell (i) (best matching unit, BMU) that is most similar to ν;
   $$\parallel \nu - \omega_i \parallel \leq \min_{\forall j \in A} \parallel \nu - \omega_j \parallel,$$
   (b) Update the weight for the BMU and its neighbors according to the rule (learning process):
   $$\omega_i(t+1) = \omega_i(t) + \varepsilon(t) \times h_{i,j} \times [\nu(t) - \omega_i(t)]$$
   where $\varepsilon(t)$ is a learning parameter that decreases to zero with iteration, $h_{i,j}$ is a time-dependent neighborhood function, often a Gaussian function, that defines the vicinity of the mesh in which other cells learn from the same input stimulus
   (c) Calculate the average change rate of the map or the mapping error and stop the learning process if it is less than a predefined threshold value

Artificial neural networks are adaptive models that change their structure during learning processes. They generalize the things learned from data and visualize the non-linear relations of multidimensional data. The data are finally represented by a hyperplane of lower dimensionality, which is embedded within the data space. This technique offers a convenient method to reduce the amount of information as well as to form an implicit model, without having to form a traditional physical model of the underlying problem.

A.2.1.2 Topological Ordering

During the learning process, the aggregation of similar objects onto a neuron is a topology preserving representation of the input data. The mapping divides the input space in a type of Voronoi segmentation (Voronoi, 1908). Each cell represents one of the gravity centers of the partially segmented input information continuum V. Therefore, it is not possible to describe the data in a simple way and with optimal quality if the dimensionality of the input data and the network differ (Li et al., 1993). Additionally, unsuitable chosen training parameters may entail topologically distorted mappings (cf. Appendix Figure A.5a). Therefore, a measure to estimate the quality of the mapping is needed. This can be provided by the calculation of the topographical product (P) (Bauer & Pawelzik, 1992). It provides a measure of topology distortions in maps between spaces of possibly different dimensionality. According to Bauer & Pawelzik (1992), two distance ratios firstly have to be defined:

$$Q_1(j,k) = \frac{D^V\left(\omega_j, \omega_{n_k^A(j)}\right)}{D^V\left(\omega_j, \omega_{n_k^V(j)}\right)} \tag{A.1}$$

and

$$Q_2(j,k) = \frac{D^A\left(j, n_k^A(j)\right)}{D^A\left(j, n_k^V(j)\right)} \tag{A.2}$$

In equations A.1 and A.2, $n_k^V(j)$ and $n_k^A(j)$ denote the k-th order (next) neighbor of the point j in the input and output space, respectively (cf. Appendix Figure A.5b). At first, the distance between the points is measured in the input space (D^V) and output space (D^A) by using the cell coordinates j and the weight vectors (ω_j). Appendix Figure A.5b illustrates the neighbors of j. In the $\mathbb{R}^2$, the neighbor is given by $n_1^V(j) = i$ and in the $\mathbb{R}^1$ by $n_1^A(j) = i'$. For the distance ratio measured in the input space V, we obtain $Q_1(j,1) > 1$, because $D^V(j,i') > D^V(j,i)$. However, in the output space A, we get $Q_2(j,1) < 1$. This indicates the neighborhood distortion in the mapping from $\mathbb{R}^2$ to $\mathbb{R}^1$. Only when $Q_1 = Q_2 = 1$, the points in A and V coincide and the topology is preserved. Thus, P measures the preservation of the neighborhood between the neural units i in A and their weight vectors ω_i lying on V. It is defined as follow:

$$P = \frac{1}{N(N-1)} \left(\sum_{j=1}^{N} \sum_{k=1}^{N-1} \log \left[\prod_{l=1}^{k} Q_1(j,l)\; Q_2(j,l) \right]^{\frac{1}{2k}} \right) \tag{A.3}$$

When the preservation of the neighborhood relations is achieved, P equals zero. $P > 0$ and $P < 0$ indicate dimensions that are too large or too small, respectively. Due to the case that this is an approximation process, a absolute zero is in most cases not achievable (cf. Appendix Table A.2 for the current simulations). An additional precondition in minimizing $|P|$ is to adjust the learning parameters. Only in this case, the error caused by the random training process can be minimized as well and therewith the network converges to a topographic map (Ritter & Schulten, 1988).

Our approach makes use of the features of both analytical concepts, because food production and food consumption have neighborhood relations in terms of its geographical distribution. Nevertheless, the topological properties can be distorted during this mapping process, due to i) an unsuitable selection of the dimension of the output space or ii) inappropriate training parameters. For concrete classification and identification of transitions, the topological ordering is of additional interest because certain transition trajectories have a topological relationship to similar time developments in the original data space. Consequently an erroneous mapping may lead to false interpretations. An optimal embedding space (network dimension) was found when $P \approx 0$ (cf. Table A.2). Due to the stochastic nature of the learning process, the challenge is to approximate P adequately. First the dimension for the SOMTOP simulations needs to be identified. For this question, we employ as a linear embedding approach, the principal component analysis (PCA) (Jolliffe, 2002). The PCA yields $d_{PCA} = 4$, i.e., 4 Eigenvalues $\gamma = 4.05, 1.98, 1.22, 1.08$ larger than 1, explaining 70% of the variance. Assuming that complex input data have a nonlinear nature the $d_{PCA} = 4$ can be used as the upper constraint for our simulations, i.e., the SOMTOP simulations were performed for a one- to four-dimensional output data space. (cf. Appendix Table A.2). These simulations provided that the best representation of the input data is guaranteed by a $4 \times 2 \times 2$ network configuration explaining a variance of 72%. Consequently, we use this result for further detailed analysis.

A.2.2 Data Sources and Processing

The input data set consists of 9,145 data sets comprising 12 input variables (animal products, cereals, pulses, starchy roots, oil crops, vegetable oils, vegetables, fruits, sugar and sweeteners, sugar crops, alcoholic beverages, and total food consumption) for 217 countries and country groups, e.g., Asia, Europe, World, etc. covering a time period from 1961–2007. The different food groups account for more than 90% of the global food supply and are measured in kcal/capita/day (FAO, 2011a). The data provide numbers regarding food availability not on actual consumption and do not cover losses which may happen due to the refining of food during the food production chain. This may limit the usability of the data, but the existing data are the most comprehensive and consequently we use them as a proxy for food consumption.

Nutritive factor data contains a conversion factor for converting the amount of crop and animal products provided from grams to calories (FAO, 2001). To estimate necessary feed for livestock in kcal/cap/day (F) per country, we consider the total crop amount used as fodder by converting its supply in t/yr into kcal/yr using the nutritive factors of crops and dividing them by the country population and by 365 in order to calculate a daily value.

As recently indicated, there exists a linear relationship between the human development index (HDI) (UNDP, 2009), which measures the development level (GDP per capita, life expectancy, enrollment rate, etc.) and log CO_2 emissions per cap (Costa et al., 2011). Due to the fact that the HDI can be considered as an indirect proxy for lifestyle changes, it was used to project food consumption pattern and their embodied emissions. To estimate the HDI related to dietary patterns, we employed data on the HDI trends 1980–2007 from UNDP (2009). The data are available starting from the year 1980 in 5 years' time intervals.

The estimation of fossil energy and the related GHG emissions embodied in certain dietary patterns was performed on energy output/input (O/I) ratio ($R_{I/O}$) data obtained from Conforti & Giampietro (1997), who estimated energy O/I ratio for agricultural products for an average of 1990–1991 for 66 countries. The energy O/I ratio is defined as the ratio between food energy obtained from agricultural products and the fossil energy necessary for its production.

For the estimation of non-CO_2 GHG emissions, data from USEPA (2006) and data on crops and livestock production from FAOSTAT were utilized (FAO, 2011a). Using respective nutritive factors for crops and livestock items we converted total crops and livestock production from tonnes to calorific values. The non-CO_2 emissions from agriculture consist of GHG emissions from enteric fermentation, rice cultivation, manure management, and agricultural soils. The emissions data was split into crop related (rice and soils) and livestock related (enteric fermentation and manure management) emissions. We calculated non-CO_2 GHG emission intensity per kcal of crop products (ec) and animal products (ea) for each country by dividing the crop and livestock production data in caloric values with the crop and livestock related non-CO_2 GHG emissions data.

Results obtained from SOMTOP simulations provide sixteen diet typologies, each of them representing a set of country and year pairs (Z) characterized by a certain food composition and total food consumption feature. Considering the set (Z) and the X' as a set of pairs of country (C) and year (Y) for which data on X (energy O/I ratio, non-CO_2 GHG emission intensity and feed use) is available, the average value (X_z) related to the dietary pattern was obtained by equation 2.1.

The total GHG emissions (ET_z) embedded in a dietary pattern was divided into GHG emissions from crops (EC_z) and livestock (EA_z) based on consumption of crop products (PC_z) (total food consumption minus animal products consumption) and animal products (PA_z). Considering crops as major livestock feed, we calculated additional non-CO_2 and fossil emissions embodied in livestock products. The GHG emissions from fossil energy was estimated using the emission intensity of diesel (eD), which is 0.36 g $CO_{2\text{eq.}}$ per kcal (DFT-UK, 2008). Applying equations 2.2, 2.3 and 2.4, we calculated GHG emissions from crop products, animal products, and total food consumption related to a specific dietary pattern, respectively and with equation 2.5 we calculated the embedded fossil energy (FE_z).

A.3 Scenario Assumptions for the Estimation of GHGs from Agriculture

For the estimation of future GHG emissions from agriculture, three different scenarios were defined and the following factors were considered: i) population change, ii) changes in food consumption, iii) non-CO_2 GHG emissions from crops and livestock, and iv) O/I ratio (cf. Section A.2.2). For the population change, data representing the midrange population scenario for 148 countries was considered from UN (2011). The estimation of future food consumption was based on a relationship between the Human Development Index (HDI) and calorie intake. Exponential relationships were found between the amount of total calories, animal products, sugar-sweeteners, vegetable oils, and vegetables consumption and the HDI values (cf. Figure 2.3). Using the HDI projections from Costa et al. (2011) and the exponential relationships between the HDI and calories intake, we forecasted the food consumption and identified the dietary patterns the countries will belong to. The pattern with the least euclidian distance to the projected food consumption of a country was considered to be the future dietary pattern of the country. Changes in the non-CO_2 GHG emission intensities (crop and livestock) and the O/I ratio (cf. Table 2.1 and Appendix Text A.2.2) for the countries were estimated, according to changes in the certain dietary pattern of a country. The scenarios analysis was performed until 2050 for time steps of 5 years. Three scenarios were analyzed.

A.3.1 Scenario A

The countries will not change their dietary pattern (2007) for the entire period of analysis. Furthermore, the non-CO_2 GHG emission intensities (crop and livestock) and the O/I ratio of the countries remain the same as the values associated with their dietary pattern of 2007. Only population changes were considered.

A.3.2 Scenario B

Food consumption changes, which are related to the projected HDI changes for the countries, were accounted for. The non-CO_2 GHG emission intensities and the O/I ratio of the countries remain the same as in scenario A. The population changes as in scenario A.

A.3.3 Scenario C

Population and food consumption change were accounted for along with non-CO_2 GHG emission intensities and the O/I ratio for the countries vary over time. Thus, this scenario not only takes into account dietary transitions, but also assumes that the countries will adapt non-CO_2 GHG efficient agricultural technologies as observed historically for countries with the corresponding dietary pattern.

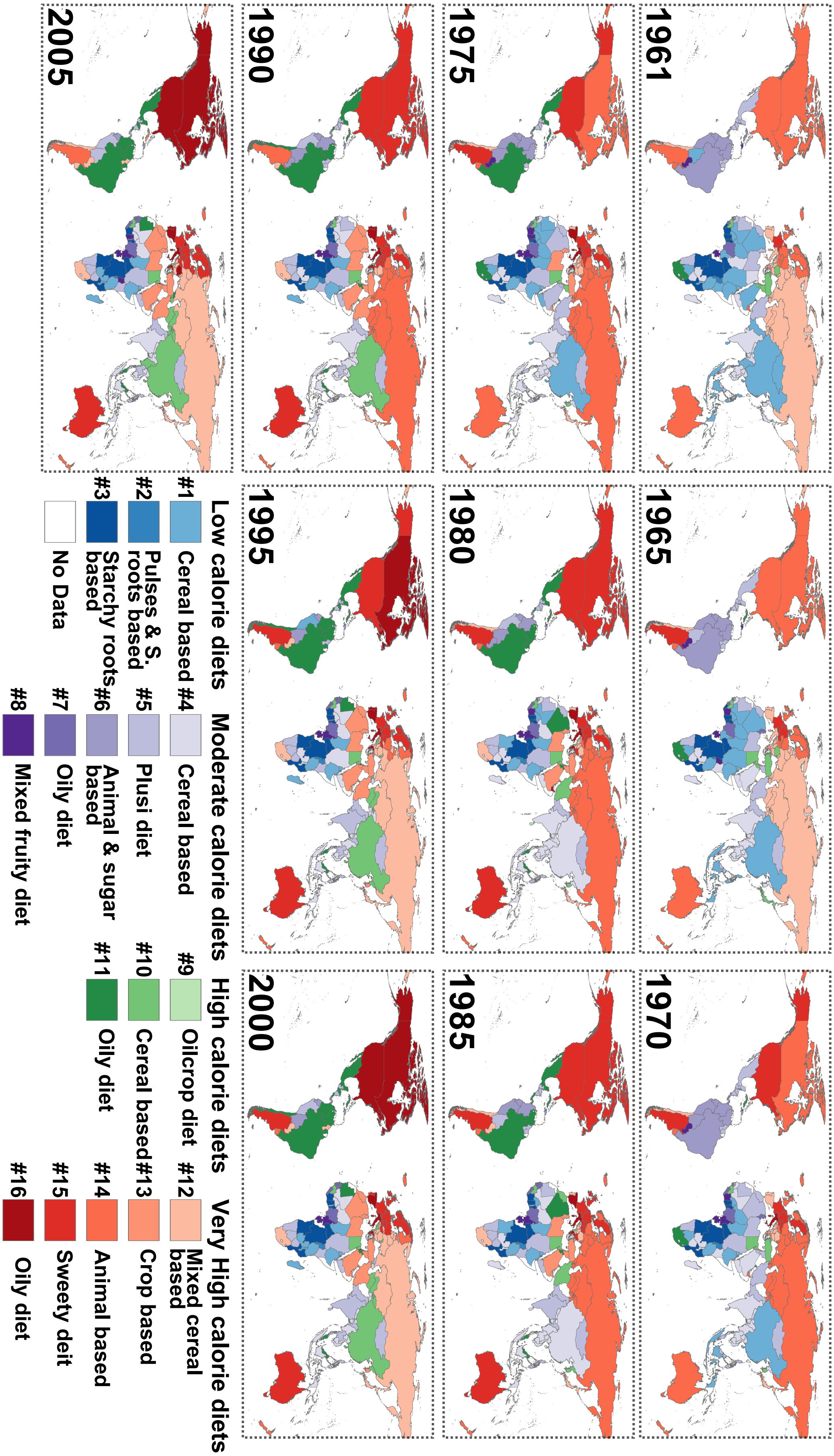

Figure A.1: World maps showing the spatiotemporal occurrence of the 16 dietary patterns.

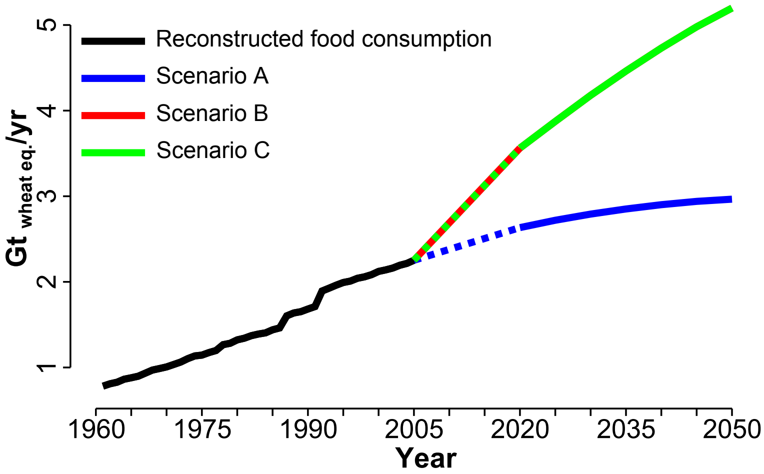

FIGURE A.2: Projected and reconstructed global food demand for three scenarios (A: population growth only, B: population growth and changes in dietary patterns, C: change in population, diets as well as technology and management). Scenario B & C overlap because the only difference, agricultural technology and management do not affect food demand. The projected calorie demand was converted to the wheat equivalent using the nutritive factor of wheat.

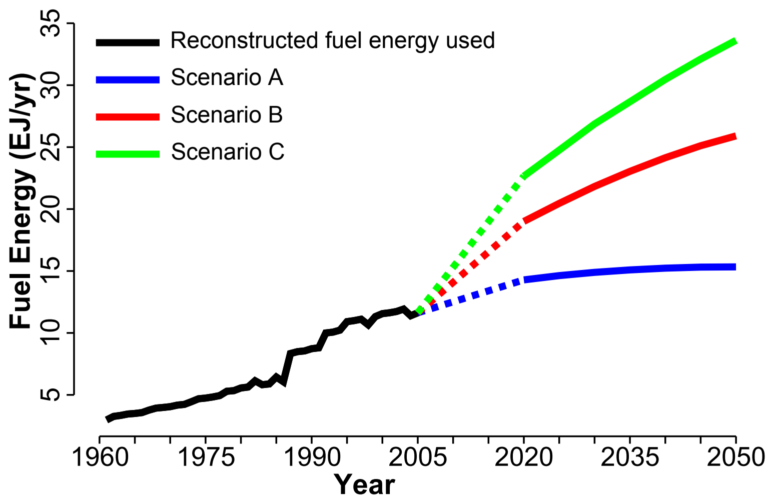

FIGURE A.3: Projected and reconstructed global fossil fuel energy demand for the three scenarios (as Appendix Figure A.2).

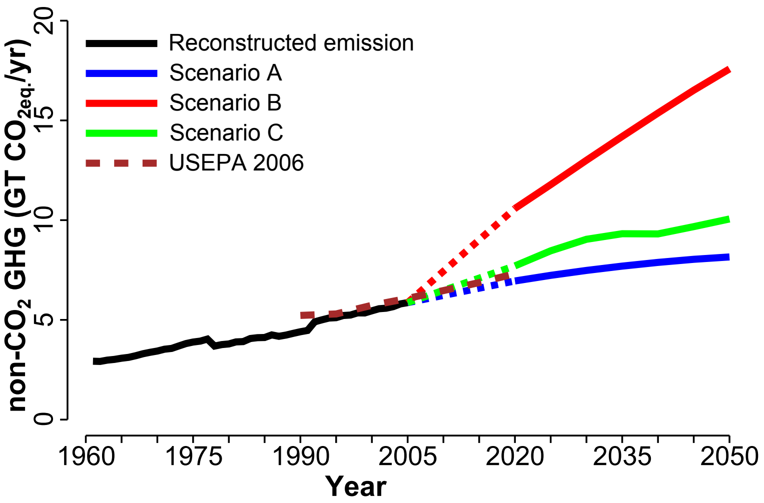

FIGURE A.4: Projected and reconstructed global non-CO_2 GHG emissions for the three scenarios (as Appendix Figure A.2). The figure also shows non-CO_2 GHG emissions from USEPA (2006). The reconstructed values slightly underestimate (less than 5%) the emissions by USEPA (2006). Reconstructed values are within the range of estimate presented by Metz et al. (2007) (5.1–6.1 Gt $CO_{2eq.}$/yr for year 2005). The projected emissions for the year 2050 (8.16 Gt $CO_{2eq.}$/yr, 17.58 Gt $CO_{2eq.}$/yr, and 10.06 Gt $CO_{2eq.}$/yr for scenarios A,B, and C, respectively) are similar to values reported for scenarios from Popp et al. (2010) for 2055 (8.69 Gt $CO_{2eq.}$/yr for constant diet scenario on level of 1995, 15.3 Gt $CO_{2eq.}$/yr for increased meat scenario based on change in GDP and 9.78 Gt $CO_{2eq.}$/yr increased meat plus technological mitigation scenario).

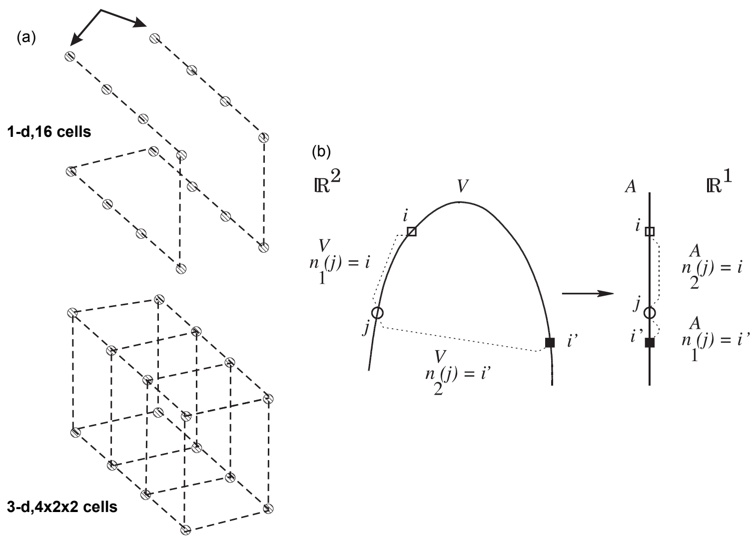

FIGURE A.5: (a) Representation of a topology distortion between two different network types. Consider the bullets as scatter plots in V. Such data distribution can be represented by a 1-d with 16 cells or by 3-d network with a $4 \times 2 \times 2$ geometry (16 cells). While for the 1-d two bullets are direct neighbors in V, while in A there have a maximum distance (black arrows). Only the 3-d network can represent this topological ordering adequately (cf. Appendix Table A.2 for the results of the actual simulations). (b) Measurement of the distances from point j to the next neighbors of order one and two, if the points lying in $\mathbb{R}^2$ are mapped onto $\mathbb{R}^1$. It is shown how distance ratios can be used in order to quantify topological distortions.

TABLE A.1: Number of observed diet transitions. The counts on the diagonal represent unchanged dietary patterns. Counts greater than 10 are used to plot the transition graph (Figure 2.4). Read from row to column, e.g., change recorded for Pattern 4 → Pattern 5 is 27.

Pattern	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	640	0	6	34	14	0	9	2	1	0	0	0	0	0	0	0
2	0	131	0	0	0	0	0	2	0	0	0	0	0	0	0	0
3	8	0	463	0	0	0	1	4	0	0	0	0	0	0	0	0
4	19	0	0	901	27	0	5	0	1	17	0	0	0	0	0	0
5	6	0	0	16	945	16	9	0	0	9	36	4	1	1	0	0
6	1	0	0	0	15	610	0	2	0	0	29	7	3	3	0	0
7	7	0	0	5	7	1	302	0	1	1	0	2	0	0	0	0
8	1	1	3	0	0	5	0	150	0	0	0	0	0	0	0	0
9	1	0	0	1	1	0	1	0	323	0	0	1	0	0	0	0
10	0	0	0	3	10	0	0	0	0	440	3	9	15	0	0	0
11	0	0	0	0	16	16	1	0	0	3	700	13	12	7	2	0
12	0	0	0	1	1	5	1	0	1	5	12	567	2	11	15	9
13	0	0	0	0	0	2	0	0	0	8	4	2	409	0	0	7
14	0	0	0	0	0	2	0	0	0	0	5	14	1	647	29	1
15	0	0	0	0	0	0	0	0	0	0	1	6	0	12	848	14
16	0	0	0	0	0	0	0	0	0	0	0	5	4	0	10	205

TABLE A.2: Topographical product and data reconstruction rates for SOM maps of certain dimensions. The map configuration with an optimal neighborhood preservation ($4 \times 2 \times 2$) indicated by a topographical product $\equiv 0$ is used for further analysis (cf. arrow). It describes the 12-dimensional input manifold by a 3-dimensional embedding space and a data reconstruction of 70%.

d_{SOM}	Network Geometry	Topographical Product	Reconstruction Rate	
1	8	-0.022 ± 0.003	0.68 ± 0.0006	
2	4×2	-0.014 ± 0.004	0.68 ± 0.0003	
1	10	-0.019 ± 0.002	0.69 ± 0.0003	
2	5×2	-0.015 ± 0.002	0.69 ± 0.0002	
1	12	-0.013 ± 0.001	0.70 ± 0.0002	
2	4×3	-0.014 ± 0.002	0.70 ± 0.0002	
2	6×2	-0.023 ± 0.002	0.70 ± 0.0003	
3	$3 \times 2 \times 2$	-0.001 ± 0.002	0.70 ± 0.0002	
1	14	-0.012 ± 0.001	0.71 ± 0.0003	
2	7×2	-0.024 ± 0.002	0.71 ± 0.0002	
1	16	-0.010 ± 0.001	0.71 ± 0.0002	
2	4×4	-0.005 ± 0.001	0.72 ± 0.0003	
2	8×2	-0.022 ± 0.002	0.72 ± 0.0002	
3	$4 \times 2 \times 2$	0.002 ± 0.001	0.72 ± 0.0005	$\longleftarrow$
4	$2 \times 2 \times 2 \times 2$	0.035 ± 0.003	0.72 ± 0.0003	
1	20	-0.011 ± 0.001	0.71 ± 0.0004	
2	5×4	-0.023 ± 0.002	0.73 ± 0.0003	
2	10×2	-0.028 ± 0.003	0.73 ± 0.0002	
3	$5 \times 2 \times 2$	-0.015 ± 0.002	0.73 ± 0.0003	
1	24	-0.015 ± 0.002	0.71 ± 0.0004	
2	6×4	-0.028 ± 0.002	0.74 ± 0.0002	
2	12×2	-0.020 ± 0.002	0.74 ± 0.0003	
3	$4 \times 3 \times 2$	-0.016 ± 0.002	0.74 ± 0.0002	
4	$3 \times 2 \times 2 \times 2$	0.009 ± 0.001	0.74 ± 0.0003	

Appendix B

Supporting Information: Embodied Crop Calories in Animal Products[1]

B.1 Data Harmonization and Aggregation

Normally data on feed, crop production and animal production are provided in mass units (see Table 3.1). For example, FAOSTAT provides data on countrywide animal products production and feed in t/yr (FAO, 2011a) and the Global Agro-ecological Zones (GAEZv3.0) provides downscaled data on crop yield for the year 2000 in t/ha (IIASA/FAO, 2012). Using nutritive factors (nf^i, i: the item representing crop or animal product for all of the equations below) from FAO (2001), we converted the data from mass units into calorie units to be able to compare and aggregate these values (Appendix Table B.1). We derived the countrywide feed calories (FC_c, c: the country for all of the equations below) based on the FAOSTAT Commodity Balances (FAO, 2011a). The Commodity Balances present balances of food and agricultural products in the eleven categories: Production Quantity, Import Quantity, Stock Variation, Export Quantity, Domestic supply quantity, Feed, Seed, Waste, Processed, Food, and Other Util. The data cover 175 countries for the year 2000. Except for sugar, oils, and beverages, the products are listed in their primary equivalents. For examples, soybeans is reported separately for soybeans, soybeans oil, and soybeans cakes, whereas, wheat is reported only in terms of wheat equivalent. We used 57 different crop products for which their use as feed is reported to estimate the countrywide feed calories. The crop products include both primary products (e.g., grains) and processed products (e.g., oil cakes). Similarly, we also estimated the countrywide crop mass used as feed (FM_c) aggregating the mass of all the crop products (FAO, 2011a) weighted respectively for their dry weight and fresh weight (IIASA/FAO, 2012).

We calculated the livestock-wise animal calories produced (AP_c^l, l: the livestock type for all of the equations below) on a country scale using the FAOSTAT Livestock Primary Production (FAO, 2011a) as presented respectively in equation B.1 and B.2. The

[1]This appendix and Chapter 3 have been published as: Pradhan, P., Lüdeke, M. K., Reusser, D. E., & Kropp, J. P. (2013). Embodied Crop Calories in Animal Products. Environ Res Lett, 8(4), 044044. http://dx.doi.org/10.1088/1748-9326/8/4/044044

production data provides information on the amount of meat, milk, and/or eggs produced by country and by livestock types ($AP_c^{(l,i)}$) in tonnes. Since the data on livestock densities is available for six livestock types (Wint & Robinson, 2007), we only considered animal calories provided by these livestock types. We use the livestock densities data which are adjusted for the year 2000. The six livestock types, with their associated animal products are: cattle, buffaloes, goats, and sheep, which all provide both milk and meat; pigs which provide meat only, and poultry which provide meat and eggs.

$$AP_c = \sum_{l=1}^{n=6} AP_c^l \tag{B.1}$$

$$AP_c^l = \sum_{i=1}^{n} \left(nf^i \times AP_c^{(l,i)} \right) \tag{B.2}$$

Gridded total crop calorie production (CP_k, k: the raster cell for all of the equations below) was calculated according to equation B.3 below using downscaled data on actual crop yields (cy_k) and area harvested (ha_k) from the GAEZv3.0 (IIASA/FAO, 2012) for the year 2000. The GAEZv3.0 estimated crop yields and area harvested on a grid for the year 2000 based on agricultural production statistics from the FAO. The data on crop yields and area harvested are available for 23 major commodities both for rain-fed and irrigated conditions. We considered 19 crop types provided by the GAEZv3.0 excluding non-food crop (e.g., cotton and fodder), stimulant cash crops (e.g., tea, coffee, and cacao) and crop commodities under residual section for this analysis. These 19 crop types account for more than 90% of the global crop calories produced in 2000. The global crop calories was estimated using production data reported for 52 different crops in the FAOSTAT Food Balance Sheets (FAO, 2011a).

$$CP_k = \sum_{i=1}^{n} \left(nf^i \times cy_k^i \times ha_k^i \right) \tag{B.3}$$

B.2 Downscaling Country Data to the 5′ Grid

B.2.1 Total Production of Animal Calories

Downscaling of total animal calorie production for the year 2000 to a grid was done based on an adapted methodology reported in FAO (2011b) using data on gridded livestock densities and livestock-wise animal calorie production on a country scale. Initially, we derived gridded livestock counts based on gridded livestock densities. We calculated livestock-wise animal calories produced (AP_c^l) on a country scale using the FAOSTAT Livestock Primary Production (FAO, 2011a) for the year 2000 (see Appendix Text B.1). We proportionally distributed the livestock-wise calorie production (AP_c^l) of the year 2000 at a country scale across country grids based on livestock counts on the grid (N_k^l) and the country (N_c^l). Finally, summing up calorie produced by the six livestock types on the grid provided the total grid livestock calorie production (AP_k) as presented by equation B.4.

$$AP_k = \sum_{l=1}^{n=6} \left(\frac{N_k^l}{N_c^l} \times AP_c^l \right) \tag{B.4}$$

B.2.2 Feed Calories

Downscaling of country feed calories for the year 2000 to a grid was done in three steps. First, we estimated countrywide feed requirements calculating the feed required per grid cell for each livestock types. Then, we aggregated the gridded feed requirements into two categories: ruminant feed requirements (FR_k^r) and non-ruminant feed requirements (FR_k^{nr}). We considered that non-ruminants are fed on feed whereas ruminants graze in pastures in addition to consuming fodder, forage, and/or crop residues (non-crop feed) for rangeland. For non-rangeland, crop products were assumed to be fed to ruminants only when the produced non-crop feed on the grid (symbolized as G_k) was not enough to meet their feed requirements. Using the M3-crop data (Monfreda et al., 2008), we estimated fodder and forage production on a grid. Similarly, crop residues for livestock on a grid was calculated adapting the approach described by Haberl et al. (2007) and based on GAEZv3.0 crop production data (IIASA/FAO, 2012). However for non-ruminants, crop products were used as feed regardless of the livestock production systems. Using above assumptions, we estimated the feed requirements for ruminants and non-ruminants on a country scale (FR_c^r and FR_c^{nr} respectively) in t/yr as presented by equation B.5 and B.6.

$$FR_c^{nr} = \sum_{k \in c} FR_k^{nr} \tag{B.5}$$

$$FR_c^r = \sum_{k \in c} (FR_k^r - G_k) \quad \text{if } G_k < FR_k^r \ \& \ \text{LPS} \neq \text{rangeland} \tag{B.6}$$

In the second step, we distributed the derived data on country feed calories (FC_c) from FAOSTAT (FAO, 2011a) to feed calories for ruminants and non-ruminants based two approaches (I and II). In approach I, we considered whether the total crop mass used as feed in a country (FM_c) is enough to meet the requirement for non-ruminants (FR_c^{nr}). If FM_c is greater than FR_c^{nr}, we divided FC_c into the country feed calories for ruminants (FC_c^r) and non-ruminants (FC_c^{nr}) as presented by equation B.7 and B.8. However, if FM_c is less than or equal to FR_c^{nr}, FC_c was allocated only to non-ruminants in the country assuming that the ruminants are fed only by fodder and forage. In approach II, we proportionally distributed FC_c into FC_c^{nr} and FC_c^r based on FR_c^{nr} and FR_c^r, respectively.

$$FC_c^{nr} = \begin{cases} FC_c \times \frac{FR_c^{nr}}{FM_c} & \text{if } FM_c > FR_c^{nr} \\ FC_c & \text{if } FM_c \leq FR_c^{nr} \end{cases} \tag{B.7}$$

$$FC_c^r = \begin{cases} FC_c \times \frac{FM_c - FR_c^{nr}}{FM_c} & \text{if } FM_c > FR_c^{nr} \\ 0 & \text{if } FM_c \leq FR_c^{nr} \end{cases} \tag{B.8}$$

In the third and final step, we disaggregated FC_c^r and FC_c^{nr} into grids to obtain data on gridded feed calories based on FR_k^{nr}, FR_c^{nr}, FR_k^r, G_k, and FC_c^r as represented by equation B.9 and equation B.10.

$$FC_k^{nr} = FC_c^{nr} \times \frac{FR_k^{nr}}{FR_c^{nr}} \tag{B.9}$$

$$FC_k^r = \begin{cases} 0 & \text{if LPS} = \text{rangeland} \\ 0 & \text{if } G_k \geq FR_k^r \\ FC_c^r \times \frac{FR_k^r - G_k}{FR_c^r} & \text{if } G_k < FR_k^r \text{ \& LPS} \neq \text{rangeland} \end{cases} \tag{B.10}$$

B.3 Projection of Feed Demand

We derived country scale total animal calorie production (AP_c), animal calorie production (AP_c') from the six livestock types, animal calories consumed by humans (AC_c), and feed calories (FC_c) for the year 2000 based on the FAOSTAT (FAO, 2011a). We estimated AP_c using countrywide production data reported for 24 different animal products including marine and aquatic products in the FAOSTAT Food Balance Sheets (FAO, 2011a). AP_c' was calculated summing up the livestock-wise animal calories produced (AP_c^l) on a country scale (see Appendix Text B.1) for the six livestock types. On global scale, AP' contributes more than 70% of AP, whereas marine and aquatic products share 13%, animal fats and offals 10%, and rest come from other livestock types (FAO, 2011a). Similarly, AC_c was estimated using data on country scale population and per capita animal product intake from the FAOSTAT Food Balance Sheets (FAO, 2011a). For, countrywide feed calories (FC_c) see Appendix Text B.1. All these data cover 175 countries for the year 2000.

We projected the future total animal calorie production AP_c and feed calorie demand FC_c by country based on their relationships with AC_c and AP_c', respectively, as presented by equations B.11–B.14. The future values of the parameters, intercept n^y (y: the year for all of the equations below) and slope m^y, were estimated applying linear extrapolation based on observations over the last decades showing a linear increase in n and linear decrease in m (Figure 3.1a′ and 3.1b′). To take into account countrywide variations from the global linear relation, we also considered residuals ($\varepsilon_{(1,c)}$ and $\varepsilon_{(2,c)}$) for each country. Additionally, we assumed that on a country scale, the share of AP_c' in AP_c will remain constant at the country mean value (f_c) from 1961 to 2007 (see equation B.14). Equation B.11 is able to reconstruct the past country animal calorie production trends for more than 85% of the countries within the mean absolute error (MAE) as fraction of actual value of 20% (see Appendix Figure B.5 for some country examples). In contrast, equation B.12 is able to reconstruct the past country feed trends only for around 60% of the countries within a MAE as fraction of actual value of 30%. This motivated us also to consider the values of the parameters, n_2 and m_2, based on the observed relation for the recent year i.e., 2007 (see equation B.13). Such a method is also used for other studies (e.g., Popp et al. (2010)). Equation B.13 that does not consider changes in the parameters across time provided a similar reconstruction error as equation B.12. In other words, equation B.12 takes into account the future changes in feed conversion efficiency based on the past global trends, whereas, equation B.13 keeps it constant.

$$\log(AP_c^y) = m_1^y \times \log(AC_c^y) + n_1^y + \varepsilon_{(1,c)} \tag{B.11}$$

$$\log(FC_c^y) = m_2^y \times \log(AP_c'^y) + n_2^y + \varepsilon_{(2,c)} \tag{B.12}$$

$$\log(FC_c^y) = m_2 \times \log(AP_c'^y) + n_2 + \varepsilon_{(2,c)} \tag{B.13}$$

$$AP_c' = f_c \times AP_c \tag{B.14}$$

We defined three scenarios to project the feed demand. Scenario A only considers population change for countries based on the midrange population scenario from UN (2011) with the same dietary pattern as in the year 2000. In this baseline scenario, we considered no changes in feed conversion efficiency and thus, used equation B.13 for estimating the future feed demand. Scenario B takes into account country specific changes in dietary patterns as provided by Pradhan et al. (2013b) in addition to population change. However, feed conversion efficiency remains constant. This is an upper bound scenario that considers changes in diet and population but not efficiency. Scenario C represents changes in feed conversion efficiency based on the extrapolated values of n_2^y and m_2^y together with changes in population and dietary patterns as scenario B. Therefore, we used equation B.12 to estimate the future feed demand in this scenario resulting in a midrange scenario. After obtaining countrywide feed demand for all the three scenarios, we proportionally distributed the projected feed calories across the country grids based on grid values for the year 2000.

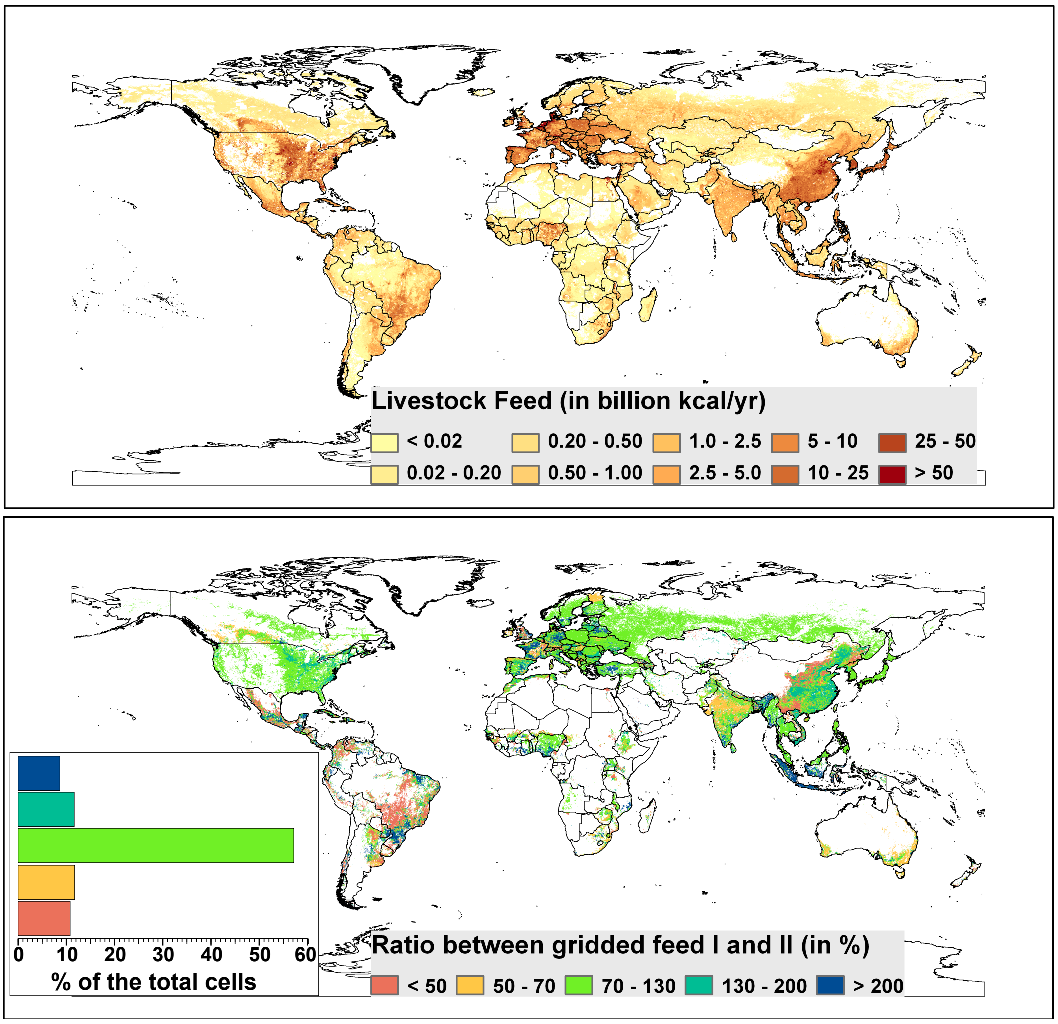

FIGURE B.1: Gridded map showing crop production consumed as livestock feed (FC_k) in billions kcal/yr based on approach II (top) comparing it with the map obtained based on approach I (bottom). Inset presents statistics for ratio between the downscale results obtained from approach I and II for the cells with the feed value larger than 0.2 billion kcal/yr.

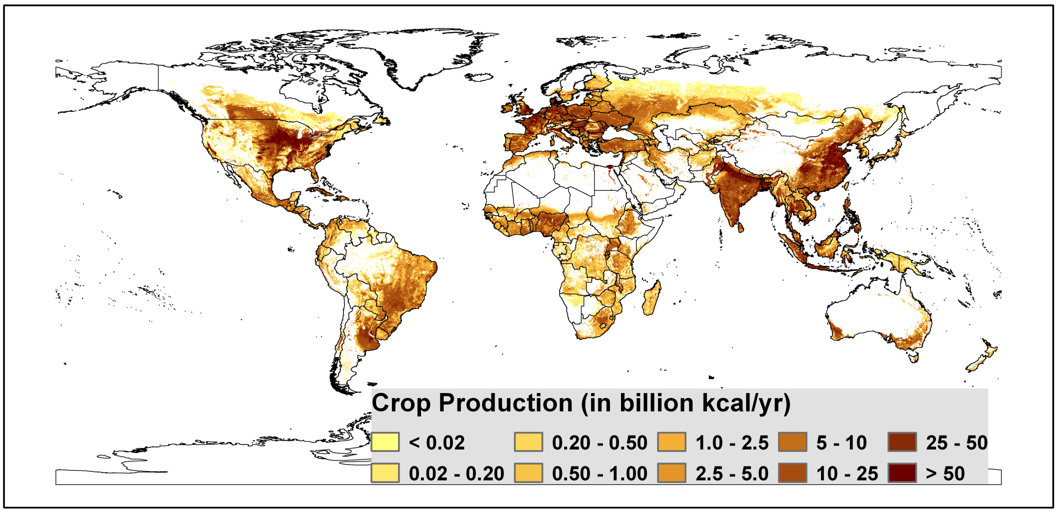

FIGURE B.2: Gridded map of crop calorie production (CP_k) in billions kcal/yr for the year 2000.

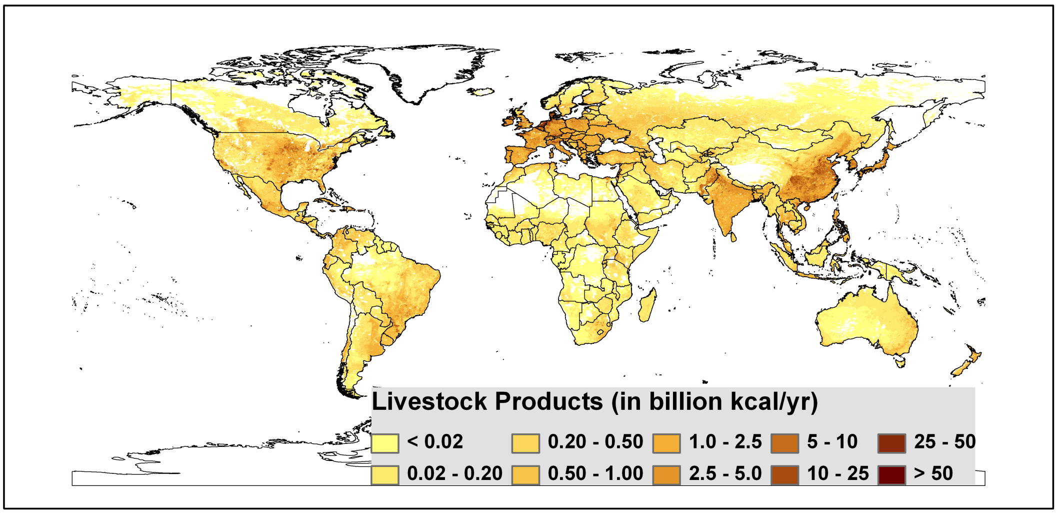

FIGURE B.3: Gridded map of animal calorie production (AP_k) in billions kcal/yr for the year 2000.

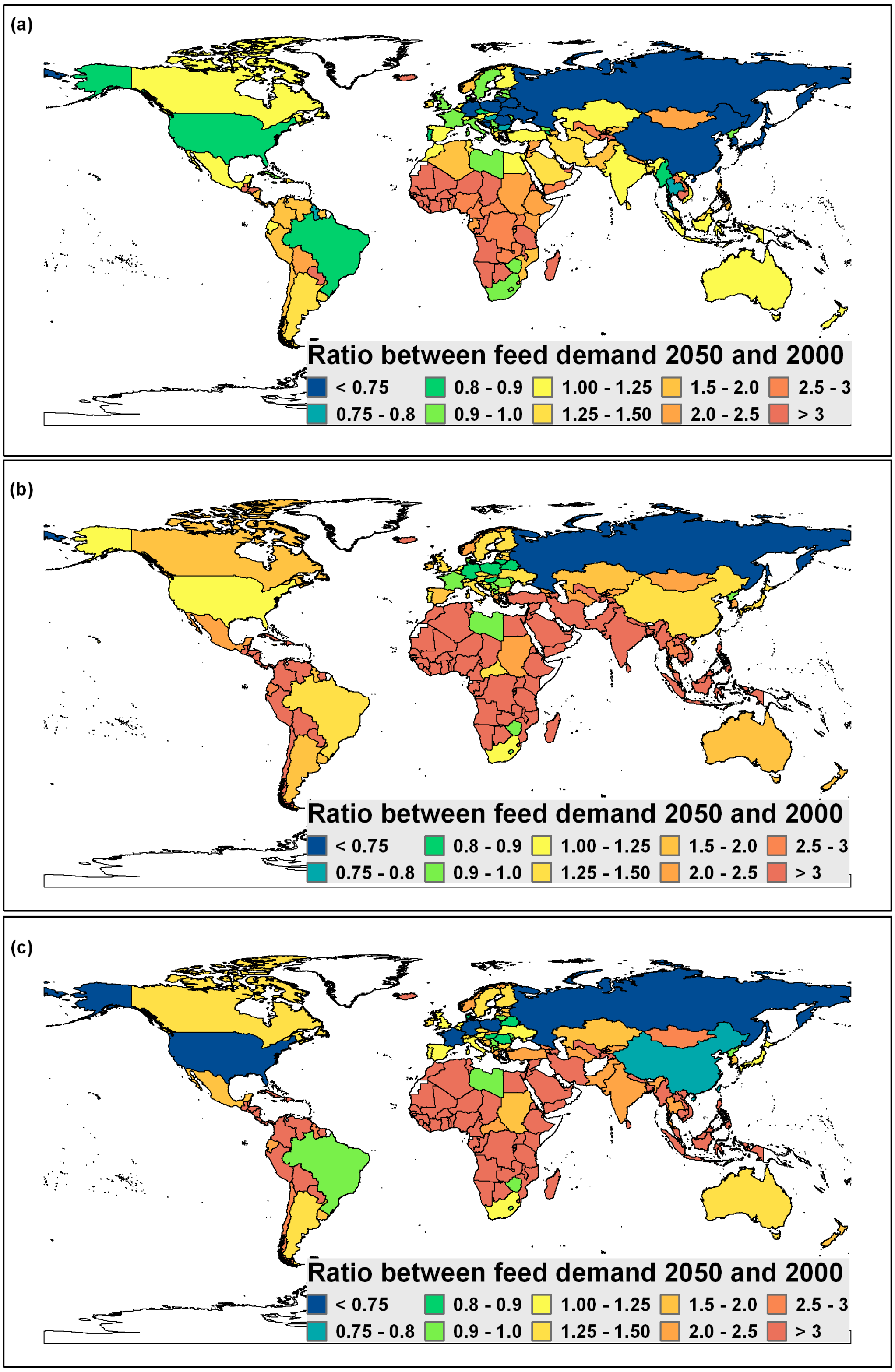

FIGURE B.4: Map of the ratio between the projected feed demand for 2050 and the feed consumed in 2000 for three scenarios. (a) without dietary pattern changes but with population changes (scenario A), (b) with dietary pattern and population changes (scenario B), and (c) with dietary pattern, population, and feed conversion efficiency changes (scenario C).

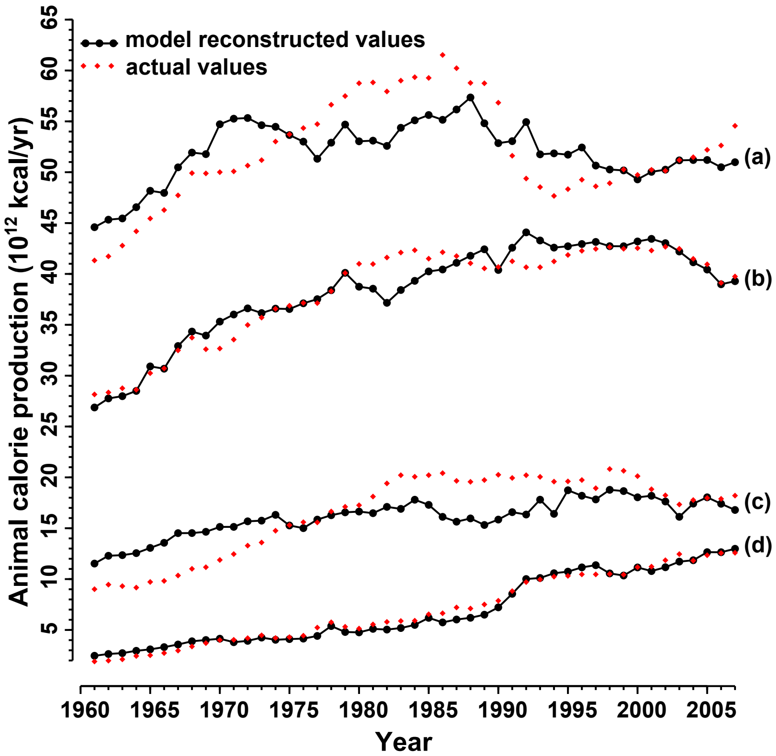

Figure B.5: Comparison between country animal calories production trends with reconstructed trends using the global linear regression model represented by equation B.11: (a) Germany, (b) France, (c) Netherlands, and (d) Thailand. Germany and Netherlands are examples of the countries for which reconstructed trends varies the observed one, whereas, France and Thailand are examples of the countries for which the model was almost able to reconstruct the observed trends.

TABLE B.1: List of nutritive factor (nf^i) and conversion factor from fresh weight to dry weight for crop products. The nutritive factors are obtained from FAO (2001) and the conversion factors are adapted from IIASA/FAO (2012).

Crop Product	Nutritive Factor (nf^i) (kcal/100 g)	Conversion Factor
apples	48	0.15
bananas	60	0.35
barley	332	0.88
beans	341	1
brans	244.5	0.9
cassava	212	0.35
cereals, other	340	0.88
cocoa beans	414	0.5
coconuts - incl copra	636	0.175
copra cake	636	0.9
cottonseed	253	0.9
cottonseed cake	253	0.9
dates	156	0.15
fruits, other	45	0.15
grapes	53	0.15
groundnut cake	363	0.67
groundnuts (shelled eq)	567	0.67
maize	356	0.87
millet	340	0.888
molasses	232	0.8
oats	385	0.888
oilcrops oil, other	884	1
oilcrops, other	387	0.9
oilseed cakes, other	261	0.9
olive oil	884	1
onions	31	0.15
oranges, mandarins	34	0.15
palmkernel cake	261	0.9
palmkernel	514	0.9
peas	346	1
plantains	75	0.35
potatoes	67	0.25
pulses, other	340	1
rape and mustard cake	376	0.9
rape and mustard oil	884	1
rape and mustardseed	494	0.9
rice (milled equivalent)	0	0.9
roots, other	91	0.3
rye	319	0.888
sesameseed	573	0.9
sesameseed cake	376	0.9
sorghum	343	0.88
soyabean cake	261	0.9
soyabean oil	884	1
soyabeans	335	0.9
sugar (raw equivalent)	373	1
sugar beet	70	0.14
sugar cane	30	0.1
sugar, non-centrifugal	351	1
sunflowerseed	308	0.9
sunflowerseed cake	376	0.9
sweet potatoes	92	0.3
sweeteners, other	310	0.12
tomatoes	17	0.15
vegetables, other	22	0.15
wheat	334	0.875
yams	101	0.35

Appendix C

Supporting Information: Food Self-Sufficiency across Scales: How Local Can We Go?[1]

C.1 Potential Crop Calorie Production

We used data on biophysical/potential yields Y of 19 crop types for the current cultivated land from GAEZv3.0 (IIASA/FAO, 2012) for estimating the potential crop calorie production in a global raster grid of 5 arc minute resolution. GAEZv3.0 provides information on the potential crop yields in t/ha in dry weight equivalents for two types of water supply (irrigated and rain-fed) and three input levels (low, intermediate, and high). The low-input agriculture is considered as labor intensive subsistence farming; the intermediate-input agriculture as partly market oriented improved farming; and the high-input agriculture as mainly commercial farming based on mechanized management with adequate application of nutrients and agro-chemicals (IIASA/FAO, 2012). Based on these levels, we calculated potential crop calorie production for two groups based on different input levels: low (Cl) and high (Ch). Since data on irrigated crop yields is provided only for intermediate-input and high-input levels, we assumed that the combination of crop yields based on low-input rain-fed agriculture (Yl_r^k) and intermediate-input irrigated agriculture (Ym_i^k) provides the potential crop calorie production for low-input as presented in equation C.1. The combination of the crop yields based on high-input rain-fed and irrigated agriculture (Yh_r^k and Yh_i^k respectively) provides the potential crop calorie production for high-input (equation C.2).

Both equations sum of all the 19 crop types $j = 1 \ldots n$. The nutritive factors (f^j) from FAO (2001) used to convert crop mass into crop calories are provided in terms of harvested weight. However, yield information from GAEZv3.0 is provided in terms of dry weight. Thus, we used conversion factor (c^k) (IIASA/FAO, 2012) to convert dry yields Y into harvested yields from the dry weight.

The inner sum is used to combine production from irrigated and rain-fed areas. The production is obtained by multiplying the potential yield Y by the harvested area H.

[1]This appendix and Chapter 4 have been published as: Pradhan, P., Lüdeke, M. K., Reusser, D. E., & Kropp, J. P. (2014). Food Self-Sufficiency across Scales: How Local Can We Go? Environ Sci Technol 48(16), 9463-9470. http://dx.doi.org/10.1021/es5005939

While data on potential yields are available for all individual crops, data on harvested area are provided only for the crop type instead of the individual crops (H_r^j and H_i^j – j: a crop type, r: rain-fed, i: irrigated– Table C.1). In these cases, for each cell we used data for the individual crop with the highest yield among this crop type (nc: number of crops).

$$Cl = \sum_{j=1}^{n}\left(f^j \times \left(max\left(\left\{\frac{Yl_r^k}{c^k}\right\}_{k=1}^{nc}\right) \times H_r^j + max\left(\left\{\frac{Ym_i^k}{c^k}\right\}_{k=1}^{nc}\right) \times H_i^j\right)\right) \tag{C.1}$$

$$Ch = \sum_{j=1}^{n}\left(f^j \times \left(max\left(\left\{\frac{Yh_r^k}{c^k}\right\}_{k=1}^{nc}\right) \times H_r^j + max\left(\left\{\frac{Yh_i^k}{c^k}\right\}_{k=1}^{nc}\right) \times H_i^j\right)\right) \tag{C.2}$$

C.2 Scenarios Analysis

The future food and feed demand will mainly be driven by changes in population, dietary patterns, and feed conversion efficiency, whereas progress on closing crop yield gaps and climate change will influence the future food and feed supply. Therefore, we defined 36 scenarios considering these five dimensions to assess local, regional, and global FSS for 2050 (Appendix Figure C.1). We classified these scenarios into three groups (I, II, and III) based on changes in population, dietary patterns, and feed conversion efficiency.

The first scenario group (scenario group I) provides baseline scenarios where the dietary pattern of a country stays the same as in the year 2000 but population changes for countries based on the midrange population scenario from UN (2011). This scenario group provides results for a low bound. The second group (scenario group II) takes into account country specific changes in dietary patterns as projected by Pradhan et al. (2013b), additional to the population changes. Pradhan et al. (2013b) estimated the future per capita food demand by country upto 2050 based on observed exponential relationship between per capita food consumption and the Human Development Index (HDI), using the HDI extrapolation from Costa et al. (2011) based on logistic regression. This scenario group provides results for upper bound based on changes in dietary patterns and population. The third group (scenario group III) considers changes in feed conversion efficiency, amount of feed need to produce a unit of animal products (Pradhan et al., 2013a), additional to changes in population and dietary patterns. The changes in feed conversion efficiency were projected based on linear extrapolation of observed changing parameters (slope and intercept) across time for linear relation between countrywide animal calorie production and crop-based feed calorie use (Pradhan et al., 2013a). This is a midrange scenario group.

In these three groups, the scenarios differ based on closing yield gaps to attain four different levels of the high-input potential crop calorie production: HI_{50}, HI_{75}, HI_{90}, and HI_{100}, and with three climate variations: constant climate, IPCC's A2 scenario (a pessimistic climate scenario), and IPCC's B2 scenario (a optimistic climate scenario). The crop yields under climate change with and without CO_2 fertilization effects are obtained from the GAEZv3.0 (IIASA/FAO, 2012) based on the global circulation model Hadley CM3. This results in 12 scenarios for each scenario group.

We considered the total calorie produced and consumed for the scenarios analysis but not dietary composition. This was because of our motivation to investigate what level of closing yield gaps would enable mankind to meet the expected global crop demand by 2050. Additionally, our analysis for the year 2000 clearly showed that closing yield gaps only would not change much the numbers of food self-sufficient people at local and regional scales while taking into account production and consumption of the six food groups (Figure C.2–FG_{HI}). Moreover, only limited data on the future dietary composition was available besides the total calories and the animal products intake.

C.3 Change in Population and Land Use

To analyze FSS for the year 2050, we considered changes in a country population based on the midrange population scenario from UN (2011), which also distinguishes a country's urban and rural population. Our FSS study is based on the raster data of a five arc-minute ($5'$) resolution, however, some of the data we used are available in different resolutions, e.g., urban-rural extents and population projection (Table 4.1). Hence, we harmonized data to $5'$ resolution. Urban-rural extents from CIESIN/IFPRI/CIAT (2011b) provides information on whether a grid cell belongs to an urban or rural area for the year 2000 and is available as gridded $0.5'$ resolution. Therefore, we aggregated to $5'$ assuming that a cell in $5'$ resolution would be urban if at least one of the belonging $0.5'$ cells is urban. The countrywide urban and rural population scenario was then downscaled to $5'$ grid by proportionally distributing the population across the country grids based on the gridded population data for the year 2000 (CIESIN/IFPRI/CIAT, 2011a) and the data on urban-rural extents.

In our next step, we calculated loss of cultivated land and crop production associated with land use changes due to population growth by 2050, which is divided into two steps. In a first step, we estimated change in built-up area driven by the population growth using land use data that provides the share of six different land use types (cultivated land, forest land, grassland and woodland, barren and sparsely vegetated land, built-up land, and water bodies) on a $5'$ grid for the year 2000 (IIASA/FAO, 2012). The population projection is not available at a grid scale but only at the country scale for urban and rural population. Thus, we estimated countrywide urban and rural built-up areas using the land use data on urban-rural extents based on the following relation on population density. For the year 2000, country scale total urban built-up area shows a linear relation with total urban population in a log–log plot as presented in Appendix Figure C.2a. Such a relation can also be estimated for the rural built-up area and the rural population (see Appendix Figure C.2b). Assuming that this relation on population density is not changing in the future, we estimated future urban-rural built-up area of a country using its urban-rural population projections (UN, 2011) until 2050 in 5 year time steps. However, we assumed that a decrease in population as projected for some countries would not reduce the built-up area.

In the second step, we downscaled the countrywide projected built-up area to $5'$ resolution for estimating associated cultivated land and crop production loss. For this, we used an iterative procedure for the five year time steps. The distribution is given for the year 2000 from the data. For later time steps, estimation was always based on the data form the previous time step. We proportionally distributed the projected built-up area across the country urban-rural extents based on the built-up area. While doing this, we assumed that only cultivated land, grassland, and woodland are available for built-up area expansion. We further assumed that the built-up area will grow first on the cultivated land because urban growth is traditionally founded close to very fertile land. However, a grid having projected area covering $> 80\%$ by water bodies, $< 2\%$ land available for expansion, $> 95\%$ of it already built-up area, or covering $> 95\%$ by built-up area and water bodies together was excluded from further urban expansion to preserve projected area and to provide some non-built-up space within the grid. Additionally, we updated the available land for built-up area expansion in a grid by reducing its previous value according to changes in the built-up area. When this resulted in grids with negative values of available land, we proportionally distributed the excess values to the neighboring grids belonging to the same country considering above mentioned assumptions and updated the available land accordingly. We estimated crop calorie loss considering that the calorie loss in a grid cell is proportional to the change in its cultivated area. Since this approach ignores the possibility of built-up area expansion without population growth, the obtained results can be considered as a lower bound.

Our motivation to use a simple approach is to estimate loss of cultivated land due to change in built-up area. Errors in these estimates will be reasonable, because globally cultivated land covers 10 times (15.7 million km^2) more land surface than built-up land (1.54 million km^2) (IIASA/FAO, 2012). While more sophisticated methods to estimate urban growth exist (e.g. Seto et al. (2012)), our efficient approach is used to estimate loss of cultivated land. Considering that most of the agriculture modeling exercises ignore (Bodirsky et al., 2012, Lotze-Campen et al., 2008) such loss, this is a first step to include the possible reduction in cultivated land.

C.4 Trade Analysis

We estimated required countrywide food and feed imports to meet their demands comparing the production and the consumption of total calories on a country scale based on the gridded data used for our FSS analysis. Data on countrywide total calories production and consumption was obtained by summing up gridded total calorie production and consumption across the country grid cells. Whenever a country total calorie consumption is larger than its total production, we assumed that the country requires food and feed imports equivalent to the difference between the consumption and the production. We considered these countries as net food importers. Summing up all the countrywide required food and feed imports, we estimated the global food and feed trade. Moreover, if a country total calorie consumption is smaller than its total production, we assumed that the country is a net food exporter. Similarly, we identified net food importer and exporters on a subcontinental and a continental scales adapting the method described above for subcontinent and continent.

The FAO Food Balance Sheet (FAO, 2011a) provides information on reported trade (import and export) for agricultural commodity. We used this data to calculate the actual volume of food and feed import for 2000 in calorific values. We converted the data provided in t/yr into kcal/yr using their respective nutritive factors (FAO, 2001). Afterwards, summing up all the imports, we estimated the global food and feed trade in terms of countrywide imports. From this we obtained gross import values because a country may import and export agricultural goods at the same time. Therefore, we estimated countrywide net import based on the difference between its calorie import and calorie export. We considered a country with higher calorie import than calorie export as a net food importer, whereas, a country with lower calorie import than calorie export as a net food exporter. Moreover, summing up all the net imports we obtained the global net food and feed imports. Similarly, we identified net food importers and exporters on a subcontinental and a continental scales based on FAO (2011a) adapting the method described above for subcontinent and continent. Finally, we compared these FAO food trade values with the above mentioned trade values estimated using the gridded data to verify our cross-scale FSS analysis based on observed similarity and discrepancies (see Appendix Figure C.7).

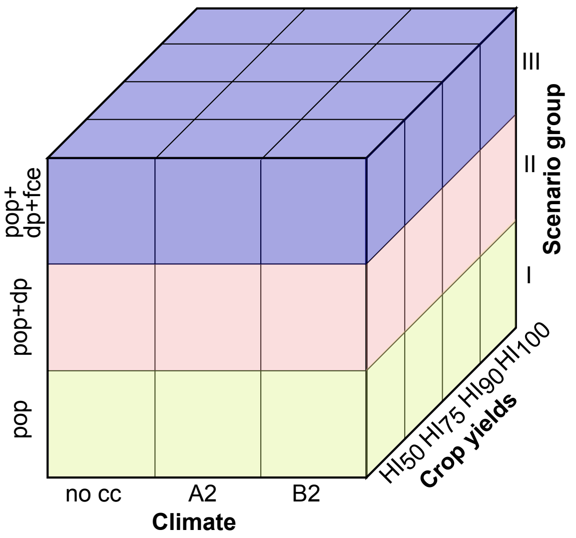

FIGURE C.1: Scenarios developed for 2050 based on the five dimensions that drive food and feed supply and demand: population (pop), dietary patterns (dp), feed conversion efficiency (fce), climate change (cc), and crop yields. Scenario group I considers population growth, Scenario group II additionally accounts for dietary pattern shifts, and Scenario group III includes feed conversion efficiency changes in addition. Within the groups, the scenarios differ based on three climate variations (constant climate (no cc), IPCC's A2 scenario and B2 scenario) as well as closing yield gaps to attain 50%–100% of the high-input potential (HI_{50}–HI_{100}).

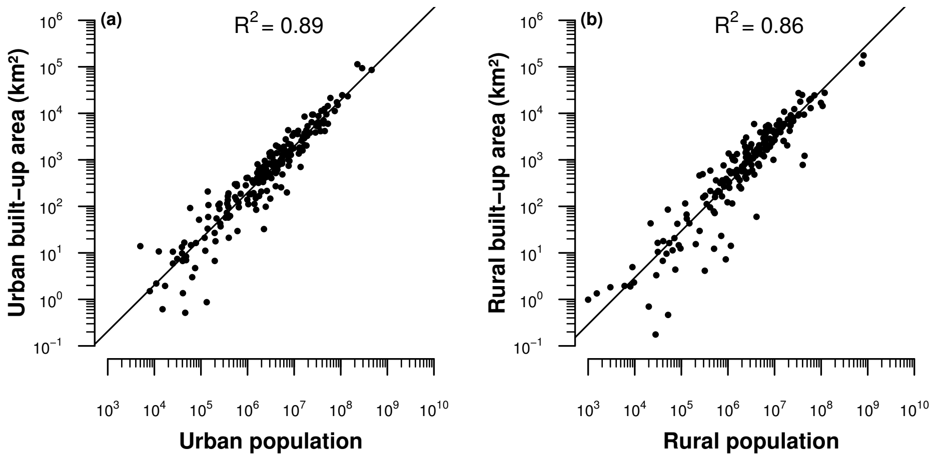

FIGURE C.2: Relations between country scale built-up area and populations in a log–log plot for the year 2000: (a) countrywide urban built-up area and urban population, and (b) countrywide rural built-up area and rural population (for the method see Appendix Text C.3).

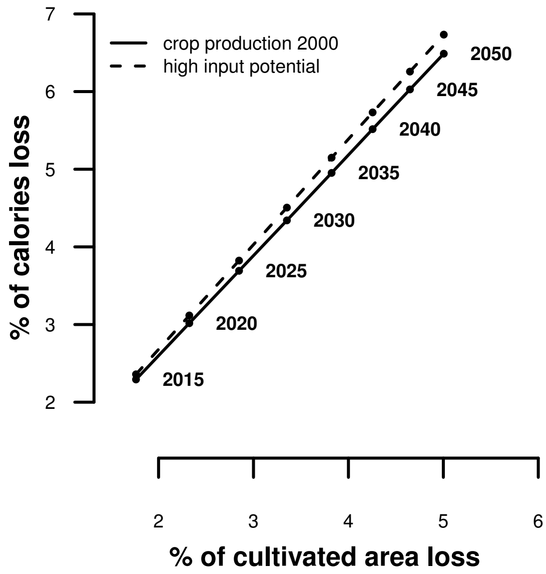

FIGURE C.3: Crop calorie loss associated with reduction in cultivated area due to increase in built-up area driven by population growth. The cultivated area of around 15.7 million km^2 in 2000 might shrink to 14.9 million km^2 by 2050 without considering potential agricultural expansion (see Appendix Text C.3). This results crop calorie loss between 6 to 7% because cities are traditionally founded close to very fertile land. This equivalent calorie loss is enough to feed around 600 million people with a daily diet of 2,800 kcal/cap/day considering crop calorie production for the year 2000 and around 1.2 billion people in case of the high-input potential production, which is near to the estimated number of undernourished people (900 million) in 2010 (FAO, 2010).

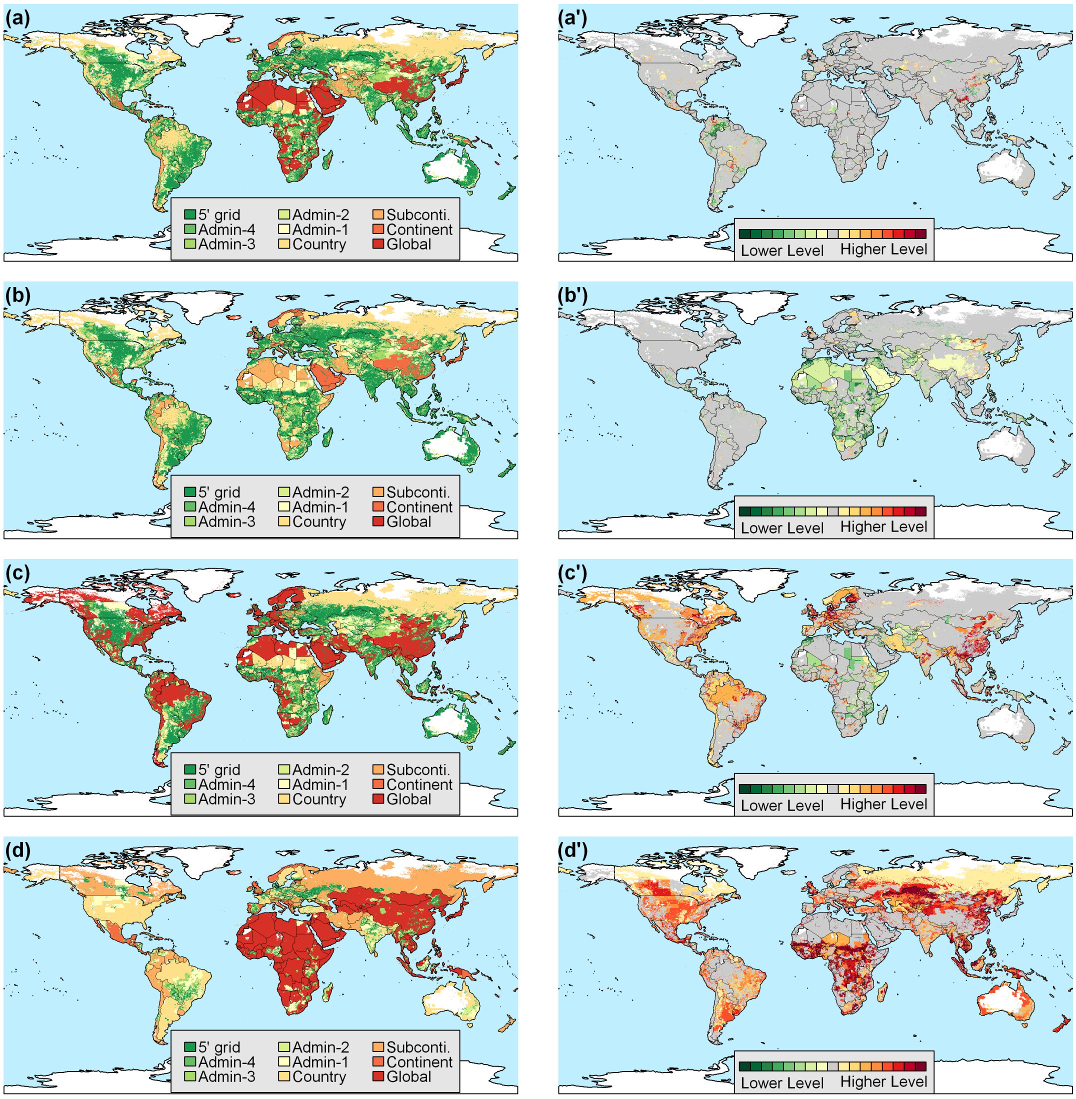

FIGURE C.4: Maps depicting the lowest possible spatial scale on which a region could obtain FSS in 2000 based on different analyses (left panel) and their differences with FSS status obtained with crop production in the year 2000 (see Figure 4.1a), showing whether FSS could be achieved in higher or lower spatial level/scale (right panel): (a) with feed data obtained from 'extreme case' approach (Pradhan et al., 2013a), (b) considering closing yield gaps to attain 50% the of high-input potential (HI_{50}), (c) the low-input crop production (LI), and (d) the food composition based on the six food groups (FG). The color coding in left panel represents the spatial scales that include 5′ grid, the fourth to the first level administrative unit (Admin-4 to Admin-1), country, subcontinent (subconti.), and continent. Pradhan et al. (2013a) downscaled data on countrywide feed calorie consumption based on two approaches: 'close to reality' that prioritized non-ruminants (e.g., pigs and poultry) for obtaining crop-based feed, and 'extreme case' that distributed crop-based feed to non-ruminants and ruminants (e.g., cattle, buffalos, sheep, and goats) based on their respective feed requirements.

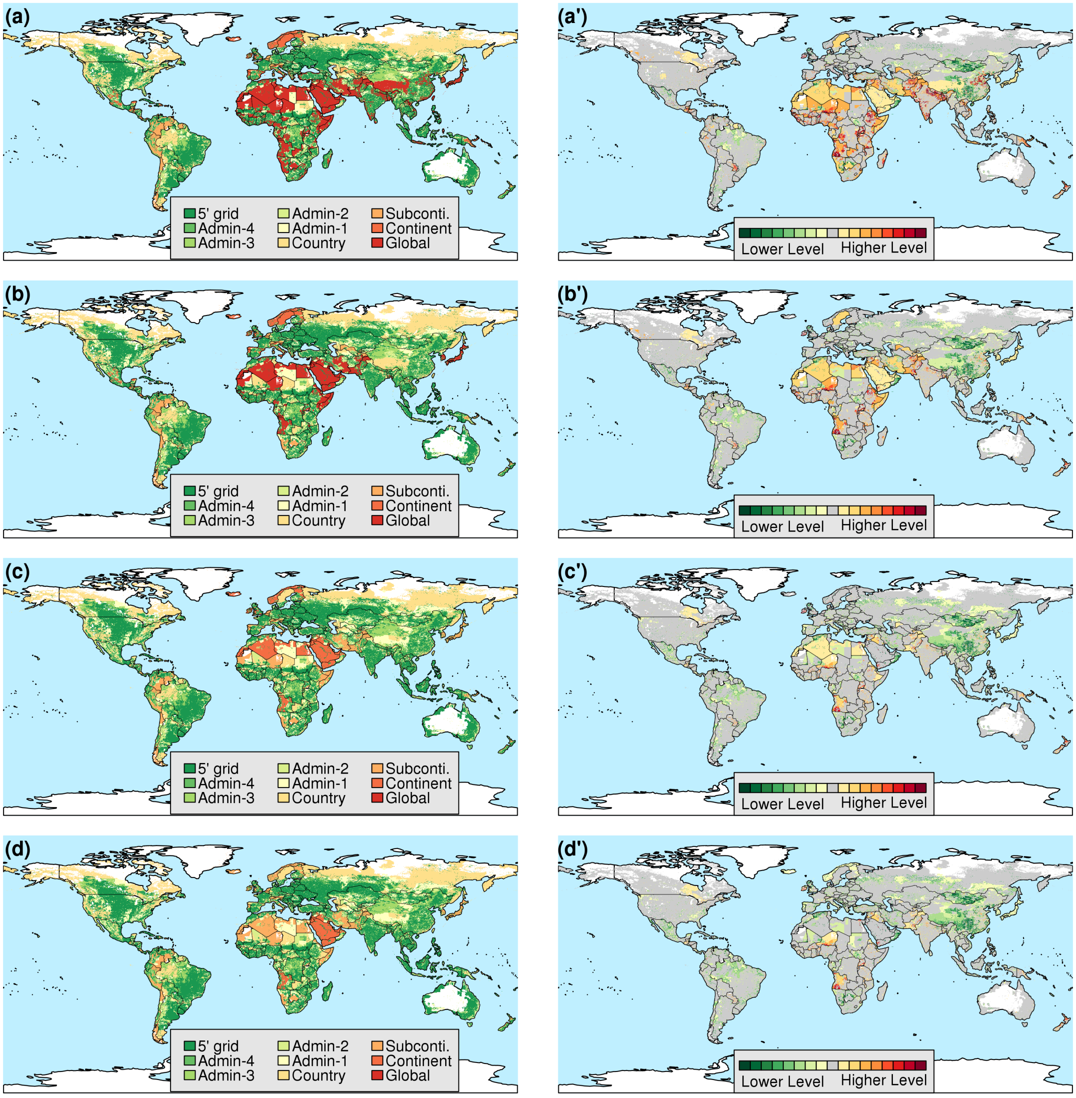

FIGURE C.5: Maps depicting the lowest possible spatial scale on which a region could obtain FSS by 2050 based on closing yield gaps to attain the different levels of high-input potential for scenarios in group I considering only population growth with constant climate and their differences with FSS status obtained for 2000 with closing yield gaps to attain 50% of the high-input potential (HI_{50}) (see Appendix Figure C.1b), showing whether FSS could be achieved in higher or lower spatial level/scale (right panel): (a) closing yield gaps to attain 50% of the high-input potential (pop, no cc, and HI_{50}), (b) closing yield gaps to attain 75% of the high-input potential (pop, no cc, and HI_{75}), (c) closing yield gaps to attain 90% of the high-input potential (pop, no cc, and HI_{90}), and (d) closing yield gaps to attain 100% of the high-input potential (pop, no cc, and HI_{100}). The color coding in left panel represents the spatial scales that include 5′ grid, the fourth to the first level administrative unit (Admin-4 to Admin-1), country, subcontinent (subconti.), and continent.

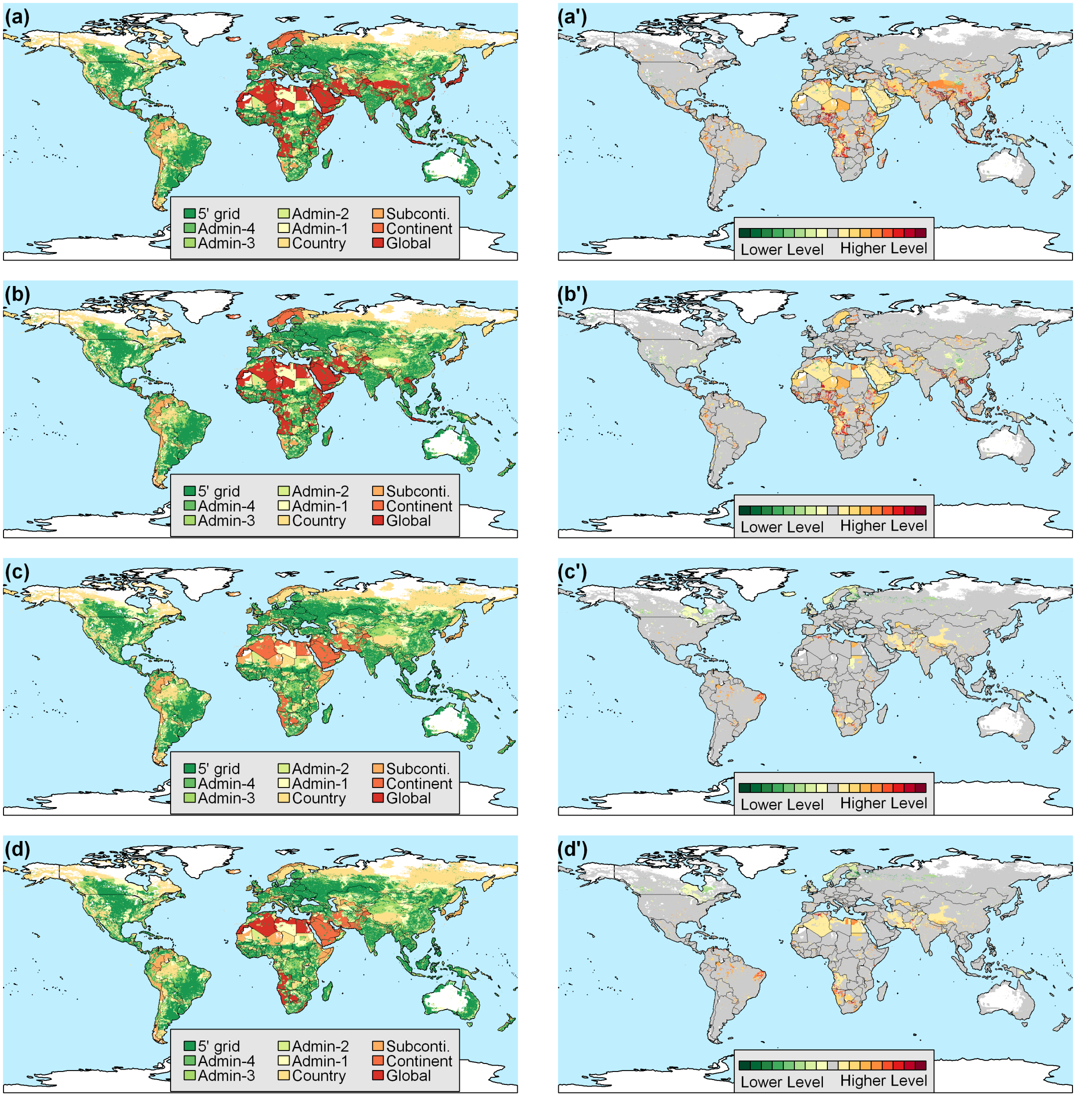

FIGURE C.6: Maps depicting the lowest possible spatial scale on which a region could obtain FSS by 2050 based on different scenarios with closing yield gaps to attain 90% of the high-input potential (left panel) and their differences with FSS status obtained for scenario group I with closing yield gaps to attain 90% of the high-input potential considering only population changes with constant climate (pop, no cc, and HI_{90}) (see Appendix Figure C.5c), showing whether FSS could be achieved in higher or lower spatial level/scale (right panel): (a) changes in population and dietary patterns with constant climate (pop+dp, no cc, and HI_{90}), (b) changes in population, dietary patterns and feed conversion efficiency with constant climate (pop+dp+fce, no cc, and HI_{90}), (c) scenario group I with IPCC's B2 scenario without CO_2 fertilization (pop, B2 no CO_2, and HI_{90}), and (d) scenario group I with IPCC's A2 scenario without CO_2 fertilization (pop, A2 no CO_2, and HI_{90}). The color coding in left panel represents the spatial scales that include 5′ grid, the fourth to the first level administrative unit (Admin-4 to Admin-1), country, subcontinent (subconti.), and continent.

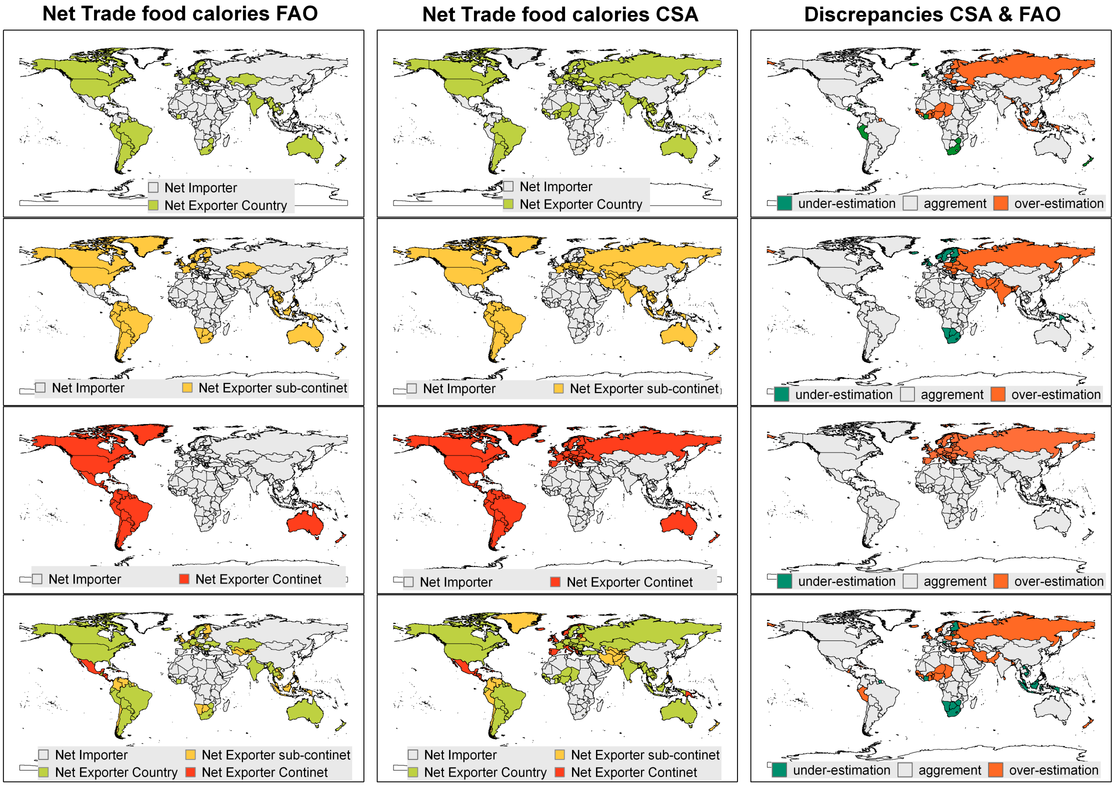

FIGURE C.7: Net food exporter and importer for the year 2000 derived using data from FAO (2011a) (first column) and from our cross-scale analysis of FSS (second column) along with their discrepancies (third column) on country scale (first row), subcontinental scale (second row), continental scale (third row), and on all these three scales together (fourth row) (for method see Appendix Text C.4). The observed discrepancies might be due to variation in crop balances our analysis and FAO (2011a) takes into account. We only consider crop balances in terms of human food and livestock feed, whereas, the FAO also considers other uses of crops, e.g., seed and other industrial utilities, for the crop balance.

Table C.1: List of crop types for which data on harvest area (H^j) (second column) and crops for which data on potential yield (Y^k) is provided by GAEZv3.0 (IIASA/FAO, 2012) along with respective nutritive factors (f^j)(FAO, 2001) and conversion factor (c^k) for harvested weight to dry weight (IIASA/FAO, 2012).

No.	Crop Type	Crop	Nutritive Factor (kcal/100 g)	Conversion Factor
1	maize	maize	356	0.87
2	millet	foxtail millet pearl millet	340	0.9
3	other cereals	rye buck wheat oat barley	340	0.888
4	rice	dryland rice wetland rice	280	0.9 0.875
5	sorghum	sorghum	332	0.88
6	wheat	wheat	334	0.875
7	banana & coconut	banana coconut	122	0.35 0.175
8	groundnut	groundnut	414	0.67
9	oil palm	oil palm	158	0.225
10	olive	olive	175	0.22
11	rapeseed	rapeseed	494	0.9
12	soybean	soybean	335	0.9
13	sunflower	sunflower	308	0.9
14	pulses	phaseolus bean pigeonpea cowpea chickpea drypea gram	340	1
15	cassava, yam, cocoyam	yam & cocoyam cassava	98.7	0.35
16	white & sweet potato	sweet potato white potato	79.5	0.275
17	sugar beet	sugar beet	70	0.14
18	sugarcane	sugarcane	30	0.1
19	vegetables	tomato onion cabbage carrot	22	0.15

TABLE C.2: Regional overview on production of crop and animal calories, and consumption/demand of food and feed. The columns present regional breakdown of crop calorie production based on data for 2000 (CP), low-input (CP_{Li}), and high-input potential (CP_{Hi}); animal calorie production for 2000 (AP) and 2050 considering population changes (AP_5) and changes in population and dietary patterns (AP_5^d); food consumption/demand for 2000 (FC) and 2050 considering population changes (FC_5) and changes in population and dietary patterns (FC_5^d); and feed consumption/demand for 2000 (FD) and 2050 considering population changes (FD_5), changes in population, and dietary patterns (FD_5^d), and changes including feed conversion efficiency ($FD_5^{d,f}$).

Regions	CP	CP_{Li}	CP_{Hi}	AP	AP_5	AP_5^d	FC	FC_5	FC_5^d	FD	FD_5	FD_5^d	$FD_5^{d,f}$
							10^{12} kcal/yr						
Africa													
East Africa	165	221	715	9	31	122	170	493	683	29	87	467	422
Middle Africa	58	59	238	2	9	29	62	175	241	10	74	272	271
North Africa	126	140	422	15	36	94	172	341	363	65	85	301	243
South Africa	56	50	128	6	9	10	50	69	65	21	23	25	25
West Africa	271	260	996	6	26	76	198	559	576	79	245	1,121	931
America													
Caribbean	23	30	84	3	5	13	27	38	48	11	13	40	42
Central America	149	119	356	22	35	76	134	206	234	87	117	272	220
North America	1,704	832	2,454	146	165	223	406	607	562	815	692	953	593
South America	756	425	1,382	28	67	261	425	678	876	150	180	819	629
Asia													
Central Asia	78	104	220	9	13	22	49	67	87	24	38	66	65
East Asia	1,774	1,114	2,390	236	329	686	1,509	1,719	1,970	803	551	1,203	695
South Asia	1,264	1,175	2,497	111	179	632	1,142	1,986	2,567	166	202	867	550
South East Asia	771	431	1,464	81	105	186	3,34	486	572	252	290	527	408
West Asia	172	185	436	21	43	114	174	321	349	101	150	408	360
Europe													
East Europe	731	721	2,319	84	61	79	329	263	273	374	240	327	287
North Europe	192	47	225	42	43	56	110	137	141	130	129	164	149
South Europe	264	167	450	49	52	74	170	192	189	226	228	333	280
West Europe	532	152	522	98	80	92	229	237	232	303	260	300	239
Ocenia													
Australia & New Zealand	149	76	218	22	12	17	23	38	43	38	42	61	49
World	9,235	6,308	17,516	990	1,300	2,862	5,713	8,612	10,071	3,684	3,646	8,526	6,458

Appendix D

Supporting Information: Closing Yield Gaps: How Sustainable Can We Be?[1]

D.1 Identification of Regions to Focus

D.1.1 Production Gaps

We used data on crop yields and crop harvest area from GAEZv3.0 (IIASA/FAO, 2012) for calculating total crop calorie production. GAEZv3.0 provides information on the current and potential crop yields for two types of water supply (irrigated and rain-fed) and the potential yields for three input levels (low, intermediate, and high) in a global raster grid of 5 arc minute resolution. GAEZv3.0 downscaled the current crop yields and area harvested on the grid for the year 2000 based on agricultural production statistics from the FAO and modeled the potential yields considering agricultural land resource conditions. Detailed methodology used to estimate the potential crop yields and to downscale the current crop yields is provided in the GAEZv3.0 model documentation (IIASA/FAO, 2012). Firstly, we calculated the current gridded crop calorie production (Ca) according to equation D.1 below using the data on the current crop yield (Ya_r^j and Ya_i^j, j: a crop type, r: rain-fed, i: irrigated) and area harvested (H_r^j and H_i^j), and respective nutritive factors for converting crop mass into calories (f^j) from FAO (FAO, 2001) (Appendix Table D.1).

$$Ca = \sum_{j=1}^{n} \left(\left(Ya_r^j \times H_r^j + Ya_i^j \times H_i^j \right) \times f^i \right) \quad \text{(D.1)}$$

Secondly, we used data on potential yields (IIASA/FAO, 2012) for estimating the potential crop calorie production. The potential crop yields are provided in t/ha in dry weight equivalents whereas the nutritive factors (f^j) used to convert crop mass into crop calories

[1]This appendix and Chapter 5 have been published as: Pradhan, P., Fischer, G., van Velthuizen, H., Reusser, D. E., & Kropp, J. P. (2015). Closing Yield Gaps: How Sustainable Can We Be? PLoS ONE, 10(6), e0129487. http://dx.doi.org/10.1371/journal.pone.0129487

are in terms of harvested weight. Hence, we used conversion factors (c^k) to convert yields in dry weight into harvested weight (IIASA/FAO, 2012). The combination of the crop production based on rain-fed and irrigated agriculture obtained by multiplying the high-input potential yields (Yh_r^k and Yh_i^k) by their respective harvested area (H_r^j and H_i^j) provides the potential crop calorie production for high-input levels (Ch) (equation D.2). As GAEZv3.0 provides data on irrigated crop yields only for intermediate and high input levels (IIASA/FAO, 2012), we assumed that the combination of crop yields based on low-input rain-fed (Yl_r^k) and intermediate-input irrigated agriculture (Ym_i^k) provides the low-input crop calorie production (Cl) (equation D.3). Data on potential yields are available for all individual crops but data on harvested area are provided only for the crop type instead of the individual crops. Hence, for each cell we used data for the individual crop with the highest yield among this crop type (nc: number of crops).

$$Ch = \sum_{j=1}^{n} \left(\left(max \left(\left\{ \frac{Yh_r^k}{c^k} \right\}_{k=1}^{nc} \right) \times H_r^j + max \left(\left\{ \frac{Yh_i^k}{c^k} \right\}_{k=1}^{nc} \right) \times H_i^j \right) \times f^j \right) \tag{D.2}$$

$$Cl = \sum_{j=1}^{n} \left(\left(max \left(\left\{ \frac{Yl_r^k}{c^k} \right\}_{k=1}^{nc} \right) \times H_r^j + max \left(\left\{ \frac{Ym_i^k}{c^k} \right\}_{k=1}^{nc} \right) \times H_i^j \right) \times f^j \right) \tag{D.3}$$

Both equations above sum up the 19 crop types $j = 1 \ldots n$, accounting for more than 90% of the global crop calories produced in the year 2000. Among 23 crop types considered by GAEZv3.0, we excluded non-food crop (e.g., cotton and fodder), stimulant cash crops (e.g., tea, coffee, and cacao) and crops under residual section for this analysis.

We defined crop calorie production gap of a region as a ratio between potential and current crop calorie production in the region (Gh). The ratio less than 1 shows the potential of the region to produce more crops. Since agricultural management varies across agro-climatic zones, regions for the production gap analyses were defined by country and by moisture regime (CMR symbolized by z, and x symbolized the raster cell) as represented by equation D.4. Information on seven moisture regimes was derived from GAEZv3.0 data on the length of growing period. The seven moisture regimes are: hyper-arid (0 days growing period), arid (1-59 days growing period), dry semi-arid (60-119 days growing period), moist semi-arid (120-179 days growing period), sub-humid (180-269 days growing period), humid (270-365 days growing period), and per-humid (365 days continuous growing period). The length of growing period represents the number of favorable days during the year for crop growth based on moisture availability and temperature (IIASA/FAO, 2012).

$$Gh_z = \left(\sum_{x \in z} Ca_x \right) / \left(\sum_{x \in z} Ch_x \right) \tag{D.4}$$

D.1.2 Calorie Deficits

We identified regions with crop calorie deficits based on the difference between production and consumption of crop calories. The crop calorie consumption consisted of human vegetal product intake and crop-based feed provided to livestock. We estimated vegetal product consumption (V_x) in a $5'$ raster grid by multiplying countrywide per capita vegetal product intake (FAO, 2011a) with the gridded population data (CIESIN/IFPRI/CIAT, 2011a) for the year 2000. Before that, we aggregated the gridded population data in $2.5'$ resolution to $5'$ by summing up population counts. Moreover, for those countries with the total food consumption of less than 2,200 kcal/cap/day we adjusted the vegetal products consumption to meet the average moderate calorie diet of 2,200 kcal/cap/day (Pradhan et al., 2013b). For crop-based feed consumption, we used the gridded feed data (F_x) (Pradhan et al., 2013a). On CMR level, we estimated crop calorie deficits (Da_z and Dh_z) based on the current and the potential crop calorie production (Ca_z and Ch_z), respectively, as represented by equations D.5 and D.6.

$$Da_z = \left(\sum_{x \in z} (V_x + F_x) \right) / Ca_z \tag{D.5}$$

$$Dh_z = \left(\sum_{x \in z} (V_x + F_x) \right) / Ch_z \tag{D.6}$$

D.1.3 Clustering Regions

In the next step, we classify regions into the six groups based on prevalence and depth of crop production gaps and crop calorie deficits. The following procedures are used:

1. If $Da_z \leq 1$, the regions achieved FSS. We considered these regions as capable of producing enough crop calories to meet their consumption demand.

2. Afterwards, we investigated the regions that are capable of producing enough crop calories by achieving the high-input potential yields. For this, we distinguished arid and humid regions as agricultural management varies across agro-climatic zones. Hence, for the remaining regions, if $Dh_z \leq 1$ and falls in one of the hyper-arid, arid, dry semi-arid, and moist semi-arid zones, we marked it $FSS_{hi,ar}$. However, if it falls in one of the sub-humid, humid, and per-humid zones, we marked it $FSS_{hi,hm}$.

3. Then, if the remaining regions with crop calorie production gap (i.e., $Gh_z < 1$) fall in one of the hyper-arid, arid, dry semi-arid, and moist semi-arid zones, we marked them $ICP_{hi,ar}$. However, if they fall in one of the sub-humid, humid, and per-humid zones, we marked them $ICP_{hi,hm}$. These are regions capable of producing more crop calories by achieving high-input potential yields but aren't food self-sufficient.

4. The final step consists of marking the entire remaining regions that are crop deficits as crop insufficient (CIS). These are the regions which almost achieved their potential crop calorie production and are dependent on trade to meet feed and food demand.

D.1.4 Scenarios

To analyze scenarios for 2050, we considered changes in population (UN, 2011) and dietary patterns (Pradhan et al., 2013b) that drives the future food and feed demand (Pradhan et al., 2013a), and progress on closing crop yield gaps that influences the future food and feed supply.

The first one (scenario A) is a baseline scenario where the dietary pattern of a country stays the same as in the year 2000 but population changes for all countries. This scenario provides results for a low bound. Moreover, for those countries with the total food consumption of less than 2,200 kcal/cap/day, we maintained a minimum calorie intake of 2,200 kcal/cap/day as described above. We used gridded population for 2050 (Pradhan et al., 2014) that was downscaled based on the mid-range population scenario from UN (2011) and gridded feed calorie demand for 2050 (Pradhan et al., 2013a). The gridded feed calorie demand is based on similar scenario accounting for population growth with constant dietary pattern.

The second scenario (scenario B) takes into account country-specific changes in dietary patterns in addition to the population growth, however, maintaining a minimum calorie intake of 2,535 kcal/cap/day, representing an average of high calorie diets (Pradhan et al., 2013b). The future per capita food demand by country is estimated up to 2050 based on observed exponential relationships between per capita food intake and the Human Development Index (HDI) (Pradhan et al., 2013b), using the HDI extrapolation based on logistic regression (Costa et al., 2011). This scenario provides results for an upper bound based on changes in dietary patterns and population. Additionally, we used data on gridded feed calorie demand for 2050 considering similar changes in population and dietary patterns (Pradhan et al., 2013a).

We carried out scenario analyses to identify regions where closing the production gaps matters to ensure the future food self-sufficiency using the methods described in Section D.1.3. The estimation of future crop calorie production needs to account for complex influences of population change, climate change and technological progress since the year 2000. However, we kept our analysis simple by considering the crop calorie production in the year 2000 and the high input potential crop calorie production with a constant climate. But we took into account loss in crop production due to an increase in population leading to an expansion of build-up land encroaching on cultivated land based on Pradhan et al. (2014). Crop production changes due to an increase in build-up land and population was kept the same for both scenarios.

D.2 Identification of Management Strategies

A number of biophysical and socioeconomic factors have an effect on the yield gaps (Fischer et al., 2011, Lobell et al., 2009). In general, such biophysical factors are: nutrient imbalances, water scarcity, climate variability, suboptimal planting, weed pressure, insect and disease damage, inferior seed quality, and climatic and edaphic workability constraints. Socioeconomic factors are: profit maximization, credit availability, limited labor supply, knowledge on best practices, accessibility to market, farm size, land tenure, and extension services. Data on spatial distribution of such factors are limited. Hence, we used the GAEZv3.0 model (IIASA/FAO, 2012) to identify spatial distribution of constraints that the above factors may exhibit. With this, we covered most biophysical factors, however, socioeconomic factors are limitedly represented and based on few indicators.

We started the analysis looking at agro-climatic constraints that represent climate related yield losses due to pests, diseases, weeds, and workability. GAEZv3.0's Module III provides spatial distribution of agro-climatic constraints factor (cf) in percentage in a 5′ raster grid for low (l) and high (h) input farming by crops, which were derived based on climatic conditions. The values of cf represent attainable percentage of the constraint free crop yields considering yield losses due to agro-climatic constraints for a specific level of agricultural inputs and management conditions. A low-input farming system is largely subsistence labor intensive agriculture, lacking application of nutrients and agro-chemicals, traditional management with minimum conservation measures and a high-input farming system is mainly commercial mechanized agriculture with optimum application of nutrients, and agro-chemicals (IIASA/FAO, 2012). This factor is related to yield reduction due to pests, diseases, weeds, and workability, of which the first three could be overcome by improved pest management, including application of agro-chemicals. However, climate related soil workability does not improve with high-input farming. We calculated the difference (df) between the agro-climatic constraints factor for low and high input farming for a crop to identify regions where the constraints could be overcome by shifting from low to high input farming (equation D.7). We used crops (j) in two crop groups (cereals and roots-tubers) to estimate weighted difference (dF) based on their respective harvested area (ha) (equation D.8).

$$df = cf_h - cf_l \tag{D.7}$$

$$dF = \left(\sum_{j=1}^{n} \left(df^j \times ha^j \right) \right) / \left(\sum_{j=1}^{n} ha^j \right) \tag{D.8}$$

GAEZv3.0's Module IV carries out edaphic assessment and simulated yield reduction due to soil and terrain limitations (IIASA/FAO, 2012). We used data on soil limitations from GAEZv3.0 to identify regions where there is a need for soil quality management to bridge the yield gap. GAEZv3.0 differentiates soil qualities into seven types: nutrient availability, nutrient retention capacity, rooting conditions, soil drainage associated with oxygen availability to roots, excess salts, toxicity, and workability. Constraints related to these soil qualities are classified mainly into four categories: no or slight constraints, moderate constraints, severe constraints, and very severe constraints. Among the seven soil qualities, constraints related to three of them (rooting conditions, excess salts, and toxicity) are difficult to overcome by high-input farming. Additionally, nutrient supply is essential for achieving high yield, which we accounted separately and elaborated in Appendix Text D.3. Therefore, we considered the remaining three soil quality factors (nutrient retention capacity, soil drainage, and soil workability) for further analysis. Subsequently, we identified regions where constraints related to one or multiple of these qualities are moderate to very severe. These are regions where improved management of one or multiple of these soil qualities would enhance crop yields.

Secondly, we attempted to capture the socioeconomic factors that play important roles in closing yield gaps based on two indicators: yield variability and travel time to the nearest market. The yield variability due to weather conditions might make farmers reluctant to take risks in terms of input applications. GAEZv3.0 also provides data on coefficient of variation of agro-climatically attainable yields for the baseline period of 1961–1990 (IIASA/FAO, 2012). We used this data for crops (j) in two crop groups (cereals and roots-tubers) to estimate weighted yield variations (CV) based on irrigated (i) and rain-fed (r) harvested area (ha), and identified regions with high overall year-to-year yield variations (equation D.9). Travel time to the nearest market is also an important factor to support agricultural productivity in two ways. Firstly, it determines farmers' accessibility to agricultural inputs. Secondly, it influences market accessibility for vending agricultural products. Consequently, we used spatially explicit accessibility data presenting travel time to the nearest market with a population of around 50,000 (IIASA/FAO, 2012) to identify regions with different connectivity to markets.

$$CV = \left(\sum_{j=1}^{n} \left(cv^j \times ha_r^j \right) \right) / \left(\sum_{j=1}^{n} \left(ha_r^j + ha_i^j \right) \right) \tag{D.9}$$

Lastly, we determined regions with similar constraint compositions from the prevalence of the four constraints mentioned above (soil related constraints, weather induced yield variability, agro-climate related pest, disease, and weed constraints, as well as market accessibility). The composite constraints factors used are as follows:

- weighted difference between agro-climatic constraints factor (dF) for low-input and high-input farming larger than 5%,
- any of the above mentioned three soil quality constraints,
- weighted yield variation (CV) larger than 20%, and
- travel time to nearest market greater than 6 hours

Beyond the application of nutrients and the use of improved cultivars, there is a need to include other specific agricultural inputs, management, and socioeconomic infrastructure that tackles the constraints described above to close yield gaps. Details on such specific input and management interventions are provided in the main text. Location specific input and agricultural management strategies depend on prevalence of one or more of the above constraints. For simplicity, we designed agriculture management strategies such that they aim to overcome and reduce constraints causing yield gaps.

D.3 Nutrients Required

We further estimated the amount of three macro-nutrients required (N, P_2O_5, and K_2O) to achieve the potential yields. To obtain a sustainable crop yield superior to the low-input yields, nutrient application is needed in addition to natural nutrient regeneration. For quantifying the required nutrients, we initially calculated crop nutrient uptake in yield and in residue. We considered differences between yields and residues of the 16 crop types from GAEZv3.0 for high and low inputs, taking into account their fallow period requirements. In low-input farming, the fallow period requirement is longer than that for high-input due to need for natural nutrient regeneration that is substituted by fertilizer application in high-input agriculture. GAEZv3.0 provides crop-specific fallow period requirements ($f_{i,j}$: for crop j in location i) for high (h) and low (l) inputs by soil type and by climatic condition. We obtained fallow factor ($\kappa_{i,j}$) for high and low inputs using the respective fallow period requirements as presented by equation D.10. Residue for a crop type ($R_{i,j}$) was estimated based on its yield ($Y_{i,j}$) and harvest index (hi_j) (IIASA/FAO, 2012) using equation D.11. Harvest index is represented by the weight of harvested crop as a percentage of the total plant weight.

$$\kappa_{i,j} = \frac{(100 - f_{i,j})}{100} \tag{D.10}$$

$$R_{i,j} = (1 - hi_j) \times Y_{i,j} \tag{D.11}$$

Afterwards, multiplying the differences in crop yields and residues by the crop specific nutrient uptake per tonne of yield (Fc_j^k: for nutrient type k) and per tonne of residue (Fr_j^k) respectively (Appendix Table D.1), we estimated the amount of nutrient uptake in the crop yield and the crop residue as shown by equation D.12 and D.13. GAEZv3.0 provides information on the current and the potential crop yields for two types of water supply (irrigated and rain-fed) and the potential yields for three input levels (low, intermediate, and high). Since data on irrigated crop yields is provided only for intermediate and high input levels, we considered the differences between crop yield and crop residue based on high and intermediate inputs for irrigated cultivated land, instead of the low input ones in equations D.12 and D.13.

$$Fc_{i,j}^k = \left(\kappa_{i,j}^h \times Y_{i,j}^h - \kappa_{ij}^l \times Y_{i,j}^l\right) \tag{D.12}$$

$$Fr_{i,j}^k = \left(\kappa_{i,j}^h \times R_{i,j}^h - \kappa_{ij}^l \times R_{i,j}^l\right) \tag{D.13}$$

In the next step, we obtained total nutrient uptake in crop yields and residues summing up the individual nutrient uptake for the 16 crop types in GAEZv3.0 excluding olive, oil palm, cotton, cash crop 1, cash crop 2, fodder, and residual as presented by equations D.14. For this, we considered crop yields in both irrigated (w) and rain-fed (r) cultivated land and respective harvest area (ha). Sum up of nutrient uptake in yields and residues provides total additional nutrient uptake (NF_i^k) by the high input crop production compared to the low input ones.

$$NF_i^k = \sum_{j=1}^{16}\left(Fc_{i,j}^{k,r} \times ha_{i,j}^r + Fc_{ij}^{k,w} \times ha_{i,j}^w\right) + \sum_{j=1}^{16}\left(Fr_{i,j}^{k,r} \times ha_{i,j}^r + Fr_{ij}^{k,w} \times ha_{i,j}^w\right) \tag{D.14}$$

Finally, the total nutrients required were estimated considering nutrient removal and nutrient losses due to leaching and volatilization. Here we assumed that both crop products (e.g., grain) and residues (e.g., straw) are removed from the field. Hence, nutrient removal that has to be replenished by nutrients (organic or chemical fertilizer), is equal to nutrient uptake in crop yields and residues. Additionally, nutrient losses depend on nutrient type and its application efficiencies. Therefore, we considered a parameter inverse of the fertilizer application efficiency τ_i^k that may vary spatially, to estimate the total nutrient required (equation D.15).

$$GF_i^k = NF_i^k \times \tau_i^k \tag{D.15}$$

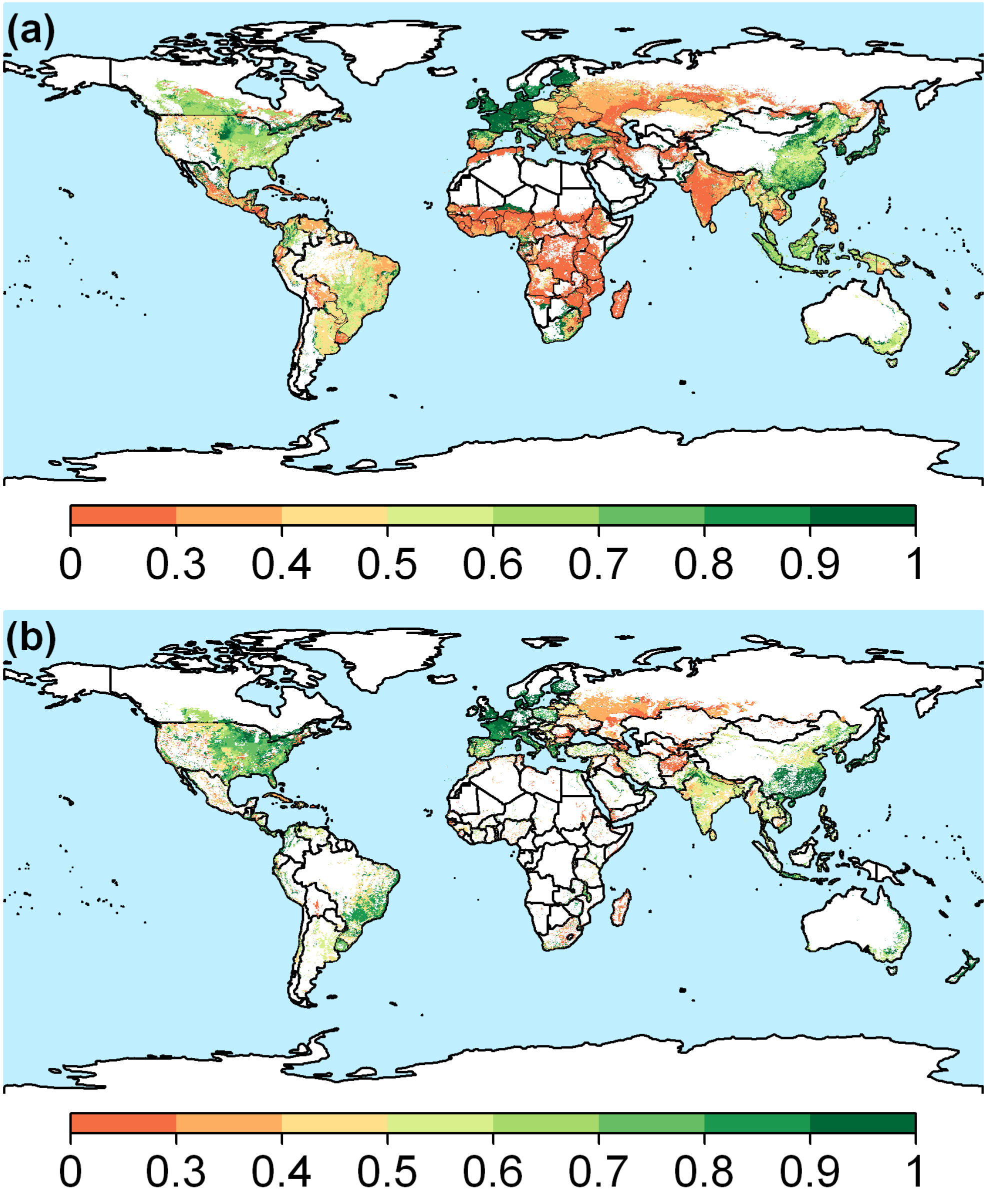

FIGURE D.1: Location specific ratio of high-input crop calorie production attained in 2000 based on types of water supply: (a) rain-fed cultivated land and (b) irrigated cultivated land. The ratio of 1 represents regions that have achieved their high-input crop calorie production.

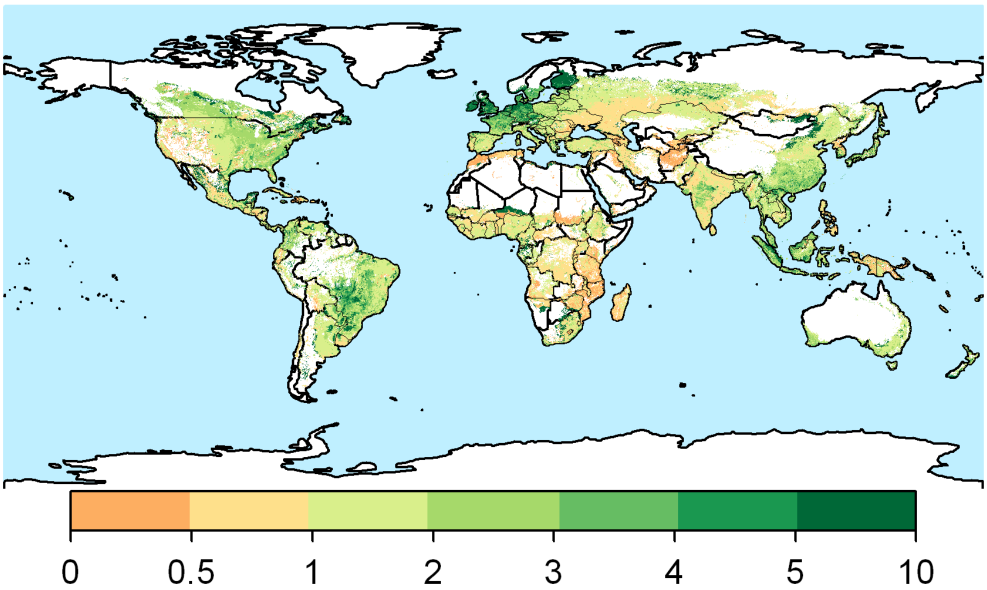

FIGURE D.2: Map depicting ratio between the current crop calorie production for 2000 and the low-input crop calorie production. The values greater than 1 represent regions with the current crop calorie production larger than the low-input calorie production.

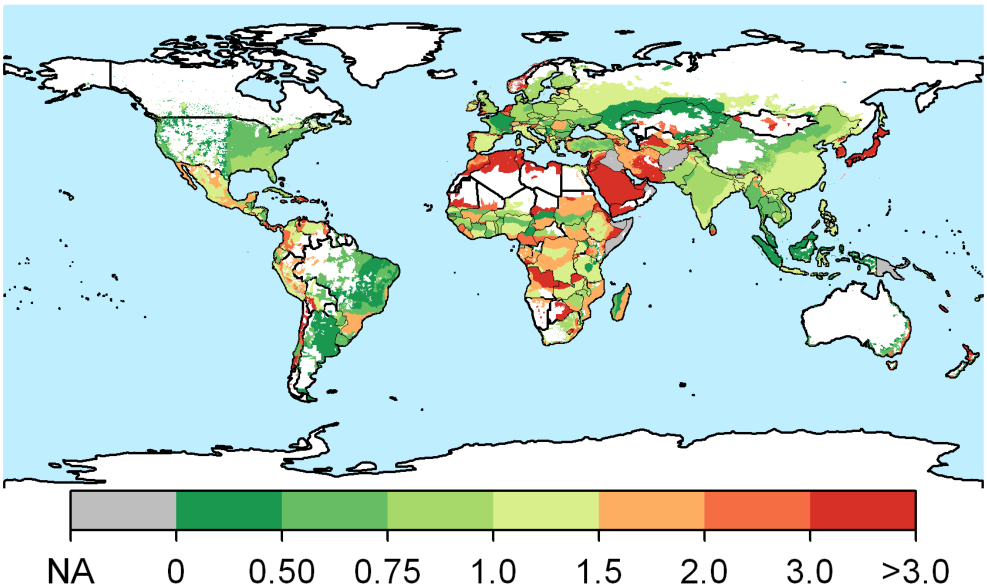

FIGURE D.3: Ratio between consumption and production of crop calories by country and by moisture regimes. The values greater than 1 represent regions with crop calorie consumption greater than crop calorie production. Since agricultural production constraints and agricultural management vary with agro-climatic conditions, the results are presented by country moisture regime going beyond national scales. NA represents regions with missing data.

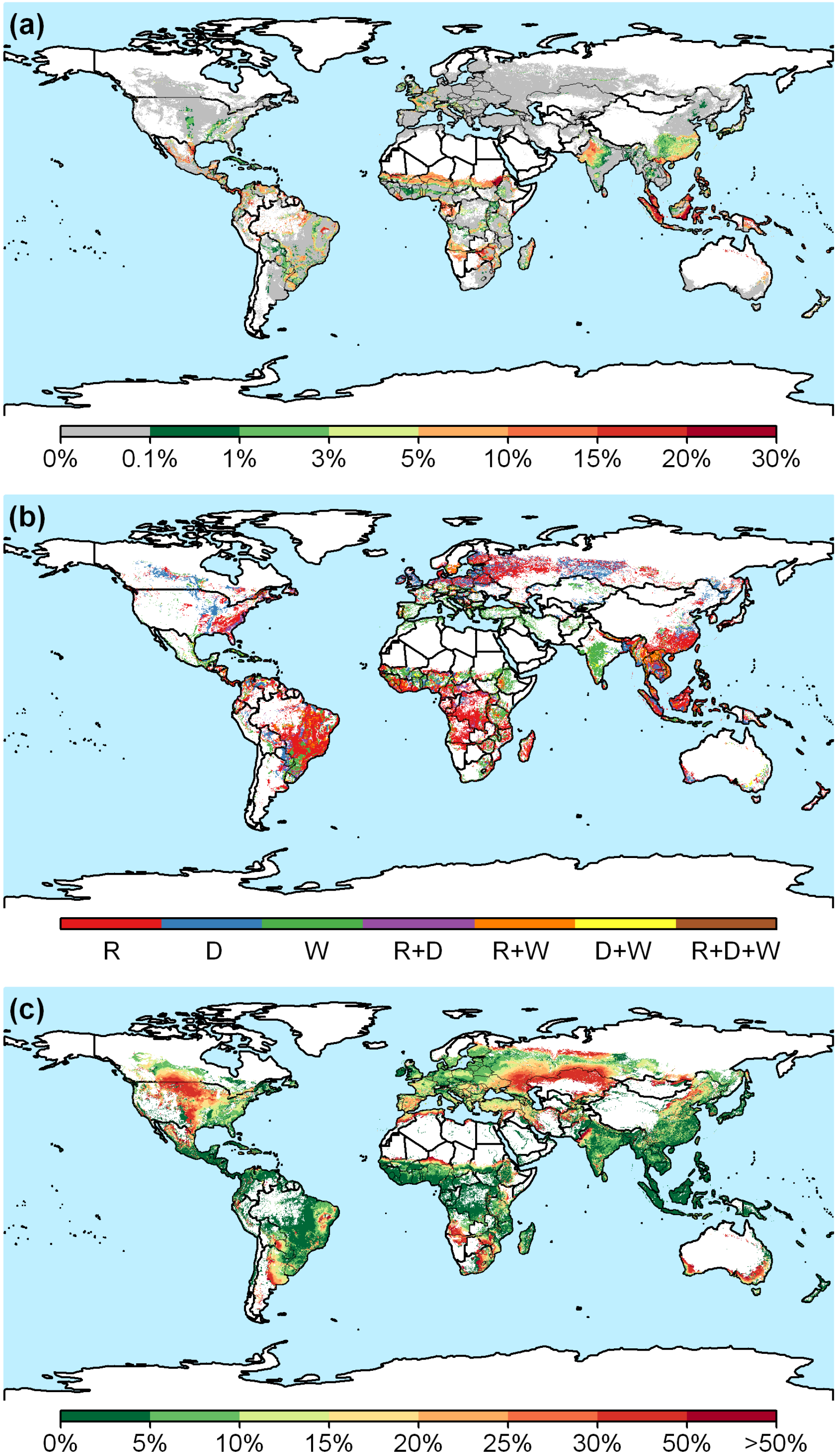

FIGURE D.4: Indicators used to distinguish yield reducing factors that could be overcome by shifting from low-input to high-input farming: (a) weighted difference between agro-climatic constraints factor in percentage for low-input and high-input farming, (b) location specific most severe soil quality constraints based on three soil qualities (nutrient retention capacity (R), soil drainage (D), and soil workability (W)), and (c) weighted coefficient of variation of agro-climatic yields in percentage.

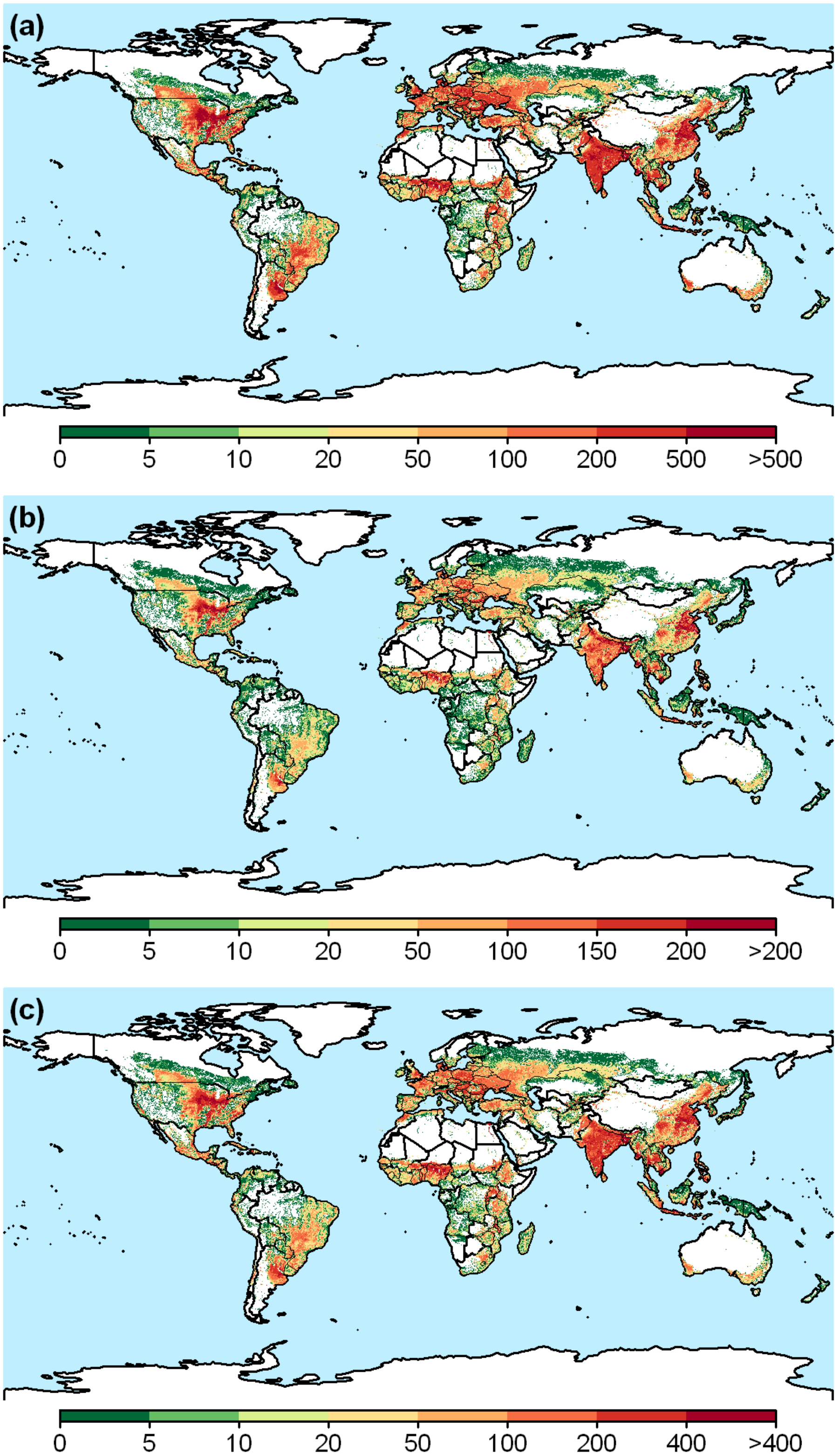

FIGURE D.5: Additional amount of macro-nutrients (in tonnes per pixel per year) uptake by crops in their yields and residues by attaining high input potential yields compared to that with low input yields: (a) nitrogen - N total nutrients, (b) phosphate - P_2O_5 total nutrients, and (c) potash - K_2O total nutrients.

TABLE D.1: List of crop types for which data on harvest area (H^j) (second column) and crops for which data on potential yield (Y^k) (thrid column) is provided by GAEZv3.0 (IIASA/FAO, 2012) along with their nutritive factors (f^j) (FAO, 2001), conversion factor (c^k) for harvested weight to dry weight (IIASA/FAO, 2012), and nutrient uptakes from various sources compiled by authors (IPNI, 2012, MSU, 1992, USDA, 2000).

No.	Crop Type	Crop	Nutritive Factor (kcal/100 g)	Conversion Factor	N–uptake (kg/t)		P_2O_5–uptake (kg/t)		K_2O–uptake (kg/t)	
					Yield	Residue	Yield	Residue	Yield	Residue
1	maize	maize	356	0.87	12.0	8.0	6.3	2.9	4.5	20.0
2	millet	foxtail/pearl millet	340	0.9	28.0	7.7	8.0	2.2	8.0	20.0
3	other cereals	barley	340	0.888	21.0	6.5	8.3	2.6	6.7	20.0
		buck wheat			14.0	12.6	5.0	1.6	4.4	13.9
		oat			24.0	6.6	8.8	3.2	5.9	19.0
		rye			25.0	6.0	8.2	1.5	5.5	11.0
4	rice	dryland rice	280	0.9	13.0	8.3	6.7	2.7	3.6	21.0
		wetland rice		0.875						
5	sorghum	sorghum	332	0.88	13.0	14.0	7.8	4.2	5.4	21.0
6	wheat	wheat	334	0.875	22.0	7.6	8.8	1.9	5.2	15.0
7	banana & coconut	banana	122	0.35						
		coconut		0.175						
8	groundnut	groundnut	414	0.67	6.4	3.6	6.9	3.2	12.0	12.0
9	oil palm	oil palm	158	0.225						
10	olive	olive	175	0.22						
11	rapeseed	rapeseed	494	0.9	38.0	6.8	24.0	2.4	40.0	11.4
12	soybean	soybean	335	0.9	55.0	20.0	12.0	4.4	20.0	19.0
13	sunflower	sunflower	308	0.9	27.0	12.0	9.7	1.0	9.0	17.0
14	pulses	chickpea/drypea/pigeonpea	340	1	38.0	22.3	4.1	4.6	11.2	10.9
		cowpea			27.2	27.2	2.7	2.7	18.2	18.2
		gram/phaseolus bean			50.0	27.2	13.0	6.0	15.0	18.1
15	cassava & yam	cassava,yam & cocoyam	98.7	0.35	3.2	2.0	0.9	1.1	4.8	3.0
16	potato	white/sweet potato	79.5	0.275	3.2	2.0	1.2	0.5	5.5	3.0
17	sugar beet	sugar beet	70	0.14	1.9	3.7	1.1	2.0	3.7	10.0
18	sugarcane	sugarcane	30	0.1	1.0	1.5	0.7	0.3	1.8	1.2
19	vegetables	cabbage	22	0.15	3.3	3.3	0.9	0.9	3.2	3.2
		carrot			1.9	1.2	0.9	0.2	3.0	3.1
		onion			2.7	3.0	1.4	7.5	2.3	4.4
		tomato			1.3	18.2	0.5	4.2	2.9	36.0

TABLE D.2: Regional overview on area of rain-fed cultivated land where different inputs and management strategies in addition to adequate fertilizer application (F) are required to close the yield gaps. The strategies consist of soil quality management (S), managing accessibility to markets (A), weather induced yield variability management (V), and management of pests, diseases, and weeds (P). The different management strategies can have combinations of the individual elements (F, S, A, V, and P).

Regions	**F**	**S**	**A**	**AS**	**V**	**VS**	**VA**	**VAS**	**P**	**PS**	**PA**	**PAS**	**PV**	**PVS**	**PVA**	**PVAS**	**Total**
	in million hectares																
Africa																	
East Africa	6.35	25.34	4.23	12.09	1.16	5.53	0.83	2.36	0.48	2.05	0.13	0.5	0.07	0.11	0.01	0.03	61.27
Middle Africa	0.98	15.84	0.67	13.21	0.07	1.72	0.05	2.15	0.07	1.34	0.03	1.37	0	0.03	0	0	37.53
North Africa	4.17	7.68	1.45	4.02	3.52	5.06	0.08	0.56	0.03	0.05	0.14	0.19	0	0	0	0	26.95
South Africa	1.4	3.49	0.4	0.98	2.31	5.55	0.32	1.31	0	0	0	0	0	0	0	0	15.76
West Africa	8.81	56.91	1.7	10.29	0.04	1.83	0.05	1.47	0.12	2.13	0.01	0.49	0	0	0	0	83.85
America																	
Caribbean	1.99	3.11	0.06	0.05	0.08	0.17	0.01	0.02	0.04	0.08	0	0	0	0	0	0	5.61
Central America	7.1	9.08	1.12	1.58	0.73	1.01	0.08	0.19	2.8	3.71	0.48	0.69	0.06	0.04	0	0.02	28.69
North America	42.75	40.58	4.42	2.79	77.04	21.28	3.28	0.55	0.49	1.42	0.01	0.05	0.01	0.02	0	0	194.69
South America	17.56	53.17	2.31	10.35	7.61	5.99	1.17	1.36	1.4	11.47	0.47	2.13	0.05	0.48	0.02	0.08	115.62
Asia																	
Central Asia	0.84	0.47	0.14	0.06	11.62	2.62	7.9	2.65	0	0	0	0	0	0	0	0	26.30
East Asia	32.98	26.73	6.28	4.51	6.09	2.29	1.63	0.32	1.37	7.03	0.17	0.37	0.02	0.02	0.01	0.01	89.83
South Asia	39.7	70.09	2.26	4.38	7.11	9.67	2.01	1.68	0.34	0.95	0.02	0.09	0	0.02	0.01	0.03	138.36
S.-East Asia	5.2	28.61	3.25	8.83	0.08	0.14	0.03	0.17	2.88	19.87	1.01	10.56	0.02	0.03	0.02	0.12	80.82
West Asia	13.38	8.42	0.49	0.38	3.79	2.38	0.13	0.1	0.03	0.06	0	0	0.01	0	0	0	29.17
Europe																	
East Europe	54.09	41.67	1.42	1.3	77.19	12.12	2.84	1.18	0.04	0.04	0	0	0.01	0	0	0	191.90
North Europe	3.87	12.1	0.03	0.09	0.03	0.13	0.01	0.03	0.33	0.68	0	0	0	0	0	0	17.30
South Europe	10.87	8.8	0.24	0.1	6.05	4.73	0.17	0.05	0.97	0.77	0.01	0.01	0.02	0.01	0	0	32.80
West Europe	12.63	12.35	0.02	0.02	0.56	0.47	0	0	2.6	2.32	0	0	0.23	0.08	0	0	31.28
Oceania																	
Australia & New Zealand	5.16	5.17	0.54	0.96	15.14	12.28	1.69	2.42	0.18	0.26	0	0.01	0	0	0	0	43.81
World	**269.82**	**429.6**	**31.01**	**75.98**	**220.23**	**94.95**	**22.29**	**18.56**	**14.18**	**54.23**	**2.49**	**16.47**	**0.51**	**0.86**	**0.06**	**0.3**	**1,251.54**

TABLE D.3: Regional overview on additional amount of macro-nutrients (N, P_2O_5, and K_2O) uptake by crop yields (Y) and crop residues (R) by attaining high input potential yields compared to that with low input yields, and regional overview on the amount of fertilizers applied in the year 2010.

Regions	**N** uptake & applied (1000 tonnes/year)			**$P_2 0_5$** uptake & applied (1000 tonnes/year)			**$K_2 0$** uptake & applied (1000 tonnes/year)		
	yield (Y)	residue (R)	applied (A)	yield (Y)	residue (R)	applied (A)	yield (Y)	residue (R)	applied (A)
Africa									
East Africa	2,455	970	581	294	967	330	1,077	1,645	90
Middle Africa	557	232	21	80	233	9	321	418	15
North Africa	1,494	533	1,723	160	648	523	507	945	76
South Africa	357	124	398	40	167	162	131	270	106
West Africa	3,450	1,484	287	450	1,360	130	1,479	2,441	97
America									
Caribbean	134	65	179	20	59	51	77	105	43
Central America	1,022	445	1,563	137	458	290	390	805	323
North America	11,976	3,216	13,472	896	4,195	4,503	4,221	5,387	4,585
South America	7,273	2,131	5,651	555	2,270	4,,721	2,693	3,102	4,676
Asia									
Central Asia	962	195	833	52	381	127	250	387	37
East Asia	8,574	2,508	35,752	803	3,688	17,504	3,367	5,110	5,766
South Asia	11,377	3,888	21,343	1,096	4,505	9,616	3,865	6,819	3,936
S.-East Asia	3,469	1,381	7,117	441	1,629	1,814	1,179	3,088	2,746
West Asia	1,895	464	1,987	127	724	737	527	852	149
Europe									
East Europe	9,697	2,261	5,002	600	3,739	1,580	2,883	4,417	1,819
North Europe	1,083	246	2,224	67	419	498	344	469	644
South Europe	1,479	401	2,033	117	594	864	459	804	789
West Europe	2,234	510	4,213	143	909	653	788	981	978
Oceania									
Australia & New Zealand	986	228	1,487	60	397	1,325	294	418	221
World	**70,513**	**21,297**	**105,890**	**6,141**	**27,356**	**45,442**	**24,874**	**38,492**	**27,112**

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Declaration of Authorship

I, Prajal Pradhan, declare that this dissertation titled, 'Food Demand and Supply under Global Change' and the work presented in it are my own. I prepared this dissertation without illegal assistance. I confirm than the work is original except where indicated by special reference in the text and no part of the dissertation has been submitted for any other degree.

This dissertation has not been presented to any other University for examination, neither in Germany nor in another country.

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