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Indirect effects of global climate change and the impact of extreme weather events on the German food system

by

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ABSTRACT

The long-term reduction of hunger has recently slowed down as a result of ongoing global climate change, increasing climate variability, and extreme weather events, disrupting our global food system. The direct impacts of climate change in Germany are expected to be comparably low and the ability to adapt to these impacts is high. However, it is likely that Germany, as part of a highly interconnected world, may become increasingly affected by climate change impacts in other world regions. This thesis investigates how adverse effects of global climate change can be transferred across borders to demonstrate the various potential indirect impacts of climate change and extreme weather events on food systems. Moreover, this study seeks to assess how far the direct effects on agricultural productivity abroad and the disruption of transportation-related infrastructures can affect the German food system to depict its level of exposure to the indirect effects of global climate change via trade of agricultural commodities. The results show that Germany is heavily dependent on the import of soybeans, palm oil, bananas, and coffee from increasingly vulnerable trading partners outside of Europe. The direct impact on the production of these commodities represents a significant threat to the German food system via trade. The evidence suggests that improved understanding of the indirect impacts of climate change on food systems is needed to be able to adapt to the full range of risks from climate change, climate variability and extreme events on agricultural production.

Keywords: Climate change, extreme weather events, climate change impacts, transmission pathways, indirect effects, agricultural productivity, food systems, trade

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LIST OF ABBREVIATIONS

°C	Degree Celsius
Ag GDP	Agricultural gross domestic product
AR4	Fourth Assessment Report of the IPCC
AR5	Fifth Assessment Report of the IPCC
BBK	Bundesamt für Bevölkerungsschutz und Katastrophenhilfe
BMEL	Bundesministerium für Ernährung und Landwirtschaft
CFS	Committee on World Food Security
CO_2	Carbon dioxide
DBV	Deutscher Bauernverband
EEA	European Environment Agency
EUR; €	Euro
EURAC	European Academy of Bolzano
FAO	Food and Agriculture Organization of the United Nations
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
GCM	General Circulation Model
GDP	Gross domestic product
IDMC	Internal Displacement Monitoring Centre
IFAD	International Fund for Agricultural Development
IPCC	Intergovernmental Panel on Climate Change
LfL	Bayerische Landesanstalt für Landwirtschaft
LSAT	Land-surface air temperature
MIT	Massachusetts Institute of Technology
NRC	Norwegian Refugee Council
OEC	Observatory of Economic Complexity
ppm	Parts per million
PRC	Plan + risk consult
PwC	PricewaterhouseCoopers
SST	Sea-surface temperature
UN	United Nations
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
US$	US Dollar
WFP	World Food Programme
WTO	World Trade Organization
WWF	World Wide Fund For Nature

1 Introduction

There is a long list of problems arising from a rapidly changing climate, however, the risks to world agriculture and the achievement of future food security is among the greatest challenges of our time. Depletion of scarce resources, land cover change, changes in the hydrological cycle and the availability of fertile soils are, among others, the major environmental challenges impacting on the global food production (Adger et al., 2009). Although great effort has been made in the last decades, the long-term reduction of hunger has recently slowed down as a result of increasingly volatile food prices, extreme weather events, and ongoing global climate change, disrupting our global food system (Wheeler & von Braun, 2013). Additionally, the world population is projected to reach 9.7 billion by 2050, with the largest increase in Africa and Asia, and a further accumulation of wealth in the developing world (UN, 2015). This, in turn, leads to a greater demand for food, often associated with a higher demand for meat products, and consequently to a higher demand for fodder. As a result, the Food and Agriculture Organization of the United Nations (FAO) estimates that the overall demand for food will increase by at least 60% until 2050 (FAO, 2016). Subsequently, carbon dioxide levels will continue to rise, followed by growing global mean temperatures and an increase in the frequency and intensity of extreme weather events (IPCC, 2012).

The direct impacts of climate change are expected to be unevenly distributed around the globe. Changing temperature and precipitation patterns will cause a shift of ecozones, leading to a global redistribution of agricultural potential, thereby posing a severe risk to national food systems (Müller et al., 2009). However, compared to the impacts of climate change in many other parts of the world, the direct impacts in Germany will be quite low, and the ability to adapt to these impacts is high (Adelphi/PRC/EURAC, 2015). Yet, most recent studies suggest that it is very likely that Germany will become increasingly exposed to the indirect effects of climate change, imported from distant countries (Benzie et al., 2016; Bren d'Amour et al., 2016; EEA, 2017). That means, Germany, as part of a highly interconnected world, may become increasingly affected by climate change impacts in other world regions, transferred to Germany via multiple pathways such as trade, migration of people, the flow of capital, or other aspects of globalization (EEA, 2017).

Particularly, the German food system rests on international trade and is increasingly dependent on the import of agricultural commodities for food and feed. At the same time, climate change is expected to reduce the yields of many crops worldwide, and is therefore projected to alter the global pattern and balance of food trade (Wheeler & von Braun, 2013). Nonetheless, present analyses on the impacts of climate change on food systems mainly focus on the effects of changing regional temperature and precipitation patterns on national crop yields, reflecting the direct nature of climate impacts. However, this strategy fails to acknowledge the many interconnections and interdependencies among and between countries and regions via trade (Bren d'Amour et al., 2016). The global food exports have increased tenfold since the early 1960s (Steinfeld, 2010), and the production and consumption of food are becoming increasingly detached, leading to a growing reliance of many countries on food imports and trade (Fader et al., 2013). As a result, no country exists in isolation, and the impacts and risks of climate change can be transferred across borders, challenging the security of our global and national food systems (Moser & Hart, 2015).

1.1 Significance and Aim of the study

There is a broad range of studies on the direct effects of climate change on agricultural productivity since already today many countries have been negatively affected by the impact of climate change, variability and an increasing number of extreme weather events. However, the international dimension of climate change impacts and the potential pathways for their transmission have not sufficiently been studied. Existing literature points to a large research gap in this field, as national adaptation strategies usually focus on the local impacts of climate change and tend to ignore the globalized structure of our food systems (Liverman, 2016). In fact, many climate impacts need to be approached on a larger scale to account for the global context of climate change and its far-reaching effects. Moreover, most recent studies suggest that especially import-dependent countries are becoming increasingly vulnerable to the indirect effects of climate change

(Adelphi/PRC/EURAC, 2015; Benzie et al., 2016; Cerveny et al., 2014). Therefore, this study seeks to raise awareness of the concept of indirect effects of climate change, likely to become increasingly important for the German food system in the near future.

The overall objective of this master thesis is to investigate how and to what extent the negative effects of climate change and the impact of extreme weather events abroad can affect the German food system. Thereby, this study seeks to advance the understanding of the concept of indirect effects of climate change and to investigate the underlying mechanisms responsible for the transmission of adverse climate change effects across borders.

Thereof, the following specific objectives arise:

I. To describe the direct impacts of climate change and extreme weather events on agricultural productivity abroad.
II. To systematically analyse the concept of indirect effects of climate change.
III. To evaluate the structure of the German food system to examine its potential level of exposure to the indirect effects of climate change via trade.

Hypothesis:

> The more dependent a country is on the import of agricultural commodities from vulnerable trading partners abroad, the more exposed it is to the indirect effects of climate change.

1.2 Research Methods

This research is primarily based on an extensive literature study. A systematic review identifies and synthesizes the most relevant yield impact studies to give an overview of the most prominent direct effects of climate change on food production. Thereafter, the outcome is combined with an analysis of the structure of the German food system, to translate the direct impacts of climate change on food production abroad into the indirect impacts of climate change on the German food system. Hereby, the study tries to exemplary investigate the level of exposure, as part of the vulnerability concept, of globalized food systems to the indirect effects of climate change. While in most previous climate change assessments the concept of vulnerability has been used as a measure of choice, this investigation prefers to use only part of the concept to avoid additional layers of complexity and to not exceed the scope of this thesis. Moreover, the concept is often used in the context of developing countries, to describe a system's particular state of marginality and powerlessness to the adverse effects of climate change. Examining the level of vulnerability of the German food system could therefore mislead people in underestimating the magnitude of the indirect effects, as previous studies have demonstrated Germany's comparably low level of sensitivity to climate change impacts and its overall high capacity to adapt (Adelphi/PRC/EURAC, 2015).

2 State of the Art

There are many potential impacts of climate change and extreme weather events on food systems. The purpose of this chapter is to give a critical overview of the existing literature on the highly interrelated fields of food systems, food security, and climate change and to position this study in the broader field of research. This section defines some general, but essential concepts because varying definitions are used in different fields of academia.

In particular, this section aims to provide an overview of the global food situation in times of global warming, with a focus on the long and short-term effects of climate change on agricultural productivity. The information given here serves as the basis for the specific analysis of the adverse indirect effects of climate change on the German food system later in this text. In addition, this section tries to link the existence of climate change and the increasing number of extreme weather events and its consequences for social and environmental systems to the influence of human activities and global change as the foundation for the transmission of the indirect impacts of climate change involve the influence of people.

2.1 Food systems and food security: concepts, relationships and trends

2.1.1 Food systems and food security

Today almost 2 billion people are food insecure of which almost 800 million are undernourished (FAO, IFAD, & WFP, 2015). Paradoxically, more than enough food is currently produced per capita to feed the world population (FAO et al., 2015). Almost all of the undernourished people live in the developing world, with the largest share of people living in Asia (510 million) and Africa (230 million) (FAO et al., 2015). Yet, it is important to note that these numbers are just a rough estimate, deficient in capturing all of the four pillars of food security: *availability*, *access*, *utilization,* and *stability*.

The concept of food security is very broad and various definitions exist that have been modified over time. Many earlier definitions focused on food production, whereas current definitions, adapted by the Committee on World Food Security (CFS) and the FAO put the socio-economic aspect in the centre, keeping with the 1996 World Food Summit definition (FAO, 1996) by stressing access to food:

> *"Food security exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life..."* (CFS, 2015).

Climate change and food security have many interrelated risks to societies and the environment, however, the methods used to measure the status of food security and the number of food insecure people in the world have serious deficiencies. First, these estimates are derived from aggregate data, not from actual household food shortages, which impedes the analysis of distributional effects of climate change (Wheeler & von Braun, 2013). Second, they only capture long-term trends and are not able to capture short-term changes, essential for examining the impacts of climate variability, extreme weather events or other short-term shocks on food production as an integral part of the global food system (Wheeler & von Braun, 2013).

There is a broad range of literature on food systems from different fields in academia that bring multiple perspectives and world views to light. Nonetheless, the most useful conceptualizations are those that define a food system as a string of activities ranging from production to consumption, including the multiple transformations of food that these steps entail and the food security outcomes of the respective activities. The most recent definition from the Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC) goes as follows:

> *"A food system includes all processes and infrastructure involved in satisfying a population's food security: gathering, growing, harvesting, processing, packaging, marketing, transporting, consuming of food, and disposing of food waste"* (Porter et al., 2014).

In other words, the food security status of any population can be considered as the outcome of its food system (Ericksen, 2007). Hence, increases in the productivity and efficiency of food systems help to reduce hunger, whereas external threats and disruptions that decrease the productivity and efficiency, reduce food security.

As the concept of food security and food systems are so tightly coupled, food systems must be understood as more than just the single processes ranging from production through to consumption. Both food systems and food security are fundamentally determined by social, economic, and environmental change (Porter et al., 2014).

2.1.2 Globalization of our food systems

Food systems and agriculture have changed tremendously since the middle of the last century. During the green revolution, occurring between the 1930s and 1960s, agricultural development has seen a rapid advance, leading to a significant increase in yields due to increased irrigation and high levels of agricultural inputs.

The globalization of the food system began 30 years later, in the 1990s, mainly as a consequence of fast technological improvements, profoundly changing the way we produce and trade agricultural products. Here, globalization can be understood as "the erosion of barriers of time and space" that constrain the movement of goods, services and capital across borders (Byrnea & Glover, 2002), leading to an increased flow of commodities, technologies, information, financial capital, and new ways of distribution and marketing (FAO, 2004). Among other factors, including urbanization, the main drivers of these changes over the past decades were increased income and strong efforts to liberalize international trade, associated markets and investment flows (Kearney, 2010). As a consequence, there are several significant differences in the organization of the modern food system and the traditional food system. First, as distribution networks have expanded and transportation routes have improved, today, food travels very long distances before it gets consumed. As a result of this "spatial decoupling of production and consumption", many countries become increasingly dependent on external resources and trade (Fader et al., 2013). Second, the foundation of the value chain has changed, as farming is no longer the main economic activity but the processing and packaging of raw materials into food products (Ericksen, 2007). Third, the overall income growth since the 1990s has led to a dietary transition, with an increasing demand for resource-intensive meat and dairy products, especially in the developing world. This, in turn, has led to a rising demand for the amount of grains, as 30-50% of the global production is fed to livestock (Tscharntke et al., 2012). Today, around 75% of the calories that humans directly or indirectly consume come from only four crops: maize, wheat, rice, and soybeans (D. B. Lobell, Schlenker, & Costa-Roberts, 2011), mainly produced in a handful of countries. In fact, the top five exporters of globally traded grains account for more than two-third of the total export volume (Bren d'Amour et al., 2016).

The environmental concerns over the globalization of our food systems, in particular, the industrialization and intensification of agricultural production systems are numerous. The FAO reports are consistent in calling the current growth in agricultural production unsustainable (FAO, 2008, 2016; FAO, IFAD, & WFP, 2012). Major trends of modern food systems lead to increasing demands of water for irrigation, an increase of pollution from agricultural inputs and large increases in energy demand. The outcome of this development is particularly dangerous as the impact of food systems on the environment create negative feedback loops that strengthen the risk posed to food systems by global environmental and climate change (Ericksen, 2007). Some of the major trends in modern food systems are summarized in Table 1.

Table 1: Trends in food systems: differences between the past "old" and the modern "new" food systems.

Food system feature	“Old” food system	“New” food system
Primary sector of employment	Food production	Food processing, packaging and retail
Supply chain	Short	Long
Production system	Diverse	Few crops; intensive monocultures
Typical food consumed	Basic staples	Processed food; more meat and livestock products
Main source of national food shocks	Poor rains; production shocks	Climate-related price fluctuations, supply disruptions and trade problems
Main environmental concerns	Soil degradation; land clearing	Water demand; greenhouse gas emissions; nutrient loading

Source: Maxwell & Slater (2003); adapted from Ericksen (2007).

2.2 Observed and projected climatic changes

2.2.1 Climate change and global warming

The patterns of observed and predicted climate change are well documented and reviewed by the Intergovernmental Panel on Climate Change (IPCC, 2013). The global mean temperature has risen by 0.85°C since preindustrial times, with plenty of temperature records being broken over land and sea in the past years (IPCC, 2013). However, averaging the temperature increase on a global scale masks the differences between land and sea, as well as differences between high and low latitudes.

An overview of the observed surface temperature change from 1901 to 2012 is given in Figure 1. The map is derived from temperature trends determined by linear regression of the combined land-surface air temperature (LSAT) and sea-surface temperature (SST) data set MLOST (see Vose et al., 2012). Clearly, there are large differences in changes of mean temperatures, not only between the land and the sea but also between continents, countries, and regions.

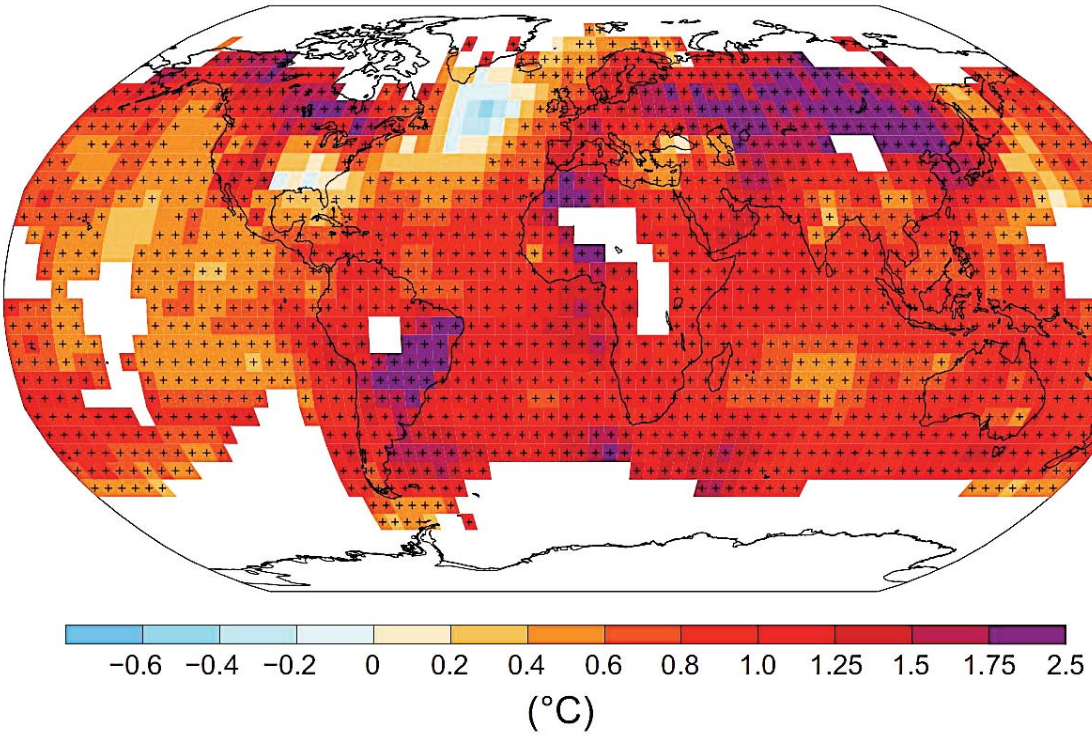

Figure 1: Observed change in surface temperature from 1901-2012. The map is derived from temperature trends determined by linear regression of the combined land-surface air temperature (LSAT) and sea-surface temperature (SST) dataset NCDC MLOST. Trends have only been calculated where robust data was available; other areas are white. Grid boxes where the trend is significant are indicated by a + sign. Source: IPCC (2013).

Since 1950, the average temperatures have risen by about 0.13°C per decade, above all, driven by the emission of greenhouse gases (IPCC, 2013). CO_2 levels have increased from about 315 parts per million (ppm) in 1958 to over 400 ppm today (US Department of Commerce, 2017). The sharp increase of such anthropogenic greenhouse gases can be attributed to the economic growth of a rising population. In 2010, the total anthropogenic emissions reached a record high of almost 50 gigatonnes of CO_2 equivalent per year (IPCC, 2014b). Vermeulen et al. (2012) estimated that almost 30% of the total greenhouse gas emissions come from food system activities alone. The largest share of these emissions come from agriculture, while the rest originates from preproduction, mainly fertilizer manufacture, and postproduction activities like processing, packaging, and transport (Vermeulen, Campbell, & Ingram, 2012). However, the share of emissions from agriculture in main producing regions of raw materials is notably higher than in import-dependent countries that generate a larger proportion of their emissions from postproduction activities (ibid.).

2.2.2 Climate variability and extreme weather events

A changing climate not only leads to an increase of the global mean temperature and variability, but in turn, also to changes in the intensity, frequency, duration and spatial extent of extreme weather events (IPCC, 2012). There is a growing body of literature on climate-related extreme events, as the public and scientific awareness of the rising intensity and frequency of such events is increasing.

According to the Munich Re, one of the world's largest reinsurance companies, the number of significant weather-related extremes per year, with at least one fatality and/or normalized losses ≥100 000, 300 000, 1 million, or 3 million US$, depending on the income group of the affected country, has quasilinearly tripled from around 200 events to nearly 600 events in the last three decades (Munich Re, 2017). A list of the major climate-related loss events from the past years is summarized in Table 2.

Since 2011, the "Bulletin of the American Meteorological Society" has published an overview of all climate impacts studies for selective extreme weather events of the year before. The evaluation of all published modelling approaches has shown that 65% of the studies concluded that the frequency and intensity of the analysed extreme weather event was influenced by climate change (Munich Re, 2017). Therefore, the analysis verifies the interrelationship of climate change and the frequency and intensity of climate-related extreme events.

Despite the number and intensity of such events and the consequent losses are seemingly increasing, there is still much doubt about the respective human influence as natural climate variability masks the potential for anthropogenic changes in the climate.

Climate is a statistical information that contains the average weather condition of a region for a specified interval usually longer than 30 years (FAO, 2007). In contrast, the weather is a day-to-day state of the atmospheric condition in a given place. It includes short-term variations such as temperature, precipitation or wind, that last hours, days, weeks, or a few months, in contrast to the long-term variations of the climate that last for years and longer (Ruddiman, 2014). Therefore, climate variability can be defined as variations in the mean state of climatic parameters and other climate statistics on all temporal and spatial scales beyond those of individual weather events (FAO, 2007).

Table 2: Major climate-related loss events from the past decades.

Date	Event	Affected countries	Overall losses [Million US$]	Fatalities
August 2005	Hurricane Katrina	United States	125 000	1 720
October 2012	Hurricane Sandy	Bahamas, Cuba, Dominican Republic, Haiti, Jamaica, Puerto Rico, United States, Canada	68 500	210
September 2008	Hurricane Ike	United States, Cuba, Haiti, Dominican Republic, Turks and Caicos Islands, Bahamas	38 000	170
November 2013	Typhoon Haiyan	Philippines	10 000	6340
August - November 2011	Floods	Thailand	43 000	813
July - August 2003	Heat wave	France, Germany, Italy, Portugal, Romania, Spain, United Kingdom	14 000	70,000
July - September 2010	Heat wave	Russia	3 600	56,000

Source: Munich Re (2017).

The general concept of climate change refers to a significant variation in the mean state of the climate or its variability that can result from either natural internal processes within the climate system, or from natural or anthropogenic external forces (McDonald, 2010). The effect of climate change on extreme weather events can be visualized in relation to their probability of occurrence as shown in Figure 2. The left panel shows a shift of the entire distribution towards a warmer climate. This shift leads to an increase of extremely hot weather and a decrease of extremely cold weather. The right panel illustrates an increase of the temperature variability, with no shift in the mean, a situation that would equally lead to an increase of more extreme cold and hot days. The bottom panel shows an altered shape of the distribution towards the hotter part of the distribution, while the

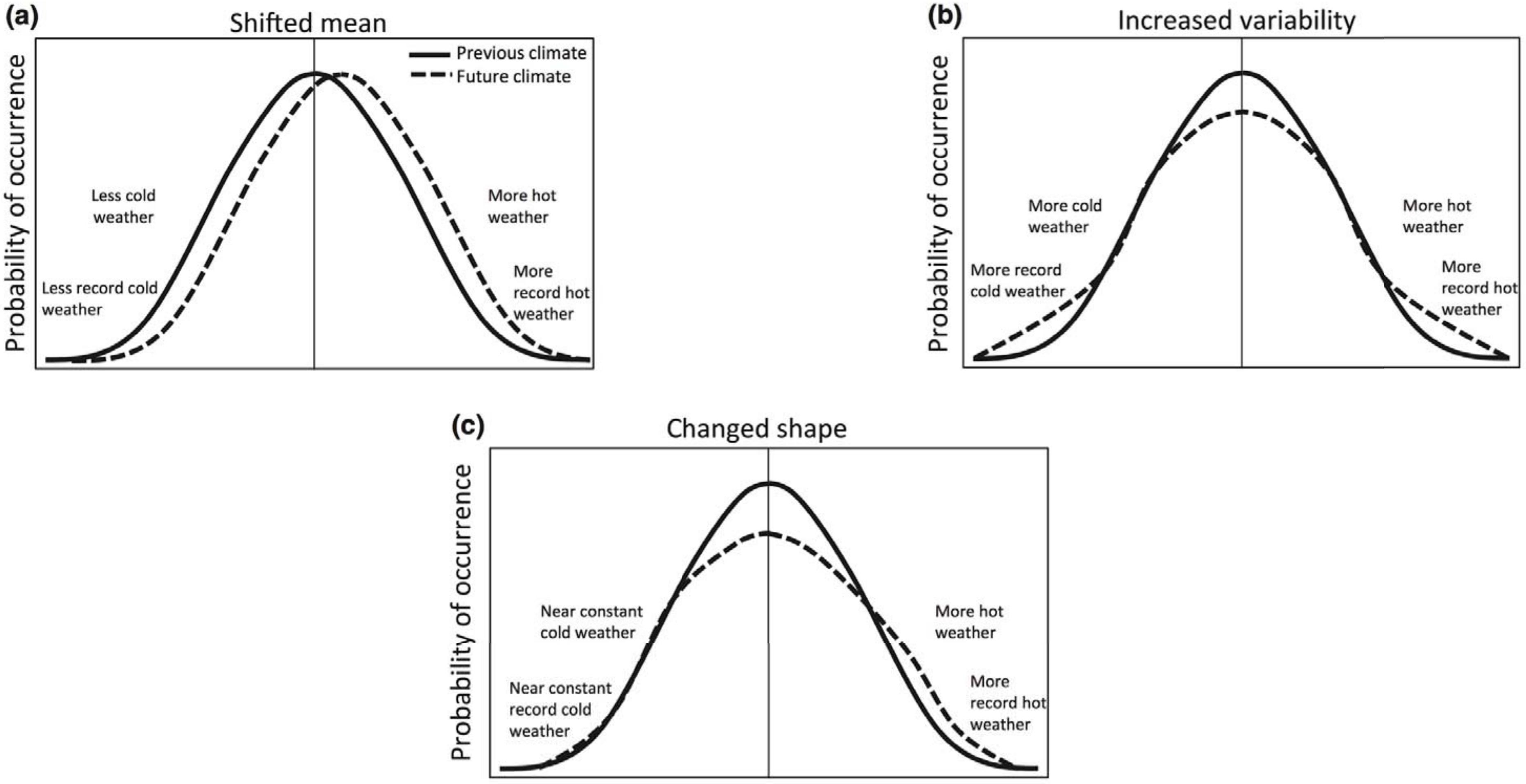

Figure 2: The effect of changes in temperature distribution on climate-related extreme events. Different changes of temperature distributions between present and future climate and their effects on extreme values of the distributions: (a) a simple shift of the entire distribution towards a warmer climate; (b) an increase in temperature variability with no shift of the mean; (c) an altered shape of the distribution. Source: IPCC (2012); adapted from Thornton et al. (2014).

temperature probability distribution keeps its mean. All of the three panels may be combined to depict how the effect of a changing climate will possibly influence the frequency and intensity of extreme events in the future.

Climate extremes are generally defined by their probability of occurrence, their exceedance of specific thresholds, or both. In the Special Report of the IPCC on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX), an extreme climate or weather event is defined as:

> *"The occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable"* (IPCC, 2012).

However, there is no ultimate definition, as they all have limitations when it comes to their respective impact for several reasons. First, the impact not only depends on the character of the extreme event but also on the level of exposure and vulnerability of the affected system. Second, not all extreme events must have extreme impacts, i.e. the impact of a weather event must not necessarily be extreme because it exceeds certain thresholds.

Variations in climatic parameters such as temperature have generally been attributed to natural causes in the past, but due to the rapid changes since pre-industrial times, an increasing number are now ascribed to human activities. While the past long-term trends of climate change are considered to be largely caused by humans, this attribution is more complicated when it comes to single extreme weather events, as such events usually result from a combination of multiple factors, and a broad range of extreme weather events could happen even if the climate is not changing (IPCC, 2012).

However, statistical climate models have helped to prove that the probability of the occurrence of such events has increased in the past decades, and much progress has been made in attributing the incidence of extreme weather events to specific causes. As a result, there is strong evidence today linking the increasing number and intensity of weather extremes to the influence of anthropogenic climate change (IPCC, 2012; Coumou & Rahmstorf, 2012; EEA, 2017).

2.2.3 Global climate change projections

The aim of the 2015 Paris Climate Conference (COP21) was to achieve a legally binding agreement between the nations to keep global warming well below 2°C above preindustrial levels since this would significantly reduce the impacts of climate change (UNFCCC, 2015). However, this seems to be truly ambitious, considering the estimates from the AR5, projecting an increase of the global mean temperature of 1.5 – 4.5°C by the end of this century (IPCC, 2013). In fact, current mitigation plans may lead to an increase of at least 3°C, not even considering the altered political situation in the United States of America, the second-largest emitter of carbon dioxide in the world (UNEP, 2015).

To assess the potential impacts of future climate change on food systems one has to use data that predicts future climate change based on storylines about future development, including driving forces such as demography, economy, technology, land use, or agriculture (IPCC, 2000). These climate change projections are based on two components: a time path of greenhouse gas emissions and a General Circulation Model (GCM), which is a mathematical model, simulating the response of the Earth's climate system to the increasing greenhouse gas concentrations (IPCC, 2013). Many such scenarios have been developed by the IPCC and are widely used for the analysis of climate change impacts and possible options for mitigation and adaptation. Most of the climate impact studies concentrate on changes in the mean climate, since abundant data is available, and in terms of model output, these changes are more robust (Thornton et al., 2014). However, by only focusing on changes in climate means, the full spectrum of climate change impacts is likely to be underestimated. Climate change projections steadily improve, and nowadays are not only able to demonstrate that global warming will continue for many decades to come, but also bring strong evidence that the frequency and intensity of climate-related extremes as well as climate variability will further increase, posing unknown threats to our globalized food systems (Coumou & Robinson, 2013; IPCC, 2012)

2.3 Direct impacts of climate change on food production

Climate change has various impacts on food systems and it affects all of the four pillars of food security, however, the main emphasis of this chapter lays on the direct impact of climate change on agricultural productivity. More precisely, it gives an overview of the recent trends and the most prominent projections of the long-term effects of climate change, and the observed and projected near-term effects of an increasing climate variability and a growing incidence of extreme events on agricultural production. The impacts are projected to be “complex in nature, geographically and temporally variable, and largely influenced by social and economic factors” (Vermeulen et al., 2012). Accordingly, there is much variation among countries and crops, particularly due to the different trends in yields and climate. Understanding the past trends is essential in estimating the future impacts on agricultural production, and therefore it helps to adapt to the adverse effects of climate change and extreme events. Moreover, identifying key agricultural commodities and countries that have been most affected by recent trends is necessary to analyse the potential indirect impacts of climate change on food systems, reaching beyond the direct impacts of climate change.

The major source of knowledge for this kind of impact studies comes from both historical statistical studies and integrated assessment models. The first category analyses the direct impact of weather anomalies and climatic trends on food production; the latter combines the direct impact from weather on yields, derived from crop models, with downstream impacts on food prices, transportation routes, food safety and/or food quality, all affecting the global food security outcome. Clearly, both climate and crop models comprise significant uncertainties as each model is composed of numerous variables derived from assumptions about the extent and rate of future climate change. Moreover, the weighting of the different variables and the predominant drivers of change, developed from knowledge about physical processes and statistical linkages, often remain controversial (Singh, 2009).

2.3.1 Sensitivity of agricultural production to climate change

The impact of climate change on food production was not heavily emphasized in the fourth IPCC assessment report (AR4). However, the results indicated that, up to 2050, temperate regions would benefit from a mean temperature rise of 1-3°C, in terms of crop yield increases, whereas most of the tropical regions would experience yield decreases, because the climate of many tropical regions is already close to the temperature thresholds of most crops (IPCC, 2007a). Higher mean temperatures, beyond 2050, would make all regions susceptible to yield losses, especially in tropical regions, where the adaptive capacity is projected to be exceeded (ibid.). In contrast, new results from the consequent AR5 suggest that more yield decreases than increases, even in temperate regions with less than 3°C of local warming (IPCC, 2014a). Moreover, AR5 gives great attention to the adverse effects of extreme events that exacerbate the impacts of a gradually warming climate. A variety of yield impact studies document a large negative sensitivity of cropping systems to climate change, climate variability, and various kinds of extreme events, particularly, high temperatures and heavy rainfall, and the associated heat waves, floods and droughts.

There are many factors that influence the metabolism and hence the growth and productivity of a plant. Thus, it is a complicated task to anticipate the influence of a changing climate on the productivity of a specific crop. Important climatic, atmospheric and environmental factors that influence yields, both positively and negatively, include the amount of CO_2 in the atmosphere, the temperature, the amount of precipitation, and the natural characteristics of the soil. The relationship between these factors, the plant, and the resulting yield, depend on the geographic location, the crop variety, the management of the soil, and the duration and timing of crop exposure to the prevalent conditions of the weather and climate (Porter et al., 2014).

To bring more clarity and order to the large number of interrelated factors that influence the productivity of crops, and hence the availability of food, a distinction between the long-term impacts of changes in climatic means on the one hand, and the short-term effects of increases in climate variability and in the frequency and magnitude of extreme events, on the other hand, must be made. Both long-term effects and short-term shocks impact on production as well as postproduction activities. Yet, in the short-term, growing climate variability and especially the occurrence of extreme events have more immediate effects on food system activities than long-term changes in means (Vermeulen et al., 2012). However, the risk to food production from changes in mean climatic values, such as rising temperatures, is growing over time.

2.3.2 Long-term effects of climate change

Temperature is one of the most important factors in determining the productivity of crops. Model results from the past have shown that various physiological processes of plant growth and development, ranging from reduced grain set (Moriondo et al., 2011), shortening of the time to plant maturity (Iqbal & Arif, 2010), increased plant sterility and plant mortality events (Sánchez et al., 2014) are, among others, all affected by temperature. Yet, the response to temperature depends very much on the availability of water. Generally, there is a negative correlation between water stress and high temperatures.

The analysis of 66 yield impact studies for major crops has shown that yields of wheat and maize drop with temperature increases of 1°C to 2°C of warming in low latitudes, and with 3°C to 5°C in high latitudes (Porter et al., 2014). Yet, the relationship between yields and temperature is nonlinear. For example, Schlenker & Roberts (2009) found the yields of wheat and soybean in the United States to be gradually increasing up to a temperature of 29° to 30°C; above these thresholds, yields rapidly decline. Accordingly, area-weighted average yields of this two crops would decrease by 30-46% under the slow-warming scenario B1, and by 63-82% under the fast-warming scenario A1FI, until the end of this century (Schlenker & Roberts, 2009).

Despite the great uncertainties in predicting global-scale yields for any time frame, Funk & Brown (2009) used a set of GCMs to predict that global per capita cereal production declined by 14% between 2008 and 2030, assuming that per capita harvested area would continue to grow faster than yields. Moreover, Nelson et al. (2009) used two GCMs to estimate yield changes for maize, wheat, and rice in developing countries between –27%

to +9%, and –9% to +23% in developed countries until 2050, assuming a positive fertilization effect of elevated CO_2.

The positive fertilization effect of CO_2 is another key issue when estimating the impact of climate change on agriculture. However, the magnitude of its positive effect is much debated and not only depends on the soil and the prevalent availability of water and nutrients, but also on the temperature, and in particular, on the crop species (Porter et al., 2014). Observational evidence shows that the positive effect of higher CO_2 concentrations is larger in C_3 plants (e.g. wheat, rice and soybeans) than in C_4 plants (e.g. maize) because C_4 plants are less responsive to increased CO_2 (Leakey, 2009). However, Singh (2009) argues that elevated CO_2 concentrations affect the nitrogen balance due to changes in the physical plant structures and, as result, reduces the tolerance to drought. Moreover, increased carbon assimilation rates are only beneficial for the plant growth if sufficient nutrients are available (Müller et al., 2009). Conversely, theory suggests that water-stressed crops will benefit more from increased CO_2 than well-watered crops because field experiments have shown that rising CO_2 concentrations increase the efficiency of agricultural water use, and thus, are expected to reduce crop water use by 4–17% by 2080 (Deryng et al., 2016). Furthermore, a meta-analysis by Taub, Miller, & Allen (2008) stated that elevated CO_2 (540–958 ppm) would indeed have a positive effect on plant growth, but reduces the protein concentration of wheat, barley, and rice by 10–15% and of soy by 1.4%. In summary, one can expect a beneficial effect of elevated CO_2 on specific crops, but the prevalent conditions must be well observed and the possible counter effects on food quality and resistance to extreme weather conditions must be taken into account.

Müller et al. (2009) studied the global effect of climate change on agricultural productivity of 11 major crops (wheat, rice, maize, millet, field pea, sugar beet, sweet potato, soybean, groundnut, sunflower, and rapeseed) between 2000 and 2050. The projected changes in yields were generated from three emission scenarios across five GCMs to compare the two 10-year periods: 1996–2005 and 2046 to 2055, neglecting possible future changes in agricultural practices or crop varieties, and the effect of elevated atmospheric CO_2

concentrations on these crops (Müller et al., 2009). The results, shown in Figure 3, suggest that climate change will depress agricultural yields in the majority of all countries. However, large geographic disparities exist between the projected outcome on yields. The map demonstrates the great difference between the northern hemisphere that is in great parts projected to benefit from climate change, and the southern hemisphere, where the opposite seems to become true. Even though there are still uncertainties in estimating the impact of climate change on yields, and specific projections differ according to the climate scenario or simulation method used, the broad-scale spatial pattern on crop productivity has remained consistent across all global-scale studies of the past decades (Wheeler & von Braun, 2013).

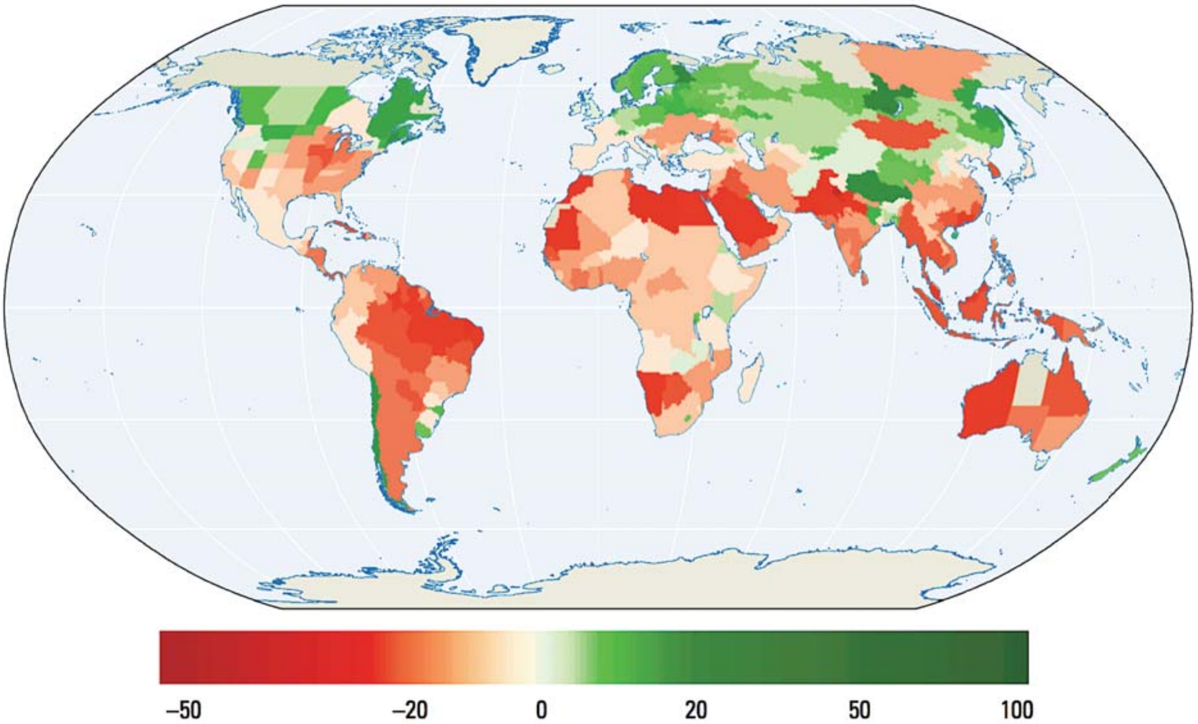

Figure 3: Global impacts of climate change on crop productivity by 2050. The figure shows the estimated percentage change in 11 major crops from 2046–2055, compared with 1996–2005. Simulated changes in yields are averaged across three emission scenarios and five GCMs, assuming no positive CO_2 fertilization effect. Areas where no robust data was available are grey. Source: Müller et al. (2009); adapted from World Bank (2010).

The results suggest that by 2050, there might be a shift of production zones from south towards north and, thereof, a redistribution of agricultural potential following the spatial pattern of the impacts of climate change. Therefore, many countries in the global south are expected to be hit the most by climate change while at the same time these countries will experience the greatest increase in population. As a consequence, many areas that are highly dependent on agriculture will be confronted by a decreased self-sufficiency in food production and, hence, in the availability of food (Müller et al., 2009).

To reveal the disparity of yield impacts at the national scale for major producing regions and for individual crops, Lobell, Schlenker, & Costa-Roberts (2011) estimated the response of average yields for four major crops to global temperature and precipitation trends for the 29-year time period of 1980 to 2008. Publicly available datasets on crop production, crop locations, growing seasons, and monthly temperature and precipitation were combined to measure the impact of historical weather on crop yields for maize, rice, wheat, and soybean. Large differences were detected between the individual crop producers, revealing winners and losers at the country-scale. Countries, most affected by past climate trends are Brazil for maize, Indonesia for rice, Russia for wheat, and Paraguay for soybean. The estimated net impacts of climate trends on crop yields for the major global producers are shown in Figure 4. At the global scale, the combined impact of temperature and precipitation trends on these four crops ranged from –0.1% for rice to –5.5% for wheat, shown in Table 3.

Table 3: Median estimates of global temperature and precipitation trends (1980–2008) on average yields for maize, rice, wheat, and soybean.

Crop	Global production, 1998–2002 average [Million tonnes]	Global yield impact of temperature trends [%]	Global yield impact of precipitation trends [%]	Total [%]
Maize	607	–3.1	–0.7	–3.8
Rice	591	0.1	–0.2	–0.1
Wheat	586	–4.9	–0.6	–5.5
Soybean	168	–0.8	–0.9	–1.7

Source: adapted from Lobell, Schlenker, & Costa-Roberts (2011).

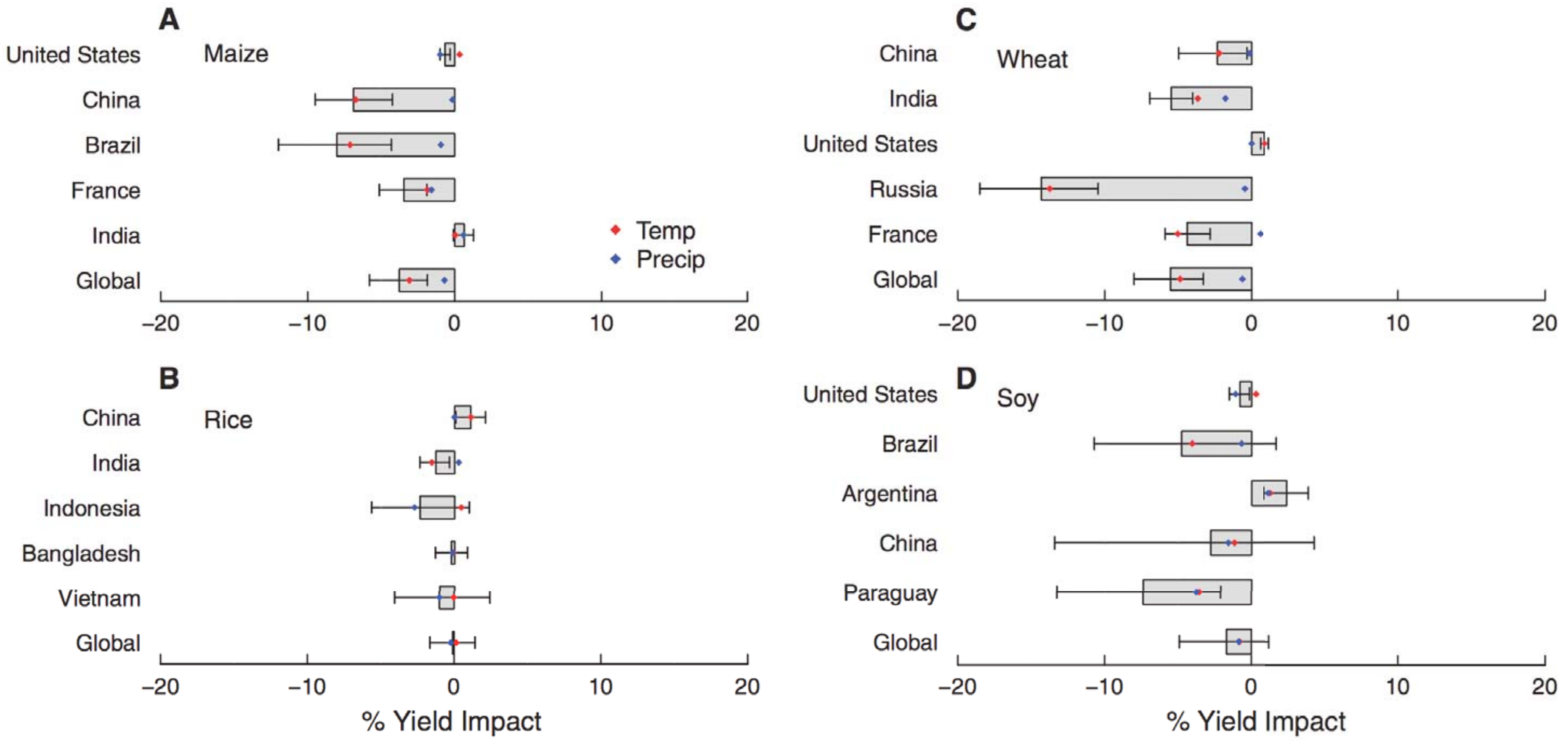

Figure 4: Estimated impact of past climate trends (1980–2008) on crop yields for major producing countries and for global production. Values are expressed as percentage of average yield. Grey bars show median estimate; error bars show 5% to 95% confidence interval from bootstrap resampling with 500 replicates. Red dots show median estimate of the impact for temperature; blue dots for the median estimate of the impact of precipitation. Source: Lobell, Schlenker, & Costa-Roberts (2011).

The results indicate a significant sensitivity of crop yields to changes in temperature and precipitation. In particular, changes in temperature seem to be more important for average crop yields than changes in precipitation. Since the magnitude of the fertilizing effect of CO_2 is uncertain, it has been excluded from the original table shown in Lobell, Schlenker, & Costa-Roberts (2011). Nevertheless, even though the positive effect of CO_2 has been excluded, so has the impact of extreme temperature and precipitation events. Therefore, the results presented here still might be too optimistic and must be viewed with caution.

2.3.3 Short-term effects of climate variability and extreme events

In contrast to the large number of quantification attempts of the impacts of climate change on crop yields, impact studies on changes in climate variability and the effects of extreme events are limited.

In terms of model output, changes in mean climate are more robust than changes in variability, and extreme events occur too rarely to be sufficiently calibrated and tested (Thornton et al., 2014). Despite the difficulty of modelling the impacts of extreme events and climate variability, they clearly have large impacts on various food system activities, reaching beyond the impacts of changes in climatic means and must be taken into account. Besides, the impacts of extreme events can be easily distinguished from the impacts of a changing climate as the effects become apparent directly after the event, posing an immediate threat to the global food production.

As discussed before, it is commonly anticipated that climate and weather variability will increase, whilst the global climate is changing (Figure 2). In fact, climate variability already today has large impacts on many cropping systems since the plant growth and development is particularly sensitive to variations in rainfall and temperature. However, the role of water availability and temperature very much depends on the region, thus, strengthening the role of rainfall and temperature variability in already warm, water prone areas. Furthermore, Craine et al. (2012) concluded that the timing of climate variability might be as important as its magnitude since key physiological processes in the development of the plant are particularly sensitive to the timing of climate variability.

Rowhani et al. (2011) have shown that both, intra- and inter-seasonal temperature and precipitation variability affect crop yields in Tanzania. Similar to other studies (e.g. Lobell, Schlenker, & Costa-Roberts, 2011), they have shown that yields typically decrease with higher temperatures and increase with more precipitation. Yet, more interesting is that an increased climate variability during the growing season can lead to major yield reductions, affecting the overall primary productivity. Climate and crop data were combined in a statistical model to estimate that, by 2050, a potential 20% increase in intra-seasonal precipitation would reduce yields of maize, sorghum, and rice by 4.2%, 7.2%, and 7.6% respectively (Rowhani et al., 2011). Although changes of mean climatic parameters have been shown to have larger impacts on agricultural yields than increases in climate variability, the overall impact on future yields will be misjudged if the latter is not taken into account. Their results indicate that, by the middle of this century, the impact of climate change on crop yields for maize, sorghum and rice may be underestimated by 3.6%, 8.9%, and 28.6% respectively, if the impact of an increasing variability is not adequately accounted for (Rowhani et al., 2011).

The importance of rainfall variability for national crop yields has also been assessed by Thornton et al. (2014) for the three sub-Saharan African countries: Ethiopia, Niger, and Mozambique. Their investigations show a clear relationship between interannual rainfall variability and agricultural gross domestic product (Ag GDP). The results of this relationship for the 21-year time period 1982-2003 are exemplary demonstrated for Niger shown in Figure 5. Since many tropical countries like Niger heavily depend on agriculture for economic growth, the relationship between rainfall variability and agricultural production can almost equally be translated into their national gross domestic product (GDP). Interannual rainfall variability is expressed as the 12-month Weighted Anomaly of Standardized Precipitation (WASP), calculated from overlapping sums of standardized precipitation anomalies (Lyon, 2004). The index ranges from –2 (severe drought) to +2 (severe wetness). The respective data was downloaded from the freely accessible online data bank of the International Research Institute for Climate and Society[1], and weighted according to the portion of mean annual precipitation at a certain time of the year (Thornton et al., 2014). Looking at the graph, shown in Figure 5, one can see that the rise and fall of both, the agricultural GDP and the GDP, are following the annual variability of the rainfall. In dry years, the agricultural production of Niger is declining, as the growth and development of the crops is disrupted by the limited amount of water. In contrast, if the crops have abundant water, the agricultural GDP is rising again, followed by an increase in the overall GDP.

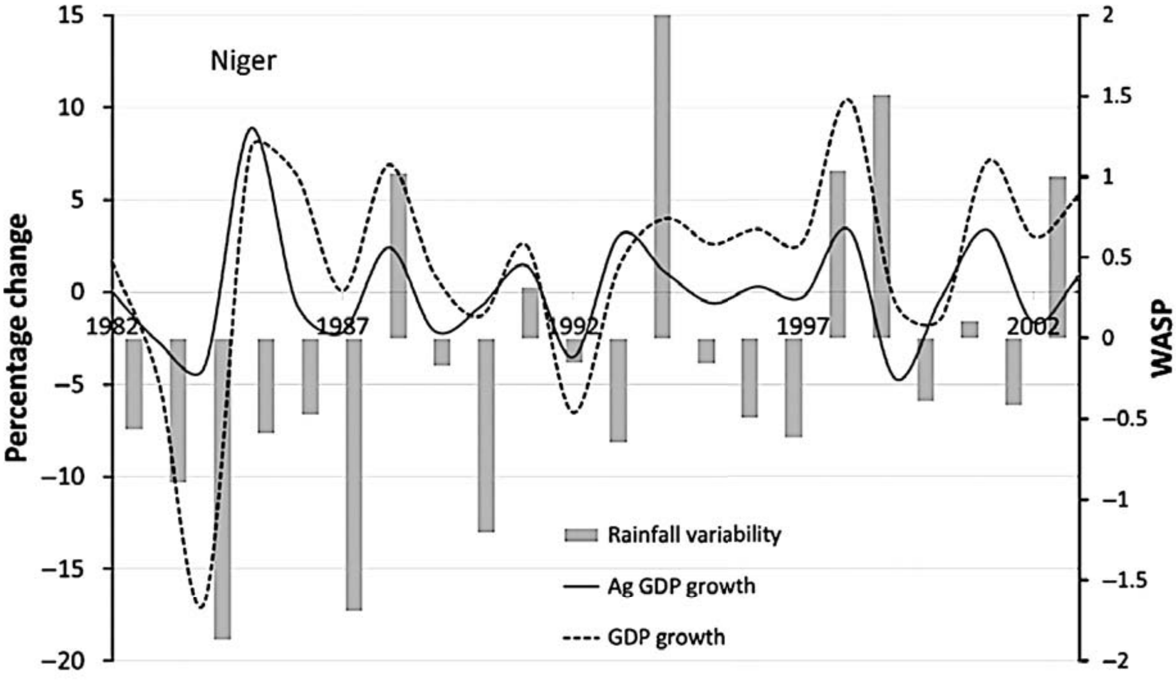

Figure 5: Relationship between annual rainfall variability expressed as the 12-month Weighted Anomaly of Standardized Precipitation (WASP) and changes in gross domestic product (GDP) and agricultural gross domestic product (Ag GDP) in Niger from 1982 to 2003. Source: Thornton et al. (2014).

Summing up, it can be said that the effect of changing weather patterns due to an increasing climate variability already today has large impacts on crop yields in many regions, but often tend to be underestimated in global yield impact studies. At the farm

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[1] http://iridl.ldeo.columbia.edu

level, these changes lead to variations in the timing and length of growing seasons that asks the farmers to adapt. However, when changes in climate and climate variability may become larger, and specific thresholds are reached, the occurrence of extreme weather events demands more fundamental changes that possibly exceed the capacity of many people to adapt. In fact, many countries are expected to experience a significant decrease in growing season length, as well as a sharp increase in the probability of season failures, that may lead to dramatic yield reductions by the end of this century (Thornton et al., 2011). A selection of available yield impact studies of extreme weather and climate events, ranging from extreme temperatures and droughts to extreme rainfall and flooding are described below.

Extreme temperatures

Battisti & Naylor (2009) used observational data and model output from 23 GCMs to calculate the difference between projected and historical averaged season temperatures to demonstrate the impact of increasing growing temperatures on agricultural productivity. Their results suggest that by the end of this century, growing season temperatures will exceed the most extreme seasonal temperatures observed from 1900 to 2006 in low latitudes, and previous extremes temperatures in high latitudes will represent the norm in many temperate regions (Battisti & Naylor, 2009). This trend in temperatures might have major impacts on agricultural production in the future, as observational evidence has shown that a few days of extreme temperatures in the development of many crops can already drastically reduce yields (Wheeler et al., 2000) and negatively affect the protein content of major grains (Hurkman et al., 2009). For example, each day with temperatures above 30°C have reduced maize yields in Africa by 1% on average, and by 1.7% und drought conditions in the past (Lobell et al., 2011). Another example from Mohammed & Tarpley (2009) has demonstrated, that rice yields are reduced by 90% with night time temperatures of 32°C, compared with night time temperatures of 27°C.

Drought

Climate models suggest that the proportion of land surface affected by drought, as defined in terms of the Palmer Drought Severity Index (Palmer, 1965), has increased from 20% to 28% in the last century, and the area affected by extreme drought may increase from 1% to around 30% over this century (Burke et al., 2006). More recently, Li et al. (2009) estimated that global harvested area impacted by drought has increased from 5–10% to approximately 15–25% since the 1960s. Accordingly, future yield reductions due to drought conditions may increase by more than 50% by 2050 (Li et al., 2009).

Heavy rainfall and flooding

Although food production is generally said to benefit from high amounts of precipitation, it can also be adversely affected by too much water, if precipitation events become too heavy and cause reductions in agricultural productivity. The percentage of rain falling in heavy rainfall events is increasing as precipitation is becoming more intense but less frequent; an alarming trend that is expected to continue as the climate is warming (Gornall et al., 2010). As a result, flash floods and runoff are expected to increase, raising the potential for soil erosion, reducing soil moisture, and in turn increasing the risk for agricultural drought (Dai, 2011). Furthermore, extreme flooding can destroy large portions of harvested area, leading to immense crop losses and farming income reductions.

Tropical storms

Another type of extreme events with large negative implications for agricultural production are tropical storms, however, the change in their frequency and intensity as a result of climate change is still much debated. Nonetheless, results from the SREX suggest, that the likelihood of more intense tropical storms is projected to increase throughout this century as winds are becoming stronger and precipitation events heavier (IPCC, 2012). Yet, to the best of my knowledge, there are no studies that try to estimate how climate change will contribute to the occurrence of tropical storms in the future and how this possibly impact on future crop yields.

3 Indirect effects of climate change on food systems

While there is a broad range of studies on the direct climate change impacts on food production, as illustrated in section 2.3, the information base on the indirect effects of climate change is very little. The majority of studies have focused on the impact of a gradually changing climate on agricultural productivity and hence the availability of food, but only a limited amount of studies focused on the impact of an increasing climate variability or the rising occurrence of extreme weather events. Even fewer studies exist that investigate the impact of climate variability and extreme events on food systems as opposed to food production. For example, of almost 600 pages in the SREX report from the IPCC (2012), only one page deals with the effects of climate and weather extremes on food systems, while the phenomenon of indirect effects is entirely overlooked. Even the most recent Fifth IPCC Assessment Report does not adequately cover the topic of the indirect effects of climate change on food systems, yet, it offers a three pages glance on the risks arising from the indirect effects of climate change under the title: “Emergent Risk: Indirect, Trans-boundary, and Long-Distance Impacts”, acknowledging that “climate change impacts can have consequences beyond the regions in which they occur.” (Oppenheimer et al., 2014).

3.1 Terminology and concept of the indirect effects of climate change

Since the AR5, much progress has been made and a broad range of terms have been used in different fields of academia to describe and analyse the indirect impacts of climate change and their transmission across borders, posing a new risk to the worldwide community of states, widely denoted as the “international dimension of climate risk” (PwC, 2013). However, no common ground has yet been found to agree on a particular term for the impacts of climate change that affect one country as a result of climate change impacts in another country. Despite the difficulties of finding a clear terminology for these impacts, this study uses the term “indirect impacts of climate change” as introduced by Benzie et al. (2013) as the opponent to the “direct impacts of climate change” that occur within one country, as described in the previous chapter. Other examples of terms that have been used in the context of indirect impacts of climate change are among others “spill-over effects” (Cerveny et al., 2014), “cascading impacts” (World Bank, 2014), “transnational impacts” (Benzie et al., 2016), and “cross-border impacts” (EEA, 2017), all linking the two global processes, climate change and globalization. Although, these terms can have differential implications in different fields of research, in this study they are used coequally to describe how the effects of climate change and extreme weather events can be transferred across borders, and hence, cause trans-boundary and/or long-distance impacts.

3.2 Transmission of climate change impacts across borders

Early attempts to investigate the cross-border effects of climate change were made by Adger et al., (2009), arguing that the vulnerability of distant people is not geographically bounded, but instead “teleconnected” through environmental and socioeconomic linkages. They stated, that the aggregated outcomes of government policies and commodity markets can impact human and natural systems at large scales, with potential negative repercussions across borders (Adger et al., 2009). Consequently, the level of exposure and sensitivity of local communities and ecosystems depend on the influence of the large-scale impacts of socioeconomic and environmental change.

Building on these findings, Liu et al. (2013) introduced the umbrella concept of “telecoupling”, merging the effects of globalization and teleconnection, to investigate the interactions of coupled human and natural systems between distant places. A schematic representation of the three linkages: “teleconnection”, “globalization”, and “telecoupling” is shown in Figure 6. While the distant interactions between both, natural systems and human systems, have been separately studied by either physical scientists or social scientists before, the integrated concept of “telecoupling” represents a new conceptual framework to analyse the interaction between humans and the environment as interrelated coupled systems. By this means, Liu et al. (2013) strengthened the need of addressing biophysical and socioeconomic dimensions simultaneously, and to investigate how humans and natural systems interact beyond borders, for instance, in the wake of increasing distant interactions such as the global trade of agricultural commodities.

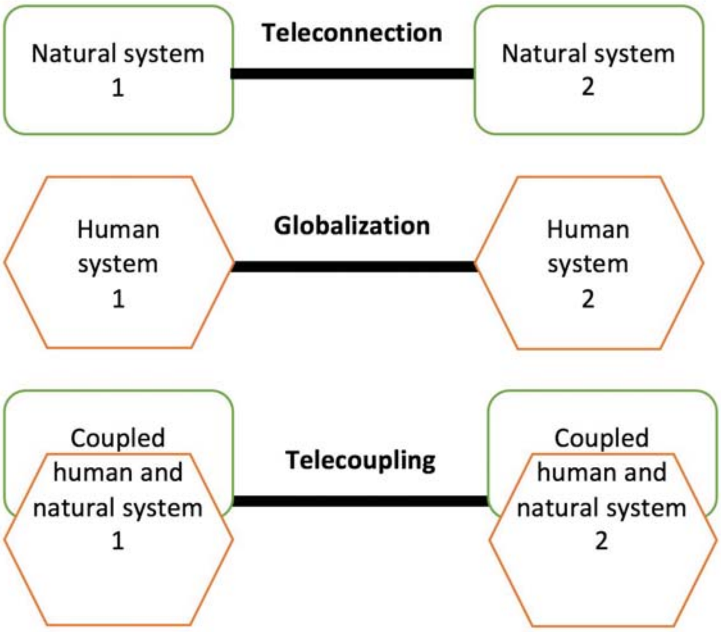

Figure 6: Interrelations between natural systems, human systems and coupled human and natural systems over distances. Source: adapted from Liu et al. (2013).

Another conceptual framework was recently developed by Moser & Hart (2015), focussing on the underlying mechanisms for the transmission of climate impacts across borders, termed "societal teleconnections". Societal teleconnections are human-made linkages, that "arise from the interactions among *actors*, and the *institutions* that guide their actions, affecting the movement of various *substances* through different *structures* and *processes*" (Moser & Hart, 2015). There is a wide range of societal teleconnections in our increasingly connected and globalized world, that can create, amplify or reduce the indirect effects of climate change, however, the factors that influence the connection of far-away places remain complex and divers (Moser & Hart, 2015). According to this framework, climate change impacts can be transferred along societal teleconnections between distant locations as shown in Figure 7.

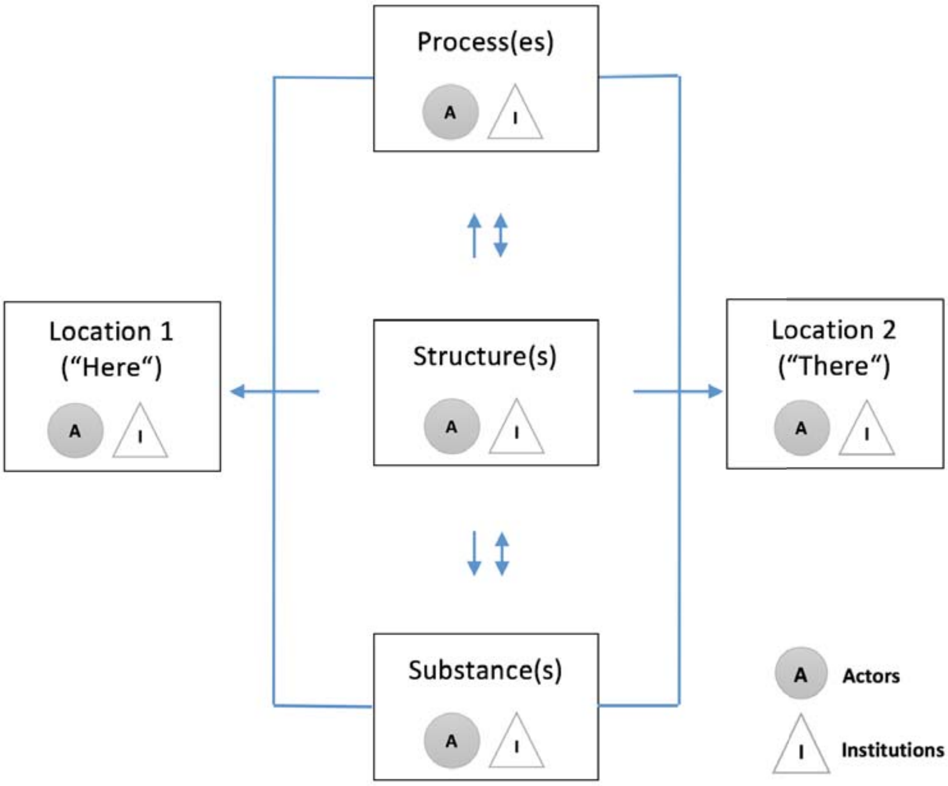

Figure 7: Transmission pathway of climate change impacts between two distant locations. Source: adapted from Moser & Hart (2015).

However, this transmission can only take place when the societal teleconnections comprise a minimum of three basic components: First, the *structure*, either a natural system or human-made construct that does not move but stays in one location (e.g. water, energy, transportation or communication-related infrastructure). Second, the *process,* that explains the causal chain for the teleconnection between two distant locations (e.g. trade, travel, or migration). Third, the *substance*, that is moved from one location to another (e.g. agricultural commodities, money or people). Furthermore, all of the components involve different *actors* that are able to establish, maintain or disrupt the teleconnection, by consuming, producing or moving substances from one location to another, enacted and controlled by different *institutions* (Moser & Hart, 2015).

In recent years, several climate impact transmission pathways between neighbouring countries or far-distant countries have been identified and discussed (Benzie, 2014; Challinor et al., 2016; EEA, 2017; Vonk et al., 2015; World Bank, 2014). Reviewing these studies points to the selection of four pathways through which the impacts of climate change may chiefly be transferred to Germany: trade, people, finance, and infrastructure. Another potential pathway that is often mentioned, but will not be discussed further, is the biophysical pathway, which transfers the impacts via transboundary ecosystems, such as rivers, across national or regional borders. For instance, a heavy rainfall event in an upstream country that cause floods in a downstream country, connected through a transboundary river, will consequently be affected by indirect transboundary impacts.

With respect to the geographical occurrence of the direct climate change impacts, two groups of indirect effects must be distinguished: (1) impacts occurring across regional or national borders via transboundary ecosystems, and (2) impacts occurring across larger distances through more remote links, involving the influence of people. Nevertheless, the primary focus of this study lays on the second group of impacts, i.e. long-distance, indirect impacts transferred through human-made linkages to Germany, as illustrated in Figure 8.

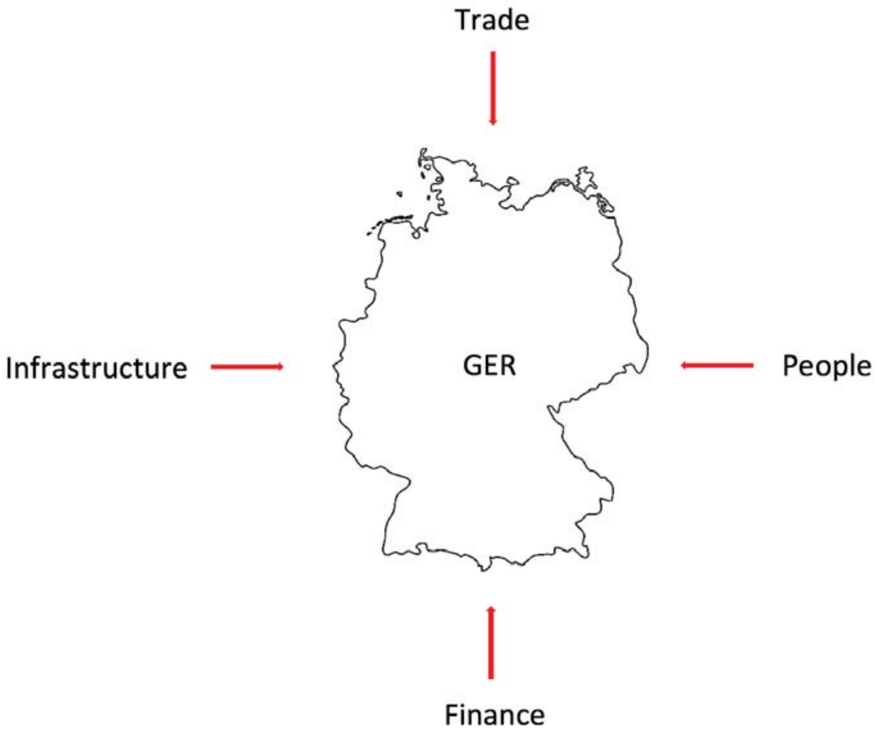

Figure 8: Major human-made pathways of long-distance, indirect climate change impacts for Germany.

3.2.1 Infrastructure

The first type of pathways refers to the direct impact of climate change and climate-related extreme weather events on water, energy, transportation or communication-related infrastructure abroad, that can have indirect effects in Germany. In fact, the rising number of extreme events is expected to increasingly damage all of the above-mentioned infrastructures in many parts of the world (IPCC, 2012) with potential negative consequences for Germany. The energy sector is of particular concern, as it is highly internationally connected and the impacts could be easily transferred along the power grid (Peters et al., 2006). For example, a prolonged period of drought and low water levels in rivers could lead to a deficiency of cooling water for power plants that in turn may have to shut down. In fact, during the recent heatwaves in 2003, 2006 and 2009, several power plants in Europe had to reduce their energy generation levels, causing a rise in electricity prices on the financial spot market (Vonk et al., 2015).

Another key infrastructure is the transportation infrastructure, since various kinds of climatic extremes, as well as a gradually changing climate and a rising sea level, are likely to increasingly damage or destroy roads, airports, railways, and ports. Impacts on coastal infrastructures are of particular concern as they are of greatest significance for international trade since more than 80% of the traded goods by volume is transported over the sea (Oh & Reuveny, 2010). An example of a climate-related extreme event with far-reaching impacts was Hurricane Katrina in 2005, which destroyed large parts of the port of New Orleans. As a result, the global oil supply was temporarily interrupted, leading to a significant increase of the global oil price (Nicholls & Kebede, 2012).

3.2.2 Finance

The financial pathway refers to the climate change impacts on the flow of capital such as remittances, global insurance or overseas investments (Groundstroem et al., 2015). The latter refers to public and private assets abroad which may be increasingly exposed to the impacts of climate change and hence experience depressed yields or devaluation as a result of major extremes or a gradually changing climate (Benzie et al., 2016). Furthermore, the projected increase in the occurrence and intensity of extreme events may lead to the disruption of global financial markets with spill-over effects for the insurance industry (EEA, 2017). Based on the rising amount of worldwide insured losses, it is expected that insurance premiums are likely to increase while the probability of damage is rising (Hirschfeld et al., 2016). Good examples of financial spill-over effects are the extreme windstorms over Europe in 1999, that caused insured damage worth 12 billion US$ (Schwierz et al., 2010), or Hurricane Katrina in 2005, generating insured losses in the amount of 60 billion US$, costs that were in large extent transferred to Europe, as much of the costs had to be carried by the London markets (Nicholls & Kebede, 2012).

3.2.3 People

Human migration is likely to be the most widely recognized transmission pathway for the impacts of climate change. While historical evidence suggests that global climate change and variability were among the main contributing factors for human migration (Lilleør & Van den Broeck, 2011), at present, climatic extreme events and sea level rise represent the most prominent direct link between climate impacts and the movement of people (IPCC, 2012). In this context, climate change has been found to be a “threat multiplier”, exacerbating already challenging circumstances to the point where people leave their homes (CNA, 2014). Generally, these threats are induced by direct impacts of climate change, reducing the availability of water, increasing the likelihood of droughts or repeated flooding events, that impede the possibility of people to sustain their livelihoods. While in most cases, people temporarily migrate within their national boundaries, past incidents have shown that migration also takes place internationally, between distant countries (Hallegatte et al., 2012). A recent study, modelling the global displacement trend for 1970 to 2014 suggests that the likelihood of being displaced after a climate or weather-related disaster has increased by 60% in just four decades (IDMC & NRC, 2015). Moreover, the study suggests that, since 2008, 26.4 million people have been displaced by extreme events on average per year(IDMC & NRC, 2015), indirectly posing a rising threat to societies and states that receive migrants from the affected countries (Hallegatte et al., 2012). In fact, many studies point to a climate-induced rise in geopolitical conflicts, indicating that climate change, climate variability and extreme events can increase the risk for riots and armed conflicts, as poverty and economic shocks are highly sensitive to climate change (Challinor et al., 2016; Hsiang et al., 2011; Oppenheimer et al., 2014).

Moreover, recent research suggests that unfavourable climate conditions might have triggered the Arab Spring (Sternberg, 2012) that eventually led to an increased migration flow to Europe, challenging the stability of states within Europe and across the world (Challinor et al., 2016; EEA, 2017).

3.2.4 Trade

Last but not least, the transmission of climate impacts via trade will be described. This section will receive special attention as it is the main pathway through which the impacts of climate change and extreme weather events can be transferred to the German food system. The transmission of climate change impacts via trade is based on the existence of globalized markets that allow the impacts and risks to be transferred along international supply chains. However, the multiple factors that initially make this transmission possible are complex and divers. Moreover, the outcome of the indirect effects not only depends on the magnitude of the direct climate change effects but also relies on various actors and institutions that can amplify or reduce the respective impacts.

Climate-induced changes in the availability and price level of agricultural and non-agricultural commodities are of great importance for countries that heavily depend on key resources and raw materials to meet their domestic demand. Moreover, the magnitude of the indirect effects will very much depend on the geographic distribution of supply (Nicholls & Kebede, 2012). In other words, the concentration of production in just a few countries can lead to major negative indirect effects for importing countries if the supply from the exporting counties will be disrupted. A prominent example of how the impacts of extreme events could be transferred along international supply chains are the Thailand floods in 2011, that caused global shortages of hard drives with repercussion for many importing countries, including Germany. The total costs of this event were estimated in the amount of 45 billion US$ (Munich Re, 2017), since companies worldwide, mainly in the automobile industry, had to reduce or temporarily stop their production as a result of delivery failures. This event demonstrates the extent of climate-related supply disruptions globally and the drawback of a global market in which many countries and their value chains heavily rely on the import of particular foreign goods and resources.

The indirect impact on food systems primarily refers to the direct impact of climate change and extreme events on agricultural productivity abroad. The specific direct long-term and short-term effects on food production and the overall sensitivity of agriculture have been discussed in chapter 2.3. The observed and projected changes in agricultural productivity of the major traded grains have been shown to be predominantly negative in most parts of the world, especially outside of Europe (Figure 3 and Figure 4), bringing about high negative implications for food systems in countries that rely on these grain imports. In recent years, international commodity prices have reversed the historical downward trend of global food prices, as prices may have become more sensitive to weather-related supply shortfalls (Porter et al., 2014). Several extreme weather events in the recent past have demonstrated how the direct impact on agricultural production can have spill-over effects on importing countries along the global food system via trade. Good examples of those climate-related extreme events are, among others, the extreme temperatures and droughts experienced in Europe 2003, in Russia in 2010, or in the United States in 2012.

3.3 Transmission of climate change impacts along food systems via trade

To further investigate how the negative effects of climate change and the impact of extreme weather events abroad could affect the German food system via trade, the conceptual framework of societal teleconnections by Moser & Hart (2015) will be applied, and the Russian heatwave in 2010 will be examined as a case study. The study Moser & Hart (2015) introduces eight different teleconnections, including trade, through which climate change impacts can be transferred across borders, yet, the qualitative analysis of how climate change could cause cross-border impacts through food systems is still missing.

While just a few decades ago, food was mostly produced locally, nowadays it travels around the whole globe before it gets consumed. As a consequence of this globalization of our food systems, anyone who is part of a food system, ranging from producers to consumers, and the multiple intermediaries involved in the transformation of food, can be exposed to the direct and indirect effects of climate change and extreme weather events (Adger et al., 2009). The teleconnections can derive from disruptions of the agricultural production process, and the associated water and energy infrastructures, or disruptions of critical transportation routes necessary for the functioning of the supply chains (Moser & Hart, 2015). More precisely, the *structure* that allows this teleconnection to occur are the particular trade routes that establish the linkage between the different exporting and importing countries around the world. The *substances* that should be transported are primarily agricultural raw materials, such as wheat, maize, rice or soy. The *process* that drives the teleconnection is the globalization of the food system and the desire for cheap food. The number of *actors* involved in this teleconnection is high, including farmers, food processing companies and consumers of food. *Institutions* that establish the teleconnection are local and national governments, responsible for trade regulations and multi-lateral trade agreements. A summary of the main components building the teleconnection for the transmission of climate-related impacts along the global food chain via trade is shown in Figure 9.

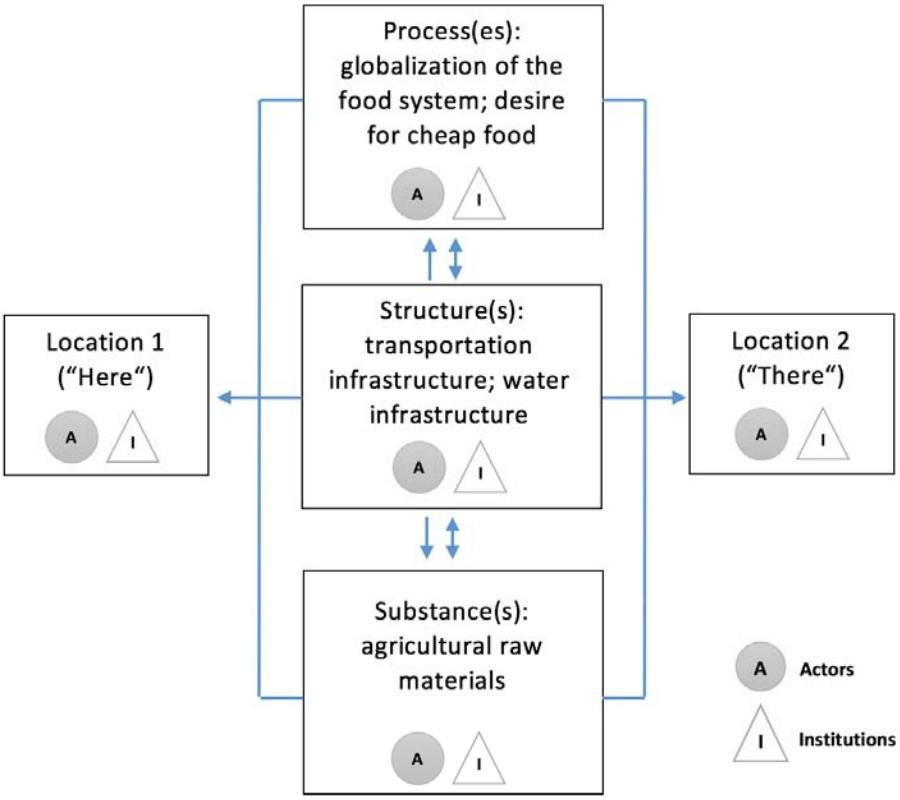

Figure 9: Key components for the transmission of climate change impacts between two distant locations along food systems via trade. Source: adapted from Moser & Hart (2015).

Case study: indirect effects of the Russian heatwave 2010

Even if the systematic framework by Moser & Hart (2015) facilitates the understanding of how the impacts of climate-related events can be transferred along food systems between distant countries, each teleconnection involves multiple different actors and institutions that are responsible for the outcome of the impacts felt in one location as a result of impacts in another location. To elucidate this complexity, one has to look closer at one particular teleconnection that allows these negative repercussions between distant countries to occur. The Russian heat wave in 2010 will therefore serve as a case study, trying to reveal key actors and institutions of the respective teleconnection, and subsequently, to examine which locations outside of Russia were affected the most by the resulting indirect effects.

The starting point for the climate-induced indirect impacts were the direct impacts from extreme temperatures on agricultural yields. Russia experienced the highest July temperatures in 130 years. The heatwave destroyed 13.3 acres of crops, around 17% of the total crop area (Welton, 2010). Annual crop yields were reduced by around 25%, ultimately leading to total economic losses of around 15 billion US$ (Barriopedro et al., 2011). As a result of the harvest failures, the national price for wheat went up, instantly followed by the international commodity prices. More precisely, the international price of one metric tonne of wheat increased in just four months by almost 40%, from ~160 US$ in May 2010 to ~220 US$ in August 2010 (IndexMundi, 2017). As the response to this sharp rise in wheat prices, the Russian government implemented an export ban, starting mid-August 2010 that continued until June 2011 (Fellmann et al., 2014). However, in contrast to the intended outcome to stabilize their own market and to protect the local consumers, the wheat prices continued to rise inside and outside of Russia. In fact, the global price of one metric tonne of wheat further increased to over 300 US$ in May 2011 (IndexMundi, 2017), before the export ban was revoked.

This raises two questions: First, what factors mainly have contributed to the large increase in international wheat prices that have amplified the indirect effects from harvest failures in Russia. Second, which countries were the most dependent on wheat imports from Russia, and therefore, the most exposed to these price effects.

A simulation of the reoccurrence of the 2010 Russian harvest failures highlights the role of countries and markets in either amplifying or reducing the impacts of extreme events on food supply. The modelling results suggest that the world market price for wheat would have increased much less if no export ban was put in place (Fellmann et al., 2014), pointing to the important role of institutional changes. In this example, the export restrictions are likely to have aggravated the negative market situation, amplifying the indirect effects through higher prices, with particularly adverse impacts on wheat net importing countries. Furthermore, other studies suggest that governance problems of public storage have led to reductions of public grain stocks in the past that could potentially have had a stabilizing effect on the national and international market price for wheat (Rashid et al., 2008).

Looking at the international trade data for wheat for the respective years 2010 and 2011 helps to answer the second question. The top five importers of wheat, averaged for the years 2010 and 2011 are shown in Figure 10. One can see that Egypt is the largest net importer of wheat in the world, importing almost half of its total domestic wheat requirements (Fellmann et al., 2014) of around 10 million tonnes per year (FAOSTAT, 2017). Wheat represents the key staple food in Egypt, mainly consumed as bread, providing one-third of the daily caloric intake of the local consumers (FAO, 2006). While the other top importers of wheat mainly received their imports from the US, Canada, Australia, or France, Egypt imported nearly half of its wheat during that time period from Russia (MIT's OEC, 2017), ultimately leading to a tripling of Egyptian bread prices with severe impacts for the local consumers (Sternberg, 2012). Even though the indirect impacts of the Russian heat wave clearly hit Egypt the most, it also had negative economic impacts for many other countries in the Middle East, Europe and the rest of our interconnected world (Bren d'Amour et al., 2016; EEA, 2017).

Summing up, the results show that harvest failures in distant producing regions can have severe impacts on spatially disconnected countries along global food systems, teleconnected via trade. Moreover, the results demonstrate that the global level of

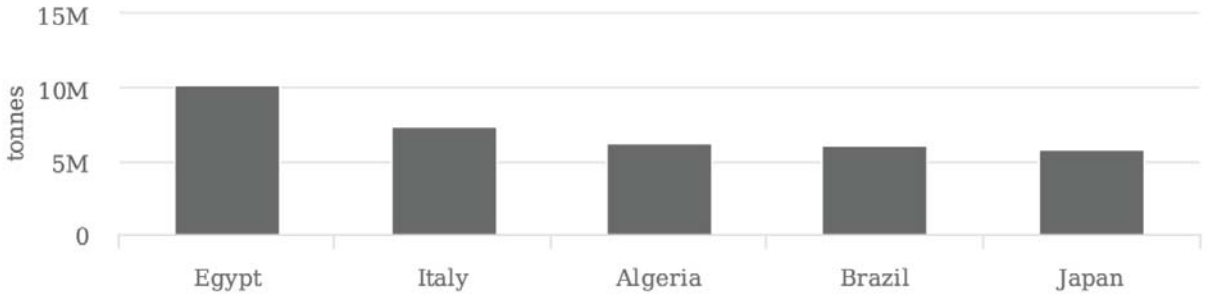

Figure 10: Global top five importing countries of wheat in 2010/11. Annual import quantities (in million tonnes) are averaged for 2010–2011. Source: FAOSTAT (2017).

yields not exclusively determine the availability of grains on global markets and their international price. Instead, socio-political factors like the Russian export ban, combined with the limited scope of importing countries to politically intervene, can largely influence the world food supply, and consequently amplify the indirect effects of climate change and extreme events via global prices. Last but not least, this brief case study indicates that countries heavily dependent on specific commodities from only a few suppliers, are likely to be the most exposed to the indirect effects from disruptions of agricultural production in distant but teleconnected countries.

3.4 Vulnerability to the indirect impacts of climate change

The term vulnerability is often used to describe the adverse effects of climate change on environmental, social and economic systems. However, a broad range of definitions and concepts exist between different scholars that can make the interpretation of certain statements difficult. One of the most prominent definitions that describes the integrative vulnerability concept, often denoted as the "outcome vulnerability" concept from the IPCC Third and Fourth Assessment report goes as follows:

> *"Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity"* (IPCC, 2007a).

According to this definition, vulnerability can be understood as a function of a system's exposure and sensitivity to climate change, climate variability and climate extremes, modified by its capacity to adapt.

A recent study by Bren d'Amour et al. (2016) merged the concept of vulnerability with an analysis of the indirect impacts of climate change, so-called "teleconnected food supply shocks". Their analysis tried to identify the most vulnerable countries to the indirect effects of harvest failures in distant producing regions. The exposure to the indirect impacts was measured by the extent to which supply shocks in exporting countries can be transmitted to the importing countries (Bren d'Amour et al., 2016). The level of vulnerability itself was determined by the reliance on foreign imports (import dependency ratio) of the three major grains: wheat, maize or rice, and the number of food insecure people living in poverty that would directly get affected by the "caloric trade deficit" (Bren d'Amour et al., 2016). The import dependency ratio is the ratio of imported crops to total domestic supply. The caloric trade dependency is the share of calories from imported food of the total consumption of cereals. Both values were calculated from the FAOSTAT's Food Balance Sheets (FAOSTAT, 2015). The poverty line is defined as the number of people living on less than 1.90$ a day (World Bank, 2015).

Their investigation identifies 33 countries that are particularly vulnerable to teleconnected food supply shocks, of which 21 countries depend on wheat, seven on maize, and five on rice (Figure 11). Their findings suggest that countries, vulnerable to supply shocks of a specific crop, are often spatially clustered in specific regions: The Middle East to supply shocks in wheat, Central America to supply shocks in maize, and Western Africa to supply shocks in rice (Bren d'Amour et al., 2016). However, weighing the number of people living under the poverty line, many countries in Africa seem to be the most vulnerable to teleconnected food supply shocks. Simulations of climate extremes affecting major producing countries followed by trade restrictions would reduce the exports of wheat, rice, and maize by 10%, and, in turn, put 200 million people below the poverty line at risk, of which 90% live in Africa (Bren d'Amour et al., 2016).

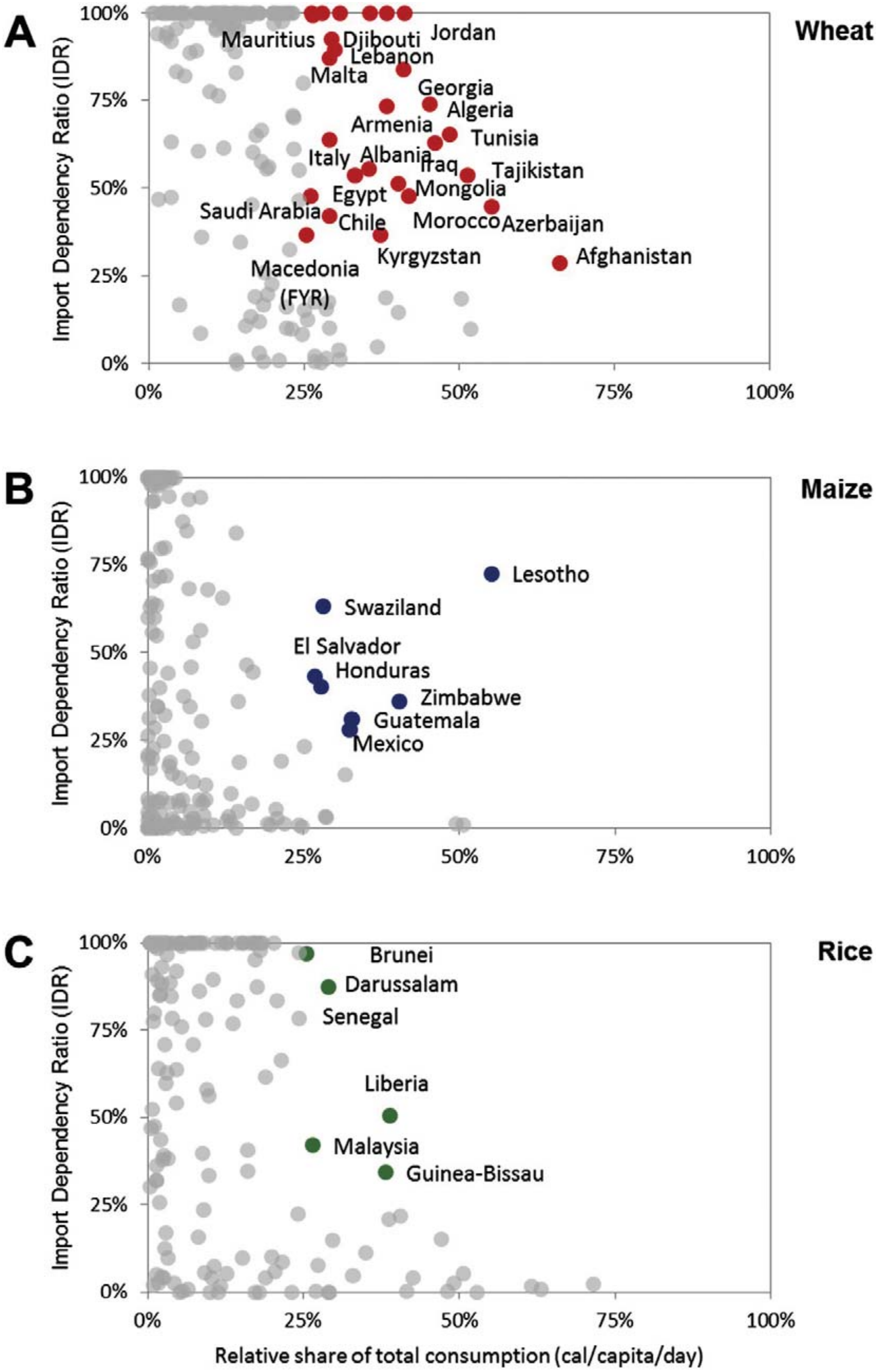

Figure 11: Vulnerability panels for supply shocks in (A) wheat, (B) maize, and (C) rice. The horizontal axis indicates a country’s caloric reliance on a specific crop, the vertical axis indicates its import dependency ratio. Countries where both ratios are ≥ 25% are highlighted. Source: Bren d’Amour et al. (2016).

4 Exposure of the German food system to the indirect effects of climate change

The direct effects of climate change and extreme weather events, as illustrated in section 2.3, have strong impacts on the productivity of agriculture in many countries, with potential negative repercussions around the world, as shown in chapter 3. Finally, transmitting the insights from the previous chapters, this section investigates how and to what extent the indirect effects of climate change and climate extremes may affect the German food system as part of a highly interconnected global food system.

The review of the existing literature on the indirect effects of climate change has shown that the level of exposure to the indirect impacts depends on the nature and extent of a countries connectedness with other countries and international systems. It could therefore be concluded that countries which are heavily dependent on specific commodities from a small range of suppliers are likely to be the most exposed to the trade-related indirect effects of climate change. Therefore, this chapter will make use of international trade data to determine the major suppliers of agricultural commodities to Germany and to assess the degree of dependency on these commodities and countries. Thereafter, the level of vulnerability of the identified exporting countries will be assessed according to existing vulnerability indices and the insights from climate change impacts on agricultural productivity from chapter 2.3. Together, the import dependency on agricultural commodities from vulnerable trading partners will represent a measure to assess the exposure of the German food system to the indirect impacts of climate change and extreme weather events.

4.1 Structure of the German food system

Once again, a food system comprises a chain of activities connecting food production, processing, distribution, consumption and waste management, as well as all the associated institutions and actors. This study chiefly focusses on the influence of climate change impacts on the production of food, the transportation-related infrastructure and the trade of agricultural commodities.

The German food system can generally be understood as a globalized system that is characterized by its integration in a global distribution network in which food travels very long distances before it gets consumed. The many factors that determine a globalized food system have been described in section 2.1.2. The outcome of this globalization process has brought many advantages in terms of increased agricultural output and lower food prices. However, in return, the German food system and part of the overall German economy now increasingly relies on the import and trade of agricultural commodities and food products (Wenz & Levermann, 2016). In fact, the German food industry relies to a considerable amount on the import of cheap sources of proteins as animal feed and various other food products that are grown in warmer climates. In addition, modern supply and management strategies, such as single-sourcing, global-sourcing or Just-In-Time production, intended to minimize slack and redundancies, further increase the likelihood of supply disruptions from extreme events (Lühr et al, 2014). Consequently, the globalization and modernization of the German food system can be seen as the main cause for its reliance on foreign imports and its susceptibility to the indirect impacts of climate change via trade and trade-related transportation infrastructure.

The magnitude of the potential indirect adverse effects become clearer while looking at the economic importance of the German food system, also referred to as the German agribusiness. The entire German food system employs 4.6 million people, approximately 11% of the whole working population (LfL, 2016), who generated a production value of approximately EUR 445 billion in 2015, accounting for 6.4 % of the total GDP (DBV, 2016). The food industry, as part of the food system, is the third largest industry in Germany. By generating a production value of EUR 172 billion, it represents the largest food industry in Europe (LfL, 2016). In 2015, imported and exported food products have ranged among the ten most important processed goods by value (Destatis, 2016). The ten major imported and exported traded goods in 2015, divided by their national product classification for production, is shown in Table 4.

Table 4: Major German import and export merchandise products in 2015.

	Imports	[Billion €]		Exports	[Billion €]
1.	Computer, electronic and optical products	102	1.	Motor vehicles, trailers and semi-trailers	226
2.	Motor vehicles, trailers and semi-trailers	97	2.	Machinery and equipment	169
3.	Chemicals and chemical products	76	3.	Chemicals and chemical products	108
4.	Machinery and equipment	73	4.	Computer, electronic and optical products	97
5.	Crude petroleum and natural gas	61	5.	Electrical equipment	72
6.	Basic metals	52	6.	Basic pharmaceutical products and pharmaceutical preparations	70
7.	Electrical equipment	52	7.	Other transport equipment	57
8.	Basic pharmaceutical products and pharmaceutical preparations	46	8.	Basic metals	50
9.	Food products	42	9.	Food products	49
10.	Other transport equipment	37	10.	Rubber and plastic products	41

Source: Destatis (2016).

4.2 Agricultural commodity-import dependency

In order to produce and export these higher value processed goods, Germany has to import a great amount of raw materials from inside and outside of Europe. Especially, the export and import of agricultural commodities have increased considerably over the past years, making Germany both, the third largest importer and exporter of agricultural products in the world (WTO, 2016).

Agricultural commodities, also referred to as soft commodities, mean all commodities that are derived from plants or animals, which are primarily used for human food or animal feed, in contrast to hard commodities, which are rather mined than grown, such as oil or gold, as defined by the FAO (2008). In 2015, Germany imported agricultural commodities in value of EUR 75 billion, creating a trade deficit between agricultural imports and exports of approximately EUR 10 billion (BMEL, 2016). This negative trade balance is particularly due to the high imports from countries outside of Europe. In comparison, Germany ranks on place 7 of the largest net importing countries of agricultural products in the world (DBV, 2016). A list of the top ten agricultural commodities imported to Germany is shown in Table 5. The international trade data was received from the FAOSTAT data base for crop and livestock products and sorted by the respective import volume. To determine the origin of the respective agricultural commodities, international trade data from the Observatory of Economic Complexity of the Media Lab of the Massachusetts Institute of Technology (MIT's OEC) was used. However, especially for agricultural trade data, one has to keep the issue of re-exports in mind. In these cases, a particular country imports specific commodities and then re-exports them without further processing. Since FAOSTAT and the MIT's OEC include re-export data into their international trade data bases, all the countries identified as major German suppliers may include countries that are not the actual country of origin of the respective commodities. Reviewing the value chain of the listed commodities identified the Netherlands as one of the main re-exporters of agricultural commodities to Germany. It can thus be concluded that potential harvest failures in the Netherlands will neither affect the supply of soy nor palm oil, as the production of these commodities originally takes place in other countries. All the other countries have been identified as major producers of the respective commodities and hence will be seen as their countries of origin.

Overall, these numbers indicate that the production of food and the profitability of the food industry in Germany relies to a considerable amount on the import of agricultural commodities. In fact, the production-related expenditures of the German agricultural sector in 2015 were estimated in the amount of EUR 15.8 billion for animal feed alone (DBV, 2016).

Being dependent on the supply of agricultural commodities from vulnerable trading partners have been found to be a good indicator to assess the level of exposure to climate-related indirect impacts of climate change. However, the magnitude of risk, arising from the import dependency, relies on three main factors concerning the respective agricultural commodity: (1) its importance for the national economy, (2) its potential for substitution, and (3) the spatial pattern of its production (Cerveny et al., 2014).

Table 5: Major German agricultural commodity imports in 2013.

Commodity	Import volume [Million tonnes]	Import value [Billion US$]	Major trading partners
1. Rapeseed	4.60	2.64	France, Poland, Netherlands
2. Wheat	3.84	1.20	Czech Republic, Poland, France
3. Soybeans	3.62	2.10	USA, Brazil, Paraguay
4. Soybean cake	2.94	1.66	Brazil, *Netherlands*, Argentina, USA
5. Maize	2.13	0.90	France, Poland, Ukraine
6. Grapes	1.50	3.34	Italy, France, Spain
7. Palm oil	1.46	1.39	*Netherlands*, Indonesia, Malaysia, Papua New Guinea
8. Bananas	1.34	1.10	Ecuador, Costa Rica, Colombia
9. Barley	1.13	0.34	France, Denmark, Czech Republic
10. Coffee	1.12	3.20	Brazil, Vietnam, Honduras

Source: FAOSTAT (2017); MIT's OEC (2017).

Clearly, the economic importance of the agricultural commodity itself, and the industries where it is needed, determine the extent of the negative impacts from climate-related supply disruptions. Consequently, the indirect impacts will be particularly severe, when alternative sources are not able to replace the affected commodity. Last but not least, the spatial pattern of production determines the extent to which an extreme event or a changing climate will ultimately affect the global supply. For example, extreme weather events that would lead to harvest failures of soybean in the US, Brazil or Argentina, would reduce much of the supply globally, since most of the production is concentrated there.

The direct impacts of climate change on agricultural productivity have been shown to follow a spatial pattern (Figure 3). While most countries in Europe are expected to benefit from changes in mean climatic values, the majority of countries in tropical and subtropical regions are expected to experience large yield decreases (IPCC, 2007b). Consequently, the critical agricultural commodities from outside of Europe will be further evaluated according to their importance for the overall German food system, their potential for substitution and the concentration of their production.

4.2.1 Soybeans

Soybeans and rapeseed are the most important protein sources as feed in Germany. While rapeseed is largely produced in the EU, most of the soybeans and its by-products have to be imported from outside of Europe. In fact, the production of soybeans is geographically concentrated in just a handful of countries, commonly referred to as "global bread baskets". The major producing countries include the Unites States, Brazil, Argentina and Paraguay, together generating more than 80% of the global soybean production of approximately 320 million tonnes per year (LfL, 2016). In 2013, Germany imported 3.6 million tonnes of soybeans and 2.9 million tonnes of soybean meal, of which almost 90% were obtained from the United States, Brazil and Paraguay (FAOSTAT, 2017). Soybean meal, also referred to as soybean cake, is the by-product that remains after the extraction of soybean oil. It represents the most important protein source to feed animals in the world.

The rising demand for animal feed, especially of soybean, can be in part attributed to the dietary transition in the developing world, leading to a growing demand for meat and livestock products on the world market, particularly in Asia. Within the past decade China has nearly tripled its demand for soybeans, now representing the major importing country worldwide in the excess of around 80 million tonnes per year, followed by Germany (LfL, 2016). Furthermore, as a result of the rising global demand for meat and livestock products, Germany has increased its meat production dramatically in the past years, and despite its own high level of consumption, it has now become a net exporter of meat products (BMEL, 2016).

4.2.2 Palm oil

Palm oil is by far the most efficient oilseed crop worldwide, producing 3.3 tonnes of oil per hectare. Generally, the replacement of palm oil with other vegetable oils is possible, but much land would be needed for its production, as the yield per hectare in all the other oilseed crops is much lower. For comparison, soybean produces only 0.4 tonnes of oil per hectare and rapeseed 0.7 tonnes per hectare (WWF, 2016).

Globally, more than 95% of all palm oil exports are produced in Malaysia and Indonesia (FAOSTAT, 2017). In other words, Germany is fully dependent on imports of palm oil to satisfy its national demand of approximately 1.5 million tonnes per year, mainly produced in Malaysia, Indonesia and Papua New Guinea. An equal share of 40% each is used for food products and bioenergy, the rest is used for industrial applications (WWF, 2016).

4.2.3 Bananas

Due to the prevalent climatic conditions, the degree of self-sufficiency with fresh fruits in Germany is very low. In 2015, the level of self-sufficiency with fruits was just below 25% (LfL, 2016). While the own harvest is largely limited to apples, Germany imports large amounts of citrus fruits and bananas from inside and outside of Europe. Almost half of the banana production is concentrated in India and China, however, many other countries around the world participate in the global production and trade of bananas. In 2013, Germany imported the total amount of 1.34 million tonnes of bananas almost exclusively from Ecuador, Costa Rica and Colombia (FAOSTAT, 2017).

The per capita consumption of fruits in Germany currently amounts to approximately 80kg per year, covered by 15% with bananas. Only apples are more popular, covering 25% of the yearly consumption (LfL, 2016). The import of fruits is not only important to provide the people with vitamin-containing food, but it also plays and important economic role for the German food industry. In fact, nowhere in the world are so many juice manufacturers as in Germany. In 2014, the fruit juice industry had a total revenue of EUR 3.6 billion, producing nearly 3.7 million litres (ITC, 2017).

4.2.4 Coffee

Green, unprocessed coffee is one of the most valuable agricultural commodities for the German economy, and hence, coffee is also called “cash crop” or “black gold”. Considering its annual import value of 3.2 billion US$, Germany represents the second largest importing country in the world (FAOSTAT, 2017). Its role as a major coffee importer and re-exporter can be attributed to the port of Hamburg, the largest transition point for coffee in the world. In 2013, Germany re-exported green coffee in the excess of 1.15 billion US$, representing the fifth largest exporting country of unprocessed coffee worldwide, ranking just behind the main producing countries Brazil, Vietnam, Colombia, and Indonesia (FAOSTAT, 2017). The rest of the coffee is further processed and then either exported to a higher price or consumed within the country. The International Coffee Organization (ICO) estimates that a German consumer drinks 6.5kg of coffee each year, corresponding to around 2.8 cups per day (ICO, 2017). Despite its economic importance for the whole coffee industry, a major part of the revenue is directly made by the state through taxes and duties. In fact, one kilogram of roasted coffee is taxed with 2.19€ and one kilogram of instant coffee with 4.78€, adding an additional one billion euros per year to the national tax income (Statista, 2017).

A large share of the global coffee production is concentrated in Central America, South America, and Southeast Asia. The top ten producing countries, including the major German suppliers Brazil, Vietnam, and Honduras, together generate more than 80% of the total global production of approximately nine million tonnes per year (FAOSTAT, 2017).

4.3 Vulnerability of the major German trading partners

In the previous step, it has been shown that the German food system relies to a great degree on specific agricultural commodities from a small range of particular countries to sustain its high revenues through the market and the various food industries. In the last step, the level of vulnerability of the identified main trading partners from outside of Europe will be assessed according to the Notre Dame Global Adaptation (ND-GAIN) vulnerability index and the observed and projected direct impacts of climate change and extreme weather events.

The concept of vulnerability has been used in a large variety of climate change assessments, and several indices have been developed to reveal the spatial patterns of vulnerability to the direct and indirect impacts of climate change. However, the outcome of the indices varies considerably, depending on the selection and weighing of the respective indicators (de Sherbinin, 2014). A prominent example of these indices is the ND-GAIN Index, measuring a countries vulnerability to the direct impacts of climate change, by considering the vulnerability of six life-supporting sectors: food, water, health, ecosystem service, human habitat and infrastructure, and a countries readiness to adapt. According to the most recent ND-GAIN Index for the year 2015, Germany was the second least vulnerable country to climate change (ND-GAIN, 2017). In 2015, the index ranged between 0.722, representing Chad, the most vulnerable country to climate change, and 0.211, scored by the United Kingdom, representing the least vulnerable country. In contrast to Germany, many of its connected trading partners can be found in the lower half of the 181 rated countries, showing a significant vulnerability to climate change (ND-GAIN, 2017). The vulnerability scores for the major German trading partners outside of Europe are shown in Table 6.

Table 6: Vulnerability of the major German suppliers of agricultural commodities from outside of Europe.

Commodity	Import volume [Million tonnes]	Import value [Billion US$]	Major trading partners	ND-GAIN Vulnerability score
Soybean produce	6.56	3.76	USA	0.247
			Brazil	0.346
			Paraguay	0.382
			Argentina	0.374
Palm oil	1.46	1.39	Indonesia	0.402
			Malaysia	0.335
			Papua New Guinea	0.649
Bananas	1.34	1.10	Ecuador	0.405
			Costa Rica	0.361
			Colombia	0.366
Coffee	1.12	3.20	Brazil	0.346
			Vietnam	0.401
			Honduras	0.446

Source: FAOSTAT (2017); MIT's OEC (2017); ND-GAIN (2017).

The outcome of the existent vulnerability indices varies considerably depending on the selection and weighing of the indicators, however, the majority of all indices draw the same picture. While rich countries in the northern hemisphere are the least vulnerable countries to climate change, many countries in the southern hemisphere are the most vulnerable countries. The ND-GAIN index generally helps to estimate a countries current level of vulnerability to climate change, yet, climate and crop models are needed to grasp the projected direct impacts on yields. A combination of the identified major agricultural import flows from outside of Europe, and the expected direct global impacts on yields is illustrated in Figure 12. However, to get a more realistic picture of the observed and projected direct impacts on yields, a more detailed analysis on the country-level is needed. Consequently, Brazil will serve as a case study to deduce the indirect exposure via imports of soybeans and soybean meal.

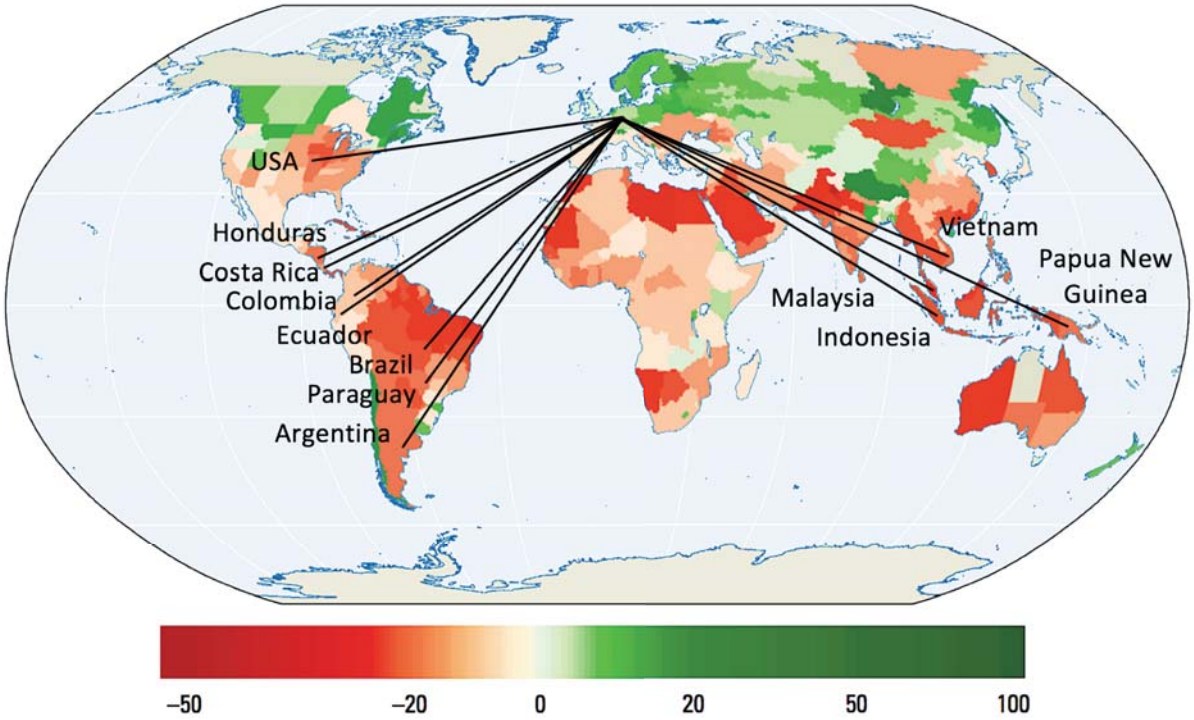

Figure 12: Global climate change effects on the agricultural productivity of the main German trading partners by 2050. The figure shows the estimated percentage change in yields between 2000 and 2050. The black connecting lines indicate the major agricultural import flows from outside of Europe. Areas, where no robust data was available, are grey. Source: Müller et al. (2009); adapted from World Bank (2010).

Case study: Brazil – soybeans

Share of global production[2]: 27%

Share of imports to Germany[3]: 49%

ND-GAIN vulnerability score: 0.346

A particular weak spot of the German food system to the indirect effects of climate change results from the large import-dependency on soybeans and soybean meal. In 2014, 38% of the soybeans and 61% of soybean meal were imported from Brazil, the largest exporter to Germany (MIT's OEC, 2017). The import of soybeans and soybean meal are essential to maintain the present performance level of the German food industry, especially of the meat industry. The growing economic importance of the meat industry in Germany increases the demand for animal feed, and simultaneously further extends the level of import-dependency. These circumstances suggest that the meat industry, as part of the German food system, is increasingly exposed to the indirect impacts of climate change and extreme weather events that may affect the agricultural productivity of soybeans in Brazil. In fact, various historical statistical studies and integrated assessment models from the past years indicate an alarming climate-related downward trend of the agricultural productivity in Brazil that can only be compensated for by the ongoing intensification of agricultural production and technological improvements. However, as the demand for soybeans is still growing, it is projected that rainfall amounts will further decline and droughts will intensify throughout the 21st century (IPCC, 2012).

In the 50-year period before the AR4, the average temperature in Brazil has increased by around 0.7°C (IPCC, 2007b) (see Figure 1 for the observed change in surface temperatures). Moreover, the increased global demand for meat products has led to a

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[2] Refers to the latest crop production data, accessed from the statistical database of the FAO, for the year 2014. Source: FAOSTAT (2017).

[3] Averaged share of imports of soybeans (38%) and soybean meal (61%) of the total import value in 2014. Source: MIT's OEC (2017).

large expansion of soybean production in Brazil, with severe consequences for local rainfall and soil erosion (Nepstad et al., 2006), significantly affecting the availability of water for agriculture and ultimately for human consumption (IPCC, 2007a). In fact, 15% of the Brazilian rainforest has already been cut down, mostly due to cattle ranching and soybean cropland expansion (Morton et al., 2006). Recent modelling results suggest that 40% of deforestation of the Amazon rainforest may represent a tipping point, leading to dramatic climate change impacts, such as significant decreases in rainfall and further global warming, representing a negative feedback loop that in turn would result in further forest losses (Sampaio et al., 2007).

Substantial crop yield impacts are already felt today, and the risk of reduced crop yields and food production losses are expected to increase rapidly above 1.5°C of warming in large parts of Latin America (World Bank, 2014), identified as a global hotspot for projected crop losses due to increasing heat stress (Teixeira et al., 2013). The optimum seasonal average temperature for soybeans is 22°C; above 29°C yields start to rapidly decline (Schlenker & Roberts, 2009). Average temperatures of 39°C or above lead to a total crop failure (Hatfield et al., 2011). In fact, short intervals of temperatures above the optimum can already lead to large yield decreases (Ackerman & Stanton, 2012; Schlenker & Roberts, 2009), posing a significant threat to the global food supply (IPCC, 2007a).

Various studies have estimated the projected impact of future climate change on crop yields of soybeans in Brazil, yet the outcome of the impact studies depend on the assumptions about the degree of warming and the positive effect of CO_2. In summary, most works conclude that the positive fertilizing effect will be more than offset by unfavourable climate conditions leading to average soybean losses of around 2.5–70% by 2050 (Fernandes et al., 2012; Müller et al., 2009; Nelson et al., 2009). While it has been proven difficult to predict the future impact of climate change on crop yields, median estimates of past climate trends (1980–2008) suggest that the production of soybeans in Brazil have already been reduced by approximately 5% (Figure 4), relative to what would have been achieved without climate change (Lobell et al., 2011).

Overall, the alarming trends of global warming and changes in rainfall patterns, projected and observed yield reductions, and the rising demand for animal feed such as soybeans pose a growing threat to the German food system, particularly through imports from Brazil. Yield reductions and harvest failures, but also disruptions of transportation infrastructures and trade restrictions can lead to disruptions of the global supply of soybeans that eventually translate into higher prices for food and fodder. While Brazil has served as a case study here, similar developments and climatic trends can be observed in many other German trading partners outside of Europe.

5 Results

This study was divided into three major tasks: (1) to describe the direct climate impacts on agricultural productivity abroad, (2) to analyse the concept of indirect effects of climate change in the context of food systems, and (3) to examine the potential level of exposure of the German food system to the indirect effects of climate change via trade. In the following, the main findings will be presented here to validate the hypothesis that a country's food system is particularly exposed to the indirect effects of climate change when it heavily relies on the import of agricultural commodities from vulnerable trading partners abroad. Accordingly, it will be demonstrated that the German food system is particularly exposed to the indirect effects of climate change via trade.

5.1 Direct impacts of climate change on food production

The present analysis shows that a changing climate not only leads to an increase of the global mean temperature and climate variability but is likely to change the intensity, frequency and spatial extent of extreme weather events. Moreover, it demonstrates that the agricultural productivity of most crops is particularly sensitive to these changes. While intra- and interseasonal temperature and precipitation variability and the exceedance of specific thresholds can have dramatic impacts on yields in the short-term, the projected impact of gradually changing climatic values, such as rising temperatures, is growing over time and poses a significant risk to the global food production in the long-term.

Overall, the investigation of the direct impacts on agricultural production has shown that average crop yields are very likely to decrease as a result of increasingly unfavourable climate conditions. Furthermore, the analysis has revealed that large geographic disparities exist between the projected impacts on yields, following the spatial heterogeneity of climate change. While most countries in temperate regions may even benefit from a changing climate in the near future, many countries in tropical and subtropical regions might experience large yield decreases, as the prevalent climate is already close to the temperature thresholds of most crops.

5.2 Indirect impacts of climate change on food systems

It was found that the direct impacts of climate change and extreme weather events can be transferred through multiple pathways across borders. The resulting indirect impacts of climate change affect one country as a consequence of direct impacts in another, trans-boundary or far-distant, country. In particular, four major pathways have been identified as the transmission lines for the indirect impacts of climate change: infrastructure, people, finance, and trade. However, the latter is the most important pathway with respect to food systems, as the existence of globalized food markets allows the impacts to be easily transferred along international supply chains. The underlying mechanisms of the transmission are complex and diverse and are mainly driven by the influence of people on social, environmental and economic systems. Accordingly, the globalization of our food systems was identified as the main driver for the transmission of indirect climate change impacts between countries and systems as it erodes the barriers for the movement of agricultural commodities and financial capital across borders.

Furthermore, it has been demonstrated that the outcome of the resulting indirect impacts not only depends on the magnitude of the direct impacts on the production of food but also relies upon socio-political factors that are able to amplify or reduce the respective indirect impacts. In fact, the analysis of the Russian heatwave in 2010 has revealed how institutional changes in form of trade restrictions can amplify the indirect effects of harvest failures on importing countries through higher international commodity prices. Moreover, the case study has shown that countries which heavily rely on particular agricultural commodities from a small range of suppliers are likely to be most exposed to the indirect effects of climate change. In other words, the magnitude of trade-related indirect climate change effects from disruptions of agricultural production in net importing countries depends on the geographic distribution of supply.

5.3 Exposure of the German food system to the indirect effects of climate change

Being dependent on the import of agricultural commodities from vulnerable trading partners has been defined as a measure to assess the level of exposure of the German food system to trade-related indirect effects from climate change impacts on agricultural production. Moreover, it has been found that the extent of potential damage from climate-related indirect impacts depends on the economic importance of the impaired commodity, its potential for substitution and the spatial pattern of its production.

Generally, the German food system can be understood as a globalized system, being progressively integrated into the global food system, and characterized by its heavy reliance on the import of agricultural commodities. Subsequently, international trade data from the Statistical Database of the Food and Agriculture Organization of the United Nations was used to determine the major imported agricultural commodities: rapeseed, wheat, soybeans and soybean meal, maize, grapes, palm oil, bananas, barley, and coffee. Afterwards, bilateral trade data was evaluated to determine the origin of the respective agricultural commodities, and hence, the main German trading partners inside and outside of Europe: France, Poland, Netherlands, Czech Republic, Ukraine, Italy, Spain, and Denmark, and USA, Brazil, Paraguay, Argentina, Indonesia, Malaysia, Papua New Guinea, Ecuador, Costa Rica, Colombia, Vietnam, and Honduras. As large geographic disparities between the projected impacts on yields have been revealed, only the agricultural commodities from outside of Europe: soy and soybean meal, palm oil, bananas, and coffee, were further evaluated regarding their potential to indirectly affect the German food system.

Altogether, all of the respective commodities have been found to be of great importance for the German food system, either as agricultural precursors or intermediate products for the food industry or as re-export or merchandise products in the economic sense of trading profits for the German economy. Furthermore, the supply of these commodities has been found to be largely concentrated in just a few countries. While the cultivation of bananas and coffee takes place in quite a few countries, soybeans and palm oil are almost exclusively produced in Brazil, USA, Argentina, or Indonesia and Malaysia respectively. Moreover, the natural characteristics of these two crops, i.e. the high protein content of soybeans, or the high oil yields per hectare of oil palm, make these two commodities very hard to be replaced.

Last but not least, the vulnerability of German's main trading partners was assessed. The majority of trading partners outside of Europe were found to score below average in the 2015 vulnerability index table of 181 countries of the Notre Dame University. However, although the ND-GAIN index may be used as a proxy-indicator to get a geographical overview of the estimated levels of vulnerability, it was found to be insufficient to determine an adequate reflexion of the particular susceptibility to the direct impacts of climate change on food production. Consequently, a case study was carried out using Brazil as an example, which is the largest German supplier of soybeans and soybean meal.

Various climate models and yield impact studies indicate an alarming climate-related downward trend of agricultural production in Brazil. In summary, unfavourable climate conditions may lead to a reduction of soybean harvests by up to 70% by 2050 (Fernandes et al., 2012), when neglecting the potential positive fertilizing effect of CO_2 and a further intensification of agricultural production. At the same time, the demand for soybeans and soybean meal can be expected to rise in Germany and globally as a result of the growing demand for meat and livestock products. This, in turn, creates high amounts of GHG, worsening the potential future impact of climate change on agricultural production, representing a negative feedback loop within the food system. Consequently, the German food system, especially the meat industry, was found to be particularly exposed to the potential indirect effects from climate-related reductions of soybeans via imports from Brazil.

Furthermore, the high import-dependency on all identified agricultural commodities, the concentration of production and export in a handful of countries, and the projected and observed yield reductions in the southern hemisphere suggest a significant threat via agricultural commodity imports from all trading partners outside of Europe.

6 Discussion

This study shows that the German food system is particularly exposed to the indirect effects of climate change via import of agricultural commodities from vulnerable trading partners. The respective impacts can be imported via trade if the exporting countries are directly affected by climate change, the imported agricultural commodities are hard to be replaced, and the commodities are important for the German food system. However, quantitative statements about the level of exposure of the German food system could not be conducted as they exceeded the scope of this thesis. The case study of the 2010 Russian heatwave may be rare in that there was a fairly direct link between the impact of extreme temperatures on wheat yields in Russia and the subsequent effects on international wheat prices with particularly adverse indirect effects for net importing countries, such as Egypt. In many instances, however, the origin of the indirect climate change impacts is more difficult to trace back, as the underlying mechanisms of their transmission are complex and diverse. Furthermore, efforts to quantify climate-related impacts on prices would have to consider effects throughout the world since agricultural commodities are traded worldwide and market prices are mainly determined by global supply and demand (Hertel et al., 2010). Besides, when dealing with indirect impacts transferred via trade, it can be difficult to get information since most data is typically considered to be a trade secret.

Generally, it is a complicated task to point to a singular cause for the indirect impacts of climate change. Hence, it is not possible to distinctly attribute the migration of people, violent conflicts, or supply shortfalls and growing commodity prices to the direct impacts of climate change or extreme weather events. Moreover, in the context of food systems, it has been shown that the extent of the indirect impacts not only depends on the magnitude of the direct impacts on yields, but is particularly influenced by various actors and institutions that can amplify or reduce the respective impacts.

The globalization of our food systems has been established as the main driver for the transmission of climate change impacts across borders, however, one should keep in mind that international trade is also able to reduce the indirect impacts, since it is able to diversify the risk of harvest failures (Bren d'Amour et al., 2016). Nevertheless, when the agricultural production of a particular commodity is geographically concentrated in just a few countries, and the demand cannot be covered from elsewhere, especially import-dependent countries, such as Germany, must anticipate to be indirectly affected through higher prices or supply shortfalls. The geographic concentration of production and supply must therefore be seen as a critical factor when estimating the extent of indirect effects of climate change via trade.

Overall, it is a very complex task to anticipate how climate change may affect agricultural yields in the future, and consequently, any statement about the future level of exposure to the indirect effects of climate change from possible reductions of agricultural production must be viewed with caution. Clearly, both climate and crop models comprise significant uncertainties as each model is composed by numerous variables derived from assumptions on the extent and rate of future climate change. In fact, most estimates may be too positive because scientist are not yet able to properly include the effects of extreme weather events into their crop models (Schlenker & Roberts, 2009), which can have dramatic impacts on yields. Moreover, it was demonstrated that the assumptions about the positive fertilizing effect of CO_2 may be overly optimistic since elevated levels of CO_2 can have negative effects on the quality of food and reduce the resistance of particular crops to extreme weather conditions (Singh, 2009; Taub et al., 2008).

7 Conclusion

This study has demonstrated that global crop yields are very likely to decrease as a result of increasingly unfavourable climate conditions. Moreover, climate change may change the intensity, frequency and spatial extent of extreme weather events, posing an additional threat to food systems via disruptions of supply chains and dramatic yield reductions in the short-term. As a result, modern supply and management strategies must consider an expansion of redundancies in order to minimize the likelihood of supply disruptions and supply shortfalls from unexpected weather events.

This thesis shows that the reliance on agricultural commodities from a limited number of trading partners is a critical factor when determining the level of exposure of import-dependent countries to the indirect effects of climate change via trade. By implication, the diversification of trade partners can help to reduce the potential indirect impacts of extreme weather events and climate change by stabilizing food supply and thus represents an important tool for future adaptation policy and planning. Moreover, public grain stocks of agricultural commodities produced in vulnerable countries may help to reduce international price volatilities.

The broad-scale pattern of climate change impacts on yields has been found to be consistent across all crop models, following the spatial heterogeneity of climate change. As a result, there might be a shift of production zones from the south towards the north, altering the balance and pattern of food trade. While industrialized, import-dependent countries in the north, such as Germany, have to deal with supply shortfalls and increasing food price volatilities, many poor countries will be confronted by a decreased availability of food, and hence, by a reduction of the overall level of food security. In this respect, the concept of indirect climate change effects is very important, as it challenges the perception that climate impacts are restricted to the place where they occur. Instead, it has been shown that climate change does not respect borders and the respective impacts can be easily transferred along international supply chains. Therefore, it offers a more complex perspective on how exposure to climate impacts may be experienced in a globalized world and demonstrates that no country, no matter how rich or poor, is fully insulated from the adverse effects of climate change. As a consequence, the costs of direct impacts on food production in the global south will also fall on rich countries in the north. Hence, it might be in the self-interest of the industrialized countries to fund adaptation plans beyond their national borders. Without ambitious adaptation plans at larger scales, that pay attention to the many interdependencies in our globalized world, the impacts of climate change and extreme weather events on the global food system may be severe.

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