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The Effects of Extreme Weather Disasters in the European Food Availability

Thesis submitted to NOVA School of Science and Technology, NOVA University of Lisbon for the degree of Doctor of Philosophy (PhD) in Climate Change and Sustainable Development Policies

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FACULDADE DE
CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE NOVA DE LISBOA

December 2020

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This work has been made possible by the financial support of Fundação para a Ciência e Tecnologia with the grant PD/BD/114570/2016

Acknowledgements

Firstly, I would like to express my gratitude and respect to Prof. Júlia Seixas, my supervisor, for her guidance during my research, for encouraging me to explore a growing research field at the Energy and Climate research group, and for her continuous and strong support that allowed me to carry out my PhD.

I am very grateful to Nuno Carvalhais and Jonas Jägermeyr, my co-supervisors, for their guidance, dedication, and fruitful discussions during my PhD. Thanks to Nuno, for encouraging me to learn a new programming language (an essential element to accomplish my research), for asking me many questions while stimulating my critical thinking, and for his positive attitude and enthusiasm that brought me confidence. Thanks to Jonas for his excellent dedication, for the sharing of knowledge, for raising the level of difficulty while motivating me to enhance the quality of my research.

I also want to thank to Prof. José Lima Santos for his valuable insights which allowed me to widen my research from different perspectives.

Thanks to Nuno Pacheco and Prof. Teresa Calvão for their availability to provide me useful clarifications on ArcGIS.

My warmest thanks to my former and present colleagues at the Centre for Environmental and Sustainability Research (CENSE), for their friendship, support and for the good lunch breaks. Big thanks to Patrícia Fortes, Sofia Simões, João Pedro Gouveia, Luís Fazendeiro, Pedro Palma, Katherine Mahoney, Filipa Amorim, Joana Monjardino, Hugo Tente, Sofia Teixeira, Paulo Pereira, Luísa Mendes, Babar Mujtaba, and Evaldo Costa for the daily companionship. Thanks also to Patrícia and Sofia for the opportunity to take part of the CLIM2POWER ERA-NET research project, which allowed me to continue with my PhD research while developing complementary data processing skills. My most sincere appreciation to Flávia Collaço, Luís Dias, and Juliana Barbosa, my comrades and good friends, for sharing the happiness of my achievements, for the fruitful discussions, and for helping me finding ways of overcoming difficulties along this journey. Thanks also to my colleagues and professors of the sixth edition of the Doctoral Program on Climate Change and Sustainable Development Policies, for the enthusiastic atmosphere that contributed to an exciting start of the PhD, and in particular to Filipa Ferreira for her friendship and for always motivating me to overcome the challenges that I came across during this journey.

This thesis have been made possible with the support of Fundação para a Ciência e Tecnologia, the Faculty of Sciences and Technology of NOVA University of Lisbon, and CENSE, which helped me with research grants and funding to take part in conferences and workshops and materials. I also thank to

the secretariat of the Department of Environmental Sciences and Engineering (DCEA), Filomena Gomes, Sandra Ferreira, and Sandra Alberto, for making bureaucracies easier.

Finally, I would like to thank my family and close friends for their encouragement and support during this journey. A special thanks to Marta Ruxa, Ana Rodrigo, and Francesca Poggi for helping me in disconnecting from the PhD, relaxing and having good times, especially through outdoor activities.

To my parents, César and Margarida, for the example of determination and strong will, love, affection, advices, unconditional support and encouragement. To my sisters Ana, Joana, Helena, and Inês for our strong sisterhood, for listening me, for their advices, unconditional support and for pushing me to do better and never give up. Thanks to my nephew Francisco for always make me smile. Finally, to my husband Bruno Baptista for always be by my side, for listening and believing in me and for being a source of strength and love during this journey.

Abstract

Over the last 20 years, it was reported an increase in worldwide extreme weather disasters (EWD), such as droughts (+29%), floods (+134%), and extreme temperature (+232%) like heatwaves. While the mortality rate of these events decreased, EWD are associated with a significant increase in economic damage and in the number of people affected (> 3 billion). The EWD can significantly impact agriculture by exacerbating fluctuations in crop yields and, consequently, in food availability and food prices. Thus, by means of the interconnections of the world food system, EWD have potential to threaten local to global food security. The challenges for agriculture are not only linked to changes in the long-term average climate, but particularly to EWD, which are usually more impactful and generally more uncertain. However, in the occasion of EWD occurrence, national and international disaster loss databases typically report populations affected and damage to human infrastructure, but rarely report damage or losses in the agriculture sector. As a result, agricultural impacts associated with these events are not well quantified across larger spatial scales. In particular, it remains insufficiently understood what are the trends in crop losses, and what are the implications that EWD may represent to food trade.

The European Union (EU) was chosen as a case study, as it is one of the largest global exporter and importer of agri-food products, with its food system deeply linked with other regions. Here, disaster records were used as a metric for extreme weather event impact analysis. Records of droughts, heatwaves, floods, and cold waves (EM-DAT) were combined with observational agricultural data (FAOSTAT) to evaluate disasters crop responses in Europe and in its Non-EU food suppliers. A superposed epoch analysis (SEA) – a time series statistical method used in data analysis – was used to estimate the impact of EWD on the average production, yield, and harvested area of selected crops. The larger implications of disaster impacts in Non-EU food suppliers to the EU food imports, were explored based on the import share per supplier (EUROSTAT). At the EU level, in addition to the SEA to estimate crop impacts, the trend of production anomalies was evaluated over time, per disaster type and per bioclimatic region. The research carried out allows to assess the effects of EWD in the EU food availability, while expanding the analysis to different crops and geographical regions. In particular, the exposure of the EU food import dependency to EWD was evaluated, and also the degree of loss in the EU crop production resulting from the occurrence of such events.

Despite a diversified external market, the EWD impacts on crops grown in Non-EU suppliers represent a substantial and negative exposure to EU food imports. Production losses of soybeans, tropical fruits, and cocoa associated to droughts and heatwaves but also floods, lead to an overall decline, up to 16%, in the EU import-weighted share of each crop. At the EU level, the severity of aggregated heatwave and drought impacts on crop production roughly tripled over the last 50 years. In particular, in every new year with a drought, the EU cereal production losses increase by 3%. The frequency of droughts, heatwaves, floods, and cold waves significantly increased over time. Major losses are found for cereals, but also vegetables and oil crops in the Eastern countries, while smaller losses are estimated in Southern but also Central European countries. Even though using a weather disaster record for crop impact analyses has limitations, it offers a unique and standardized metric indicating that, at the EU level, climate change is already driving increasing crop losses in observational records. Understanding the effects of EWD on crop responses in the past and present climate contributes to the discussion of strategies and priorities in view of improving food systems resilience, including on the potential role of trade policies to support adaptation actions.

Keywords

Extreme Weather Disasters; Historical Impacts; Agricultural Crops; European Union; Non-EU Food Suppliers; EU Import Share-Weighted Impacts; European Bioclimatic Zones; Food Security; Food Availability; Climate Change.

Resumo

Nos últimos 20 anos foi registado, a nível global, um aumento dos desastres climáticos extremos (EWD), tais como secas (+29%), cheias (+134%) e temperaturas extremas (+232%) como ondas de calor. Embora a taxa de mortalidade desses eventos tenha diminuído, os EWD estão associados a um aumento significativo nos danos económicos e no número de pessoas afetadas (> 3 biliões). Os EWD podem causar impactos significativos na agricultura, exacerbando as flutuações na produtividade das colheitas e, consequentemente, na disponibilidade alimentar e nos preços dos alimentos. Por conseguinte, através das interconexões do sistema alimentar global, os EWD podem potencialmente ameaçar a segurança alimentar global e local. Os desafios para a agricultura não estão apenas ligados a mudanças médias no clima no longo prazo, mas particularmente, à ocorrência de EWD, que geralmente são mais impactantes e mais incertos. No entanto, aquando a ocorrência desses eventos, as bases de dados nacionais e internacionais que registam as perdas associadas aos EWD, geralmente reportam as populações afetadas, assim como danos à infraestrutura humana, mas raramente reportam danos ou perdas no setor agrícola. Como resultado, os impactos agrícolas associados a esses eventos não estão bem quantificados em grandes escalas espaciais. Em particular, também não é claro quais são as tendências nas perdas das colheitas, e quais são as implicações que os EWD podem representar para o mercado de alimentos.

A União Europeia (UE) foi escolhida como caso de estudo, por ser um dos maiores exportadores e importadores mundiais de produtos agroalimentares, estando o seu sistema alimentar profundamente ligado a outras regiões. Neste trabalho, os registos de desastres climáticos foram usados como uma métrica para análise do impacto de eventos climáticos extremos. Os registos de secas, ondas de calor, cheias, e ondas de frio (EM-DAT) foram combinados com dados agrícolas observados (FAOSTAT) para avaliar a resposta das culturas agrícolas aos EWD na UE e nos países exportadores de alimentos. A análise de época superposta (SEA) – um método estatístico de análise de séries temporais – foi usada para estimar o impacto dos EWD na produção, produtividade, e área de colheita de um conjunto de culturas. Avaliou-se o impacto dos EWD nos países produtores de alimentos que exportam para a UE, bem como as implicações associadas às dependências comerciais da região (com base nas estatísticas de balanços comerciais da EUROSTAT). Ao nível da UE, para além da implementação da SEA para estimar o impacto dos EWD nas culturas produzidas na região, avaliou-se também a tendência das anomalias da produção agrícola ao longo do tempo, por tipo de EWD e por região bioclimática. Este trabalho de investigação permite avaliar os efeitos dos EWD na disponibilidade alimentar da UE, sendo a análise expandida a diferentes culturas e regiões bioclimáticas. Em particular, foi avaliada a exposição da dependência das importações de alimentos da UE aos EWD, e também o grau de perda na produção agrícola da UE resultante da ocorrência de tais eventos.

Apesar da UE ter um mercado externo diversificado, os impactos dos EWD nas culturas produzidas nos países exportadores não Europeus, representam uma exposição substancial e negativa à importação Europeia de alimentos. As perdas de produção de soja, frutos tropicais e cacau, associadas à ocorrência de secas e ondas de calor, mas também de cheias, podem potencialmente reduzir, até 16%, a importação alimentar da Europa. Ao nível da produção na UE, as perdas agrícolas associadas às ondas de calor e secas praticamente triplicaram nos últimos 50 anos. Em particular, em cada novo ano com uma seca, as perdas na produção de cereais na UE têm vindo a aumentar 3%. A frequência de secas, ondas de calor, cheias, e ondas de frio aumentou significativamente ao longo do tempo. As maiores perdas são estimadas para os cereais, mas também vegetais e oleaginosas nos países do Leste Europeu, enquanto perdas menores são estimadas no Mediterrâneo, mas também nos países da Europa Central. A utilização de registos da ocorrência de EWD na análise do seu impacto na produtividade agrícola, apesar de ter limitações, consiste numa métrica única e padronizada que indica que, ao nível da UE, as alterações climáticas já estão a causar perdas crescentes na agricultura. Compreender os efeitos que os EWD tiveram e têm na agricultura, contribui para a discussão de estratégias e prioridades com vista a melhorar a resiliência dos sistemas alimentares, incluindo o potencial papel das políticas comerciais para apoiar ações de adaptação.

Palavras-chave

Desastres climáticos extremos; Impactos históricos; Culturas Agrícolas; União Europeia; Fornecedores não Europeus de alimentos; Impactos ponderados por percentagem de importação; Zonas Bioclimáticas Europeias; Segurança Alimentar; Disponibilidade de Alimentos; Alterações Climáticas.

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Acronyms

AQUASTAT – FAO's Global Information System on Water and Agriculture

CAP – Common Agricultural Policy

CER – Cereals

Cfb – Temperate Oceanic Climates

Csa – Hot-Summer Mediterranean Climates

Dfb – Warm-Summer Humid Continental Climates

Dfc – Subarctic Climates

EM-DAT – The International Disasters Database

EU – European Union

EUROSTAT – European Statistic Database

EWD – Extreme Weather Disasters

FAO – Food and Agriculture Organization

FAOSTAT – Food and Agriculture Organization Database

IPCC – Intergovernmental Panel on Climate Change

ISIMIP – Inter-Sectoral Impact Model Intercomparison Project

KG – Koeppen-Geiger Classification

Non-CER – Non-Cereals

RCP – Representative Concentration Pathways

SEA – Superposed Epoch Analysis

"I encourage all of us, whatever our beliefs, to question the basic narratives of our world, to connect past developments with present concerns, and not to be afraid of controversial issues."

Yuval Noah Harari (2015)

Sapiens: A Brief History of Humankind

1 Introduction

1.1 Relevance of the study

As for many civilizations that have come and gone, also today, food is the weak link in our modern society (Yearley, 2013). World population is growing and, demanding more food, while grain stocks have been falling (Benton, 2019; Torero, 2016). From water scarcity to an increasing reliance on fossil fuels, and ending on climate change, a set of unsustainable human practices are threatening the production of food (Lang and Ingram, 2013; Santos, 2010). Food has been produced under the maximization of commerce based on the production of fewer crops supplying excessive calories and standardised diets (Benton, 2019; Lang and Ingram, 2013). As a result, more than 60% of the calories in the human diet is highly dependent on just four grains – wheat, maize, rice, and soybeans – which are grown in only a handful of countries. Such high level of concentration implies that the world's capacity in coping with geographical risk is limited (Global Food Security Programme UK, 2015a; Tai *et al.*, 2014).

Weather-related shocks are particularly damaging to crops and to food production systems, as they can significantly influence the year-to-year variability in crop yields at various spatial scales, and trigger price spikes (Jägermeyr and Frieler, 2018; Lesk *et al.*, 2016; Puma *et al.*, 2015; Ray *et al.*, 2015; Rosenzweig *et al.*, 2014b; Vogel *et al.*, 2019). By means of the interconnections of the world food system, extreme weather events have thus potential to destabilize food systems and threaten local to global food security (Lesk *et al.*, 2016; Nelson *et al.*, 2014; Rosenzweig *et al.*, 2014b), affecting producers and consumers (Haile *et al.*, 2017; Rosenzweig *et al.*, 2001). The severity of an extreme weather event and the vulnerability and exposure of the human and natural systems to it will determine whether it results in a disaster (IPCC, 2012). National and international disaster loss databases typically report populations affected and damage to human infrastructure, but rarely report damage or losses in the agriculture sector (FAO, 2015). As a result, there are major data gaps of the extent that extreme weather disasters (EWD) impact the agricultural sector.

The European Union (EU) is one of the world cereals breadbaskets (Berkhout *et al.*, 2018; Ciscar *et al.*, 2018). The EU is also highly dependent on crops that do not naturally grow in the region, and come from countries considered to be highly vulnerable to a changing climate (EU, 2018; Hanks and Craeynest, 2014; IPCC, 2014). Consequently, the effects from EWD on trade dependencies, and in the EU agricultural productivity are growing concerns (EEA, 2019). As an example, the European heatwave and drought, in summer 2018, led to widespread cereal production losses (8%) and triggered a sharp increase in commodity prices (<48%), in many countries across the continent (DG AGR, 2018; EC, 2018). Future projections suggest an increase in summer dryness in most parts of Europe, with longer and more intense heatwaves and droughts (IPCC, 2019). In view of potential future aggravations in global EWD frequency and intensity due to climate change (IPCC, 2019, 2012), there is still little quantitative evidence of how historical impacts of such events affected the production of different crops and in different European regions. It remains also unclear how the agricultural impacts of EWD in Non-European countries, affect the EU food availability. This information is crucial to define appropriate risk reduction policies and investments in agriculture (FAO, 2015), and also to understand if and how trade policies can support climate adaptation strategies (EEA, 2019).

1.2 Research background

1.2.1 Brief history of food

At the end of Pleistocene or early Holocene, about 10 000 years ago, the Agriculture Revolution changed the way humans lived and paved the path for significant interventions in the Earth systems (Duarte Santos, 2012; Harari, 2015; Simmons, 2010). The transition from nomadic hunter-gatherer lifestyles to farming was a long evolutive process where humans learned how to domesticate plants and animals, and to develop techniques for drying, smoking, and storing food (Duarte Santos, 2012; Harari, 2015). The earliest known developments of agriculture began in the Near East and slowly, sprang up in different parts of the world although in an independent way (Harari, 2015), as by the end of the last glacial period (i.e. between 110 000 to 10 000 years B.P.), the sea level rise did not allow for any physical connection between Eurasia with the Americas, Australasia or with the West Pacific islands (a few of which populated for at least 30 000 years) (Christian, 2018). About 18 000 years ago, although with erratic episodes, temperatures and precipitation started rising and, slowly, climate become humid and warmer, and also more stable, thus setting the scene for a viable agriculture (Duarte Santos, 2012). With the gradual movement to permanent villages and with the increase in food supply, the population began to grow from 5-8 million nomadic foragers before the transition to agriculture, to 200 million humans 2000 years ago (Harari, 2015). The challenge to sustain an increasing population was settled, and there was no turning back.

During the Industrial Revolution, which lasted from roughly the mid-1800s through World War I, a major human intervention in the nitrogen cycle was made with the production of artificial fertiliser. Peru and Chile, for example, exported to North America and Europe, hundreds of millions of tonnes of sodium nitrate and nitrogen-rich guano, intensely increasing agricultural productivity (Mellilo, 2012). Other crucial advances included the use of agricultural machines powered by fossil fuels, improved crop rotation systems, selective breeding, or the production of chemical pesticides. Such innovations contributed to amplify food production and underpinned a rapid growth of population – to 900 million by 1800 – and major increases in life expectancy (Christian, 2018; Jägermeyr, 2020).

After World War II, when many developing nations struggled to feed their people, disease-resistant and high-yield crops – in particular cereal grains – were introduced by using genetic modification through the work of Norman Borlaug (Christian, 2018; Mellilo, 2012). Cereal yields tripled as a result of the generalized adoption of new varieties of high-productivity crops combined with a threefold expansion in irrigated areas and the widespread use of fertilisers (Santos, 2010). The increasingly large-scale, intensive and productive agriculture, and also the possibility to import food from an expanding global and liberalised trade marked, have promoted the surplus of food at prices that were, on average, cheaper decade by decade (Benton, 2019; Santos, 2010). As a result, the Green Revolution favoured global crop production and underpinned a demographic explosion – from 2 600 million in 1950 to 7 795 million people in 2020 (Christian, 2018; The World Bank, 2019; UNFPA, 2020).

The food trade has then being developed under the maximization of commerce based on the production of fewer crops supplying excessive calories and standardised diets (Benton, 2019). Consequently, more than 60% of the calories in the human diet is highly dependent on just four grains – wheat, maize, rice, and soybean (Yearley, 2013) – which are grown in a reduced number of countries (Fig. 1.1) (Global Food Security Programme UK, 2015b; Tai *et al.*, 2014). This high level of concentration implies that the world's capacity in coping with geographical risk is limited, since any shock to production in those countries will have an effect on global prices and price volatility (Puma *et al.*, 2015; Torero, 2016).

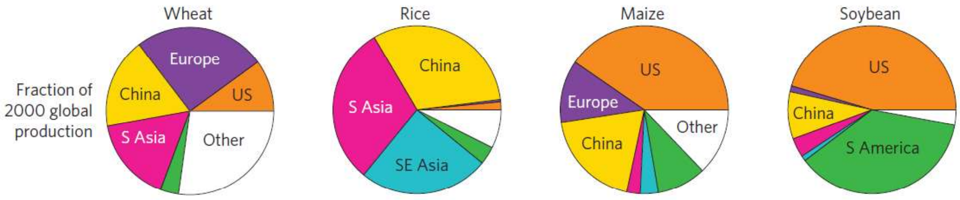

Figure 1.1 Contributions to global production from major producing regions in 2000.
Regions or countries: US – United States of America; Europe – all countries in Europe, not including Russia; China – mainland China only; S Asia – all member countries of the South Asian Association for Regional Cooperation; SE Asia – all member countries of the Association of Southeast Asian Nations; S America – all countries in South America (excluding Central American countries) (Tai *et al.*, 2014).

The economic growth, particularly the rising incomes in China, India, and more recently in sub-Saharan Africa, lead to substantial changes in consumption patterns which are more varied but also richer in animal-protein-based (i.e. also called western diets), thus driving crop utilisation for livestock feed (Lang and Ingram, 2013; Santos, 2010; Timmer, 2005; Torero, 2016; Yearley, 2013). As a result, worldwide cereal demand has been growing at 2-3% per year, while cereal reserves have been declining – from 700 million tonnes in 2000 to less than 400 million tonnes in 2007 (meaning about 64 days of carryover stocks in 2007) (Lang and Ingram, 2013; Santos, 2010; Timmer, 2005; Torero, 2016; Yearley, 2013). When cereal stocks are low relative to use, markets are less able to cope with supply and demand shocks. Thus, supply shortfalls or a rise in demand will lead to larger price increases (FAO, 2009).

The food problem starts being particularly noticeable after a series of small weather-related production shocks in 2007–2008 that coupled with historically low stock levels, a financial crises and also due to the strong link with the energy markets (FAO, 2009), led to dramatic and sustained increases in the price of cereals, and food in general (Global Food Security Programme UK, 2015a; Santos, 2010). As a result of these series of events, some countries imposed export barriers to ensure their own food supply, leading to a doubling of world grain prices (FAO *et al*., 2011). A similar grain price spike in 2010-2011 occurred when intensive heatwaves hit Eastern Europe, Russia, and the United States. These price spikes (Fig. 1.2) created a number of significant impacts around the World, particularly in the countries hit with the weather shocks but also in import food-dependent nations through the interconnections of the world food trade (Global Food Security Programme UK, 2015a; Yearley, 2013). Particularly in countries with fragile governance, food price spikes spawned numerous food protests and riots, such as in Thailand, Egypt, Haiti, Mexico, and also in Middle East and North Africa partially sparkling the Arab Spring and triggering national and international refugee movements and social fragmentation (Global Food Security Programme UK, 2015a; Puma *et al*., 2018; Yearley, 2013).

Food supplies and grain stocks are tightening, and food security – the state of having, at any time, a reliable access to a sufficient quantity of affordable, and nutritious food (Committee on World Food Security, 2015) – is undermined by a combination of threats driven by dramatically unsustainable human practices (Duarte Santos, 2012; Lang and Ingram, 2013; Santos, 2010; Yearley, 2013). As for many civilizations that have come and gone, also today, food is the weak link. For the Sumerians (4100-1750 B.C.), food shortages resulted from salinisation as a consequence of over-irrigation (Yearley, 2013), while for the Mayans (from 2000 B.C.), deforestation (to give place to agricultural crops) lead to soil erosion and to the intensification of droughts (Cook *et al*., 2012). Now, even though we know what have failed with ancient civilizations, our growing population – who is demanding more food and higher animal-protein-based diets –, is facing water scarcity (driven by over-irrigation and depletion of aquifers), a lessening response in crop productivity to the use of fertilisers, an unacceptable level of food waste, a loss of biodiversity and agricultural land (driven by urbanization and desertification), and a high reliance on fossil fuels (Table 1.1). On the top of these threats, climate is changing (FAO, 2019a, 2011a; Lang and Ingram, 2013; Santos, 2010; Yearley, 2013).

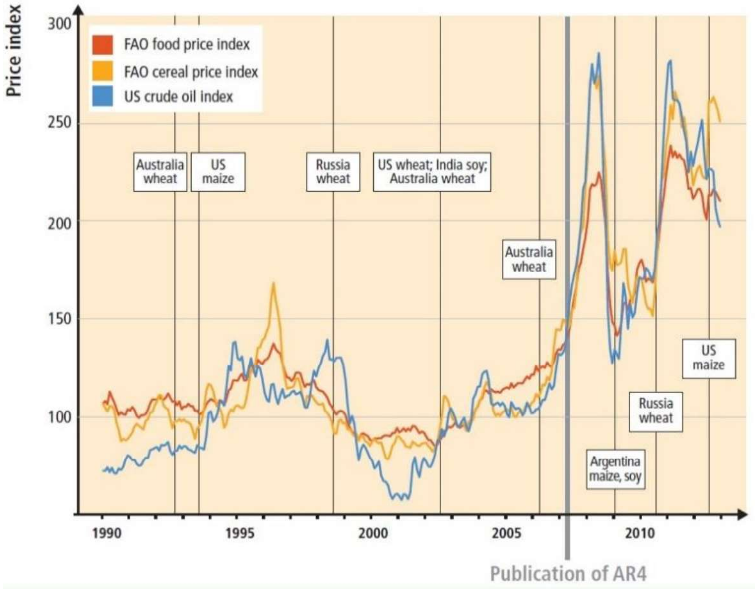

Figure 1.2 Weather-related food price increases. Historical FAO food and cereal price indices (as percentage of 2002–2004 averages), with vertical lines indicating events when a top five producer of a crop had yields 25% below trend line which is indicative of a seasonal climate extreme. At the same time, food prices are increasingly associated with the price of crude oil (blue line), thus making difficult the attribution of price changes (Porter *et al*., 2014).

By 2050, with projections pointing to a population of 9.7 billion (UN, 2013) that will demand 60-70% more food (Alexandratos and Bruinsma, 2012; The Government Office for Science, 2011), 55% more water, and with over 40% of the global population living in river basins experiencing severe water stress (HLPE, 2015), feeding a growing population within the limits of sustainability, and under the threat of climate change, becomes a bigger challenge (Jägermeyr *et al*., 2017). Notwithstanding, the problem is already at the table. There are 821 million people undernourished, mainly as a result of vulnerable and low-yield agricultural systems (FAO *et al*., 2018; Jägermeyr, 2020), often in countries which are stage of political instability, armed conflicts and, overall, with a poor governance. Controversially, 2 billion are overweighted (World Health Organization, 2017) and 672 million obese (FAO *et al*., 2018), as food-insecure families tend to choose less expensive foods that are often high in caloric density and low in diversity, micronutrients and fibre (FAO *et al*., 2018).

Recognizing that the food problem is a complex and major global issue and is being undermined by a combination of social, economic, and environmental threats, the effects of a changing climate – per se an unique threat because of the millennial time scale of anthropogenic carbon within surface carbon reservoirs – on food availability are the focus of this study.

Table 1.1 Food security threats driven by unsustainable human practices

Threat	How the threat is undermining Food Security?
Water scarcity	Water scarcity, exacerbated by a changing climate, is driven by the needs of an increasing population, by over-irrigation and depletion of aquifers. Worldwide, 16% of the cultivated land produces 44% of crop production but consumes 70% of global freshwater withdrawals (HLPE, 2015). Nearly 20% of the water used for irrigation is estimated to be provided by non-renewable groundwater (Wada *et al*., 2012). Overall, the efficiencies of irrigation systems are very low (<30%), particularly in south Asia and sub-Saharan Africa (Jägermeyr *et al*., 2015). Such inefficiency along with the increasing consumption of water, is leading to a rapid depletion of aquifers in key grain producers – China, India, and the United States (Dalin *et al*., 2017; Holden *et al*., 2018). However, without irrigation global cereal production – providing > 60% of the food energy intake (FAO, 1997)) – would decrease by 20% (Siebert and Döll, 2010).
Biodiversity loss	Biodiversity underpins a wide range of ecosystems services, such as keeping soils fertile, pollinating crops, cleaning water, and fighting pests and diseases (FAO, 2019b). The loss of biodiversity is decreasing the resilience of ecosystems, including agricultural systems. The fact that more than 6000 crop species have been cultivated for food, but just nine account for 66% of total crop production, means that agriculture is highly based on monocultures, which are less resilient to temporal fluctuations in climate, and to shifts in pest occurrence and diseases, thus potentially undermining food production (FAO, 2019b; Lin, 2011).
Soil loss	Desertification – intensified by climate change, and driven by unsustainable farming practices and deforestation – as well as urbanization – resulting in the impermeabilization of soil for the construction of cities and its infrastructures – are leading to the loss of fertile soil at rates that are orders of magnitude greater than mechanisms that replenish soil (Amundson *et al*., 2015; Santos, 2010).
Low fertiliser responses	The fact that crop productivity is responding less and less effectively to fertilisers is showing the limits of the genetic improvements that we have induced on cereals up until now. The technological model that was at the basis of the Green Revolution – and was responsible for a triplication of the world cereal production since 1950 – is highly focus on the grain, regardless on the plant roots and leaves, thus constraining its potential of maximum efficiency (Santos, 2010).
Fossil fuel reliance	The food sector accounts for about 30% of the world's total energy consumption (FAO, 2011b), which is used to produce fertilisers, herbicides, pesticides, diesel for machinery, electricity for irrigation, heating, drying, processing, storage and packaging (Vermeulen *et al*., 2012)). The sector represents 19-29% of global emissions (Vermeulen *et al*., 2012), and thus is a considerable contributer to climate

Threat	How the threat is undermining Food Security?
	change (IPCC, 2019). From those emissions, agricultural contributes with 80-86% including indirect emissions associated with land-cover change, livestock, rice fields and synthetic fertilisers (FAO, 2016a; Vermeulen *et al.*, 2012). The food crises and the energy crises are thus very much interlinked. Moreover, the rise in oil prices have led to investments to new sources of energy – such as biofules – which, through soil occupation – directly competes with food production, thus leading to higher prices of food (Santos, 2010).
Food waste	Roughly one-third of food produced for human consumption is lost or wasted globally, which amounts to about 1.3 billion tonnes per year (FAO, 2011a). In the developing world, food waste is driven by poor production, harvesting and storage practices and by food losses due to pests and diseases. In developed countries, consumers behaviour is pointed as the major cause of food waste, such as the rejection of imperfect products or the poor management of their food inventory (FAO, 2011a).
Changing diets	The economic grow and higher incomes, particularlly in emergent societies, coupled with urbanization and the increasing influence of the retailing sector, is pushing up the consumption of varied, high-quality but also meat-based diets, which require more energy, water and land resources (Lang and Ingram, 2013; von Braun, 2007).
Climate change	A warming climate is directly affecting the amount of food through its direct impacts on crop yields, and also through impacts on water availability and quality, pests and diseases, pollination services, and through higher CO_2 concentrations in the atmosphere – which is today higher than at any point in time since the past 800 000 years B.P., thus amplifying the Earth's natural greenhouse effect (NOAA, 2020) – affecting biomass and nutritional quality of crops (IPCC, 2019). Such adverse effects may potentially be exacerbated with the occurrence of extreme weather events which are increasing in frequency and intensity with climate change (IPCC, 2019).

1.2.2 The effects of a changing climate in the food system

Climate stability is under threat, largely because of a growing reliance on fossil fuels and (but not only) industrialised and unsustainable forms of agriculture (Rockström *et al.*, 2009). Since the Industrial Revolution, changes in the long-term mean of temperature and precipitation, as well as changes in weather variability, have been observed.

Most of agriculture – and thus the production of food – remains highly dependent on climate even despite major technological improvements, because solar radiation, temperature, and precipitation are the main drivers of crop growth (Rosenzweig *et al.*, 2001). Thus, the spatial patterns of crops yield across the Planet are governed by the current spatial distribution of climate drivers. In the same way, the relative productivity of the seasons is determined by the weather variability. Climate change affects climate variables by changes in their means but also in their variability, which is just as important as changes in the average (Global Food Security Programme UK, 2015a).

Under high temperatures the plant curls its leaves in order to reduce its exposure to the sun, which reduces the photosynthesis and thus crop yield. High temperatures and reduced soil moisture by means of a decline in precipitation, can lead the stomata to close (to diminish the evapotranspiration), which reduces the CO_2 intake and thus crop photosynthesis and yield (Yearley, 2013). Long-term average climate can, however, bring some localized benefits for agriculture, such as the increased precipitation, the length of growing seasons or the influence of higher levels of CO_2 on yields (Christidis *et al.*, 2015; Deryng *et al.*, 2014; Elliott *et al.*, 2015; Hov *et al.*, 2013; Iglesias and Garrote, 2015; Mueller *et al.*, 2015; Rosenzweig *et al.*, 2014a)

Evidence shows that average changes on long-term temperatures are shifting production seasons, and that crop responses are highly variable, and not only negative, from place to place and for different food items. Future impacts are expected to be consistent with the trajectory of past impacts, with the majority of locations experiencing crop losses, while some locations may benefit particularly under crop adaptation (IPCC, 2019; Porter *et al.*, 2014). A changing climate raises new factors and possibilities potentially exposing societies to risk, such as potential changes in the current spatial production patterns – in particular in the world breadbaskets (see Chapter 2).

In addition to those uncertainties, climate change – through an increase weather variability – may lead to crop yield fluctuations, which can have major impacts on the livelihoods of subsistence farmers and may trigger significant global price fluctuations (Frieler *et al.*, 2017; Piesse and Thirtle, 2009; Porter *et al.*, 2014; Puma *et al.*, 2015). Low yield variability shall lead to stable food supply (and thus to stable farmer incomes), preventing price spikes. On the contrary, high yield variability is particularly damaging to crops and to food production systems, as it can trigger price spikes, thus potentially destabilizing food systems and threaten local to global food security (Lesk *et al.*, 2016; Nelson *et al.*, 2014; Puma *et al.*, 2015; Ray *et al.*, 2015; Rosenzweig *et al.*, 2014b). Globally, nearly one third of observed yield variability (i.e. 22 million tonnes for maize, 9 million tonnes for wheat, 3 million tonnes for rice and 2 million tonnes for soybean) can be explained by the additional climate variability that derives from climate change (which in some world regions can be more than 60%) (Ray *et al.*, 2015). Other study shows that growing season climate factors – including mean climate as well as climate extremes – explain 20% to 49% of the variance of yield anomalies (depending on the crop); 18% to 43% of the explained variance is attributed only to climate extremes (Vogel *et al.*, 2019). By means of trade and sufficient grain storage, under normal climate conditions or small weather year-to-year fluctuations, the global food system can compensate for local crop losses. However, under extreme weather conditions – as in 2007-2008 or 2010 – and in the absence of grain reserves coupled with an intensive, little diversified in crops, and thus less climate-resilient agriculture, the global food system is extremely under threat. The severity of an extreme weather event and the vulnerability and exposure of the human and natural systems to it will determine whether it results in a disaster (IPCC, 2012).

While long-term average climate may benefit few locations, at least up to a certain level of temperature and CO_2 increase, the impacts from extreme weather disasters (EWD) – like droughts, heatwaves, and floods – are invariably negative (Global Food Security Programme UK, 2015a; Hov *et al.*, 2013; IPCC, 2019, 2012; Lesk *et al.*, 2016; Vogel *et al.*, 2019). Particularly, the most extreme events imply robust disaster risk reduction and management strategies in the structure of the food system, in addition to the long-term average climate adaptation. For example, climate change may result, on average, in an area getting wetter, but if the variance on precipitation is also increasing, it is also possible for both floods and droughts to become more common. Another example is an increase in temperature variance without a change in the mean, which may imply an increase in the frequency of both hot and cold extremes, as well as in the intensity of the extremes (Global Food Security Programme UK, 2015a; IPCC, 2013). The rarest conditions are the most uncertain and difficult to study, but because they are also typically the most impactful, their study is most important (Global Food Security Programme UK, 2015a).

The challenges for agriculture are therefore not only linked to changes in the long-term average climate, but particularly to changing weather extremes. Climate models provide a good understanding of how climate may change in the future, thus by means of crop-based models or statistical models, one can better quantify its impacts on crop yields (Moore and Lobell, 2015; Ray *et al*., 2019). However, our understanding of the way extreme events change is much less certain, as well as any inference on their impact (Global Food Security Programme UK, 2015a; IPCC, 2013; Min *et al*., 2011; Müller *et al*., 2017; Roberts *et al*., 2017). Empirical research has investigated the impacts of extreme weather events on crops for individual countries, regions, at the farm level (Lüttger and Feike, 2018; Powell and Reinhard, 2016; Troy *et al*., 2015), or across world regions by using crop data at sub-national spatial resolution (Vogel *et al*., 2019), all combined with climate data by means of extreme weather indicators, such as absolute, threshold or duration indices. Such empirical approaches may, however, underestimate the crop effects from EWD because similar extreme weather events may have divergent effects depending on the vulnerability of the exposed system (Lesk *et al*., 2016). That recent study (i.e. Lesk *et al*., 2016), by means of a statistical approach, estimated the influence of EWD in cereal production on aggregated world regions. The EWD impacts on other important crops and regions, as well as, the associated implications to import dependences have, however, not been explored.

National and international disaster loss databases typically report populations affected and damage to human infrastructure, but rarely report damage or losses in the agriculture sector (FAO, 2015). As a result, there are major data gaps of the extent to which EWD impact crop yields. In particular, there is still little quantitative evidence of increasing trends in crop losses associated to disasters, and also on its implications through trade (Lesk *et al*., 2016; Puma *et al*., 2015). The main focus of this thesis is on the impact of EWD on agriculture. A better understanding of the crop responses to EWD is of most importance to defining appropriate risk reduction policies and investments for agriculture (FAO, 2015). Such knowledge is also crucial to understand if and how trade policies can support climate change adaptation strategies and actions (EEA, 2019). More emphasis must be given to the study of the impact of EWD in agriculture, especially because there is an agreement that some of these events are becoming more likely as a result of climate trends (IPCC, 2019; Porter *et al*., 2014).

1.2.3 The European Union in the food system

1.2.3.1 The international dimension

The European Union with 28 Member States (EU) is one of the leading global players in food and agriculture, and its food system is deeply linked with other regions (Berkhout *et al*., 2018; Ciscar *et al*., 2018). The EU produces about 13% of world's cereal production – 6% of the world's maize and 18% of the world's wheat –

representing 24% of global cereal exports (Ciscar *et al.*, 2018; FAO, 2019c; Knox *et al.*, 2016). The EU represents nearly 50% of the world's wine (Wine Institute, 2017), and 70% of the world olive oil exports (International Olive Council, 2018). The region is also the world's leading producer of sugar beet, contributing 50% of the global sugar production (Ciscar *et al.*, 2018; Knox *et al.*, 2016).

The EU is a large market with over 500 million consumers and is deeply integrated into global markets through the World Trade Organization. The international dimension of the agricultural sector is part of the *Common Agricultural Policy* (CAP), which is set out in the *Treaty on the Functioning of the European Union* (that specifically targets the stabilizing of imports and exports as a means to address market volatility and deliver on the objectives of the CAP) (European Commission, 2019). The majority of the EU-trade is internal, with nearly 73% of the EU food exports and imports being directly traded within EU countries (Berkhout *et al.*, 2018). The EU exports account for 50% of agricultural food and feed products (i.e. commodities, other primary and processed agricultural products), 33% of food preparations and beverages, and 11% of non-edible agricultural products. The agricultural food and feed products account for 80% of total EU imports, followed by food preparations and beverages (9%), and non-edible products (10%) (EU, 2018).

On the extra-EU trade, nearly 40% of exports – mostly beverages and food preparations – are to the United States of America, China, Switzerland, Russia, and Japan. The top EU-extra suppliers are Brazil, the United States, Argentina, Ukraine, and China, and in a lower extend but increasing, Indonesia and India. Third countries account for nearly 30% of total EU extra imports (Berkhout *et al.*, 2018), supplying the EU with products that are not grown in the EU itself due to its natural conditions (e.g. tropical fruit, coffee and fresh or dried fruits), products that are mostly used for animal feed (e.g. oilcakes and soybeans), and also used as ingredient in further processing (e.g. palm oil) (EU, 2018).

1.2.3.2 The agricultural sector

Agriculture and food-related industries and services provide over 44 million jobs in the EU, and 22 million people are directly employed in the sector itself (EEA, 2019). The agricultural sector contributes, on average, with 2.5% of the GDP (FAO, 2016b), whereas income from agriculture varies across European regions, and is generally high in relative economic terms in Portugal, Spain, Greece, France, Bulgaria and Romania (European Commission, 2009). The sector is, on average, the second major consumer of freshwater resources (27%) after industry (42%) and followed by municipal (25%), thus contrasting with estimations at the global level where agriculture irrigation accounts for 70% of total water withdrawal (FAO, 2016b).

Nearly 39% (or 173 million hectares) of the total EU land area is used for agricultural production (EUROSTAT, 2019). Denmark and Hungry have the highest rates (>40%) of cultivated area among the total area of the country and The Netherlands, Greece and Italy have the highest shares (>40%) of irrigation among their cultivated areas (FAO, 2016b). Cropping area is mostly occupied with cereals (65%) largely grown in the North and Central Europe, vineyards and olive trees (9%) both cash crops and mostly grown in the Mediterranean region. The cropping area also grows oil crops (13%), vegetables (4% each), roots and tubers, sugar and orchards (2% each) (FAO, 2019c). The highest producers of wheat and barley are France (24%), Germany (17%), and the United Kingdom (10%); of maize is France (23%), Romania (15%), Italy (12%), and Hungry (11%); and of sugar beet is France (30%), Germany (23%), and Poland (10%). The main EU producers of olives are Spain (52%), Italy (23%), and Greece (20%), while for grapes are Italy (31%), France and Spain (each with 24% of production) (Fig. 1.3).

In the EU, cereals are used for animal feed (66%), human consumption (33%), and biofuels (1%). Oilseeds (mostly rapeseeds, sunflower and soybeans) are used for food, feed, fuel, and industrial purposes, but also for vegetables oils and meal (which are an important component of animal feed). Less than 10% of the soybean consumed in the EU (i.e. soybean, soybean meal and/or soy oil) is grown in the region, being the remaining imported from Brazil, Argentina, the United States, Paraguay, and Canada (Berkhout *et al.*, 2018). Nearly two thirds of the rice consumed in the EU is grown in the region, being the remaining supplied by India, Thailand, Pakistan, Egypt (among other countries) (European Commission, 2020; EUROSTAT, 2016; FAO, 2017).

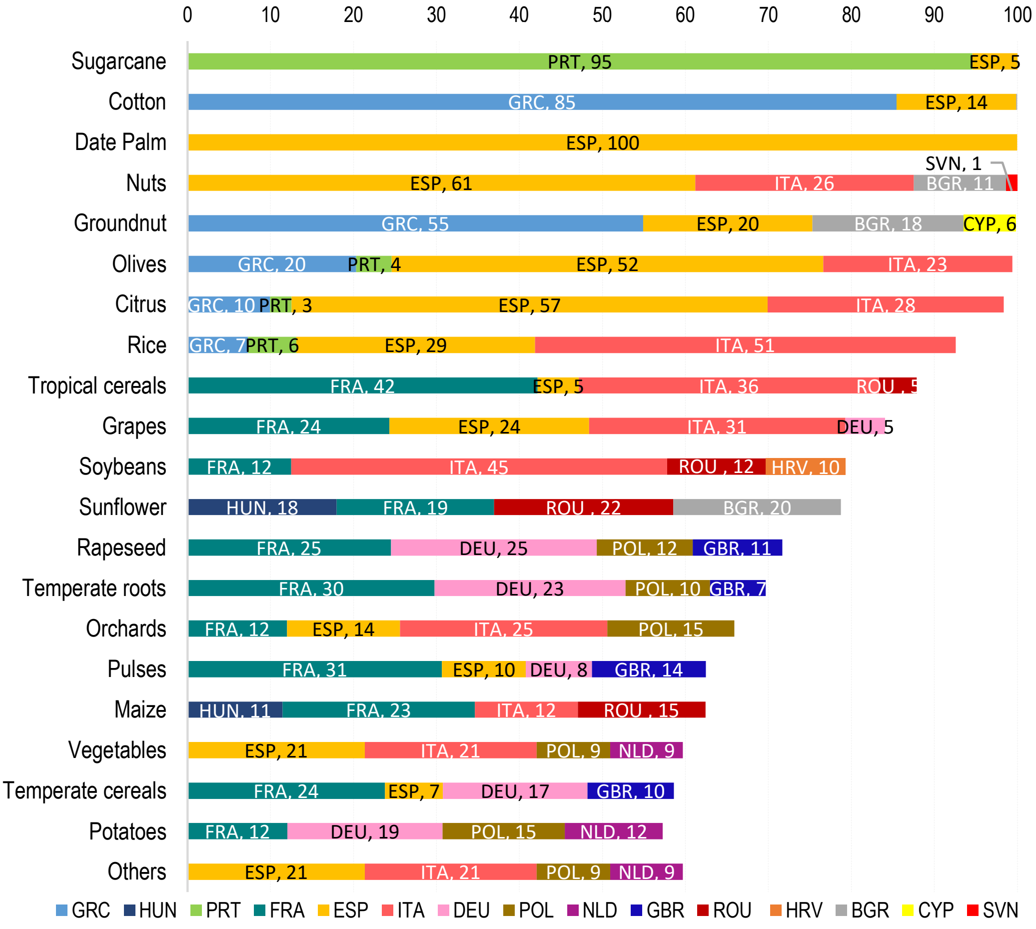

Figure 1.3 Top four EU countries with the highest crop category production share.
Countries acronymus according to ISO3 codes. Crop data is acquired from FAO (2017) and is averaged between 2008 and 2017. Temperate cereals include wheat and barley; Tropical cereals include millet and sorghum, Temperate roots include sugar beet.

1.2.3.3 The impacts of a changing climate in Europe

As in the majority of the world regions, the EU food system has been adversely affected by a changing climate. For example, from 1974 to 2008, it is estimated that, on average, a combination of changes in temperature and precipitation patterns negatively affected yields of maize (up to -25%) and wheat (up to -15%), although yield gains are estimated for rapeseed (3%) (Ray *et al*., 2019). Higher yield losses have been estimated for the Mediterranean countries, and gains in few northern European countries (Moore and Lobell, 2015). Recent studies confirm that observed changes in climate have already affected crop suitability in Europe, raising concerns about changes mostly for the cultivation of typical local crops, such as olives and grapevines in the Mediterranean area. On the other hand, longer growing seasons – favouring crop yields – are recorded particularly in Northern and Eastern Europe, as a consequence of increased temperatures (EEA, 2019).

As discussed in section 1.2.2, while negative but also positive changes are projected with a changing climate, the effects of EWD are invariably negative. Most recently, the 2018 heatwave and drought lead to overall cereal production 8% lower than the previous five-year average (DG AGR, 2018), which lead to crop production losses, fodder shortages for livestock, and triggered sharp commodity price increases (up to 48%) (DG AGR, 2018; EC, 2018; EM-DAT, 2018; Hanel *et al*., 2018). In the EU, droughts and heatwaves are projected to become more frequent and intense (IPCC, 2019), and crop yields are therefore expected to increasingly vary from year to year. This may increase the sector's vulnerability to further climate impacts, particularly without adaptation (IPCC, 2014).

On the other hand, especially for crops that are not naturally grown in the EU, there is a high dependence of food imports from the developing world, particularly from regions considered highly vulnerable to climate change (EU, 2018; Hanks and Craeynest, 2014; IPCC, 2014). With the expectation of EWD becoming more frequent and intense with a changing climate (IPCC, 2019), a cascade of climate impacts outside Europe may affect the price, quantity, and quality of products, and consequently trade patterns, which in turn may affect the food sector's income in Europe (EEA, 2019).

The *EU Strategy on Adaptation to Climate Change* and the CAP, in particular the new proposal 2021-2027, represent two main policy groups in the agriculture sector that encourage the implementation of climate adaptation measures in Member States (EEA, 2019; European Commission, 2017). In order to specifically define and implement a set of adaptation measures there is, however, the need to better understand the consequences of EWD in the EU agriculture, and in the trade of agricultural commodities. Such information is also of relevance to understand if and how trade policies should support climate adaptation strategies and actions (EEA, 2019). In particular, how historical impacts of EWD affected the production of different crops and in different European regions remains insufficiently understood. How EWD affecting crop yields in Non-European countries will have effects in the EU remains unclear. This thesis contributes to close these research gaps.

1.3 Research questions

The general goal of this research is to contribute to a better understanding of the effects of EWD on food production and on its implications through trade dependences, while taking advantage of observational records. To this end, the European Union (EU) was selected as a case study due to its profound connections within the global food market. It is recognized that the EU has been, and is foreseen to be, negatively affected by average climate change. It remains, however, insufficiently understood how the historical impacts from EWD affected the EU in terms of its own food production and also through its import dependences. This work provides contributions to answer to the following research questions (RQ):

RQ#1: What is the exposure of the EU food imports to extreme weather disasters?

RQ#2: What are the impacts of extreme weather disasters in the EU food production?

RQ#3: What are the trends on EU crop losses during extreme weather disasters years?

1.4 Research design and structure of the dissertation

In order to answer to the research questions identified in Section 1.3, two original research studies were developed, in addition to a literature review. The research questions addressed in each chapter, and the main methodologies used, are displayed in Table 1.2.

Table 1.2 Research design, including the general goal of this thesis, the research questions that are addressed in each chapter, and the main methodological approaches

General goal	To contribute to a better understanding of the effects of extreme weather disasters on food production and on its implications through trade dependences, while taking advantage of observational records.		
Chapter	**Title**	**Research questions**	**Methods**
Chapter #2	Review on the climate change impacts on food availability and access	What are the current and future hotspots of climate change impacts on food production? (context question)	Systematic literature review of scientific literature
Chapter #3	Exposure of the EU food imports to extreme weather disasters in exporting countries	**RQ#1:** What is the exposure of the EU food imports to extreme weather disasters?	Time series statistical analysis based on a compositing approach (i.e. superposed epoch analysis)
Chapter #4	Drought and heatwave crop losses tripled over the last five decades in Europe	**RQ#2:** What are the impacts of extreme weather disasters in the EU food production? **RQ#3:** What are the trends on EU crop losses during extreme weather disasters years?	Time series statistical analysis based on compositing approach and on normalised anomalies

Chapter 1 introduces the dissertation, by presenting the relevance of the study and the research background while explaining the scope and the research questions directing the work.

Chapter 2 consists in a systematic analysis of peer-reviewed literature about climate change impacts on food availability and access. This research study is performed for a deeper understanding of the average climate change impacts on food supply. It identifies the hotspots of the food system exposure to current and future long-term average climate, while considering the effect of adaptation. It contributes for the selection of a case study to answer the identified research questions **–** the European Union, an exposed region considering the climate change impacts on the food system. This review study is under review in a peer review journal (October 2020).

Chapter 3 highlights the Extreme Weather Disasters (EWD) impacts on specific crops in export-oriented countries by using a compositing approach. It presents the larger implications of such impacts through trade dependencies, based on the import share per external supplier country. The focus is on the EU agri-food sector, for which its external dependency is mapped, and its potential exposure to EWD is assessed. This work contributes to answering RQ#1 and is published in *Food Security* (2019).

Chapter 4 provides important, new information on how historical EWD affected crop production in Europe, being the analysis stratified for different crops, time periods and bioclimatic zones. Averaged event impacts are quantified by using a compositing approach based on observational crop and EWD data. The severity of the events over time is evaluated by assessing the normalised crop production anomalies. While the answer to RQ#2 quantifies the impact (e.g. the degree of change in crop production) due to EWD, the answer to RQ#3 evaluates the trend of such impacts over time. This work is under review in *Environmental Research Letters* (October 2020).

Chapter 5 contains a general discussion that summarizes the key contributions of this thesis along with the answers to each research question. This chapter also discusses contributions at the policy level – on the food supply and consumption sides – with potential to overcome the exposure to EWD. This chapter also includes final remarks and future research, and the outputs that resulted from this work.

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2 Review on the climate change impacts on food availability and access

This study is under review in the journal Global and Planetary Change:

Brás, T.A., Seixas, J. Review on the climate change impacts on food availability and access.

Author contributions:

T.B. and J.S. designed the research. T.B. compiled and analysed the data. The paper was written together with contributions from both authors.

Abstract

Climate change is affecting food security through increasing temperatures, changing precipitation patterns and higher frequency of extreme events. Here, we perform a systematic literature review on the observed and future impacts of the long-term climate trends on crop responses and on prices, considering papers published between 2013 and 2019. We also discuss the usefulness of the reviewed material for the food-climate governance schemes.

Our review shows that impacts are highly variable, and not only negative, from place to place and for different food items. However, in a medium-term future, under the higher emission scenarios and even considering crop adaptation in few countries, global breadbaskets – USA, China, Europe, Southern Asia, and Southern America – may see a decline on crop production, from -5% to -55% (depending on crop and region), with harmful consequences on the worldwide food supply and on its prices. Other countries or regions may see positive changes, especially if crop adaptation is implemented. The acknowledgement of regional climate impacts variability on production and consumption spatial patterns, along with a cross-regional analysis on water scarcity, highlights the need for a climate-food-governance towards food security for all countries.

Keywords

Climate Change; Food Security; Availability; Access; Observed and Future Impacts; World Regions

2.1 Introduction

Within the past decades, food security has remained a major global issue, especially in less developed countries (FAO, 2007; Barret *et al.*, 2010). The increased attention on the subject was particularly noticeable after the 2007–2008 and 2010 world food price crises (FAO, 2008). In 2017, 821 million people in the world were estimated to be undernourished, a figure that is increasing in almost all regions of Africa and in South America (FAO *et al*., 2018). An integrated analysis on food dimensions, through a set of indicators, allows to highlight the causes and consequences of food insecurity (FAO, 2013) in a country or region and may foster the definition of strategies, policies and the design of governance schemes to guaranty food security at the long-term (FAO, 2013; FAO *et al*., 2014). Food *availability* considers the supply of food (i.e. production and imports including food aid), with adequate nutritional levels and according to cultural standards (FAO *et al*., 2014; Fukuda-Parr and Orr, 2013), and food *accessibility* refers to the physical and economic access for people to acquire the food they need. The access dimension comprises indicators of physical access and infrastructure, as railway and road density, and economic access represented by the domestic food price index, and family income, among others. The stability of food security accounts for the risks to availability, and access from shocks, such as natural disasters, food price volatility, fluctuations in domestic food supply and political instability (FAO *et al*., 2014; Stringer, 2016).

Food security is being undermined by a combination of threats which could be grouped (according to Lang and Ingram (2013)) in economic and territorial forces, such as inappropriate price signals, fossil fuel reliance, urbanization, globalization and armed conflicts; social forces such as population growth and demand for food, the nutrition transition and diet-based ill-health patterns, the culture of choice, and the high levels of food waste. In addition to those, climate change is also a major threat to food security and intensifies other environmental forces such as water scarcity, soil and biodiversity losses (Lang and Ingram, 2013). Climate change may disturb the stability of the food system by affecting any of the food security dimensions (Krishnamurthy *et al*., 2015). Long-term changes in the patterns of temperature and precipitation will shift production seasons, increase the supply variability and the risks in agriculture livestock, forestry, and fisheries.

Identifying the food commodities and regions that have been and will be most affected by climate trends will contribute to build resilient food systems and support the definition of adaptation measures. These will feed food policies and governance schemes that can anticipate and better manage different types of shocks affecting the food system. This study presents a systematic and integrated literature review on the climate change impacts (observed and future projections) on food security availability and access in world regions, by analysing papers published between 2013 and 2019. We perform a critical analysis on the usefulness of the reviewed material for a food-climate governance scheme aiming to tackle and manage food security for all countries, under climate change impacts. The paper is organised around five sections: section 1 introduces the scope and goal of the paper, section 2 presents the methodology used, and section 3 systematizes the reviewed climate change impacts on food security dimensions for different world regions. Section 4 discusses the usefulness of considering climate change impacts for food governance and policy coherence, and section 5 concludes.

2.2 Methods

We perform a systematic literature review following Pickering and Byrne (2014) methodology for data search, by considering 42 studies, published between January 2013 and May 2019, with observed and projected climate change impacts on selected food items. Only original scientific papers written in English are considered for the literature review although other literature (e.g. synthesis, reports and working papers) is used to support the analysis.

The process for data collection, characterization and analysis is described in Figure 2.1. Data on climate change impacts on food availability and access is grouped according to (a) producer region: Africa (which expands to Northern Africa and Sub-Saharan Africa), Europe (i.e. European Union, but also Western and Southern Europe, and Eastern and Northern Europe), Asia (i.e. Western and Southern and Southeast Asia, and Central and Eastern Asia), America (i.e. Northern and Central America, and Caribbean and South America), and global scale; and (b) food item: "Cereals" (which expand to wheat, maize, rice, barley, sorghum) that are key to human and livestock feeding and together represent nearly 60% of the worldwide energy supply (Mouillé *et al.*, 2008)), and "Other crops" (which expand to oil crops (i.e. soybean, rapeseed, oil palm, groundnuts), roots and tuber (i.e. cassava, yam, potato), sugar crops (i.e. sugar beet and sugarcane), and coffee).

For an easier analysis of future projections, three temporal scales are considered: near-time future (NF) from 2020s-2030s (5 papers), medium-time future (MF) from 2040s-2060s (22 papers) and long-time future (LF) from 2070s-2100 (11 papers). Detailed results are presented for the MF, on section 3, since most projections among reviewed papers refers to this period. All the results identified on the reviewed papers are listed in Tables A1-A3. The usefulness of the reviewed material for food-climate governance schemes is discussed on section 4 by considering past and future climate change impacts on each food security dimension.

2.3 Reviewed climate change impacts on food security dimensions

Relevant reviews were published between 2013 and 2019 outlining major impacts of climate change on relevant food items (Sanchez *et al.*, 2014; Tripathi *et al.*, 2016), mostly focused on observed (Zinyengere *et al.*, 2013) and projected impacts and uncertainties (Rötter *et al.*, 2014). Recent developments on the use of multi-model ensembles in climate change impacts on crop diseases were reviewed (Newbery *et al.*, 2016), as well as, on the effect of adaptation measures in yields by using ensemble and climate modelling and observed data (Challinor *et al.*, 2014, 2013). Zhao *et al* (2017) investigates the impacts of temperature on yields of grain crops by compiling published results from different analytical methods (i.e. global grid-based and local point-based models, statistical regressions, and field-warming experiments). All these published reviews focus in a specific dimension of food security, while here we perform an integrated overview by reviewing the available scientific material regarding past and future climate change impacts on food availability and access. While the recent Intergovernmental Panel on Climate Change report (2019) reviews relevant literature on past and future climate change impacts on food security dimensions, we enrich the assessment by also including results on the projected impacts with and without crop adaptation measures, across spatial scales, and in particular for the world breadbaskets. In addition, this manuscript discusses the usefulness of considering climate change impacts for food governance and policy coherence.

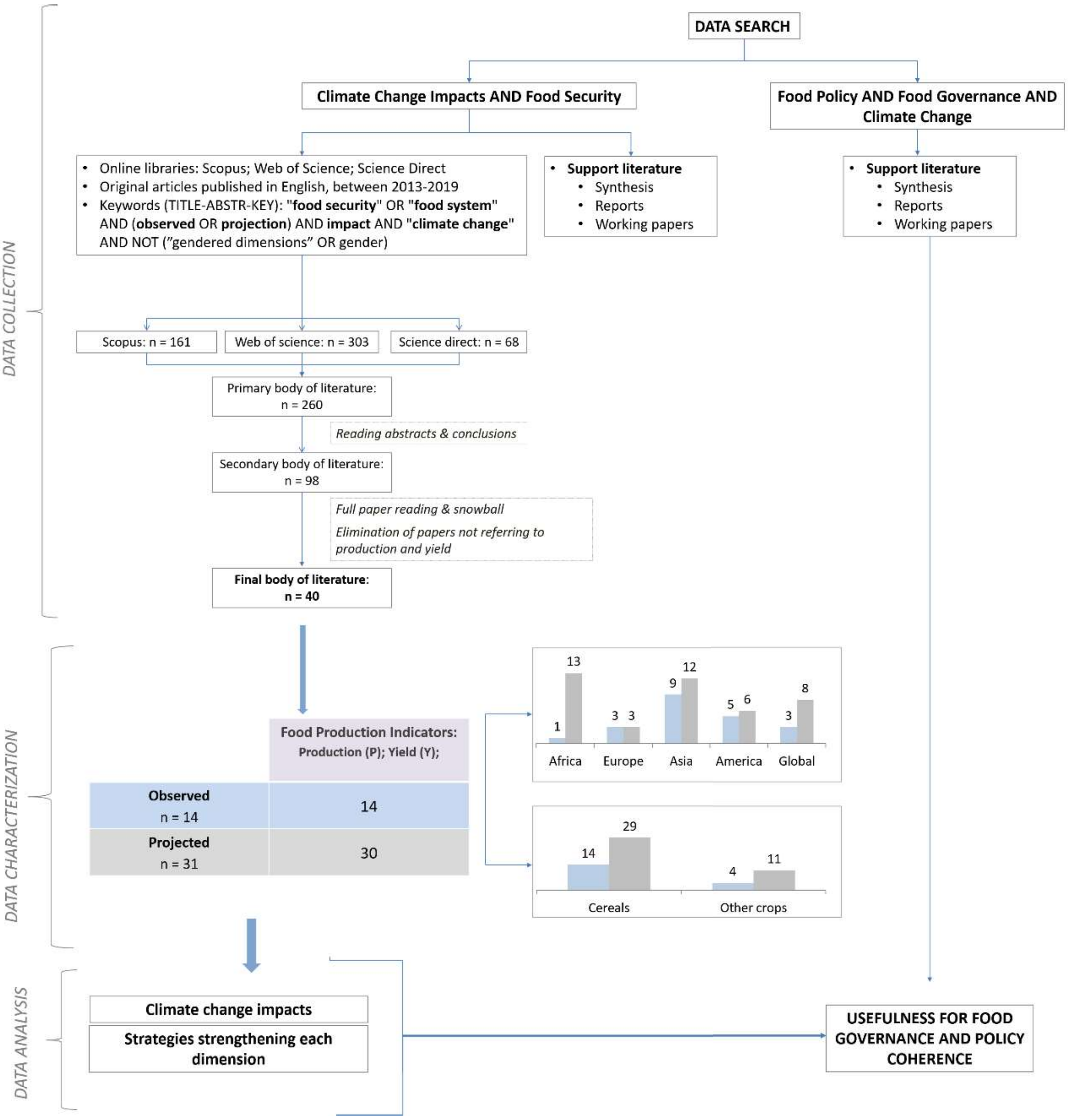

Figure 2.1 Methodology for a systemic literature review.
Data collection through systematic methodology (following Pickering and Byrne (2014)) and data characterization and analysis according to the number of studies (n) on observed (blue) and future (grey) climate change impacts on food availability and access. These impacts are analysed for the indicators (ind.) of each food security dimension, such as yield and production (for availability), price and prevalence of undernourishment (for access). The published literature considered in this review is indicated in Tables A1-A3.

The next sections present the observed and future climate change impacts, organised per food security dimension, namely on availability and access. As explained in section 2, results on the future projected impacts are presented only for the medium-term future (MF) from 2040s-2060s, but the results for all three periods are indicated in Appendix A.

2.3.1 Impacts on food availability

2.3.1.1 Observed impacts

Observed climate change impacts on food availability are based in 14 papers, with considerable results for worldwide regions taken from Ray *et al* (2019). Nine of the papers are relative to Asia (mostly China), five to America, three to Europe and one to Africa (Fig. 2.1 , Table A1).

Global climate change impacts are estimated to have affected yields (or production) mostly for wheat, maize, rice, barley, sorghum, soybean, oil palm, rapeseed, cassava and sugarcane, with losses ranging from -24.5% (i.e. maize in Eastern and Northern Europe) to -0.1% (i.e. rice in Northern and Central America), and gains ranging from +0.2% (i.e. soybean in Central Eastern Asia) to 24.9% (i.e. rapeseed in Sub-Saharan Africa) (Fig. 2.2, Table A1). Most of the historical crop losses are estimated in European and Sub-Saharan African countries, gains are estimated in Latin American countries, and mixed impacts in Asia and Northern and Central America (Ray *et al.*, 2019). Worldwide, for each Celsius degree in global mean temperature, yields are estimated to decrease, on average, by 7.4% for maize, 6.0% for wheat, 3.2% for rice, and 3.1% for soybean (Asseng *et al.*, 2015; Zhao *et al.*, 2017).

Asia (in particular, China) is the most studied region and where climate change impact on crop yield is varied. Overall, even though in Central and Eastern Asia (CEA) and in the Western and Southern and Southeast Asia (WSSA) there are, respectively, yield gains up to 5.9% and 1.9% (both for rapeseed), most of climate change impacts are associated to crop losses: in CEA up to -12% for maize and -4.8% for rice, and in WSSA up to -15.9% for oil palm (Ray *et al.*, 2019; Wang *et al.*, 2016; Wei *et al.*, 2014).

In China, mean climate changes overall benefited yields by 2% across ten crops - barley, cassava, maize, rice, oil palm, rapeseed, sorghum, sugarcane, soybean and wheat – although there are exceptions in a few provinces with rice and wheat yield declines (Ray *et al.*, 2019). Such variance in results has also been reported in other studies: Chen, Zhou and Zhou (2014) estimated a decrease in wheat production attributed to an average temperature increase and to a decrease on diurnal temperature range (at a national scale). However, increasing temperature trends leading to wheat yield increases is reported by Wang *et al* (2014), who considered aggregated provincial data of China, highlighting the implications of the inconstant elasticities for crop yield with variations of climate variables. A decline in rice yield has been attributed to a warming trend, which has been pointed to offset or even reverse the positive effect of CO_2 enrichment in rice yields (Wang *et al.*, 2016), and to a shortened growth duration (0.15 - 0.27 day/y) (Wang *et al.*, 2014).

On the other hand, a positive effect on rice yield in China due to an increase of the minimum daily temperature was observed by Zhou *et al.* (2013). In that study, the contribution of climate change explained nearly 7% of rice yields increase, while non-climatic factors were major drivers. In addition, the implementation of adaptation measures to warming have greatly facilitated rice production (e.g. breeding new varieties and adapting cold-resistant cultivars) (Zhou *et al.*, 2013). It was also reported that precipitation change has not significantly been attributed to variations in rice yield (Wei *et al.* 2014, Chen *et al.* 2014). Also in China, a declining in maize yield has been attributed to a warming trend, although a decrease in diurnal temperature range has been associated to an increase in maize production at a national scale (Bu *et al.*, 2015; Chen *et al.*, 2014; Wei *et al.*, 2014; Zhao *et al.*, 2015). Regarding other Asian countries, Ray *et al* (2019) estimated production and yield losses in rice across India, Vietnam and Philippines, and losses in wheat production in India and Turkey.

In Europe, most of climate change impacts are associated to crop losses. In the Eastern and Northern Europe (ENE) yield losses are widespread for maize (-24.5%), sorghum (-9.5%), barley (-9.1%), wheat (-2.1%), and in a less extend for rice (-0.4%). However, averaged gains are estimated for rapeseed (3.1%) and sugarcane (2.7%) (Ray *et al.*, 2019). More specifically, Moore and Lobell (2015) attribute to the long-term temperature and precipitation trend losses on barley in the United Kingdom (UK) (-2%) and in Ireland (-1%) but also gains for wheat (4 and 9%, respectively), and for sugar beet yields in Denmark and UK (3 and 4%, respectively).

In Western and Southern Europe (WSE) averaged yields decreased between -3 to -6% for rice and maize, -8 to -15% for barley, rapeseed and wheat, and -18 to -21% for sorghum and soybean, whereas yield increased by 2.7% for sugarcane (Moore and Lobell, 2015; Ray *et al.*, 2019). Moore and Lobell (2015) estimate yield losses in the Mediterranean countries for wheat from -15 in Italy to -2% in Portugal, barley from -8 in Greece to -4.5% in Portugal, maize from -8 in Italy to -1% in France but with gains in Greece (+9%). Losses in sugar beet yields are also estimated from -12.5 in Italy to -10% in Greece, while gains of 1.5% are estimated in France. That study also refers that climate trends explain nearly 10% of the stagnation in European wheat and barley yields, being the changes in agriculture subsidies and environmental policies as likely explanations for a declining in yield growth.

A decrease in yields of major crops – wheat, barley, maize, and rapeseed – is estimated for parts of the steppe region in Russia and in the grain belt of Western Siberia. In Ukraine yield of barley, maize and sorghum have been negatively affected (Ray *et al.*, 2019).

In Northern Africa (NAf), climate change benefited cassava (18%) and sorghum yields (17.9%), in addition to wheat (12%) and soybean (10.9%). But in a less extend, gains of a heat- and drought-tolerant sorghum (0.7%) and cassava (1.7%) are estimated in Sub-Saharan Africa (SSA), and in a higher extend of rapeseed

(24.9%). On the other hand, in both regions, losses are estimated for maize (-4.3 in Naf, -5.8% SSA), rice (-1.3%, -3.1), barley (-6.8, -0.6%) and sugarcane (-5.1, -3.9%) (Ray *et al.*, 2019).

In Northern and Central America (NCA), climate change impacts on crop yields are mixed: gains are estimated mostly for sorghum (4.3%), soybean (3.3%), sugarcane (1.7%), and slightly for maize (0.5%), while losses are observed mainly for oil palm (-7.2%), cassava (-2.9%), and barley (-2.5%) (Ray *et al.*, 2019). In the USA, barley, rice and wheat yields declined whereas maize, sorghum, soybean and sugarcane yields increased (Ray *et al.*, 2019). In Mexico, a gain in wheat yields by 19.6% is associated to a CO_2 increase. As in the NCA, also in the Caribbean and South America (CSA), yield gains are estimated for maize, soybean, and sugarcane (all around 3%), while losses of rice (-0.7) and wheat (-1.6%), and mostly of oil palm (-7.2%) are observed. In Central America and Colombia, Avelino *et al.* (2015) reported the impact of temperature range decrease on coffee production due to coffee rust epidemics (caused by a fungus), with impacts on local profitability, which constrained food access, since coffee is often the only source of income to buy food and supplies for grain cultivation.

2.3.1.2 Projected impacts

Projections on food availability (Fig. 2.3, Table A2) analysed by 30 papers, highlight that 80% of the number of assessments of worldwide crop yield change is negative in 2050s (in comparison to a baseline ranging from 1961 to 2010, according to the study considered), while only 20% is positive. A few of these positive projections include adaptation measures, the effect of CO_2 fertilisation or the impacts of ozone (O_3) pollution.

Projections for a medium-term future (MF) show that impacts on yield will be mostly negative across world regions – especially for cereals, soybean, and roots and tubers (i.e. cassava and yam in Naf) (Fig. 2.4). There are, however, projected yield gains even though most of them are associated to the adaptation measures or to the effect of higher concentrations of CO_2 and O_3.

The effect of higher CO_2 concentration remains one of the largest uncertainties of the climate change impacts on agriculture. In theory, and especially for C3 crops (such as wheat, rice, soybeans, and trees), higher CO_2 concentration in the atmosphere has the potential to increase photosynthesis and water productivity of plants, thus reducing crop water requirements. However, the effect of CO_2 can be offset by higher temperatures and altered precipitation patterns and varies according to the crop type (i.e. C3 or C4 (such as maize and sugarcane)) (Fader *et al.*, 2015). Even though there are uncertainties about how climate and O_3 pollution interact to affect agriculture, Tai, Martin and Heald, (2014) found that O_3 trends can exacerbate but also offset significantly climate impacts, depending on the scenario, thus suggesting the importance of air quality management in agricultural planning.

In a few SSA countries, maize yields are projected to decline, on average by -6% (RCP8.5) but to increase up to 24% (RCP8.5) if a drought tolerant variety is considered. Without adaptation, yield changes could be even more negative in Burkina Faso (-8%, RCP8.5) (Waongo *et al.*, 2015), Nigeria (up to -30%, A1B) even by considering the effect of CO_2 fertilisation (Mereu *et al.*, 2015), or in Gambia (up to -40%, RCP8.5) (Ahmed *et al.*, 2015). Maize yields are, however, projected to increase in South Africa (from 5 to 25% depending on the climate scenario and impact model used) (Dube *et al.*, 2013), in Guinea-Bissau (8.9%, RCP8.5) (Ahmed *et al.*, 2015), or in Ethiopia (up to 84%, RCP8.5) but only by considering fertilizer application (Kassie *et al.*, 2015). Across SSA countries, sorghum and millet yields are projected to decline from -45.5% to -4% (RCP8.5), even by considering drought and heat tolerant varieties (Islam *et al.*, 2016). The effect of adaptation is also studied by Srivastava, Gaiser and Ewert (2015) in the Republic of Benin, where yam yields are projected to decline by -30% (A1B or B1) but to increase from 7 to 49% (A1B), depending on the implementation of fertilizer application, irrigation, or late maturing cultivar. According to the climate scenario, but without considering adaptation measures, yields of soybean are projected to rise in South Africa by up to 20%.

In Europe, wheat, soybean, and maize production are projected to decline, on average and respectively, by -12%, -20% and up to -40% for RCP8.5 and when the effect of O_3 pollution is considered. For RCP4.5 and with the effect of O_3 pollution, wheat and rice production are projected to increase, respectively, by 5 and 7% (Tai *et al.*, 2014). Nelson *et al* (2014) project yield declines of wheat and rice by -15%.

In Asia, losses of wheat, maize, soybean, rice, and potatoes are projected to occur under RCP8.5 scenario. However, under lower emission impact scenarios and/or under the effect of CO_2, O_3 pollution, or with the implementation of improved crop varieties, future climate impacts in countries or regions may be positive or negative. For example, in Asian countries, rice yields may decline around -5 to -55% under A2 scenario but are projected to increase around 20 to 26% when the CO_2 fertilisation effect is considered (Li *et al.*, 2015).

In China, rice yield is projected to decline by -12% under A2, -4.3% under B2 (Ju *et al.*, 2013) or -2% under RCP8.5 and with the effect of O_3 pollution (Tai *et al.*, 2014). Tai *et al* (2014) project maize and soybean production gains, respectively, by 5 and 10% under RCP4.5 but that may turn negative under RCP8.5 (by ~-5% for both crops). Wheat production is projected to decline by nearly -15% (RCP8.5), but to increase up to 15% under RCP4.5 (Tai *et al.*, 2014) or up to 68% under the A1F1 scenario and only if the uncertain effect of CO_2 is considered (Tao and Zhang, 2013).

Wheat production is projected to decline by -35% in South Asia, and up to -10% in Southeast Asia (both with RCP8.5) (Tai *et al.*, 2014). At the country level wheat yield losses are projected, for example, in Pakistan by -18% (A1B) (Shi *et al.*, 2015; Zhu *et al.*, 2013) or, under RCP8.5: around -7% in Pakistan, Bangladesh, India, Nepal even if drought and heat tolerance varieties are considered (Islam *et al.*, 2016). In WSSA, on average and under RCP8.5 and by considering the effect of O_3 pollution, rice production is projected to decline by -1% (Tai *et al.*, 2014). Losses in rice yields are, however, projected to rise around -30% in Pakistan (A1B) or in India (A2) (Banerjee *et al.*, 2014; Zhou *et al.*, 2013).

In USA, high production losses are projected for maize (-50 to -45% under RCP4.5 and RCP8.5) and for soybean (-5 to -10%) (Tai *et al*., 2014). Wheat yields are projected to decline up to -30% under A2 (Jiang and Koo, 2014) and production to decline up to -10% according to the climate scenario (Rosenzweig *et al*., 2014; Tai *et al*., 2014). However, if technological advances are considered and under A2, wheat yields may reach 60% in the country. Rice production is projected to increase, respectively, by 2 to 5% under RCP8.5 and RCP4.5 under O_3 pollution (Tai *et al*., 2014).

In the CSA region, crop models project production losses of maize and soybean of -25%, and wheat losses of -10% under RCP8.5 under the effect of O_3 pollution (Tai *et al*., 2014). An average decline of -20% on yields of oil seeds, wheat, and rice is projected, under RCP8.5, in Brazil by Nelson *et al* (2014).

2.3.2 Impacts on food access

2.3.2.1 Observed impacts

Due to a low number of case studies it is difficult to derive conclusions on the observed climate change impacts on the access dimension. Nevertheless, it is reported that local food supply is strongly determined by local weather, and for the cases that food market is barely connected with foreigner markets, food access becomes a serious problem. Brown and Kshirsagar (2015) found that almost 20% of local market prices (wheat, maize and rice) were affected by domestic weather disturbances in 51 developing countries. They estimated 9% of local market prices were associated with international price changes, while 4% with both domestic weather disturbances and international price changes. Understanding how local weather disturbances and variability of international prices affect rural economies is key to define policies to mitigate the effects of climate disturbances and prevent the lack to food access. Avelino *et al.* (2015) reported the impact of temperature range decrease on coffee production due to coffee rust epidemics (caused by a fungus) in Central America and Colombia, with impacts on local profitability, which constrained food access, since coffee is often the only source of income to buy food and supplies for grain cultivation.

2.3.2.2 Projected impacts

On average, future climate scenarios are likely to increase commodity prices and thus, may negatively impact food access, with exception of Japan (and within the analysed papers) (Figure 2.5) (Table A3). According to Nelson *et al* (2014), price of oil seeds, wheat, and rice are projected to increase, on average, by 10% in European countries and Brazil, 15% in China, USA and SSA countries, and 25% in India. They showed that a large part of climate change shock is transferred to the production-side and trade responses. With a negative productivity effect from climate change, prices increase (due to the inelastic nature of global demand) and trigger more intensive management practices, area expansion, reallocation through international trade and reduced consumption, with especially negative effects for the poor in rural areas.

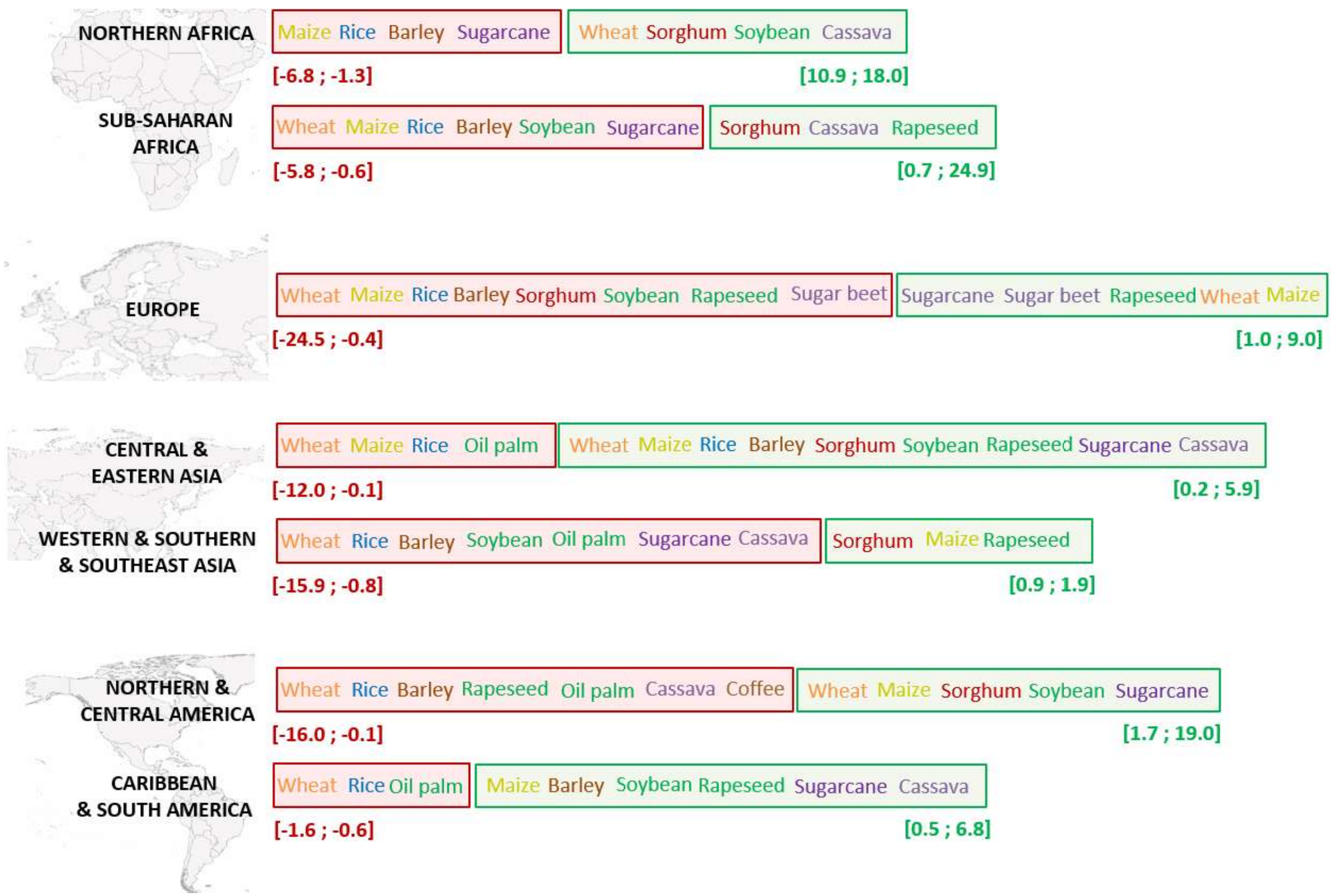

Figure 2.2 Observed climate change impacts on food availability.

Percentage of change of crop yield (or production) due to historical temperature and precipitation trends in world regions. Crops with negative yield (or production) changes are indicated inside the red boxes, while the positive ones are inside green boxes. The lowest and highest change (%) per region is indicated in square brackets. The historical period may differ for each estimated impact but is within the interval 1960-2014. The distribution of the impacts is based on published literature indicated in Table A1.

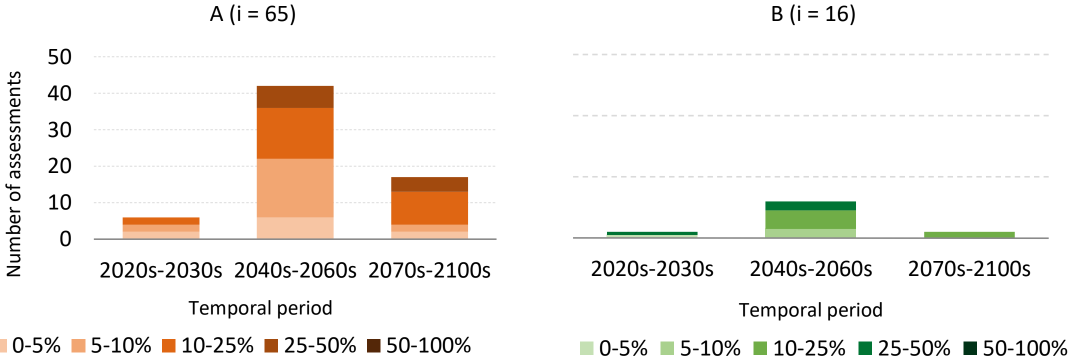

Figure 2.3 Projections on worldwide crop yield change due to climate impacts.
Number of assessments (i) on future projections of worldwide crop yield percentage of change in comparison to a baseline, per temporal period . Studies reporting negative changes are 65 (A, left side) and positive changes are 16 (B, right side). Detailed results from literature review are presented in Table A2.

Mosnier *et al.* (2014) projects (under A2) an increase of world crop price index (including cereals, oil crops, sugar crops, tubers, fibers) up to 5%, which for China and Mongolia may rise up to 6 and 38%, respectively. Higher prices in Mongolia are explained by demand increase, which is concentrated on few products, and by less flexibility in trade (i.e. high transportation costs and negative climate change impacts on few trading partners may lead to higher import prices). China has more flexibility to adjust trade partners. On the contrary, for Japan it is foreseen a decrease on crop price index up to -5%, justified by a higher domestic productivity that compensate higher import prices. Zhu *et al* (2013) projected, in Pakistan, a price increase for wheat (18–27%), rice (26–32%), and maize (14–28%) (for B1 and A1) compared to a no-climate-change scenario. Pakistan is expected to become a net food importer (due to its moderate growth in agricultural production, water scarcity and population growth), which will likely be exacerbated by climate change (Zhu *et al*., 2013). Dube *et al.* (2013) expected soybeans production to remain largely constant, in South Africa, while net imports are expected to considerably increase, leading to a commodity price rise by 60% (for averaged A1B and B1).

The prevalence of malnutrition is a result of a lack to food access (FAO *et al*., 2014). Dawson, Perryman and Osborne (2016) predicted (under A1B) an increase of 50% or more in the population in risk of undernourishment as a result of climate change in South America and Africa, Australia and Central Asia, with some European areas, South-East Asia, USA and Russia also seeing an increase in population at risk. Hertel and Baldos (2016) (under RCP8.5) highlighted the effect of market integration (in line with environmental policies protecting sensitive lands) on attenuating the increase of undernourishment rate.

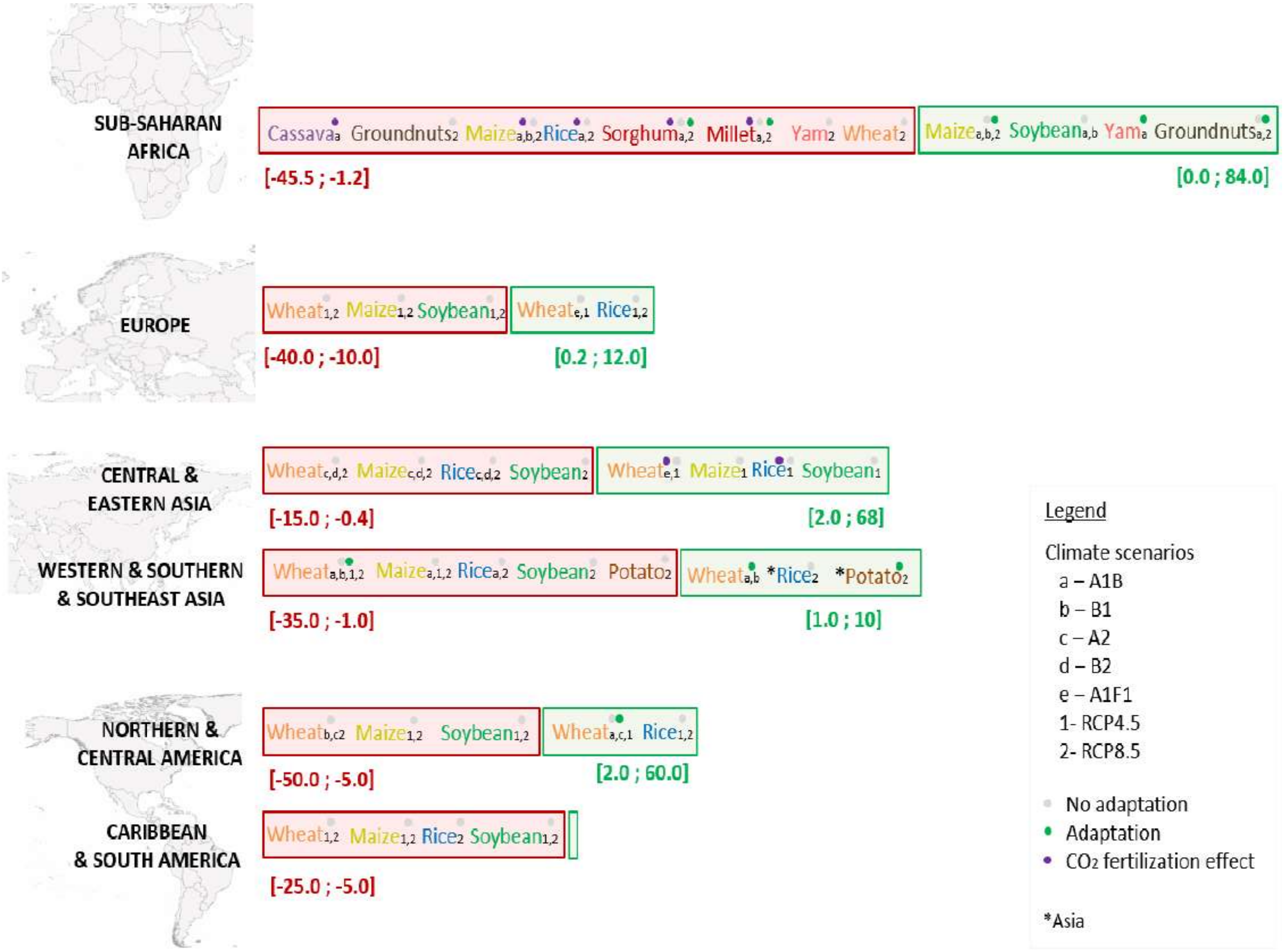

Figure 2.4 Future climate change impacts on food availability.
Percentage of change of crop responses, projected for the medium-term period (2040s-2060s), due to future climate trends in world regions. The reference period varies according to the published study but is within the interval 1961-2010. Crops with negative yield or production changes are indicated inside red boxes, while the positive ones are inside green boxes. The lowest and highest changes (%) per region are indicated in square brackets. For one crop in one region, the impact may vary according to the climate change scenario, the simulation of adaptation actions and/or the effect of O_3 or CO_2 concentrations (see legend in figure). Adaptation measures include fertilizer application, irrigation, delayed planting, late maturing cultivars, drought and heat tolerance, and/or other technologic advances. Climate change scenarios are indicated in the IPCC Special Report Emissions Scenarios (SRES: A1, A1FI, A1B, A2, B1, B2); and in the IPCC Representative Concentration Pathways (RCP: RCP4.5, RCP8.5). For example, in the Sub-Saharan region (or in one or more countries in this region), rice yields are projected to be negative under climate scenarios A1B1, RCP8.5, considering the effect of CO_2 fertilisation and/or without adaptation measures. The distribution of the impacts is based on published literature indicated in Table A2.

Globally, within segmented markets, the undernourishment rate is likely to increase by 45%, but with market integration it increases only by 27%, since a greater economic integration can work as a food security insurance against the most negative climate impact predictions.

2.4 Contribution for food governance and policy coherence

Food security governance is commonly stated at the transnational level, referring to the institutionalised process of bringing state and non-state actors for a cooperation action to solve problems that affect more than one state or region (De Haen and MacMillan, 2010). However, food security governance has expanded to other scales, national, community and household level, to overcome the barriers and problems that put at risk any dimension of food security (Candel, 2014). Modern food policies face (1) new conceptions, as pointed by McKeon (2015), opposing pathways between those upholding the dominant status quo model of industrial agriculture and those struggling for alternative models emphasising local diversified and resilient food systems, and (2) new drivers like regionalization, consumerism and the culture of choice, climate mitigation and adaptation, sustainability, and the spread and flow of information and technologies. However, trade rules have been defined primarily towards the maximization of commerce rather than to living within planetary boundaries (Lang and Ingram, 2013; Yearley, 2013), meaning the quest for sustainability has not been taken in the food domain.

A fragmentation of governance and leadership and apparent redundancy among big organizations is criticized by Lang and Ingram (2013). The inefficiency of the system makes it unable to define coherent policies across multiple scales to feed 9 billion people in 2050 (Candel, 2014).

Governance schemes must assure the interface with the multitude of issues that influence the short and long-term food security. That interface will be facilitated if, at different scales and across them, policies governing food security include the aspects of sectoral policies affecting any of its dimensions – here we focus on the availability and access dimensions.

Accomplishing this multidimensional policy and governance is a challenge of 21 century towards food security. The reviewed material on the impacts of climate change on food security dimensions, as well as, the selected strategies strengthening each dimension (Table 2.1), may contribute to respond to this challenge, by taking into consideration the high variability of impacts and, consequently, the potential for differentiated adaptation pathways.

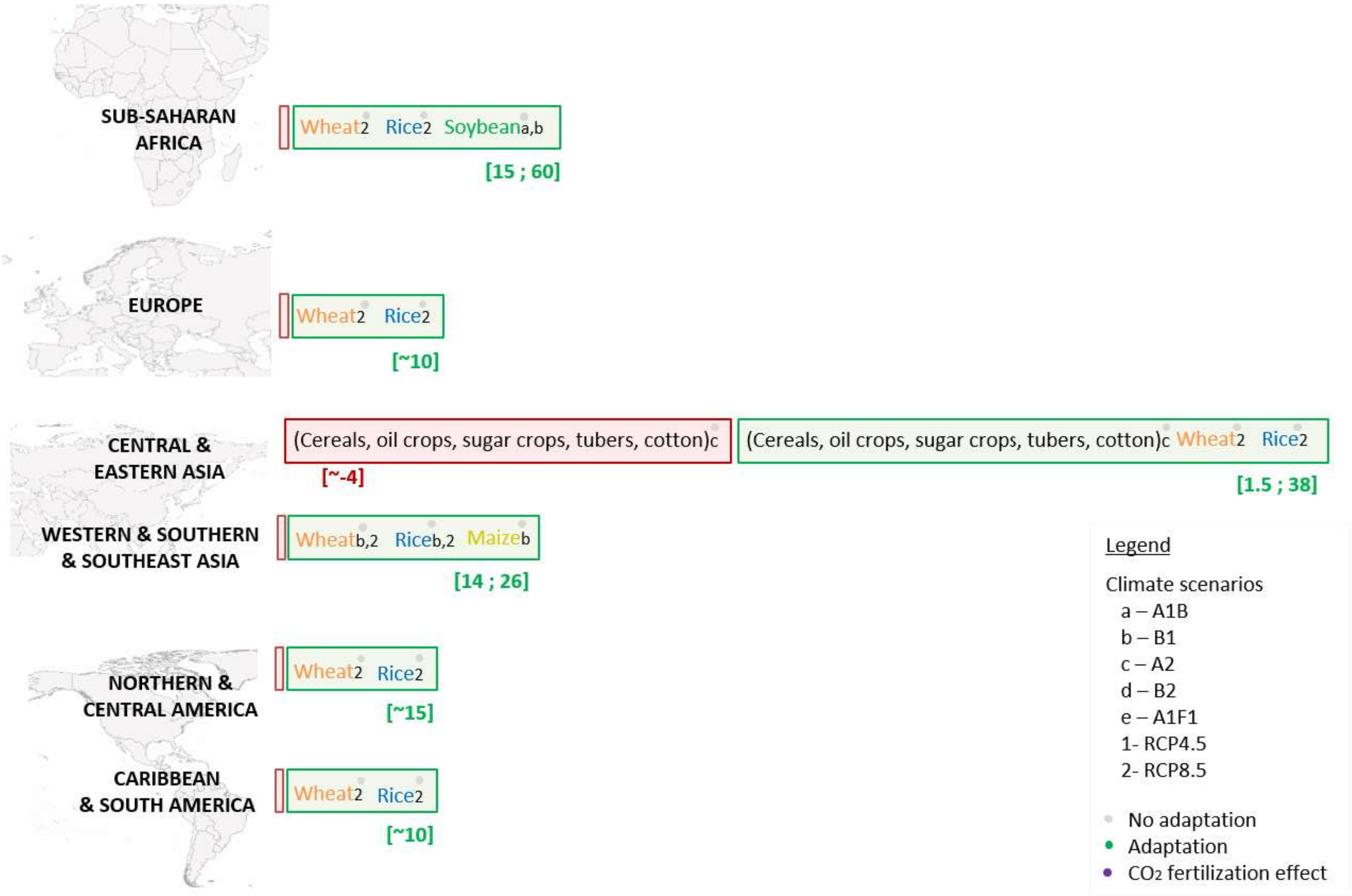

Figure 2.5 Future climate change impacts on food access.

Percentage of change of crop prices, projected for the medium-term period (2040s-2060s), due to future climate trends in world regions. The reference period varies according to the published study but is within the interval 1961-2010. Crops with negative price change (i.e. price decrease) are indicated inside the red boxes, while the positive ones (i.e. price increase) are inside green boxes. The lowest and highest price change (%) per region is indicated in square brackets. Climate change scenarios and adaptation actions are indicated in the legend box (see Fig.2.4 for details on adaptation). The distribution of the impacts is based on published literature indicated in Table A3.

Results show that the type and magnitude of climate impacts on food availability is highly variable from place to place and for different food items: observed impacts on the availability dimension are mostly, but not only, negative (section 2.1.1) and projections highlight a majority of negative changes on crop responses, while few positive projections already include adaptation measures, as well as the effect of CO_2 fertilisation (section 2.1.2); it is also foreseen an increase in crop prices among projections but with a high variability (section 2.2.2), as it is the example of on the projected crop price increase in China (in medium future from 6% to 15%), depending on the emission scenario used. The high variability among projections call for mechanisms of governance and policy coherence that consider an adapted monitoring and foresight arrangements, moving away from pure projection and one size fits all solutions, which are not adapted to build intelligence for such complex issues.

Despite the richness and usefulness of the analysed material, we consider that there is the need to assess more studies on the climate change impacts on food access. Furthermore, we considered studies that look at regions from the point of view of production and not consumption, expressing thus a supply point of view. Such approach could be undertaken in follow up studies oriented to the nutritional value of food consumption, including the impacts of climate change on malnourishment. In addition, even if the selected future climate change impacts on food commodities can vary according to the climate change scenarios used, we provide a picture on the present and future hotspots of the impact on different crops – particularly cereals which are relevant in terms of caloric food consumption but also for providing feed to maintain the livestock sector.

The impacts of observed and projected changes in climate raise new factors and possibilities potentially exposing societies to risk, such as changes in spatial production patterns and water scarcity. These factors affect per se food security dimensions, and need to be taken into the design of policies and governance schemes. The spatial patterns of crops yield across the Planet are governed by the current spatial distribution of climate drivers, and may change with future climate and with the adaptive capacity in each region. For example, >60% of the calories in the human diet is highly dependent on just four grains – wheat, maize, rice, and soybean – and the population that relies most on these grains is rising (Yearley, 2013). These crops are grown in only a handful of countries (Global Food Security Programme UK, 2015), and where observed climate trends are associated to yield losses, and to a lower extend to yield gains, but where future climate (i.e. 2050s) is projected to cause mostly negative impacts: >55% of the global wheat production is grown in the EU, China, South Asia, and the USA, but prospects for changes of wheat response to climate change, points to a decrease up to, respectively, -12, -15, -35, and -30% (for the highest emission scenarios). While in South Asia, even by considering drought and heat tolerant wheat varieties, the projected impact is negative, wheat yields in the USA could increase up to 60% with technological advances. The USA, China, Europe, and CSA produce >65% of the worldwide maize, where future climate change is expected to lead to yield declines up to, respectively, -50, -5, -40, and -25%. On the other hand, in the SSA region even though the observed climate impacts are associated to overall losses of -6%, the region may see its maize production increase by 24% if improved drought varieties are considered. More than 50% of global rice production is grown in Asian countries and (depending on the region and under higher emission scenarios), yield losses may reach -55% (-12% only in China). However, the uncertain CO_2 fertilisation effect may reverse such trend and lead to yield gains up to 26% across Asian countries. Finally, >88% of the worldwide soybean is grown in USA, CSA, and China, where future climate projections point to negative crop responses up to, respectively, -10, -25 and -5% under RCP8.5. On the other hand, for example South Africa may see its soybean yield to increase by 20% even without adaptation.

The potential climate change impacts on the spatial production patterns would potentially have direct consequences on the interconnections of the global food market. For example, the EU imports food and fisheries much more from Latin America (37,4 M€, representing 40% of total imports from the region) than from China (6,7 M€ representing 2% of total imports from the region) (EC, 2015a, 2015b). Prospects for changes of soybean yield for CSA, due to climate change, point to a decrease of 25% in the medium future. This means that Europe may be forced to change the countries food sources, which will be a challenge if a complete cross-regional analysis of the world regions will not be carried. Even though if in high income regions food security might not be an issue, the increase in food demand along with the cascading climate change impacts on trade patterns, could exert pressure on food prices and affect agricultural income in those regions, as it might be the case of the EU (European Environment Agency, 2019). With the negative productivity effect from climate change, the price of oil seeds, wheat, and rice are projected to increase by 10% in European countries and Brazil, 15% in China, USA and SSA countries, and 25% in India. The lack of food access may lead to a projected increase of the undernourishment rate by ~50%, in particular in South America and Africa, and Central Asia, and with some European areas, South-East Asia, USA and Russia also seeing an increase in population at risk.

The other critical factor is water scarcity, since agricultural activities are responsible for consuming, on average, 70% of the fresh water available on the planet, (FAO, 2012) and climate change adds significant uncertainty to the availability of water in many regions. It will impact both rainfed systems through precipitation patterns, and irrigated systems through availability of water at basin level. According to FAO, in 2009, 311 million hectares were equipped with irrigation, 84% of those actually being irrigated, corresponding to 16% of all cultivated land and contributing to 44% of total crop production (HLPE, 2015). Irrigation, as nitrogen fertilisation, is key to climate change adaptation, which requires financial resources that, if not available, will likely imply significant changes in the food trade movements. Moreover, competing uses of water are expected to exacerbate with climate change, as under a business as usual scenario, global water demand is projected to increase by 55% by 2050, with over 40% of the global population living in river basins experiencing severe water stress, especially in North and Southern Africa, and South and Central Asia (HLPE, 2015).

Climate change decision framework and governance bodies, especially regarding adaptation, must contribute to food policies at different scales, as already happens for the global scale regarding recommendations from the Committee for World Food Security (Committee on World Food Security, 2016). On other scales, crossing knowledge of climate change impacts and vulnerability into food policies eventually occurs, although no specific policies or governance schemes make it explicit. For example, at EU countries, as Portugal, strategies on food security and nutrition mostly focus on increasing knowledge on food habits and literacy of citizens to prevent health regimes, and on mechanisms to assure food access for social-economic vulnerable groups (DGS, 2015), taking for sure sufficient level of food availability. Issues relating climate change with food sources, water scarcity at importer countries or potential vulnerability of own food production systems, are not considered at all in food security strategies, representing a serious gap for a country food security.

Finally, aspects of low carbon and efficient use of resources along the food production, distribution and consumption must also be included in modern food security policies, primarily due to the need for a transition from current fossil fuels use to renewable and efficient energy sources, implying technological and cultural changes. Otherwise, adaptation options and practices counteract the aim of climate stabilization, as stated in the Paris Agreement, and sustainable consumption and production, as stated in SDGs (UNEP, 2015).

As pointed by Candel (2014) a sustainable food security asks for the (re)organization of the fragmented governance system by establishing connectivity between policy domains, scale levels, leadership and to clearly allocate responsibilities, costs and benefits. Climate change issues, as shown in this paper, provide the scope and key reasons to accelerate such renovation.

Table 2.1 Strategies selected from the literature that strength food availability and access.

Scope	Description	Reference
Consumer-oriented food policy	To strengthen and train the capacity of communities to cope with adverse climate and to implement a consumer strategy for improving reliance on trade. Strengthen FOOD ACCESS.	(Avelino *et al*., 2015; Mosnier *et al*., 2014)
Policy definition and coordination	To implement policies to: (a) ensure availability of imports of vital commodities and an effective distribution of food resources from nations and regions and (b) define coordinated goals concerning public health and food security by strengthening collaboration between stakeholders (farmers, agricultural policymakers and air quality managers). Strengthen FOOD AVAILABILITY	(Dube *et al*., 2013; Tai *et al*., 2014)
Market access, credit, and social insurance	Institutional and infrastructural support in the form of access to governmental funds. Strengthen FOOD ACCESS	(Mosnier *et al*., 2014)
	Adaptation of the international trade in agricultural production, diversification of trading partners and access to international and local markets. strengthen FOOD AVAILABILITY and ACCESS	(Dawson *et al*., 2016; Dube *et al*., 2013; Hertel and Baldos, 2016; Mosnier *et al*., 2014; Nelson *et al*., 2014; Stevens and Madani, 2016)

Scope	Description	Reference
Agriculture planning and strategy	Definition of strategies to: (a) stabilize crop production and shifts in crop varieties, (b) improve soil quality and fertility and (c) combine investment in agricultural research and increased water-use efficiency in agriculture. Strengthen FOOD AVAILABILITY and ACCESS	(Bu *et al.*, 2015; Emam *et al.*, 2015; Lobell and Tebaldi, 2014; Ray *et al.*, 2015; Stevens and Madani, 2016; Zhu *et al.*, 2013)

2.5 Conclusion

Climate change poses significant risk of disruption on food security, meaning a risk for the resilience of global to local food systems, and hence a challenge to food policies and, ultimately, to food security governance. The review of current evidence and projections of the impacts of climate change on food availability and access provides inputs for food policy design by gathering the regional differences.

Evidence shows that crop responses to climate change are highly variable, and not only negative, from place to place and for different food items. Future climate trends, on the other hand, are projected to lead mostly to negative changes, while few positive changes on crop responses may occur if adaptation measures and the effect of CO_2 fertilisation are considered. However, even if adaptation measures may decrease or even offset the adverse climate change for certain crops and regions, our review shows that, overall, the current global breadbaskets are projected to be negatively affected, with harmful consequences on the food supply and on its prices through the interconnections of the global food market. In a medium-term future, under the highest emission scenarios and if no adaptation takes place, wheat yields or production are projected to decline in the EU (up to -12%), China (-15%), South Asia (-35%), and the USA (-30%) where here yields could still increase (+60%) with technological advances. Maize production is projected to decline in the USA (up to -50%), China (-5%), and Europe (-40%). In Asian countries a decline in rice yields (up to -55%) may be reversed (with gains up to 26%) when the still uncertain CO_2 fertilisation effect is considered. Under RCP8.5, the change in soybean responses may be negative in the USA (up to -10%), Caribbean and South America (-25%), and China (-5%). On the other hand, for example South Africa may see its soybean yield to increase by 20% even without adaptation, and Sub-Saharan countries have potential to increase maize production (up to 24%) if improvements on crop adaptation are implemented. Without further adaptation, by 2050s, crop prices are projected to increase in different regions and among different scenarios, for example for aggregated oil seeds, wheat and rice by 15% across Sub-Saharan countries and China, 25% in India, and 10% in Brazil, and between 14 to 32% for maize, wheat and rice in Pakistan which is expected to become a net food importer.

The knowledge acquired with this review is useful for food governance schemes and policy coherence as it draws the attention to the high variability of impacts among regions and for different food items and, consequently, for differentiated adaptation pathways. Studies addressing a cross-regional analysis of the world regions in terms of water scarcity and spatial patterns change of production and consumption need to be considered for the design of food policies and governance schemes. These factors may imply significant changes in the food trade movements, therefore potentially compromising food security. Finally, climate-food-policies combining adaptation and mitigation is key to answer to regional specific adaptation measures, while adjusting the transition from current fossil fuels use to renewable and efficient energy use.

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3 Exposure of the EU food imports to extreme weather disasters in exporting countries

This study is published in the journal Food Security:

Brás, T.A., Jägermeyr, J., Seixas, J., 2019. Exposure of the EU-28 food imports to extreme weather disasters in exporting countries. Food Security. https://doi.org/10.1007/s12571-019-00975-2

Author contributions:

T.B. , J.J., and J.S. designed the research. T.B. compiled and analysed the data and wrote the paper. The paper was discussed and revised by all authors.

Abstract

EU relies on a diversified foreign market, even for crops for which it has a high self-sufficiency. This study contributes to the discussion on the vulnerability of agri-food supply to the impacts of extreme weather disasters (EWD). We focus on the largest import commodities of the EU and we aim to (1) map external dependencies of EU agri-food sector, (2) estimate the impact of EWD on crop production in countries from where the EU receives their imports, and (3) assess the exposure of EU agri-food imports to such impacts. Crop and trade data are acquired through EUROSTAT and FAOSTAT, EWD records from EM-DAT, all between 1961 and 2016. A superposed epoch analysis is used to estimate the impact of EWD on the average national production, yield, and harvested area of selected crops in exporting countries.

The EU imports between 35-100% of its consumption of soybeans, banana, tropical fruits, coffee, and cocoa. Our study reveals a substantial impact of EWD, especially due to droughts and heatwaves, on the production of soybeans, tropical fruits, and cocoa, with import weighted impacts of 3, 8, and 7%, respectively. Floods cause weighted impacts of 7% (soybeans) and 8% (tropical fruits). Coffee production shows gains during cold waves, but the inter-annual variability offsets these effects.

This study provides conclusions that may support EU on the development of adaptation schemes in external supplier countries to secure EU food supply. Such schemes may prioritize provisions contributing for the stability of crop production and incomes in those countries, while dealing with future adverse EWD impacts.

Keywords

Extreme Weather Disasters, Crop Production, Yield, Harvested Area, EU External Suppliers, EU Import Share-Weighted Impacts

3.1 Introduction

Extreme weather events can cause damage to crops and food production systems, and associated price spikes have the potential to destabilize food systems and threaten local to global food security (Lesk *et al.*, 2016; Nelson *et al.*, 2014; Rosenzweig *et al.*, 2014). The severity of an extreme weather event and the vulnerability and exposure of the human and natural systems to it will determine whether it results in a disaster (IPCC, 2012).

In the last four decades, droughts and heatwaves have caused between 1200 and 1800 million tonnes of losses in national maize, rice, and wheat production, respectively (Lesk *et al.*, 2016). Jägermeyr & Frieler (2018) confirm these findings with global crop modeling and show that heatwaves and droughts predominantly affect rainfed rather than irrigated yields.

This first line of evidence suggests that damages are about 10% stronger in developed countries (Europe, North America and Australasia) compared to the developing world (Asia and Africa), where the crop and management diversification across many small fields allows for drought resistance (Lesk *et al.*, 2016). In addition, it is shown that smallholders tend to minimize the risk of crop loss, whereas in higher-income countries the priority is to maximize yield, which can compromise the resistance to droughts. The EWD impacts on specific crops in tropical export-oriented countries and associated implications through trade dependencies have, however, not been explored in that study.

Our study is focused on the exposure of 28-Member States of the European Union (EU) agri-food supply to extreme weather disasters (EWD). The EU is one of the world's largest suppliers and producers of food (EU, 2018). Previously published impacts of EWD on agricultural production within the EU are summarized in Table B1 (in the Appendix B). As a central example, during the 2003 heat wave >10% declines in crop yields were reported in Italy, Germany, Austria, Spain, France, and Portugal (Jägermeyr *et al.*, 2018). Wheat and maize were the most damaged crops, with reductions of 11% (10 Mt) and 21% (9 Mt), respectively (COPA-COGECA, 2003). Impacts were amplified regionally, across the Iberian Peninsula, cereals production fell on average by 40% during the 2004-2005 drought (EEA, 2010).

Extreme weather implications for the European food production system causes higher food import demands, but exporting countries can be affected as well (IPCC, 2014). Consequently, in view of potential future aggravations in global extreme weather event frequency and intensity due to climate change (Hanks &

Craeynest, 2014; IPCC, 2012, 2014), there are growing concerns about Europe's food availability and access not just in terms of its own production (since the EWD can affect crop availability and its prices in the EU), but especially through cascading effects due to trade dependencies. In fact, Europe is the world's biggest importer of food, with about 70% of food EU-external imports from the developing world, regions considered highly vulnerable to climate change (EU, 2018; Hanks *et al.*, 2014; IPCC, 2014). Trade dependencies propagate weather-related food production shocks throughout the global food system (Puma *et al.*, 2015; Rosenzweig *et al.*, 2001) and the reliance of the global food system on trade is expected to become even more substantial (Brooks & Matthews, 2015).

This study sets out to (1) map the external dependency of the EU agri-food sector, (2) estimate the impact of EWD on crop production, yield and harvested area in countries from which the EU receives their imports (also referred as exporting countries or external supplier countries throughout the text), and (3) assess the exposure of the EU agri-food imports to such weather-related shocks. This work does not consider any food price analysis.

Table 3.1 List of goals and respective data sources used in this study.

Goal	Data sets (country-based data)	Time series	Source
1. Mapping dependencies of EU agri-food supply	Agri-food products at EU: production, imports and exports	2005-2014	(FAO, 2017), (EUROSTAT, 2016)
	Agri-food products at EU supplier countries: production		
2. Influence of EWD in the agri-food products among supplier countries	Agri-food products at EU supplier countries: production, harvest area and yield	1961-2016	(FAO, 2017)
	EWD in EU supplier countries': floods, droughts, heatwaves and cold waves	1964-2013	(EM-DAT, 2018)
	Percentage of irrigated area per agri-food product in each country	Latest available value	(FAO, 2016), (FAO, 2017)
	Koppen Geiger climate classification	2000	(Kottek, Grieser, Beck, Rudolf, & Rubel, 2006)
3. Exposure of EU agri-food imports due to EWD in supplier countries	Agri-food products at EU supplier countries: production, harvest area and yield	1961-2016	(FAO, 2017)
	EWD in EU supplier countries': floods, droughts, heatwaves and cold waves	1964-2013	(EM-DAT, 2018)
	EU import share per supplier country	2005-2014	(FAO, 2017)

3.2 Methods

3.2.1 Mapping external dependency and sufficiency of EU agri-food supply

The EU imported crop categories, between 2005 and 2014, are selected trough EUROSTAT (EUROSTAT, 2016) and FAOSTAT (FAO, 2017). Datasets used in this study are listed in Table 3.1. Processed food products are not considered for the analysis, as it is difficult to identify the exporting countries providing production statistics of such commodities. From the 48 crop categories imported by EU, we selected the following 12, representing 86% (in quantity) of the total imported: (1) soybeans, (2) maize, (3) wheat and meslin, (4) bananas, (5) rice, (6) cane or beet sugar, (7) coffee, (8) rape or colza seeds, (9) citrus fruit, (10) cocoa, (11) tropical fruits (dates, figs, pineapples, avocados, guavas, mangoes) and (12) apples, pears and quinces. For these crops, the import dependency and self-sufficiency are calculated, according to equations (1) and (2) respectively, by using data on imports, exports and production reported for EU along ten years. The food import dependency means the reliance on imports for a country's food consumption needs, while food self-sufficiency refers to a country's ability to meet its own food requirements from domestic production without imports (Clapp, 2015). For simplification, and due to lack of data, crop reserves are not considered in the equations.

Eq. (1):

$$\mathrm{Id_{crop}} = (\sum_{i=1}^{10} \mathrm{I_{crop}})/(\sum_{i=1}^{10} \mathrm{P_{crop}} + \mathrm{I_{crop}} - \mathrm{E_{crop}}) * 100$$

Eq. (2):

$$\mathrm{Ss_{crop}} = (\sum_{i=1}^{10} \mathrm{P_{crop}})/(\sum_{i=1}^{10} \mathrm{P_{crop}} + \mathrm{I_{crop}} - \mathrm{E_{crop}}) * 100$$

Where,

$\mathrm{Id_{crop}}$ = Crop import dependency (%)

$\mathrm{SS_{crop}}$ = Crop self-sufficiency (%)

$\mathrm{I_{crop}}$ = Crop imports (tonnes)

$\mathrm{P_{crop}}$ = Crop production (tonnes)

$\mathrm{E_{crop}}$ = Crop exports (tonnes)

crop = each of the twelve crops

i = number of years, from 2005 to 2014

By selecting the world exporting countries supplying at least 95% of each crop (in quantity) to EU, we can map the main exporting countries per crop and the geographic distribution of EU import dependency (Fig. 3.1). Figure 3.2a shows that the EU exhibits a self-sufficiency above 70% for rice, citrus, maize, rape and colza seeds, apples, pears, quinces, wheat, and sugar beet, even though these crops are among the 12 most imported in quantity. In fact, wheat, apples, pears, and quinces, show an EU self-sufficiency above 100%, meaning that the region produces more than what it consumes, and the remainder is exported.

For soybeans, bananas, tropical fruits, coffee, and cocoa, the EU self-sufficiency is below 9%, and 35 to 100% is being imported (between 2005 and 2014). The EU import dependency of coffee is even higher than 100% as there are coffee exports, but no production. Soybeans shows a similar picture; demand exceeds by far the internal production mostly due to the livestock sector (Ercin *et al.*, 2016).

Figure 3.2b presents the 41 countries that collectively provide more than 35% of the EU imports for soybeans, banana, tropical fruits, coffee and cocoa. Soybeans is mostly provided by North American and South American countries, banana from Central and South American countries, tropical fruits mostly from Central America, coffee from South America and Asia, and cocoa from the African countries. Those are the five crops and the exporting countries that are considered for further assessment of the impact of EWD on crop production, yield, and harvested (section 3.2.2).

3.2.2 Impact of EWD on crop production in exporting countries relevant for the EU

We use a Superposed Epoch Analysis (SEA), a time series statistical method used in data analysis, to isolate the average response signal of EWD on national crop production, while reducing noise due to extraneous variables, such as human decision making and agronomic management. This methodology is based in Lesk *et al.*, 2016 who estimated national cereal production losses across the globe resulting from reported EWD, and in Jägermeyr *et al.*, 2018 who represented spatially explicit information of growing seasons and surface water constraints in global gridded crop model simulations to quantify, through a SEA, the associated gains in model performance regarding annual fluctuations in national maize and wheat yields. The SEA analysis, also known as compositing, was mainly introduced by Mass *et al.*, 1989.

The SEA is applied to national production, yield, and harvested area from each of the five crops supplied by each exporting country. Crop data are obtained from FAOSTAT, between 1961 and 2016. The cases of banana from Suriname, tropical fruits from Panama and Ghana, coffee from Ethiopia, and cocoa from Togo and Guinea were excluded from the analysis since there is missing data on production, yield and/or harvested area. Therefore, this analysis consideres 37 out of the 41 external supplier countries. Due to an increasing trend in crop production, yield and harvested area, observational data are detrended. The trend is removed by subtracting the linear best-fit function from each time series. The result is a time series with normalised fluctuations from year to year.

Data on EWD is gathered for the same period through The International Disaster Database (EM-DAT, 2018). According to EM-DAT, for a disaster to be entered into the database at least one of the following criteria must be fulfilled: ten or more people reported killed, one hundred or more people reported affected, declaration of a state of emergency or call for international assistance. For this study we consider floods, droughts, heatwaves, and cold waves.

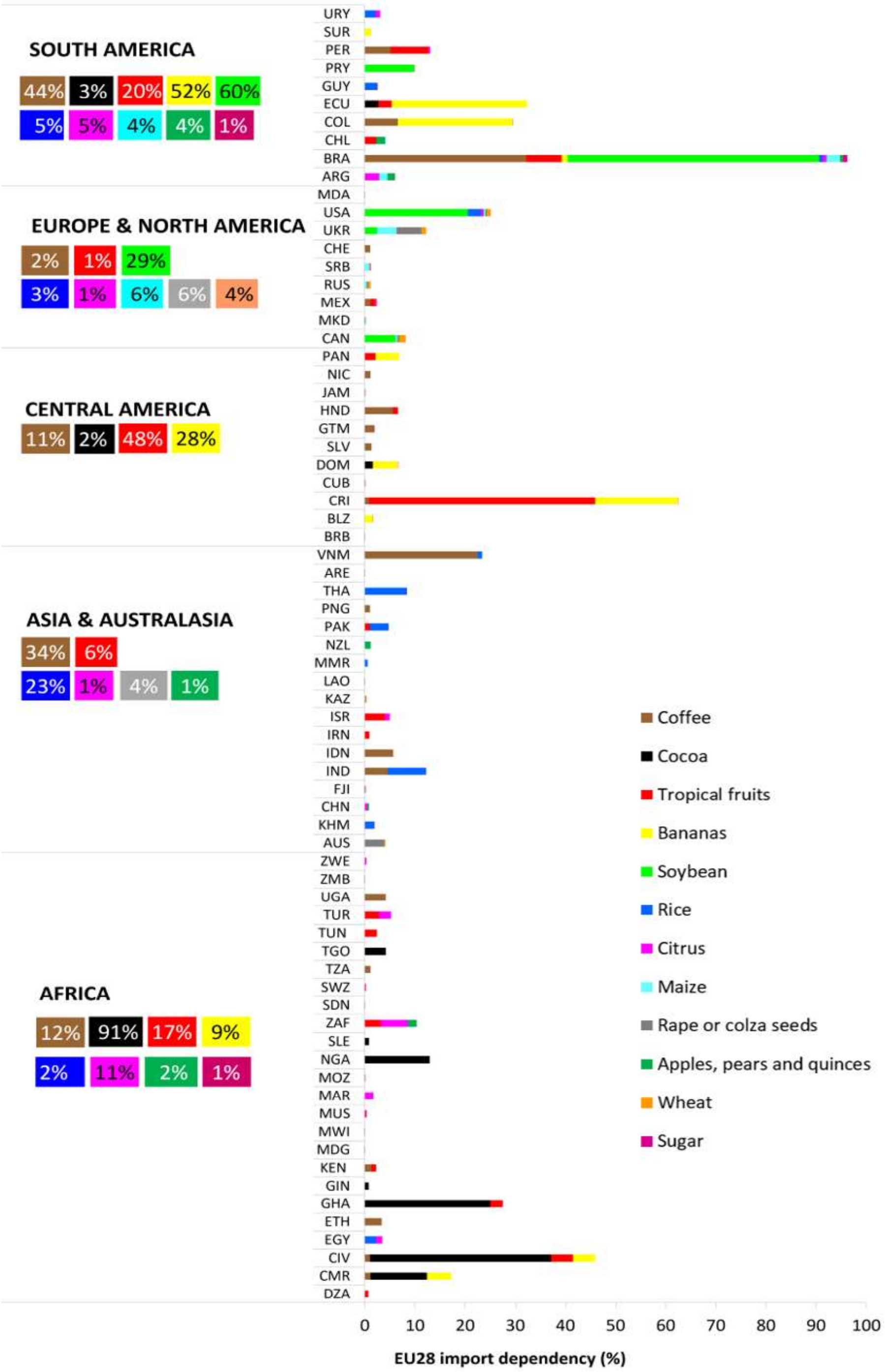


Figure 3.1 Geographic distribution of EU food import dependency.
Data is presented per crop, per world region and per exporting country (ISO3 codes), between 2005 and 2014. For simplicity "tropical fruits" aggregate dates, figs, pineapples, avocados, guavas, mangoes, and "sugar" aggregates sugar beet and sugar cane. Data acquired through (FAO, 2017) and (EUROSTAT, 2016).

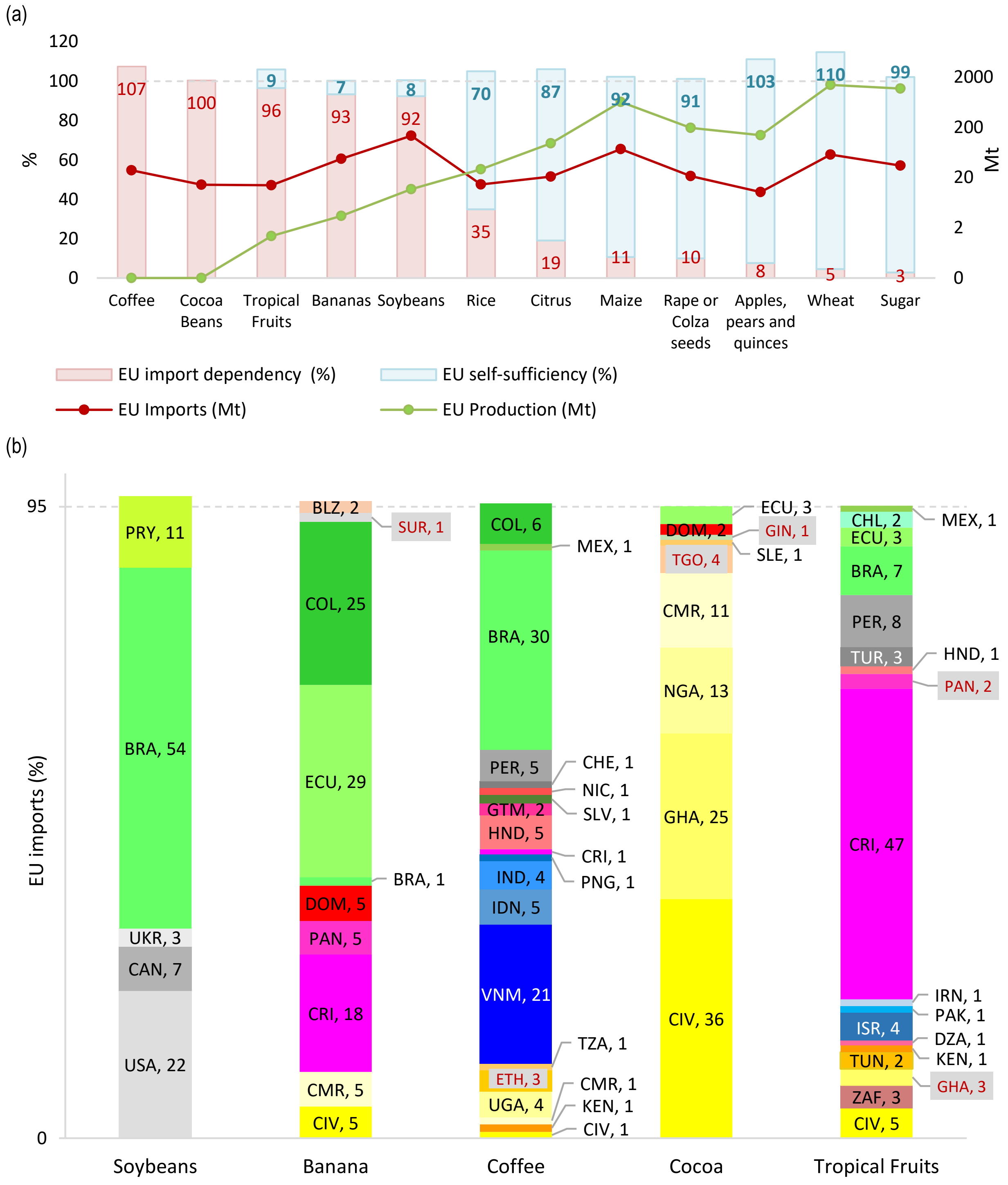


Figure 3.2 EU self-sufficiencies per crop category and import shares per external supplier.

(a) EU import dependency and self-sufficiency ratios, and amount of imports and production per crop category (Mt., secondary y-axis). (b) EU import share per exporting country (ISO3 codes) for soybeans, banana, coffee, cocoa, and tropical fruits (i.e. crops for which EU import dependency is higher than 35%).

Tropical fruits include dates, figs, pineapples, avocados, guavas, mangoes. Colors: grey for European and North American countries, green for South American countries, pink and red for Central American countries, blue for Asian countries and yellow for African countries. All data are obtained from the FAO (FAO, 2017) and (EUROSTAT, 2016) and refer to the time period 2005 to 2014. Grey boxes with countries acronyms in red indicate the countries that (due to lack of data in the original data bases) are excluded from estimating the impact of EWD on crop production.

As in Lesk *et al.*, 2016, from each time series of crop production (i.e. one time series per crop and per exporting country) we extract shorter time series using a 7-year window centered on the year of occurrence of an EWD type, with 3 years of data preceding and following the event. For example, if in the period of analysis, ten years of droughts are reported (in non-consecutive years), then we would have ten time series of a 7-years window centered in each drought (which we call "Drought TS"). For production time series, this procedure is implemented four times, one per EWD type. Each 7-year window time series is normalised (year-wise) to the average of the 3 years preceding and following the EWD. We stress that the average of those six adjacent years is calculated only for the years with no EWD of the same type (i.e. non-disaster years). Therefore, whenever there is an EWD in one of the 3 years preceding and following the event, that year is excluded from calculating the mean. Also, for the same reason, the EWD occurring between 1961 and 1963, and 2014 and 2016 are not considered. Whenever an EWD of the same type occurs in multi-years, we average crop production across all EWD years to produce a single disaster year datum, which is then centered in the 3 years preceding and following the event. This procedure results in a reduction in the total number of events since the average of sequential EWD years (of same type) is considered as one event. By centering the time series in EWD years we are strengthening the signal (positive or negative) at the year of the event while also cancelling the noise in the non-disaster years. After implementing those procedures, we obtain a composite which is the mean of all the time series for an EWD type (in the above given example the composite would be the column average of the "Drought TS"). A list of the EWD that took place in the exporting countries supplying the EU with each crop is provided on Tables B2-B4. These are the EWD considered in this study.

The composites are calculated by the following approaches: 1st) by aggregating all time series per EWD type, regardless the crop, and 2nd) by aggregating the time series of the exporting countries supplying the EU with each crop. This is done to enlarge our samples of EWD and to detect whether there is a signal in production data corresponding to when the disasters occurred.

We combine droughts and heatwaves in the same composite and then perform the analysis by aggregated and by individual crops. Since the effect of those events on crop production may be offset, or even enhanced, if the crop is irrigated and/or if grown in a tropical wet climate (characterized by high surface temperatures with plentiful precipitation), we also analyse the effect of droughts and heatwaves by considering only the exporting countries supplying the EU with crops grown in rainfed and non-tropical systems (Table B5).

For that case, only the countries with a percentage of irrigated harvested area higher than 40% are removed from the analysis. The percentage of irrigated area per crop, in each exporting country, is calculated through the ratio of the irrigated harvested area (provided by AQUASTAT (FAO, 2016)) with the total harvested area (provided by FAOSTAT (FAO, 2017)). This is calculated only for the most recent year with information available in AQUASTAT. According to the Koppen-Geiger classification (Kottek *et al.*, 2006), exporting countries having ‘Tropical rainforest climate’ (Af) and ‘Tropical monsoon climate’ (Am) as a dominant climate classification are removed from the analysis.

For simplification an equal weight is attributed to all EWD regardless the EWD type, location, duration, and impact. The above-mentioned procedure is applied to production, yield and harvested area time series, in total 12 time series per crop (i.e. a time series for production, yield, and harvested area considering the impact of floods, the combined droughts and heatwaves, and cold waves).

With the SEA we estimate the associated loss or gain in production, yield, and harvested area of each crop. The assessment of the statistical significance of the averaged normalised mean at the EWD years is performed from bootstrap replicate data sets, which are obtained by resampling (with replacement) the time series of crop production, yield, and harvested area. Bootstrapping resamples a dataset with replacement thousands of times to create simulated datasets. Specifically, per each crop and EWD type, each one of the 7-years’ time series is resampled (column-base), while applying the SEA, to create 1000 different composites. The normality of the normalised 1000 means at the EWD years is assessed with the histogram. For all crops we observe a normal distribution, therefore, for simplification, and as an example, histograms showing a normal distribution of the data are presented only for the resampled normalised means of aggregated crop production (Fig. B.1). The normalised mean at the EWD year of the 1000 resamples is considered to be statistically significant for the confidence intervals (CI) of 95%, 90%, 85%, 80%, and not significant for CI below 80%. This technique is well adopted in statistical models linking climate and crop yields (Leng & Huang, 2017). The MATLAB code to create a bootstrap to replicate a data set can be found at: https://www.mathworks.com/help/stats/datasample.html.

3.2.3 Exposure of EU agri-food imports

The averaged impact estimated for each crop and EWD type (section 3.2.2), results from the arithmetic average of the impacts estimated from all the EWD that occurred in external supplier countries. This means that, among all the exporting countries relevant for the EU, only the ones with reported EWD are considered for the estimation of the averaged impact in that crop. To elaborate on the exposure of the EU agri-food imports due to the occurrence of EWD in the crop exporting countries, we estimate the import share-weighted impact of those events on crop production by considering the import share per exporting country. For each crop, the import share-weighted impact of each EWD type is done by: i) calculating the normalised composite of the estimated impact for each exporting country, ii) multiplying the normalised composite by the corresponding import weight to EU. The weighting scheme allows us to draw direct conclusions of the overall exposure of EU agri-food imports to specific EWD types across exporting countries. This analysis is performed only for the statistically significant impacts of EWD on crop production.

3.3 Results

3.3.1 Assessing the impact of EWD in crop production in the exporting countries relevant for the EU

The Superposed Epoch Analysis (SEA) is applied to the 37 countries (Fig. 3.2b) supplying the five crops for which EU had an import dependency above 35% (soybeans, banana, tropical fruits, coffee, and cocoa). This provides a good sample size of EWD (310 floods, 190 droughts and heatwaves and 56 cold waves) to estimate its impacts on crop production, yield, and harvested area, with importance for the EU food supply regarding exporting countries.

The results on the impact of each type of EWD, including its statistical significance, for aggregated and individual crops, are shown in Figure 3.3. By aggregating the five crops (Fig. 3.3, 1st row) the results are the following ones: during years of floods an average loss of -2% and -1% (CI 95%) is observed for crop production and yield, respectively. During years of droughts and heatwaves, an average impact on the aggregated crop production of -1% (CI 80%) is observed, although for yield and harvested area no significant impact is detected (since the CI is below 80%, i.e. not statistically significant (n.s.)). We did not find statistically significant impacts from droughts and heatwaves in rainfed or in non-tropical systems (Fig. B2).

Overall, considering the different EWD, the aggregation across crops results in smaller average impacts as specific crops can have opposing responses under the same EWD type. We therefore present results individually for each crop hereinafter: (a) Soybeans - both production and yields were negatively affected by floods (-7% and -5%, respectively, CI 95%) and droughts and heatwaves (-4% and -3%, respectively, CI 95%). The average impact of these events in production is estimated in a loss of 555 Mt; (b) Banana - production and yield declined by 6% (CI 95%) and 10% (CI 95%), respectively during cold waves, while harvested area was found to increase by 5% (CI 95%). Yields were also negatively impacted by floods, by -5% (CI 95%), while the harvested area increased by 3% (CI 75%). Droughts and heatwaves did not have significant impacts on production, yield, or harvested area; (c) Tropical fruits – production was negatively affected by floods (-4%, CI 95%) and droughts and heatwaves (-3%, CI 95%). The overall impact in years of these events represent a loss of nearly 40 Mt. The low relative negative impact in yield is statistically significant for floods (-1%, CI 80%) and for droughts and heatwaves (-2%, CI 90%); (d) Coffee – a positive response to the EWD types analysed here is detected. Both production and yield increase during droughts and heatwaves by 2% (CI 80% and 90%), respectively, as well as, during cold waves by 4% and 3%, respectively (CI 95%). However, we find a substantial decrease in production and yield in the year after the extreme event (by about 7%, respectively). The effect of flood is not statistically significant for production and harvested area, but yield increased by 1% (CI 80%); (e) Cocoa – we detect significant losses during years of droughts and heatwaves by -6% (CI 75%, equivalent to 6 Mt), -2%, and -3% (CI 90%) for production, yield, and harvested area, respectively.

3.3.2 Assessing the exposure of EU agri-food imports

Soybeans, tropical fruits, and cocoa show the largest impact during EWD years, which can have potential implications for the EU agri-food supply. We therefore weight country-level EWD impacts by EU import shares, which highlights the EU exposure (Fig. 3.4). The combined impact from floods, and from droughts and heatwaves in soybeans production was -11% (-7% from floods and -4.3% from droughts and heatwaves). However, the import share-weighted impact was -9%, meaning that the negative impact is higher in exporting countries from which EU has a lower import dependency. For tropical fruits the picture is different, the arithmetic mean production impact of about -7%, caused by both floods and droughts and heatwaves together, more than doubles to about -16% when weighted by import shares. This indicates that most of the crop loss occurs in exporting countries from which EU has a higher import share. The import share-weighted impact of droughts and heatwaves in cocoa production (-7%) is slightly higher comparing with the average impact in exporting countries (-6%).

Banana and coffee are crops for which there is not a potential implication for the EU agri-food supply. Cold waves negatively impacted banana production (-6%) but those events took place only in Brazil and Belize (Table B5), which together represent only 3% of the EU import share of that crop and thus the weighted banana exposure is marginal. Coffee production increased, on average, during years with cold waves and droughts and heatwaves with an overall gain of nearly 6%. This overall impact slightly decreases to 4% (mostly due to cold waves) when considering the share of EU imports per external supplier countries. This could be explained with the fact that nearly 70% of the cold waves took place in a group of exporting countries representing a lower share of EU coffee imports (8%). Therefore, the weighted coffee gain decreases comparing with the overall gain.

3.4 Discussion

The 12 crops most imported by EU are provided by a diversified foreign market since, for most external suppliers, the dependency on imports is below 10%. Seven of those crops are largely grown in the EU, with a self-sufficiency above 70%. For the other five crops (i.e. soybeans, banana, tropical fruits, coffee, and cocoa) more than 35% of what is consumed in EU is produced in 41 exporting countries.

The SEA revealed significant negative impacts from EWD on soybeans, banana, tropical fruits, and cocoa in exporting countries. Despite a diversified external market, the impacts from EWD in soybeans, tropical fruits, and cocoa, have the potential to negatively affect the EU imports of these crops. For banana the EU import share-weighted impact is negligible. Coffee production shows gains during cold waves but consistent loss in the following year with large inter-annual variability, in general, offsets these effects (see discussion below).

The estimated loss in soybeans production represents an EU import share-weighted impact of -9%, and this negative impact is higher in exporting countries from where EU has a lower import dependency. Nevertheless, such impact may imply a potential decrease on the crop availability in the EU market. Since soybeans is a common substitute of wheat and maize, any fluctuation on its production, and consequently on its prices, may influence the demand and supply chain of the other commodities as well (Ercin *et al*., 2016).

The impact of floods in soybeans crops have been reported for many areas of the United States of America and the world (Sullivan *et al*., 2001), and vary according to the crop growth stage during the flood, the duration of the flooding or if in presence, or not, of a flood-tolerant soybean variety (Wu *et al*., 2017). Such factors were not, however, considered during this first national-level analysis and would be useful for further risk assessments. Flooding can cause physical injuries and anaerobic stress to soybean crops, which in turn can result in a poor vegetative growth and in a low photosynthetic activity, leading to yield loss (Tewari & Arora, 2016). Our estimation on the impact of droughts and heatwaves in soybeans production is in line with Siebers *et al*. (2015) who, by using infrared heating technology in an open-air field experiment, as a way to impose heatwaves on soybeans, showed that short high-temperature stress events resulted in losses in crop production in the Midwest, in the USA.

We found that cold waves and floods lead to increased banana harvested area, indicating that these events might not have been harmful for the entire area, or that the impact was offset as a result of farmer decision when faced by beneficial economic influences such as governmental subsidies (Iizumi & Ramankutty, 2015). During years of droughts and heatwaves, no significant impact is observed in banana production, yield or harvested area. Most of the exporting countries that are banana growers are under the influence of a wet tropical climate or use irrigation, which are factors that can offset the impact during those events. As demonstrated by Jägermeyr *et al*., 2018, at the global scale, heat wave and drought events predominantly affect rainfed over irrigated yields and in case water demand is fulfilled (through irrigation, or as a result of a humid climate), the additional available radiation during those years can offset losses, or even be beneficial for crop growth. This might also contribute to the observed gains in coffee production during droughts and heatwaves.

For tropical fruits, there is a high exposure of EU imports to the impact of EWD. The adverse effect of floods is significant for crop production, yield and (in a less extend) harvested area. This indicates a potential trend for complete crop failure during years with floods. Nonetheless, one year after floods, there are no changes on average production and harvested area, meaning that the crop potentially recovers from the impact.

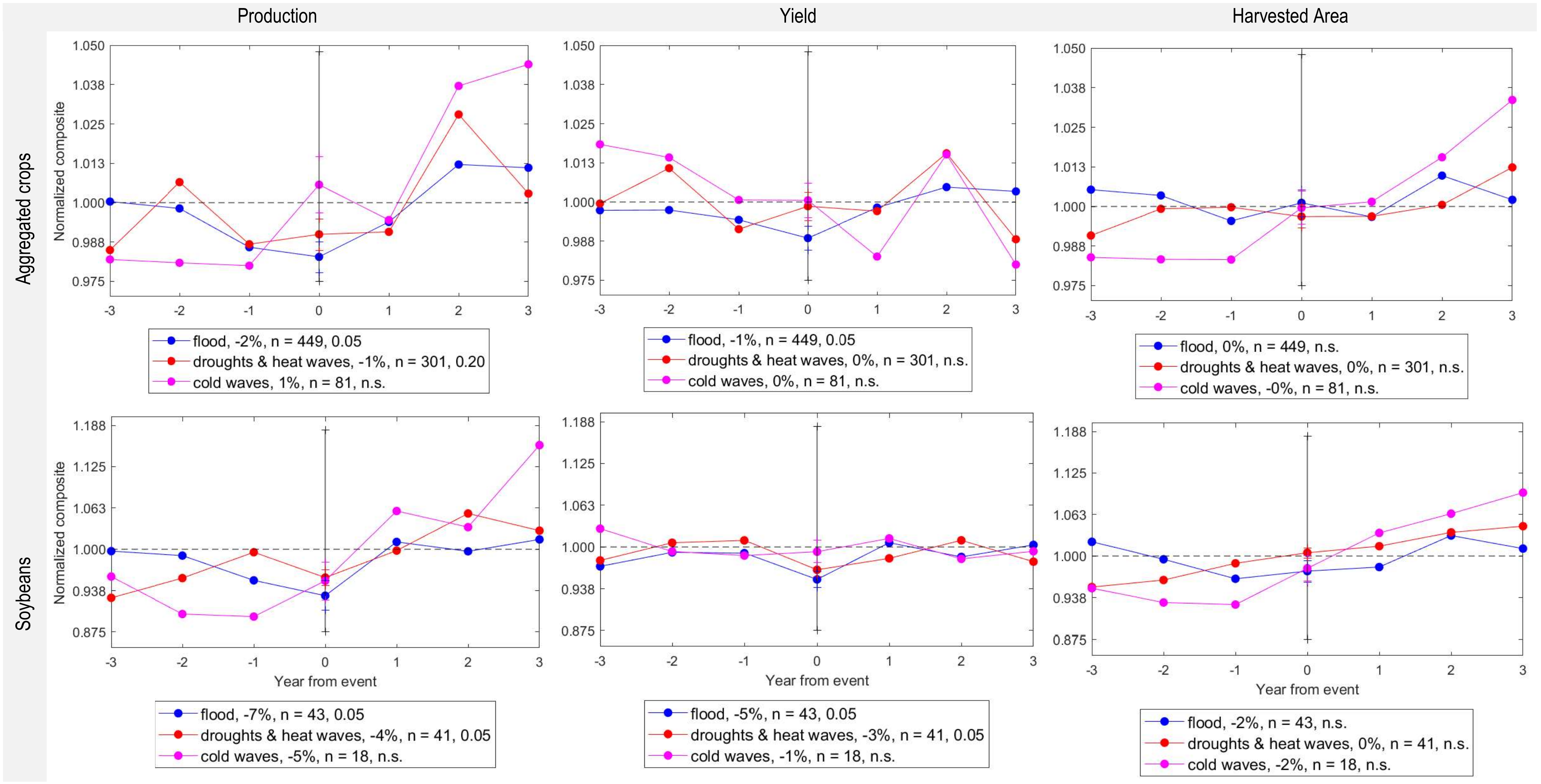
Cocoa production is substantially affected by droughts and heatwaves, with import share-weighted impact of nearly -7%. This comes with a lagged effect and even higher observed losses in the first year after the event. Such multi-year impact of droughts and heatwaves might affect the recovery of perennial crops and soil moisture, but also changes in planting habits (see discussions in Lesk *et al*. (2016) on cereals). Since the EU completely relies on cocoa imports to satisfy its consumption, a weighted loss of 7% in cocoa production may have consequences to market speculations and may result in economic volatility.

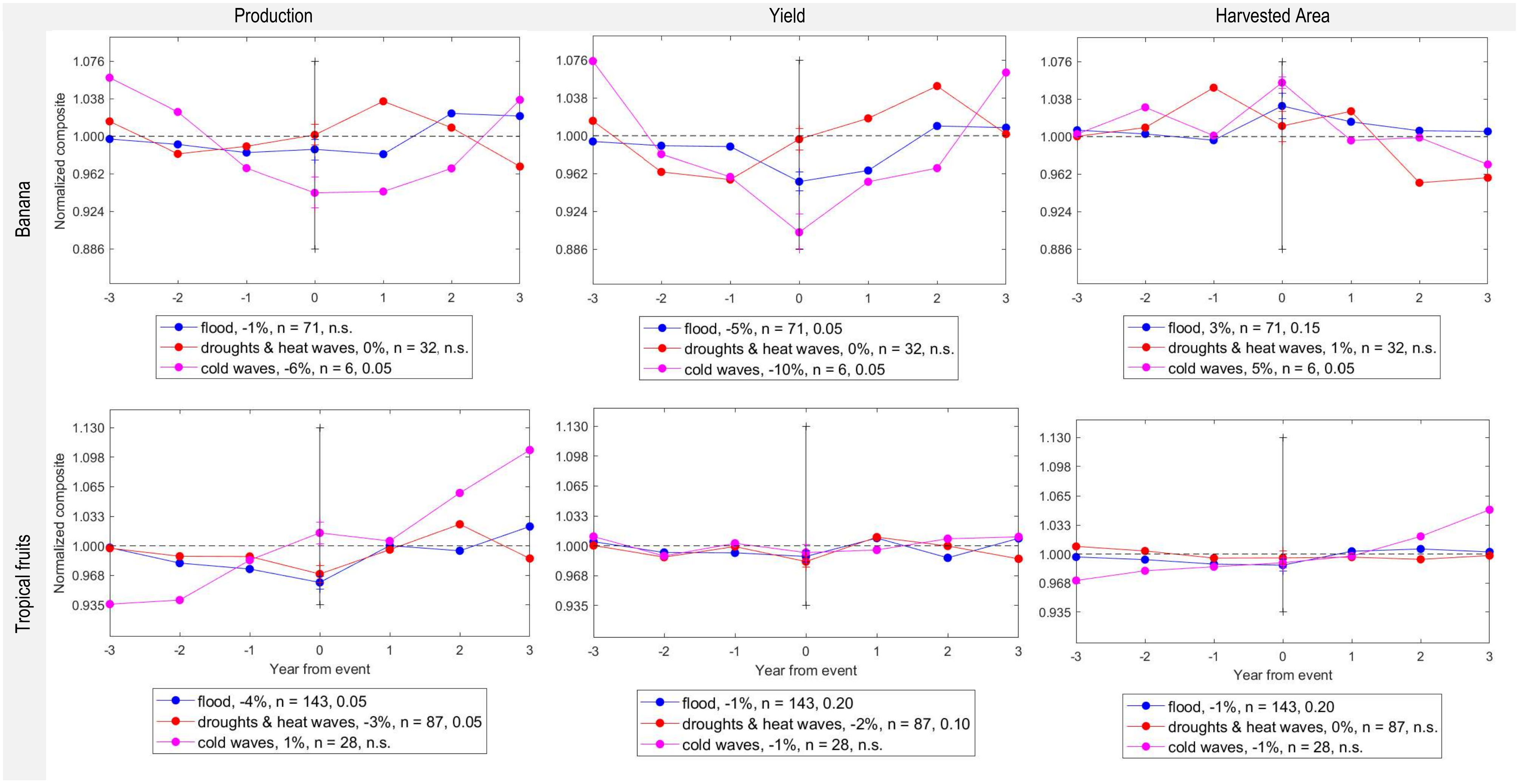
This study assesses EWD impacts on crops selected according to the EU import-dependency ratio. This includes staple crops (such as soybean), which are relevant for caloric consumption in the EU, but also cash crops (such as tropical fruits, coffee, and cocoa). Production anomalies of these crops can therefore potentially reduce caloric availability to some extent in the EU but are not expected to fundamentally impair EU food supply. Import-induced market volatility and resulting market speculations, however, can lead to price spikes. This can have significant adverse effects on food access and, therefore, on food security -- especially for the poor -- which has the potential to exacerbating social unrest.

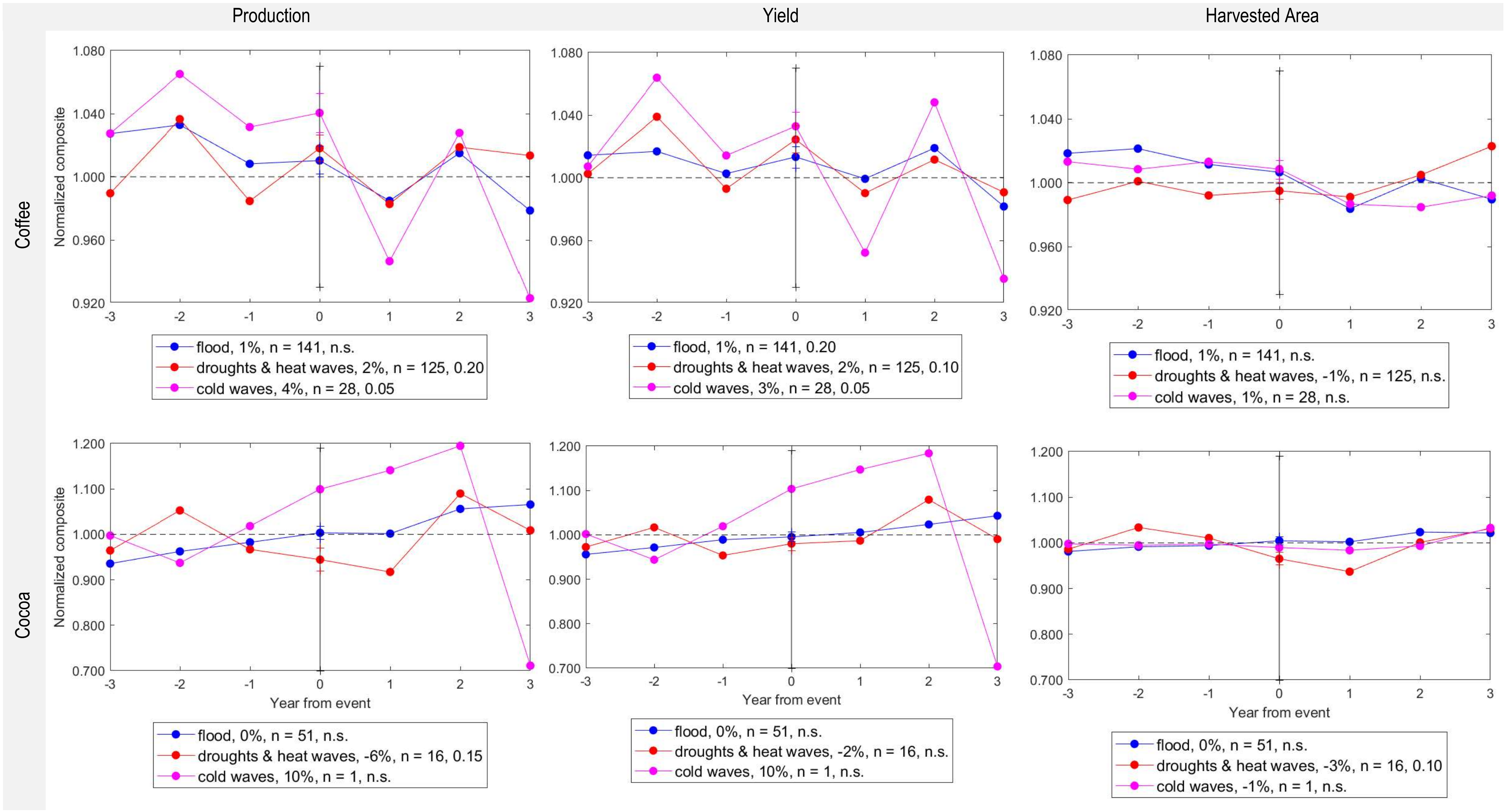
In order to guarantee the imports of cocoa, tropical fruits, and soybeans, the EU could assist on adaptation schemes in exporting countries, for example by establishing partnerships for research and innovation in crop tolerance to extreme weathers, and by supporting the definition and implementation of disaster risk reduction and management actions, while also supporting the implementation of fair and ethical food policies. This would also be helpful to promote the stability on the production of such crops and, consequently, the stability of incomes in exporting countries, contributing for local food security.

Our study includes assumptions and limitations that include the following: The presented impacts from EWD on crop production, yield, and harvested area are based on a first-order approach at national level with limited data availability. The effect of extreme weather disaster can be much stronger locally, especially in large countries where only part of the cultivated area is being affected. Not all the weather events with impact on agriculture are reported or classified as natural disasters recorded in EM-DAT. Information on the effects of local extreme events are tracked in local statistics only and not available at the international level (Kocur-Bera, 2018). We also did not attribute weights to the magnitude and duration of EWD as there is no such data available, meaning that we treated all events listed in the same way. Moreover, since we aggregated data for each crop from many external supplier countries, it could result in the attenuation of the impact of those events, i.e., losses in one country could be offset by gains among the others. The EWD were not selected based on the crop growth stage, and we did not consider the type of crops varieties in each country (i.e., if tolerant or not to a type of an EWD).

Future research could take advantage of data on EWD that occur in a medium to local scale. It could also be improved if benefited from a detailed georeferenced information on the agro-climatic zones from crop growing regions and on the major agricultural systems (i.e. if irrigated or rainfed).


Production
Yield
Harvested Area
Aggregated crops
Soybeans
Normalized composite
1.050
1.038
1.025
1.013
1.000
0.988
0.975
1.188
1.125
1.063
0.938
0.875
-3
-2
-1
0
1
2
3
Year from event
flood, -2%, n = 449, 0.05
droughts & heat waves, -1%, n = 301, 0.20
cold waves, 1%, n = 81, n.s.
flood, -1%, n = 449, 0.05
droughts & heat waves, 0%, n = 301, n.s.
cold waves, 0%, n = 81, n.s.
flood, 0%, n = 449, n.s.
droughts & heat waves, 0%, n = 301, n.s.
cold waves, -0%, n = 81, n.s.
flood, -7%, n = 43, 0.05
droughts & heat waves, -4%, n = 41, 0.05
cold waves, -5%, n = 18, n.s.
flood, -5%, n = 43, 0.05
droughts & heat waves, -3%, n = 41, 0.05
cold waves, -1%, n = 18, n.s.
flood, -2%, n = 43, n.s.
droughts & heat waves, 0%, n = 41, n.s.
cold waves, -2%, n = 18, n.s.


Production
Yield
Harvested Area
Banana
Tropical fruits
Normalized composite
Year from event
1.076
1.038
1.000
0.962
0.924
0.886
1.130
1.098
1.065
1.033
0.968
0.935
-3
-2
-1
0
1
2
3
flood, -1%, n = 71, n.s.
droughts & heat waves, 0%, n = 32, n.s.
cold waves, -6%, n = 6, 0.05
flood, -5%, n = 71, 0.05
droughts & heat waves, 0%, n = 32, n.s.
cold waves, -10%, n = 6, 0.05
flood, 3%, n = 71, 0.15
droughts & heat waves, 1%, n = 32, n.s.
cold waves, 5%, n = 6, 0.05
flood, -4%, n = 143, 0.05
droughts & heat waves, -3%, n = 87, 0.05
cold waves, 1%, n = 28, n.s.
flood, -1%, n = 143, 0.20
droughts & heat waves, -2%, n = 87, 0.10
cold waves, -1%, n = 28, n.s.
flood, -1%, n = 143, 0.20
droughts & heat waves, 0%, n = 87, n.s.
cold waves, -1%, n = 28, n.s.


Production
Yield
Harvested Area
Coffee
Cocoa
Normalized composite
1.080
1.040
1.000
0.960
0.920
1.200
1.100
1.000
0.900
0.800
0.700
-3
-2
-1
0
1
2
3
Year from event
flood, 1%, n = 141, n.s.
droughts & heat waves, 2%, n = 125, 0.20
cold waves, 4%, n = 28, 0.05
flood, 1%, n = 141, 0.20
droughts & heat waves, 2%, n = 125, 0.10
cold waves, 3%, n = 28, 0.05
flood, 1%, n = 141, n.s.
droughts & heat waves, -1%, n = 125, n.s.
cold waves, 1%, n = 28, n.s.
flood, 0%, n = 51, n.s.
droughts & heat waves, -6%, n = 16, 0.15
cold waves, 10%, n = 1, n.s.
flood, 0%, n = 51, n.s.
droughts & heat waves, -2%, n = 16, n.s.
cold waves, 10%, n = 1, n.s.
flood, 0%, n = 51, n.s.
droughts & heat waves, -3%, n = 16, 0.10
cold waves, -1%, n = 1, n.s.

Production Yield Harvested Area

Figure 3.3 Composite figure of EWD influences on observed crop production, yield and harvested area.
Results are shown for all crops aggregated, and individually for soybeans, banana, tropical fruits, coffee and cocoa (rows). EWDs include floods (blue), droughts and heatwaves (red) and cold waves (purple). The mean event impact (%) refers to the offset in year 0. The number of EWDs composited (n) and the statistical significance of the mean impact is indicated in the legend. Dashes along the y axis indicate the 25th and 75th percentile of the observations. Statistical significance is based on 1000 bootstrap samples and considered not significant above 0.20 (n.s.). The legend thus reads: event type, mean event impact, number of observations, level of significance.

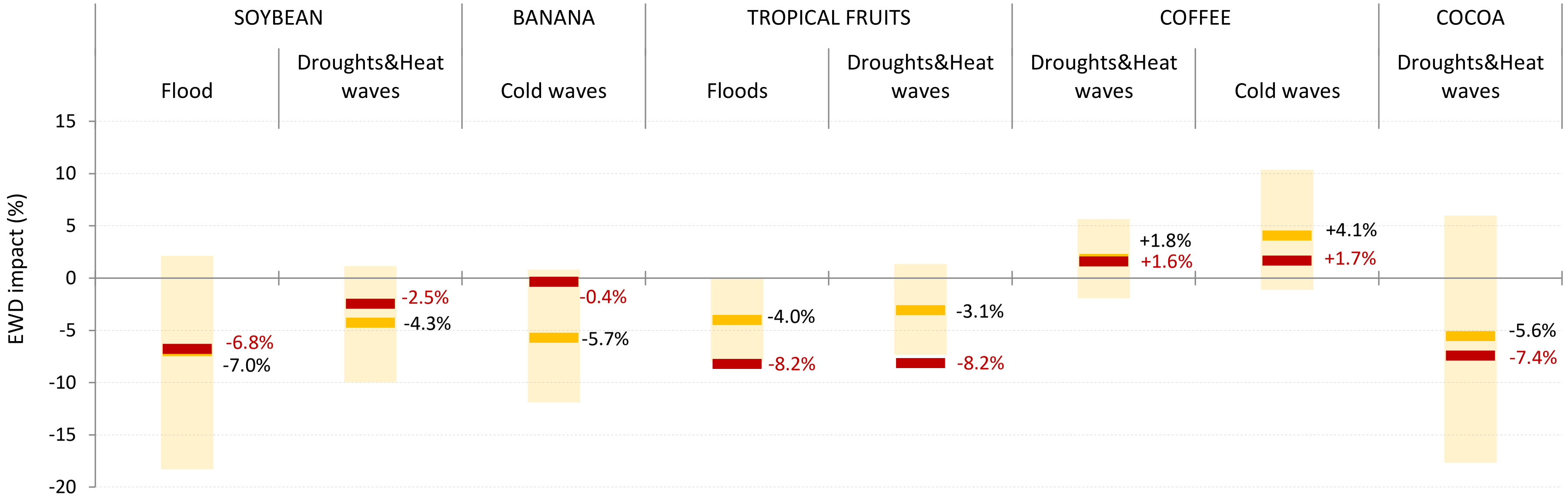


Figure 3.4 Impacts of EWD on external EU suppliers and on EU imports per crop category.
Averaged production (yellow marker) and import-weighted (red marker) impact of EWD (%) on soybeans, banana, tropical fruits, coffee and cocoa. The range of impacts in supplier countries is illustrated by yellow bars. Weighted impact is calculated according to the EU crop import shares from supplier countries. Results are shown only for the statistically significant impacts of EWD on crop production among EU suppliers.

3.5 Conclusion

This study highlights the Extreme Weather Disasters (EWD) impacts on specific crops in export-oriented countries and presents the larger implications of such impacts through trade dependencies based on the import share per external supplier country. The focus is on the EU agri-food sector, for which we mapped the external dependency and assessed its potential exposure to EWD. This was done by estimating the overall impact of EWD on production, yield, and harvested area in exporting countries. To the best of our knowledge this is the first study to perform it.

The EU imports between 35-100% of its consumption of soybeans, banana, tropical fruits, coffee, and cocoa, which are grown in 41 countries. Floods, droughts and heatwaves significantly decreased the overall averaged production of soybeans (11%) and tropical fruits (7%), while cocoa production decreased (6%) during years with droughts and heatwaves.

Despite a diversified external market, such losses represent a substantial negative exposure of EU imports to EWD, namely from floods, that cause import share-weighted impacts of -7% (soybeans) and -8% (tropical fruits), while droughts and heatwaves of -3% (soybeans), -8% (tropical fruits), and -7% (cocoa). Since the impacts from floods in tropical fruits, and from droughts and heatwaves in cocoa, have a significant negative impact on the respective crop production, these events potentially imply negative consequence for EU imports. This can potentially lead to market speculations and to higher volatility in commodity prices in the food industries.

To stabilize the EU food imports, the European Union could support the implementation of adaptation schemes in external supplier countries. Improved crop production stability would be associated with important co-benefits regarding the stability of local incomes in exporting countries, and therefore contributing to local food security.

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4 Drought and heatwave crop losses tripled over the last five decades in Europe

This study is under review in the journal Environmental Research Letters:

Brás, T.A., Seixas, J., Carvalhais, N., Jägermeyr, J., Drought and heatwave crop losses tripled over the last five decades in Europe.

Author contributions:

T.B. and J.J. conceived the study with contributions from N.C. and J.S.; T.B. and J.J. performed the analysis with valuable contributions from N.C.; T.B. and J.J. wrote the manuscript. All authors discussed and commented on the manuscript.

Abstract

Extreme weather disasters (EWD) can jeopardize domestic food supply and disrupt commodity markets. However, historical impacts on European crop production associated with droughts, heatwaves, floods, and cold waves are not well understood — especially in view of potential adverse trends in the severity of impacts due to climate change. Here, we combine observational agricultural data (FAOSTAT) with an extreme weather disaster database (EM-DAT) between 1961 and 2018 to evaluate EWD responses in European crop production. Using a compositing approach (superposed epoch analysis), we show that historical droughts and heatwaves reduced European cereal yields on average by 9 and 7.3%, respectively, associated with a wide range of responses (inter-quartile range +2 to -23%; +2 to -17%). Non-cereal yields declined by 3.8 and 3.1% during the same set of events. Cold waves led to cereal and non-cereal yield declines by 1.3 and 2.6%, while flood impacts were marginal and not statistically significant. Production losses are largely associated with yield declines, with no significant changes in harvested area. While all four event frequencies significantly increased over time, the severity of aggregated heatwave and drought impacts on crop production roughly tripled over the last 50 years, from -2.2 (1964-1990) to -7.3% (1991-2015). Both the trend in frequency and severity can possibly be explained by different reporting schemes and underlying climate change impacts.

Keywords

Extreme Weather Disasters; Historical Impacts; Climate Change; Crop Responses; European Bioclimatic Zones

4.1 Introduction

The European Union with 28 Member States (EU) is one of the world's major food producers and exporters. EU cropland expands across four main bioclimatic zones (Kottek *et al* 2006) (Table C1), from the hot-summer Mediterranean climate (Csa) to the Subarctic climate (Dfc). The 173 million hectares of the EU agricultural area (i.e., 39% of the EU's total land area) (EUROSTAT, 2019) is used for growing a variety of crops. About 65% of the cultivated area is allocated to cereals (mostly wheat, rye, barley, maize, millet and sorghum), followed by oil crops, olives, vegetables and grapes, roots and tubers, sugar and orchards (Fig. C1a) (FAO 2019a). Cereals and vegetables are the food commodities with the highest production by weight (FAO 2019b) accounting for nearly 30% (26 billion EUR) of the total EU food exports, while maintaining domestic staple food supply.

The EU food system has been affected by a number of extreme weather disasters (EWD; Fig. C1b), which caused significant crop production losses (EM-DAT 2018, Hanel *et al* 2018, Russo *et al* 2015). Most recently, the 2018 heatwave and drought lead to overall cereal production 8% lower than the previous five-year average (DG AGR 2018). These losses caused fodder shortages for livestock and triggered sharp commodity price increases. Soft wheat and barley prices jumped by 34 and 48%, respectively (DG AGR 2018, EC 2018). The 2003 heatwave and drought led to >10% cereal yield declines (particularly wheat and maize) with largest losses in Italy, Germany, Austria, Spain, France, and Portugal (Jägermeyr and Frieler 2018, COPA-COGECA 2003, EUROSTAT 2020).

Depending on human and economic losses, extreme weather events may result in an extreme weather disaster (EWD). The International Disaster Database (EM-DAT) recognizes EWDs if at least 10 people die, 100 or more people are injured, made homeless, or required immediate assistance, or if a country declared a state of emergency, or called for international assistance (EM-DAT 2018). The reporting of EWDs therefore depends on the vulnerability and exposure of human and natural capital, which can confound crop impact analyses.

Extreme weather events significantly influence the year-to-year variability in crop yields at various spatial scales (Ray *et al* 2015, Vogel *et al* 2019, Jägermeyr and Frieler 2018). Climate change is expected to further increase the frequency, intensity, spatial extent, and duration of extreme weather events (IPCC 2012, Russo *et al* 2015, Diffenbaugh *et al* 2017). Future agriculture adaptation challenges are therefore not only linked to changes in the long-term average climate, but particularly to changing weather extremes and interannual fluctuations in general. In view of large uncertainties associated with long-term average climate change impacts — in some regions crop yields might even benefit (i.e., through the lengthening of the growing season and through the influence of higher CO_2 concentration (Mueller *et al* 2015, Deryng *et al* 2014, Rosenzweig *et al* 2014)) — adverse effects of extreme events on crop production are of increasing concern (Christidis *et al* 2015, Glotter and Elliott 2016, Hov *et al* 2013). However, the historical impacts of extreme weather events on the production of different crops and in different regions remain insufficiently understood. While climate model projections agree that the frequency and severity of extreme weather events are expected to increase under unabated climate change, as of yet there is little quantitative evidence of increasing trends in crop production losses due to such events based on observational records (Lesk *et al* 2016).

Here, we use observational crop statistics from the EU member states (FAO 2019a) in combination with the EM-DAT record (EM-DAT 2018) for a standardised account of historical EWDs to evaluate associated impacts on crop production, yield and harvested area. We consider droughts, heatwaves, floods and cold waves from 1961 to 2018 and separate impacts for different bioclimatic regions. We consider all crops currently grown in the EU as listed by the UN's Food and Agricultural Organization (FAO). Crops are mainly aggregated to two main groups — cereals (CER) and non-cereals (Non-CER) — to avoid limitations due to sample size and to facilitate the evaluation of individual event types for two different time windows. Yet, further analyses consider 12 crop groups individually (Table C2).

We use a Superposed Epoch Analysis (SEA) to estimate the impact of EWDs for different crop groups, climate regions, and time periods. SEA is a statistical method to isolate the average response signal of different events, while reducing noise due to extraneous factors (Lesk *et al* 2016, Jägermeyr and Frieler 2018, Brás *et al* 2019). The SEA analysis is based on detrended national crop statistics, and the statistical significance is tested based on a bootstrapping approach (see Methods for details).

This study addresses the following research questions: (1) How large are historical crop losses associated with different EWD types in Europe? (2) Has the frequency and impact of EWDs increased over the past 50 years? (3) In what climate regions are the EWD impacts most severe?

4.2 Methods

We use national crop production, yield and harvested area obtained from FAOSTAT (2019a) and national EWD occurrence including droughts, heatwaves, floods and cold waves from the EMDAT International Disaster Database (EM-DAT 2018), all from 1961- 2018. Table C3 provides a list of all EWDs considered in this study: 32 droughts, 61 heatwaves, 399 floods and 99 cold waves across the 28 EU countries (Fig. C1b and Table C1). The number of events evaluated for crop impacts is smaller as FAO production, yield, and harvested area data is not available in all countries and years included in EMDAT. The composite analysis

(Fig. 4.1 and 4.2) further decreases the event number as the first and last three years are omitted (before 1964 and after 2015), and because events listed in consecutive years are averaged to a single event datum (see below).

A total of 129 food crops are cultivated in the EU, which we group into the following categories: cereals, including wheat, barley, maize and other cereals, and non-cereals including oil crops, olives, vegetables, grapes, roots and tubers, sugar, orchards, treenuts, citrus, soft fruits and others (Table C2). In case of occasional zero values which we interpret as missing values, in the FAO data record, all other variables (yield, harvested area, production) are set to missing to ensure the same number of records for each variable. All missing values, as well as, countries with reported crop data of less than 10 years are excluded from the analysis.

The averaged EWD impact on crop production, yield and harvested area is estimated through a Superposed Epoch Analysis (SEA), a statistical method is used to isolate the average crop response signal to each EWD type at national level, while reducing noise due to extraneous factors, such as human decision making and agronomic management (Lesk *et al* 2016, Jägermeyr and Frieler 2018, Brás *et al* 2019).

From the national crop data time series, we extract 7-year windows centred on each year of an EWD occurrence, with three years of data preceding and following the event. Each 7-year window is normalised to the average of those 6 adjacent years but by excluding any year coinciding with another EWD of the same type. In order to always have a complete 7-year window, we disregard all the events between 1961-1963 and 2016-2018, in order to normalise each event impact with the average of the 6 adjacent non-disaster years. For calculating the composite signal for two distinct time periods, we consider EWDs between 1964-1990 (crop data 1961-1993) and 1991-2015 (crop data 1988-2018).

If an EWD of the same type occurs again in a subsequent year, we average the data across all years with successive EWD occurrence (e.g., multi-year drought) to produce a single disaster year datum, which is then surrounded by the 6 adjacent years. This procedure results in a reduction in the total number of events since the average of sequential EWD years of same type is considered as one event. After normalisation, we calculate the composite vector, which is the column-based mean of all 7-year windows for a specific EWD type, crop category or climate zone. The composite vector thus always consists of seven elements. We detrend the composite vector by subtracting its linear regression line and subsequently add the composite vector mean. The fourth element of the detrended composite vector is the event signal: the average normalised EWD impact. To calculate the detrended composite signal across different crops — and for droughts and heatwaves together, as pointed out below — 7-year windows are grouped together to calculate the mean composite signal.

The statistical significance of the EWD composite signal is assessed based on bootstrap replicates, obtained by resampling the full 7-year windows. Specifically, each of the 7-year windows is resampled with replacement (column-based) 1000 times before normalising each year with the average of the 6-adjacent non-disaster years and before calculating the average composite vector to create 1000 different composite vectors, which will then be detrended. Resampling with replacement means that a particular observation from the original data set could appear multiple times in a given bootstrap sample (which has the same number of elements in each original data set). We repeat this process to obtain 1000 detrended composite signals. This represents an empirical bootstrap distribution of the mean impact during EWD years, which we use to test the normality hypothesis and to derive confidence interval. We test if the empirical bootstrap distribution is statistically different from the normal distribution using the Kolmogorov–Smirnov test with a significance level of 0.05 (Öner & Deveci Kocakoç, 2017). If data approximates a normal distribution, we assess the statistical significance of the mean event impact, which is the deviation of the detrended composite signal from 1 in year 0. To test the null hypotheses (i.e., the detrended composite signal equals 1), we first calculate the confidence interval (CI) of the empirical bootstrap distribution for different significance levels. If both end points of the CI are smaller (or larger) than 1 and if the composite signal lies within the CI, it is considered statistically significant at the respective significance level, i.e. 5%, 10% and 20%, and not significant if ≥20% . For further details, see Brás *et al.* (2019), Leng & Huang (2017) and Wong & Easton (1980).

We first calculate the detrended composite signal of droughts, heatwaves, floods and cold waves for production, yield and harvested area data using the entire time series from 1964-2015, separating the two main crop categories cereals and non-cereals. In a second step we calculate the composite signal for two time slices (i.e. 1964-1990, 1991-2015) for cereals, non-cereals and for both categories aggregated. To improve statistical significance, droughts and heatwaves are grouped to evaluate the composite signal i) separately for the first and second time slices, ii) for the 12 crop categories individually, and iii) in each Koeppen-Geiger climate zone. The analysis by climate zone is done by aggregating all countries according to its dominant Koeppen-Geiger classification (Table C1).

Since the FAO crop data contain many more non-cereal crop categories than cereal categories, we calculate the average cereal and non-cereal signal, respectively, in each country for each EWD, before aggregating both. This way cereals and non-cereals receive the same weight when combined in the overall composite signal (Fig. 4.2).

In addition to the composite signal of multiple events, we evaluate the trend in EWD frequency (Fig. 4.4), and the trend across normalised crop production anomalies over time (1961-2018) for each event type (Fig. 4.3 and Fig. C4). This is done by first calculating the sum of annual cereal production at country level. We then detrend each country-level cereal time series by subtracting its second order polynomial; these anomalies are then normalised by dividing with its standard deviation. Normalised anomalies are calculated separately for cereal and non-cereal crops, and also stratified by individual climate zone. The statistical significance of time trends (for both event frequency and production anomalies) is assessed by fitting a linear regression and testing its slope parameter for significance using the *t*-test. Significance levels are classified according to the following thresholds: *** if *p-value* < 0.05, ** if *p-value* < 0.1, * if *p-value* < 0.20, and n.s. (not significant) if *p-value* >= 0.20.

4.3 Results

4.3.1 EU crop response to extreme weather disasters

Between 1961 and 2018, the EM-DAT record lists a total of 591 events across the 28 European countries (Fig. C1b), specifically 32 droughts, 61 heatwaves, 399 floods, and 99 cold waves (Table C3). On average, droughts and heatwaves reduced EU cereal yields by 9% (inter-quartile range: +2 to -23%, 28 events) and 7.3% (+2 to -17%, 47 events), respectively (Fig. 4.1). The same events reduced non-cereal yields by 3.8% (+6 to -13%) and 3.1% (+4 to -12%), respectively. Cold waves led to cereal and non-cereal yield declines by 1.3% (+7 to -9%, 60 events) and 2.6% (+6 to -11%), while flood impacts on yields were not statistically significant for cereals, and marginal (-0.4%) for non-cereal crops. Yield observations are not indicating a lagged yield level response in the year following reported EWDs, except heatwaves, which are followed by a year with increased cereal yield levels (Fig. 4.1). Due to FAO crop data availability and methodological requirements, the number of events evaluated for crop impact is lower than the original EM-DAT list (see Methods).

Changes in crop production are largely driven by yield declines, with comparatively small and not statistically significant changes in harvested area (Fig. 4.1). During flood and cold wave years, non-cereal harvested area decreased by 1.8%, which generally indicates the abandoning of areas hardest hit (Iizumi and Ramankutty 2015).

Overall, cereals — covering two thirds of European cropland — show consistently larger losses associated with droughts and heatwaves compared to non-cereal crops. This can be explained by generally widespread irrigation in non-cereal crops. Combined drought and heatwave production responses for cereals are: wheat (-11.3%), barley (-12.1%) and maize (-12.5%). Non-cereals include: oil crops (-8.4%), olives (-6.2%), vegetables (-3.5%), roots and tubers (-4.5%), sugar beet (-8.8%), among others (Table 4.1). We combine droughts and heatwaves into a single event category to overcome limitations due to sample size in order to assess the statistical significance of the EWD impact for these individual crop groups, but also during shorter time periods (Section 4.3.2), and different bioclimatic regions (Section 4.3.3).

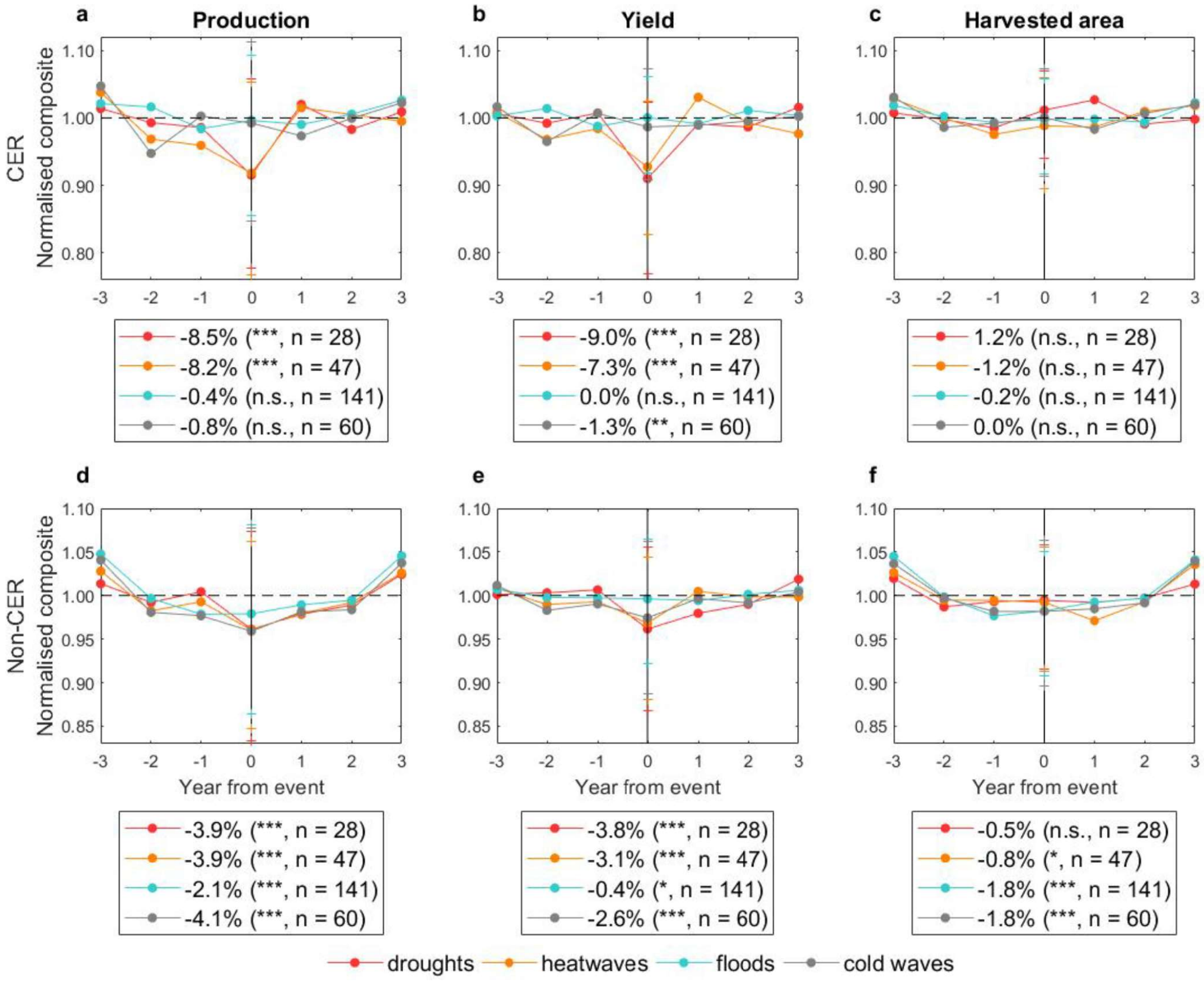

Figure 4.1 Impacts of Extreme Weather Disasters on European crops.

Composite impacts in terms of crop production (first column), yield (second column) and harvested area (third column) are shown for cereal (CER, first row) and non-cereal crops (Non-CER, second row), individually for: droughts (red); heatwaves (orange); floods (blue); and cold waves (grey). The composite analysis includes all EWDs in the EM-DAT record between 1964 and 2015, based on 7-year time windows of country-level data centred on the respective event. The mean event impact (%) is the deviation of the composite signal from 1 in year 0, highlighted in the legend box underneath each plot, along with its significance level (*** if *alpha* < 0.05, ** if *alpha* < 0.10, * if *alpha* < 0.20, n.s. for not significant if *alpha* ≥ 0.2) and the number of events included (n). Dashes along the y-axis indicate the 25th and 75th percentile of the observations. Statistical significance is based on 1000 bootstrap samples (see Methods).

4.3.2 Crop impact and frequency of extreme weather disasters over time

The impact of droughts and heatwaves on European crop production roughly tripled between the first (1964-1990) and second (1991-2015) half of the observation record: from -2.2 to -7.3%. While cereals show larger absolute losses in both time periods (increasing from -3.6 to -9.8%), non-cereals' impacts increase more than fivefold from -0.9 to -4.8% (Fig. 4.2). This aggravating signal in cereals is largely driven by more severe yield losses: cereal yield declines doubled from -4.4 to -8.9%. For non-cereal crops, however, yield declines changed less substantially (from -3.2 to -3.7%), but additional harvested area declines (1.8 to -1.4%) cause steep changes in overall production (Fig. 4.2e,f). Importantly, while these numbers reflect the average impact across all recorded events, Figure 4.2 also illustrates that the most severe events become disproportionally more severe. For example, the 25 percentile of production impacts decreased from -8.1 to -13.5%, whereas the 75 percentiles only changed from 4.1 to 0.7% (Fig. 4.2a,b).

For floods (Fig. C2) and cold waves (Fig. C3) the results draw a slightly more complex picture. While we find somewhat less severe production declines for both event types among more recent observation, for cold waves this signal is driven by much less affected harvested area despite increasing yield losses (Fig. C3d,f). For floods on the other hand, the production signal is driven by less severe yield impacts in the second time period (Fig. C2c,d), which is in line with an overall positive trend across flooding yield declines presented next.

Observations show a negative trend in normalised anomalies of cereal production over time for all evaluated event types except floods (Fig. 4.3). Even though the drought category comes with the lowest number of cases, the trend is statistically significant (at the 0.05 level) and indicates increasing annual cereal production losses by more than 3%, the steepest decline among the four EWD types. For heatwaves the trend line is more marginal and not significant. Flood events indicate a slightly positive trend cereal production anomalies that is also not statistically significant. Cold waves on the other hand show a surprisingly steep and significant negative trend. No significant trends are found for non-cereal crops (Fig. C4).

After all, droughts, heatwaves, floods, and cold waves became more frequent over the last five decades, all following statistically significant trends (Fig. 4.4). Results indicate an annual increase in event frequency of 1% (droughts), 6% (heatwaves), 29% (floods), and 10% (cold waves). The number of reported droughts and heatwaves increased from 13 in the first half of the observation period to 62 in the second half (Fig. 4.2). Similarly, there were 38 floods and 4 cold waves on record in the first half, and 103 and 56 in the second half, respectively (Fig. C2 and C3).

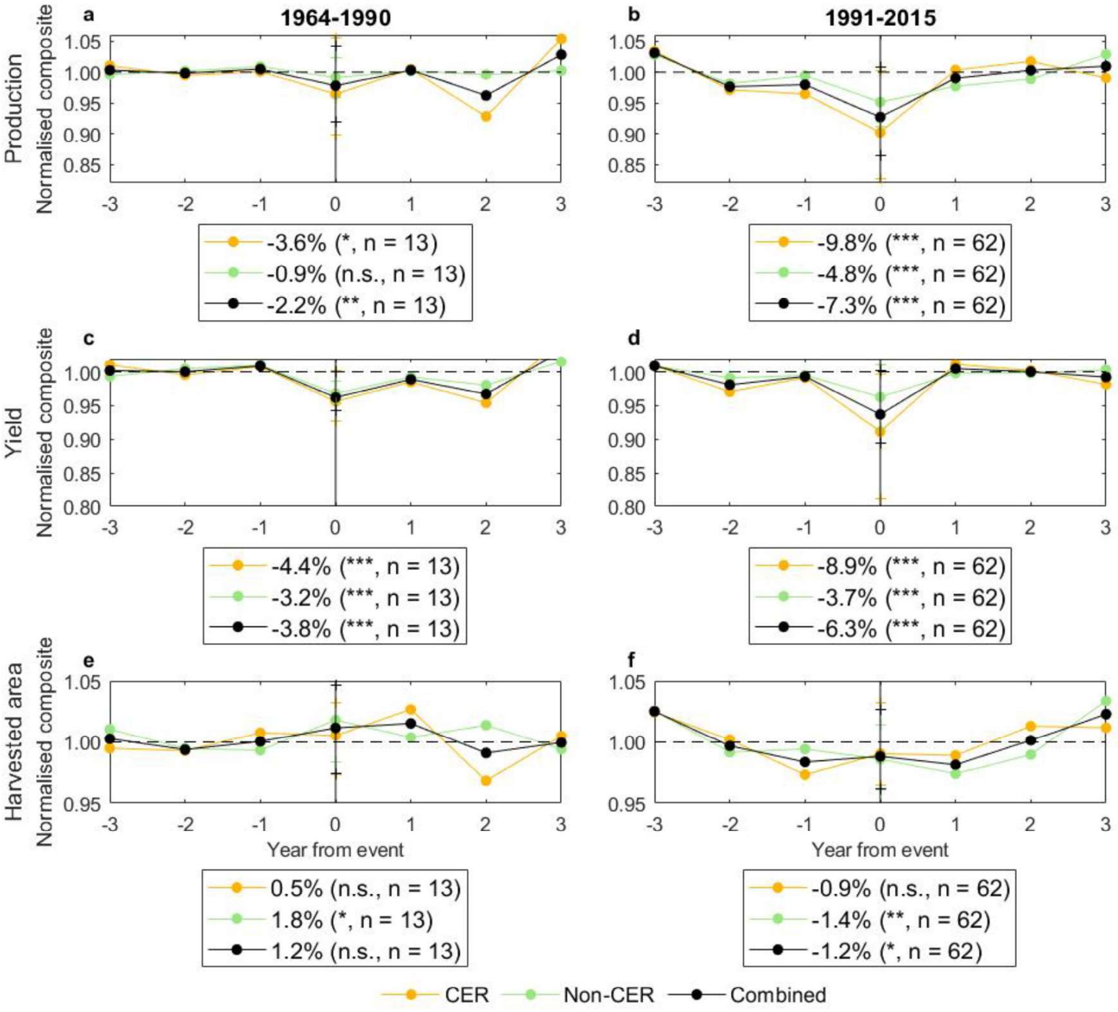

Figure 4.2 Drought and heatwave crop responses in the first and second half of the observation record.
The composite impact of cereal (CER), non-cereal (Non-CER) and both categories aggregated (Combined) is shown for production (1st row), yield (2nd row) and harvested area (3rd row), and is separated for the time slices 1964-1990 (1st column) and 1991-2015 (2nd column). Droughts and heatwaves are aggregated to avoid limitations due to sample size. Significance levels are as in Figure 4.1. Similar plots for floods and cold waves are shown in Figures C2 and C3.

4.3.3 Severity of extreme weather disasters across different climate regions

Between 1964 and 2015, the average cereal yield response to both droughts and heatwaves combined, shows largest relative losses (-12.8%) in warm-summer humid continental climates (Köppen-Geiger zone Dfb, see Table C1) covering eastern European countries such as Romania, Slovakia, Estonia, and Austria (Table 4.1). The response in temperate oceanic climates (Cfb; remaining central European countries plus France and the United Kingdom) is -6.6% and in hot-summer Mediterranean climates (Csa; Portugal, Spain, Italy, Greece, Cyprus and Malta) cereal yield declines by -6.9%. Overall production declines are mostly driven by yield changes with comparatively small (and mostly not significant) changes in harvested area. While countries in the Csa climate zone show smallest average production losses for wheat and not significant impact for maize, they show largest losses for barley (as well in yield and harvested area), even though barely is most commonly grown in central and northern European countries (Table 4.1).

Non-cereal crops also show largest yield and production losses in the Cfb and Dfb climate zones, namely staple crops such as vegetables, sugar, soft fruits, roots and tubers (Table 4.1). Olives, a relevant cash crop in the EU also show production losses in the Cfb region (-13.2%), driven by declines in yield (-11.3%) and harvested area (-2.8%). We did not find significant signals among countries in the subarctic climate zone (Dfc; Sweden and Finland).

While floods do not show a significant effect on cereal yield at overall European level (Fig. 4.1), in Cfb countries, barley (largely grown in temperate central and northern EU countries) exhibit significant yield declines by 3.4 which is offset by a positive response in maize (largely grown in drier Mediterranean countries) by 5.3% (Table C4). Years with flood events are likely to have a generally wetter growing season, which might benefit overall maize growth especially in more semi-arid climates. Cold waves have a negative effect on crop production especially across continental Dfb climates: wheat -11.1%; barley -15.4%; maize -7.8%; oil crops -15.9%; vegetables -4.6%; grapes -9%; treenuts -26.6%, largely associated with yield declines (Table C5). But the response in Cfb countries is largely positive for cereals, which could be explained by faster achievement of vernalization requirements of winter crops in colder years (Jägermeyr *et al* 2020).

4.4 Discussion

Here we use observational data to systematically evaluate European crop responses to droughts, heatwaves, floods, and cold waves included in the EM-DAT disaster data base. While the frequency of reported EWDs increased for all four event types, results suggest that impacts associated with droughts and heatwaves on European crop production roughly tripled over the observation period starting in 1964. Even though there are several issues linked to using disaster events as a metric for extreme weather event impact analysis, our findings support the hypothesis that climate change is among the factors driving increased crop losses due to extreme weather events in the historical data record.

Especially droughts show increasing crop losses over the last five decades, most prominently for cereal production. These findings are in line with evidence reported by the Intergovernmental Panel on Climate Change (IPCC) that Southern Europe is experiencing more intense and longer droughts (Bocchiola *et al* 2013). Lesk *et al.*(2016) also find increasing drought-related crop losses for cereals between 1964-2007 at the global level. The IPCC (2012) and other more recent studies (Pfleiderer *et al* 2019, Christidis *et al* 2015, Stott 2016, Coumou and Rahmstorf 2012) find that heatwaves are becoming more severe in most parts of Europe. Our results indicate only a slightly negative and not significant trend in the heatwave response, which might be explained by the fact that expanding irrigation helps to attenuate adverse heatwave impacts especially among Central European and Mediterranean countries. Irrigation can largely mitigate adverse heatwave impacts by cooling surface temperatures and thus reducing direct heat damage, but also resulting water stress impacts through maintaining increased soil moisture requirements (Jägermeyr and Frieler 2018, Vogel *et al* 2019, Leng 2017, Leng and Hall 2019, Troy *et al* 2015). According to AQUASTAT statistics (FAO 2016), nearly 28% of European cereal area is under irrigation, predominantly in Cfb and Csa regions. An additional factor that can help explain the missing significance in the heatwave trend line is that the EM-DAT time series is substantially shorter for heatwaves (starting in 1985) than for the other events (droughts start in 1976, floods in 1965, cold waves in 1971).

We evaluate the impact of each event individually, not integrated over time. An increase in event frequency thus does not affect the composite severity signal in this analysis. Observational evidence, however, shows an increase in the frequency of extreme weather events in Europe, especially for heatwaves, and most strongly in the Mediterranean region (IPCC 2012). Our findings also indicate a strong increase in the frequency of EWD for droughts, heatwaves, floods, and cold waves. The recently published report of the United Nations Office for Disaster Risk Reduction (UNDRR) (2020) supports our findings showing a sharp increase in worldwide heatwaves (+232%), droughts (+29%), and floods (+134%) over the last 20 years. While the mortality rate of these events decreased, they are associated with a significant increase in economic damage and the number of people affected. The increase in event numbers may partially be explained by better recording and reporting, yet much of it is attributed to a significant rise in the number of climate-related disasters (UNDRR/CRED 2020).

An extreme weather event can become an EWD if a specific human or economic damage occurs. The EM-DAT data base is a standardised record of large EWD and thus commonly used for advancing the understanding of their impact, but the linkage to capital loss weakens the direct linkage to the weather signal. The increased EWD frequency is therefore a confound signal of an increased extreme weather event number, and increased capital exposure and vulnerability to such events.

Climate change is leading to fewer extremely cold days and nights on average (EASAC 2013). On the other hand, climate change is also expected to increase general weather variability, for example through more stationary atmospheric wave pattern that can cause intensified heatwaves, but also cold snaps (Kornhuber *et al* 2019, Mann *et al* 2018). We expect that the increasing trend in cold wave events found in the EM-DAT record (Fig. 4.4d) is likely a combination of increased event reporting and underlying climate change. The increasing frequency of flooding events is in line with other studies (e.g. Kundzewicz *et al*.(2017)).

Additional limitations associated with using a national EWD record for agricultural impact analysis include the following aspects. (1) affected areas in a specific country accounting for the EWD damage might not coincide with the crop production areas and is therefore not always representative for the agriculture sector, which is especially important in large countries such the U.S. or Russia. (2) related to the confounded frequency trend, not all extreme weather events causing crop production losses are reported in EM-DAT. Therefore, the number of extreme weather events will be higher than the associated EWD reported. (3) reported EWDs are not necessarily occurring during the crop growing period, but anytime within the calendar year, which likely contributes to an underestimation of the overall impact signal. (4) no weights are attributed to individual EWDs accounting for the magnitude or duration of events. These points are reflected in the wide range of impacts shown in the 25th and 75th percentiles (Fig. 4.1 and 4.2) and are discussed in Brás el al. (2019).

The aggregation of data to the European level can mask more severe regional impacts as losses in one region can be offset by gains in others, such as seen for cold waves in Table C5. But the limited number of events and countries on record hamper finer-grained analyses in many cases as the composite impact signal becomes statistically insignificant without a sufficient number of cases (Tables C4-C5). In follow-up studies some of these limitations could be overcome by using spatially explicit and index-based event metrics focused on actual cropland areas and different agricultural system. That said, quantifying EWD impacts as conducted here is a different, equally important contribution to understanding food system vulnerabilities.

Droughts led to higher European cereal yield and production losses than heatwaves, while for non-cereal crops the impacts were similar between both events. The geographic difference in EWD impacts with larger losses in the Warm-summer humid continental climates (i.e. Dfb region) and smaller losses in Southern Europe (i.e. Csa regions) but also in countries with a temperate oceanic climate (i.e. Cfb) can be possible explained by the share of cropping area under irrigation.

In Csa countries, 87 and 9% of the area for maize and wheat production is irrigated, respectively. In the Cfb region maize is irrigated to 19% and in the Dfb to 2%, and wheat is generally not irrigated (FAO 2016) (AQUASTAT records from 2003-2011). As an example for non-cereals, Olives are irrigated to 20% in Csa regions, and only to 4% in Cfb regions (FAO 2016). In general terms, the area under irrigation could be expanded in Europe as a measure to alleviate exposure to extreme weather events. But substantial investments would be required (Elliott *et al* 2014), energy consumption would increase (Daccache *et al* 2014) and the cost of crop production and consequently food prices would potentially be affected. Importantly, the evaluation of the irrigation potential must be guided by water sustainability standards such as the European Water Framework Directive (European Comission 2000). Moreover, traditional and sustainable water management practices such as conservation tillage, organic mulching, and water harvesting for supplemental irrigation during dry spells are shown to offer large and synergistic opportunities to buffer impacts of extreme weather in both rainfed and irrigated systems (Jägermeyr 2020, Rosa *et al* 2018, Jägermeyr *et al* 2016, Rost *et al* 2009).

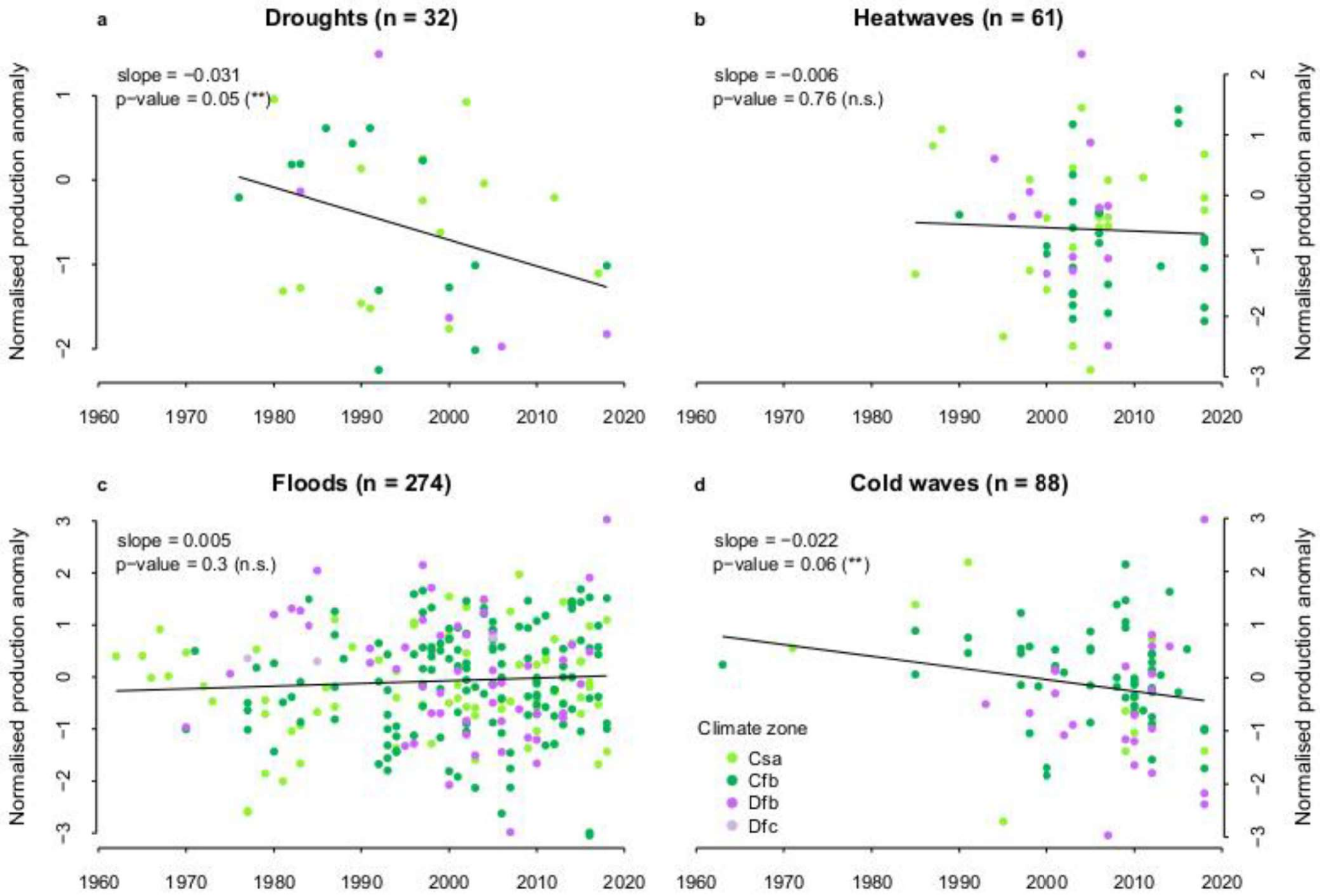

Figure 4.3 Cereal production anomalies during years of reported EWDs.

Normalised anomalies are shown for all years with droughts (a), heatwaves (b), floods (c), and cold waves (d) listed in the EMDAT record (EM-DAT 2018) until 2018 (currently the last year with FAO yield statistics available). Cereal production is shown as the sum of all cereal production in a specific country. Countries are colored according to the Koeppen-Geiger climate zone: Cfb - Temperate oceanic, Csa - Hot-summer Mediterranean, Dfb - Warm-summer humid continental, and Dfc – Subarctic (see Table C1). The straight line indicates the regression line; its slope parameter and significance level are shown in the top-left corner (*** if *p-value* < 0.05; ** if *p-value* < 0.1; * if *p-value* < 0.2; n.s. for not significant if ≥ 0.2). The number of events (n) is indicated in the title. A similar plot for non-cereal production is shown in Figure C4.

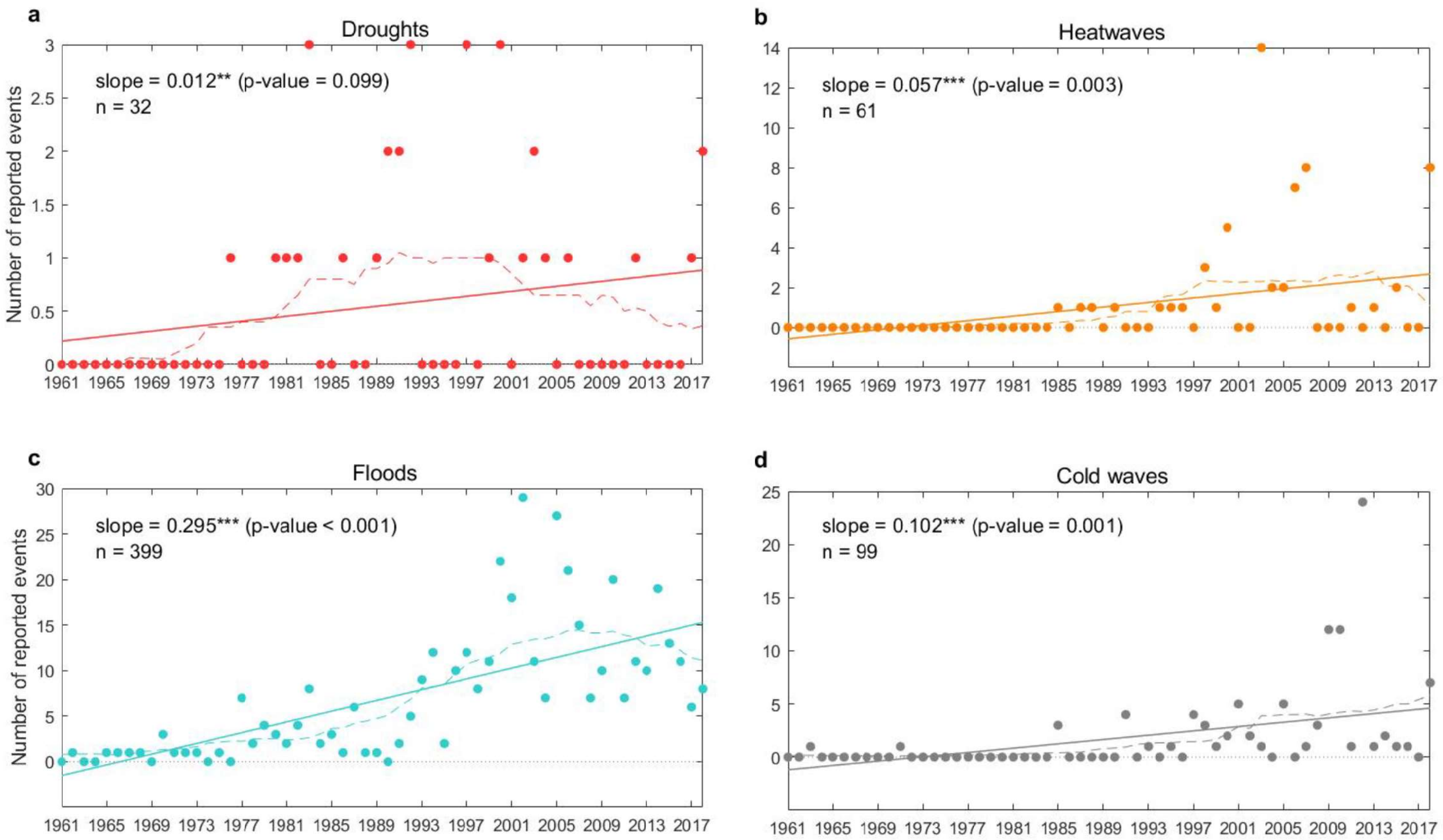

Figure 4.4 Number of annually reported EWDs in Europe.

The number (n) of country-level droughts (a), heatwaves (b), floods (c) and cold waves (d) in the EM-DAT record (EM-DAT 2018) are shown between 1961 and 2018. The solid line indicates the regression line, its slope parameter and significance level are shown in the top-left corner (*** if *p-value* < 0.05; ** if *p-value* < 0.1; * if *p-value* < 0.2; n.s. for not significant if ≥ 0.2). The dashed line represents the 20-year moving average.

Table 4.1 Composite drought and heatwave impacts by crops and climate region.
Observed production, yield and harvested area impacts (%) associated with droughts and heatwaves (combined to overcome limitations due to sample size) are separated for the EU level and for each Koeppen-Geiger (KG) region (Kottek *et al* 2006) between 1964 and 2015. Results are shown for major crop categories, ordered by the respective fraction of the total EU cropping area (%). Average event impacts are shown (red if negative, green if positive) if statistically significant (*** if *alpha* < 0.05, ** if *alpha* < 0.10, * if *alpha* < 0.2, n.s. for not significant if *alpha* ≥ 0.2); n.n. if empirical bootstrapped distribution of the normalised mean is not normal. Statistical significance is based on 1000 bootstrap samples (see Methods). Column n indicates the number of events. Blank cells mean that a crop is not grown in the respective KG region. Impacts for floods and cold waves are shown in Tables C4 and C5.

Crops	European Union-28					Cfb - Temperate oceanic climate				Csa - Hot-summer Mediterranean climate				Dfb - Warm-summer humid continental climate			
	% cropping area	Production	Yield	Harvested area	n	Production	Yield	Harvested area	n	Production	Yield	Harvested area	n	Production	Yield	Harvested area	n
CEREALS	***65.0***	**-8.3 *****	**-7.9 *****	**-0.3 n.s.**	**75**	**-6.4 *****	**-6.6 *****	**1.1 n.s.**	**33**	**-6.8 *****	**-6.9 *****	**-0.3 n.s.**	**28**	**-15.6 *****	**-12.8 *****	**-3.8 ***	**14**
Wheat	29.5	-11.3 ***	-9.6 ***	-2 ***	75	-10.5 ***	-7.3 ***	-3.3 ***	33	-9.5 ***	-11 ***	1.4 n.s.	28	-17 ***	-12 ***	-5.8 ***	14
Barley	14.1	-12.1 ***	-11.6 ***	-0.7 n.s.	75	-5.7 ***	-7.4 ***	1.7 *	33	-19.2 ***	-15.5 ***	-4.5 **	28	-13.2 ***	-13.7 ***	1.3 n.s.	14
Maize	10.2	-12.5 ***	-12.2 ***	-0.6 n.s.	67	-17.2 ***	-16.4 ***	-0.8 n.s.	30	-2.5 n.s.	-3.4 ***	1 n.s.	23	-18.6 ***	-17.6 ***	-2.5 n.n.	14
Other cereals	11.2	-6.4 ***	-6.3 ***	0.1 n.s.	75	-4.2 ***	-4.9 ***	2 *	33	-4.5 **	-5 ***	0 n.s.	28	-15.2 ***	-12 ***	-4.5 n.s.	14
NON-CEREALS	***35.0***	**-3.9 *****	**-3.4 *****	**-0.7 ***	**75**	**-5.4 *****	**-4.5 *****	**-1.3 ****	**33**	**-1.4 *****	**-1.6 *****	**0.1 n.s.**	**28**	**-7.4 *****	**-5.9 *****	**-1.5 n.s.**	**14**
Oil crops	13.4	-8.4 ***	-5.7 ***	-1 n.s.	75	-8.2 ***	-7.6 ***	-1.9 n.s.	33	-5.5 n.s.	-2.9 n.s.	1.7 n.s.	28	-13 ***	-6 *	-3.1 n.s.	14
Olives	5.5	-6.2 **	-3.6 n.s.	-2.4 ***	39	-13.2 **	-11.3 *	-2.8 ***	12	-3 n.s.	-0.2 n.s.	-2.3 ***	27				
Vegetables	4.5	-3.5 ***	-3.9 ***	0 n.s.	75	-4.1 ***	-3.5 ***	-0.9 n.s.	33	-1.3 ***	-2.6 ***	0.5 n.s.	28	-7.7 ***	-8.4 ***	1.1 n.s.	14
Grapes	3.7	-0.3 n.s.	-0.2 n.s.	-0.2 n.s.	71	-0.9 n.s.	-0.4 n.s.	-0.7 n.n.	32	-1.6 n.s.	-1.8 n.s.	0.3 n.s.	28	4.7 n.s.	4.5 n.s.	0.1 n.n.	11
Roots & tubers	2.3	-4.5 ***	-4.8 ***	0.1 n.s.	75	-11 ***	-11.1 ***	0.8 n.s.	33	2.4 n.s.	1.3 *	0.2 n.s.	28	-10.6 ***	-9.2 ***	-2.4 *	14
Sugar	1.7	-8.8 ***	-8.2 ***	-1 n.s.	69	-14.2 ***	-11.8 ***	-3.4 ***	32	-2.5 n.s.	-3.4 ***	1.9 n.s.	23	-11.6 ***	-11.4 ***	-2.5 n.s.	14
Orchards	1.6	0.9 n.s.	-0.6 n.s.	0.8 n.s.	74	-3.8 ***	-1.8 n.s.	-2.2 ***	33	0.9 n.s.	-1.1 n.s.	2.1 ***	28	15.1 n.n.	5.5 **	4.9 ***	13
Treenuts	1.1	-1 n.s.	-0.4 n.s.	-1.1 n.s.	62	-4.2 *	-2.8 *	-2.1 n.s.	26	0.6 n.s.	1.8 n.s.	-1.8 **	28	1.8 n.s.	-7.5 ***	9.8 ***	8
Citrus	0.6	-5.1 ***	-3.4 ***	-2.6 ***	39	-11.4 ***	-8.7 ***	-3.1 n.s.	11	-3.2 **	-1.7 n.s.	-2.4 ***	28				
Soft fruits	0.4	-6.9 ***	-4 ***	-3 ***	74	-5.3 ***	-4.9 ***	0.2 n.s.	33	-4.2 n.n.	-2.9 ***	-2.1 *	28	-14.2 ***	-4.2 ***	-10.5 ***	13
Other crops	0.2	-8.2 ***	-3.1 **	-5.5 ***	74	-5.5 n.n.	-4.4 **	-3.5 **	32	-4 n.n.	0.9 n.s.	-2.8 n.n.	28	-21.2 ***	-8.7 ***	-14.6 ***	14

This study highlights that droughts and heatwaves are particularly harmful for cereal production, with a loss twice as high as for non-cereal crops, especially in Mediterranean and Eastern European countries, but also in Central Europe with similar relative losses in both crop categories. Production losses of wheat in Central and Eastern Europe, as well as of barley in the Mediterranean region, are largely associated to yield declines but also to a reduction in harvested area, which is an indicator for partial crop failure (Iizumi and Ramankutty 2015). On the other hand, barley production in Cfb is associate to yield declines but also to an increase in the harvested area, suggesting that farmers may have offset production losses by expanding the harvested area. This is an observed behaviour incentivised by crop insurances and governmental subsidies (Iizumi and Ramankutty 2015).

Cereals are especially relevant in terms of caloric food consumption (providing > 60% of the energy intake (FAO 1997)), but also for providing feed to maintain the livestock sector. In 2014, the EU represented 13% of global cereal production (Knox *et al* 2016), contributing 24% of global cereal exports (FAO 2019a) (mainly originated from Dfb and Cfb climate zones, while countries in the Csa climate zone only produce 81% of their cereal demand resulting in a net import of cereals (FAO 2019a)). The EU contributes for example almost 50% of the global sugar production (Knox *et al* 2016), 70% of the world olive oil exports (International Olive Council 2018), but also to nearly 50% of the world's wine (Wine Institute 2017). The size and trend of extreme event impacts on both cereal and non-cereal production is of concern as it can cause ripple effects in the global food trade system and affect food prices and food availability worldwide (e.g. Puma *et al*.(2015), Jägermeyr *et al*.(2020)). Such cascading effects are particularly relevant in already food insecure regions.

Future projections suggest an increase in summer dryness in most parts of Europe, with longer and more intense heatwaves and droughts (EASAC 2013, IPCC 2012, Christidis *et al* 2015). Especially the Mediterranean region is likely to experience severe multi-year droughts (Guerreiro *et al* 2017). The historical agricultural losses associated to EWD illustrated in this study, especially for droughts, are therefore expected to further increase in the future.

4.5 Conclusion

Agricultural impacts associated with droughts, heatwaves, floods, and cold waves are not well understood across larger spatial scales, especially in view of potential adverse trends due to climate change. Here, we use a superposed epoch analysis to estimate average per-disaster crop losses across Europe due to reported extreme weather disasters from 1964-2015. While the frequency of all four event types significantly increases over time, our results suggest that the average crop production impact of droughts and heatwaves has tripled over the last fifty years. Even though using a weather disaster record for crop impact analyses has limitations, it offers a unique and standardized metric indicating that climate change is already driving increasing crop losses in observational records. Our study contributes to the discussion of strategies and priorities in view of improving food system resilience.

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5 General discussion and conclusions

5.1 Key contributions

The research carried out in this dissertation brought the attention to the needs of better quantifying and assessing the impacts from extreme weather disasters (EWD) on food production, and for the implications they may represent to the EU food import dependencies. EWD can significantly exacerbate annual variability in crop yields, and, consequently, the fluctuations in food availability and in food prices (Jägermeyr and Frieler, 2018; Lesk et al., 2016; Nelson et al., 2014; Ray et al., 2015; Vogel et al., 2019). Therefore, by means of the interconnections of the world food system, these events have the potential to immediately, or indirectly, threaten local to global food security (Puma *et al*., 2015; Rosenzweig *et al*., 2001). The challenges for agriculture are associated to changes in the long-term average climate, and also to the occurrence of EWD, which are usually more impactful and generally more uncertain. However, there are major data gaps of the extent that EWD impact agriculture (FAO, 2015), as national and international disaster loss databases rarely report damage or losses in the sector. In particular, there is still little quantitative evidence of increasing trends in crop losses associated to disasters, and also on its implications to food trade (Lesk *et al*., 2016; Puma *et al*., 2015).

The European Union with 28 Member States (EU) is a major player in the global food market, and also a world leader in the fight against climate change (Bas-Defossez et al., 2018; Berkhout et al., 2018; Ciscar et al., 2018; Tai et al., 2014). Thus, the way the EU addresses the challenges of agriculture, sustainability and healthy diets has implications at the global level. My motivation with this dissertation is to slightly contribute for such discussion, while advancing the knowledge on the impacts of EWD in the EU food system. Specifically, this dissertation contributes to answering the following research questions: (1) What is the exposure of the EU food imports to extreme weather disasters?; (2) What are the impacts of extreme weather disasters in the EU food production?, and (3) What are the trends on EU crop losses during extreme weather disasters years?

We took advantage of records of EWD – droughts, heatwaves, floods, and cold waves – provided by EM-DAT (2018), which is the most comprehensive global database of natural and technological disasters occurred from 1900 to present (Lesk et al., 2016; Park et al., 2019). Records of EWD were combined with observational agricultural (FAO, 2017) and trade data (only in Chapter 3) (EUROSTAT, 2017), between 1961 and 2018 (2016 in Chapter 3). Through the use of time series statistical analysis based on superposed epoch analysis (SEA), we estimated the impact of EWD on the average production, yield, and harvested area of selected staple and cash crops. The SEA was implemented to estimate the impacts of EWD in agriculture across Non-EU suppliers, and to estimate the exposure of EU agri-food imports to EWD impacts based on the import share per supplier country (in Chapter 3). Also, the SEA was implemented at the EU level and per bioclimatic region to estimate the EWD responses in multiple crop categories (in Chapter 4). At the EU level, we also evaluated the trend across crop production anomalies over time, per disaster type.

Several innovative scientific contributions were achieved with this dissertation (Table 5.1):

1. Statistically significant losses due to historical droughts and heatwaves (soybeans, tropical fruits, and cocoa), floods (soybeans and tropical fruits) and cold waves (banana production) were estimated in countries from which EU has a reasonable import share;
2. Despite a diversified external market, the EWD crop losses in Non-EU suppliers represent a substantial and negative exposure to EU food imports. Production losses of soybeans, tropical fruits, and cocoa associated to droughts and heatwaves but also floods, lead to an overall decline, up to 16%, in the EU import-weighted share of each crop;
3. At the EU level, on average, droughts reduced European cereal yields by 9%, and heatwaves by 7%;
4. Major losses are found for cereals, but also vegetables and oil crops in the Eastern countries, while smaller losses are estimated in Southern but also Central European countries;
5. The severity of aggregated heatwave and drought impacts on crop production roughly tripled over the last 50 years, from -2 (1964-1990) to -7% (1991-2015);
6. Results suggest that droughts are significantly becoming more severe over time as, in every new year with a drought, the EU cereal production losses increase by 3%;
7. Results indicate an annual increase in event frequency on droughts (1%), heatwaves (6%), floods (29%), and cold waves (10%), in Europe;
8. Even though using weather disaster records as a metric for extreme weather event impact analysis has limitations, it offers a unique and standardized approach suggesting that, at the EU level, climate change is already driving increasing crop losses in observational records.

In particular, the following outcomes are provided to each Research Question and are consolidated in Table 5.1, along with the main methodological limitations.

RQ#1: What is the exposure of the EU food imports to extreme weather disasters?

The published paper Brás *et al*. (2019) (in Chapter 3) highlights the EWD impacts on the EU largest import commodities – soybean, banana, tropical fruits, cocoa, and coffee – grown in Non-EU food suppliers, and presents the larger implications of such impacts through trade dependencies based on the import share per supplier (Fig. 5.1). It includes staple crops – which are relevant for caloric consumption in the EU – but also cash crops, most of them not grown in the region itself due to its natural conditions. More than 90% of the EU consumption of those crops is produced in 41 Non-EU countries. We found that, despite a diversified external market, the EWD impacts on crops grown in Non-EU suppliers represent a substantial and negative exposure to EU food imports. Specially droughts and heatwaves lead to a decline in EU import-weighted shares for soybeans, tropical fruits, and cocoa, but also floods for soybeans and tropical fruits. For example, cocoa production is substantially affected by droughts and heatwaves (-5%), with import share-weighted impact of -7%. Such impact difference means that major losses took place in exporting countries from where EU has a higher import dependency. Since the EU completely relies on cocoa imports to satisfy its consumption, such weighted loss in cocoa production may have consequences to market speculations and may result in economic volatility.

Regarding soybeans – that in the EU is mostly used for animal feed (EU, 2018) – overall production losses from droughts and heatwaves, and floods of -11% across Non-EU exporters, represent a total EU import share-weighted impact of -9%. This means that major relative losses took place in exporting countries from where EU has a lower import dependency. Nevertheless, such impact may imply a potential decrease on the crop availability in the EU market. Since soybean is a common substitute of wheat and maize, any fluctuation on its production, and consequently on its prices, may influence the demand and supply chain of other commodities as well (Ercin *et al*., 2016). We argue that production anomalies of these crops can potentially reduce caloric availability to some extent in the EU but are not expected to fundamentally impair EU food supply. Import-induced market volatility and resulting market speculations, however, can lead to price spikes in the EU and this can have significant adverse effects on food access (see section 5.2 for further discussion).

RQ#2: What are the impacts of extreme weather disasters in the EU food production?, and *RQ#3: What are the trends on EU crop losses during extreme weather disasters years?*

While the answer to RQ#2 quantifies the impact (e.g. degree of change) in crop responses due to EWD, the answer to RQ#3 evaluates the trend of such impacts over time.

A key outcome of Chapter 4 refers that European crop losses tripled over the last five decades (from -2.2 (1964-1990) to -7.3% (1991-2015)) due to aggregated droughts and heatwaves. At the European level, major averaged production losses, associated to such events, are found for cereals, but also for sugar, oil crops, and olives (Fig. 5.2a). In a regional assessment (Fig. 5.2b) we found that higher crop losses associated to droughts and heatwaves are estimated in Eastern Europe, while smaller losses are found in Mediterranean and Central European countries. The geographic difference in EWD impacts can be possibly explained by the share of cropping area under irrigation. It can largely mitigate adverse impacts from droughts and heatwaves by cooling surface temperatures and through maintaining increased soil moisture requirements (Jägermeyr and Frieler, 2018; Leng, 2017; Leng and Hall, 2019; Troy *et al*., 2015; Vogel *et al*., 2019). In general terms, the area under irrigation could be expanded in Europe as a measure to alleviate exposure to droughts and heatwaves, but substantial investments would be required (Elliott *et al*., 2014). It would correspondingly impact water resources availability and energy consumption for crop irrigation (Daccache *et al*., 2014; Fader *et al*., 2016). This might have an impact in the cost of crop production and on food prices. Additionally, if this additional energy is to be provided by fossil fuels, irrigation demand will also correspond to a rise of greehouse gas emissions (GHG), which is not aligned with EU climate goals. Notably, the evaluation of the irrigation potential must be guided by water sustainability standards such as the *European Water Framework Directive* (European Comission, 2000; Iglesias and Garrote, 2015). Specific measures, such as traditional and sustainable water management practices like conservation tillage, organic mulching, and water harvesting for supplemental irrigation during dry spells, as well as, using drought and heat tolerant crop varieties, are shown to offer large and synergistic opportunities to buffer impacts of extreme weather in both rainfed and irrigated systems (Iglesias and Garrote, 2015; Islam et al., 2016; Jägermeyr, 2020; Jägermeyr et al., 2016; Rosa et al., 2018; Rost et al., 2009).

Most importantly, and especially for droughts, we found an increasing trend on the annual cereal production losses: on average, in every new year with a drought, EU cereal production losses increase by 3%, thus suggesting that these events are becoming more severe. Even though we used records of disaster events as a standardized metric for extreme weather event impact analysis (which has limitations listed in Table 5.1), our results suggest that climate change is already driving increased crop losses in observational records.

At the EU level, results indicate an annual increase in event frequency on droughts (1%), heatwaves (6%), floods (29%), and cold waves (10%), which is in line with the recently published report of the United Nations Office for Disaster Risk Reduction (UNDRR) (2020) showing a sharp increase in worldwide EWD over the last 20 years. The increase in the events frequencies may partially be explained by better recording and reporting, yet much of it is attributed to a significant rise in the number of climate-related disasters (UNDRR/CRED, 2020). In view of future projections in summer dryness in most parts of Europe, with longer and more intense heatwaves and droughts (IPCC, 2019), agricultural losses as estimated in this study may increase in the future.

With this dissertation, we found that specially droughts and heatwaves, have potential to negatively impact the EU food imports, namely for crops not grown in the EU (such as cocoa and tropical fruits), but also staple crops such as soybean and for which EU only produces about 10% of its consumption. At the EU level, and across its bioclimatic regions, significant averaged production losses, particularly from droughts and heatwaves, are estimated for staple crops such as cereals and vegetables. These are the food commodities with the highest production by weight (FAO, 2019a) accounting for nearly 30% of the total EU food exports. In the EU more than 60% of the cereals consumed are used for animal feed and nearly 30% are used for human consumption. Thus, a decline in soybean and cereals availability is particularly relevant because more than 60% of the calories in the human diet is highly dependent on these crops (i.e. wheat, maize, soybeans, and also rice), and their consumption is increasing with the growing demand for animal protein-based diets. More than 50% of EU citizens are overweight, 5% are at risk of undernutrition and around 8% live in food poverty (Bas-Defossez et al., 2018). Thus, to some extent, potential losses in the availability of staple crops can contribute to food insecurity, especially for the most vulnerable groups, potentially exacerbating social unrest. Potential actions to overcome such challenges are addressed in section 5.2.

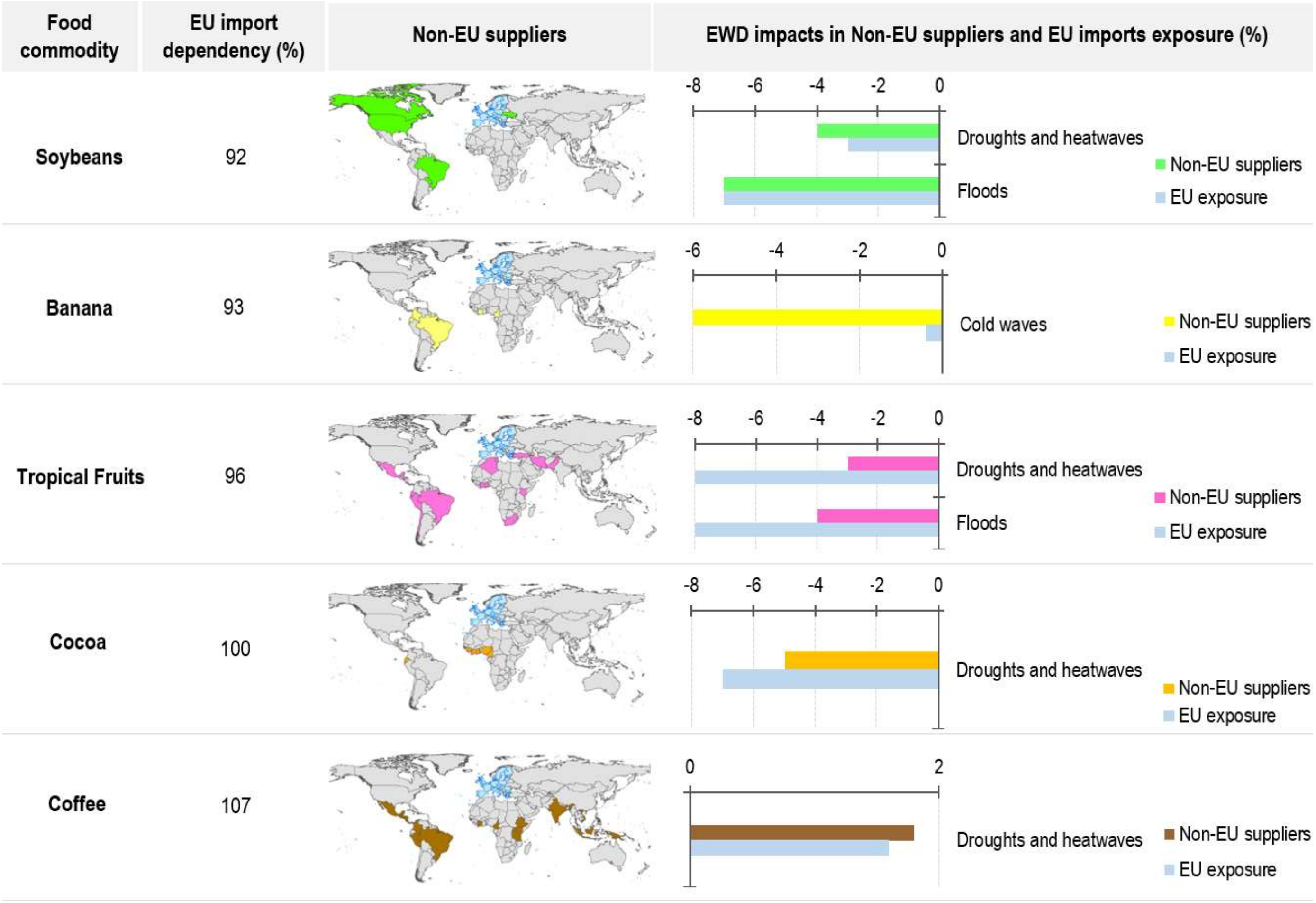

Figure 5.1 Potential exposure of EU food imports to EWD in Non-EU suppliers.

For each food commodity and EWD type (i.e. droughts and heatwaves, floods and cold waves), it is indicated the EU import dependency (%) (2nd column), the spatial location of Non-EU suppliers (3rd column), and the percentage of change in crop production in Non-EU suppliers and in the EU imports (4th column). Results consider the EWD reported in EM-DAT (2018) from 1964 to 2013, and are shown only for crop production anomalies, across Non-EU suppliers, with significance levels above 0.10 (see Chapter 3 for details).

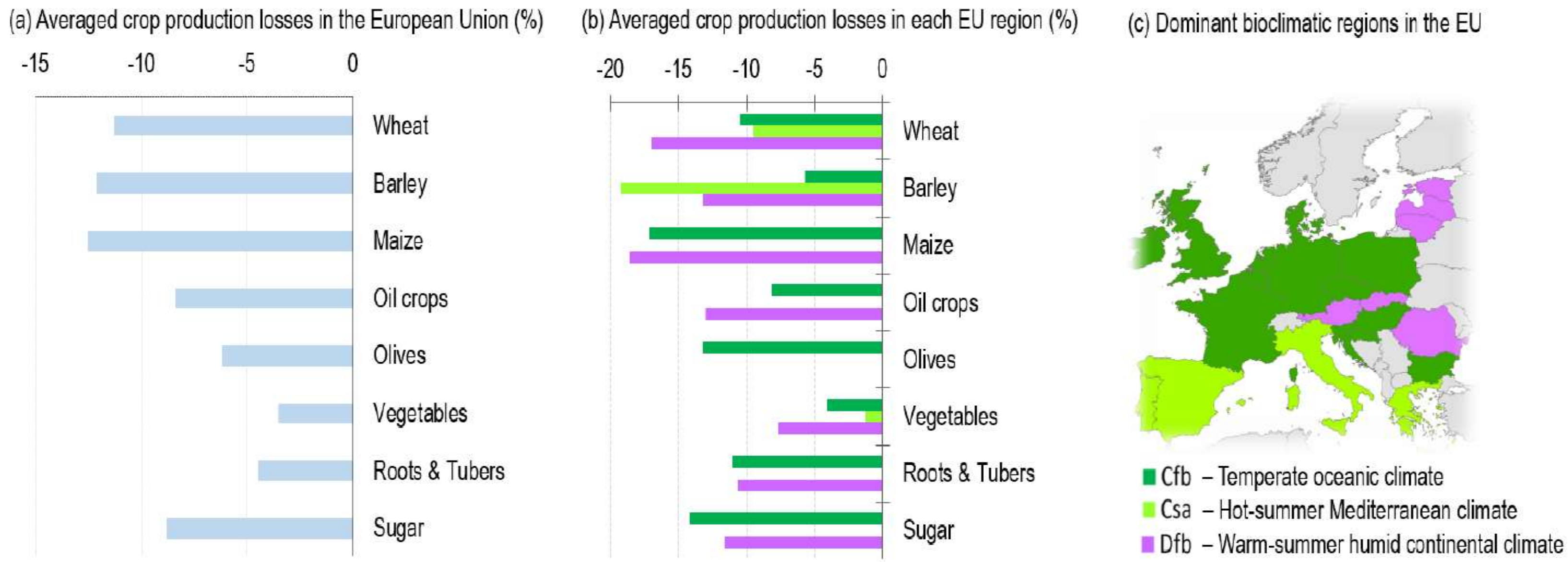

Figure 5.2 Drought and heatwaves impacts on crop production in the EU and in its bioclimatic regions.
Averaged impacts on crop production (%) from droughts and heatwaves, reported in EM-DAT (2018) from 1964-2015, are indicated for the EU (a), and per bioclimatic region (b). Bioclimatic regions are according to Koeppen-Geiger (KG) (Kottek *et al*., 2006) classification (c): Temperate oceanic climate (Cfb, dark green), Hot-summer Mediterranean climate (Csa, light green), Warm-summer humid continental climate (Dfb, purple)). Results are shown only for the production anomalies with significance levels above 0.10 (see Chapter 4 for details).

Context Question#: What are the current and future hotspots of climate change impacts on food production?

Even though we cannot picture the potential future EWD impacts on the four main produced crops – wheat, maize, soybeans, and rice –, we expect that their production is compromised under a future average climate, in the EU and worldwide (Fig. 5.3). The literature review carried out in Chapter 2 highlights that, by 2050, under the higher emission climate scenario, and even considering crop adaptation in few countries, the global breadbaskets – USA, China, Europe, Southern Asia, and Southern America – may see a decline in crop production, from -5% to -55%. This will come with harmful consequences on the worldwide food supply and on its prices through the interconnections of the global food market. Particularly, the European wheat and maize production may decline by 12 and 40%, respectively. The EU may then be forced to import these crops from other regions to satisfy its current levels of grain consumption. But world regions growing crops that EU highly imports, may also see their production decline.

For example, the EU has an import dependency of 60% of the soybean grown in southern America, where future production losses are estimated in 25% (Fig. 5.3). Southern and southeast Asia may have declines up to 55% on rice production, a region that currently satisfies 20% of the EU consumption. Nearly 29% of the soybean consumed in the EU is grown in the USA and Canada, and where average losses up to 10% are projected by 2050. Few positive changes on crop responses may occur if adaptation measures and the effect of CO_2 fertilisation are considered. In fact, other countries or regions may see their crop production increase (see section 2.2). Still, while few aspects of climate change may bring localized benefits for agriculture, the impacts from EWD may offset those gains.

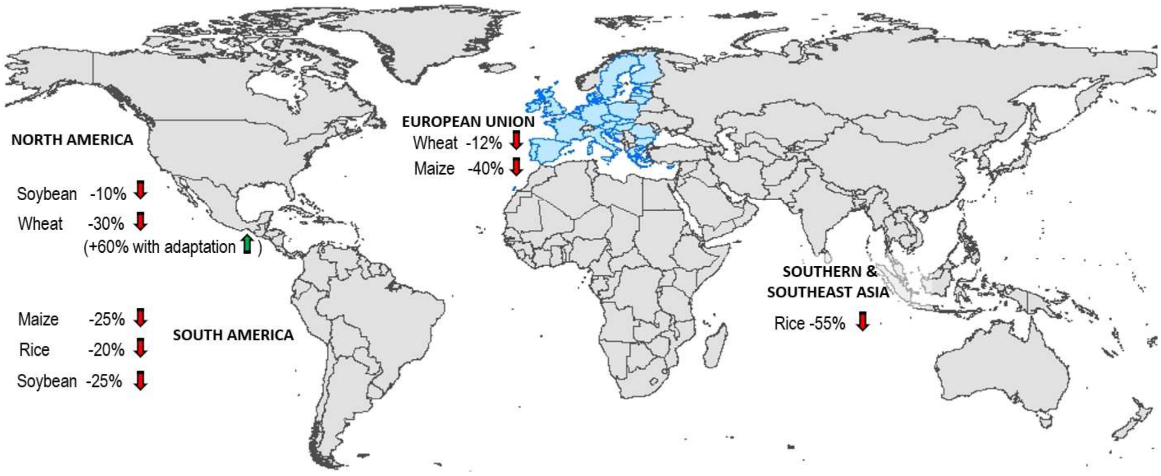

Figure 5.3 Projected climate change impacts on crop production by 2050 under RCP8.5.
Results are shown only for crops currently grown in the EU and on regions from where EU is mostly dependent (see Fig. 3.1 in Chapter 3). The projected climate change impacts are based in Figure 2.2 in Chapter 2.

Table 5.1 Revisiting the research design including the main findings to the research questions.

General goal	To contribute to a better understanding of the effects of extreme weather disasters on food production and on its implications through trade dependences, while taking advantage of observational records.		
	Chapter #2	**Chapter #3**	**Chapter #4**
Title	*Review on the climate change impacts on food availability and access*	*Exposure of the EU food imports to extreme weather disasters in exporting countries*	*Drought and heatwave crop losses tripled over the last five decades in Europe*
Research question	What are the current and future hotspots of climate change impacts on food production? (context question)	**RQ#1:** What is the exposure of the EU food imports to extreme weather disasters?	**RQ#2:** What are the impacts of extreme weather disasters in the EU food production? **RQ#3:** What are the trends on EU crop losses during extreme weather disasters years?
Methods	Systematic literature review of scientific literature.	Time series statistical analysis based on superposed epoch analysis (SEA). EU import exposure based on the import share per supplier.	Time series statistical analysis based on SEA and normalised anomalies trends.
Main findings	• In a medium-term future, under the higher emission scenarios and even with crop adaptation, global breadbaskets may see a decline on crop production. • Specifically, EU may see its wheat and maize production decline by 12 and 40% correspondingly.	• Droughts and heatwaves caused production losses to soybeans (4%), tropical fruits (3%), and cocoa (5%) with import weighted impacts of 3, 8, and 7%, respectively. • Floods caused weighted impacts of 7% (soybeans) and 8% (tropical fruits). • Cold waves negatively impacted banana production but those events took place in countries which together represent only 3% of the EU import share of that crop. • Coffee production shows gains during cold waves, but the inter-annual variability offsets these effects.	• The severity of aggregated heatwave and drought impacts on EU crop production roughly tripled over the last 50 years • Droughts are leading to cereal production losses by more than 3% per year. • Frequencies of droughts, heatwaves, floods, and cold waves significantly increased over time in the EU. • Using a weather disaster record for crop impact analyses offers a unique and standardized metric indicating that climate change is already driving increasing crop losses in observational records.
Methodological limitations	• This study would benefit from more studies assessing climate change impacts in access dimension, and from studies oriented to the nutrition value of food consumption.	1. The effect of EWD can be much stronger locally, especially in large countries where only part of the cultivated area is being affected. 2. Not all the weather events with impact on agriculture are reported or classified as natural disasters recorded in EM-DAT, as information on the effects of local extreme events are tracked in local statistics only. Thus, the number of events will be higher than the associated EWD reported. 3. No weights were attributed to the magnitude and duration of EWD as there is no such data available, meaning that we treated all events listed in the same way. Moreover, since we aggregated data for each crop from many countries, it could result in the attenuation of the impact of those events, i.e., losses in one country could be offset by gains among the others. 4. The EWD were not selected based on the crop growth stage, agricultural systems, and we did not consider the type of crops varieties in each country (i.e., if tolerant or not to a type of an EWD) as there is no such data available.	

5.2 Contributions at the policy level

With the expectation of EWD becoming more frequent and intense in the future (IPCC, 2019), the results achieved by this dissertation raise questions and possibilities – on supply and consumption sides of the food system. A set of plausible future actions, under climate-proof food policies, may potentially contribute to better deal with the exposure to EWD, not only in the EU but worldwide. Even though this dissertation does not directly contribute to the United Nations Sustainable Development Goals (SDG) 2 and 12 – Zero Hunger, and Responsible Consumption and Production –, the bellow discussed contributions at the policy level have potential to tackle SDG targets.

Contribution#1: Diversification of EU external market while "exporting" resilience to Non-EU exporting countries

Food and trade policies may be re-designed in view of a higher investment in EU food imports. To secure imports of cocoa, tropical fruits, and soybeans, but also other food commodities whose production in the EU has been significantly affected from EWD, the EU could diversify even more its external market. Concurrently, the EU can assist on adaptation schemes in exporting countries, for example by establishing partnerships for research and innovation in crop tolerance to extreme weathers, and by supporting the definition and implementation of disaster risk reduction and management actions, while also supporting the implementation of fair and ethical food policies. This would also be helpful to promote the stability on the production of such crops and, consequently, the stability of incomes in exporting countries, contributing for local food security.

Contribution#2: EU as a key player in dietary shift

Another line of action refers to the relation between crop production and the dietary patterns. The world grows about 2.5 times more cereals, and overproduces fats and sugars, while production of fruits and vegetables is about 20% of what would be needed (according to USA dietary guidelines) (Benton, 2019). The food system thus supplies excessive calories by means of standardised diets, whose major ingredients (i.e. wheat, maize, rice, and soybean) are grown in monocultures and in geographically concentrated. This implies that agricultural systems are less resilient to temporal fluctuations in climate and that the world's capacity in coping with geographical risk is limited.

As an alternative, if we produce and consume more fruits and vegetables – while choosing less water intensive crops – as well as, move our diets to plant-based protein, worldwide it would be feasible to eat a nutritionally balanced diet, while reducing pressure on land, and also reduce GHG emissions (Benton, 2019; KC *et al.*, 2018). This would also potentially reduce monocultures and increase agricultural resilience to climate variability, including EWD. In the EU, vegetables occupy about 4.5% of the total cropping area, whereas cereals 65% (Fig.C1a). By reducing grain production for livestock feed – and even though by 2050 the EU population may decrease 1.3% (EUROSTAT, 2020) – such measures could contribute to alleviate the pressure on natural resources from a growing world population.

Another action to reduce the cropping area used for cereals production, highlighted by Santos (2010) is taxing, at the global level, cereals used in animal feed. If such tax is implemented at a sufficiently high rate, it would turn meat sufficiently expensive that the wealthier moderate their consumption, and simultaneously, would make cereals cheaper for food.

An additional and complement line of action in view an increase in vegetables production, while reducing the direct EWD impacts on crops, is a greater focus on urban agriculture for high-value, nutritious crops grown in the urban environment and peri urban fringe, in line with the Milan Urban Food Policy Pact (Edmondson *et al.*, 2020; 2015).

To support such actions, EU agricultural policies could be more driven by nutritional needs and not by economic growth considerations. Governments could also promote preventive healthcare, so people consume less fats, sugar and grains (by means of animal protein), which would thus reduce pressure on natural resources (Benton, 2019).

5.3 Final remarks and future research

This dissertation identifies the effects of droughts, heatwaves, floods, and cold waves in the EU food availability, in terms of its food import dependency and own crop production, while expanding the analysis to different crops and geographical regions. The results achieved are a flagship for policymakers, and food-related stakeholders, to potential develop adaptation and disaster risk management interventions relevant to agricultural and trade policies. In view of such potential contribution, a number of conceptual improvements shall be implemented to this research, and further research shall be explored:

1. From a conceptual point of view, the research carried out in this dissertation would benefit if it includes an econometric analysis, as well as, all crop categories imported by the EU, and additional categories of EWD. An assessment of crop prices variability, during EWD years, would support the identification of potential price spikes and also impacts-induced market volatility (i.e. in the EU and in Non-EU supplier countries). In addition, to provide information that supports an economic decision – i.e. weather if, due to EWD impacts on crop production the EU shall invest on imports or, rather, on own production –, the assessment has to include all crops that are grown in the EU but also the ones imported, and preferably, expanded by bioclimatic region. Moreover, the analysis could be extended to other types of EWD such as storms, that are becoming more frequent, but perhaps not hail due to its very localized nature. Future research could take advantage of data on EWD that occur in a medium to local scale. It could also be improved if benefited from a detailed georeferenced information on the agro-climatic zones from crop growing regions and on the major agricultural systems (see additional methodological limitations in Table 5.1).

2. To better contribute to specific crop adaptation actions, it would be useful to identify and assess the main climate drivers of EWD, in particular droughts and heatwaves. The degree of change in temperature,

precipitation, or in the aridity index, during droughts and heatwaves, would allow, for example, to identify if such events are becoming hotter and drier. Such assessment would also allow to identify which European regions are becoming more arid. This work is currently under preparation and is foreseen to be submitted to a peer review journal in April 2021.

3. Droughts and heatwaves lead to an increase on crops' evapotranspiration and, thus, to higher irrigation requirements. It is not, however, yet quantified to what degree irrigation can compensate or alleviate drought and heatwave impacts in the EU agriculture. To answer this question, one could take advantage from EWD records combined with gridded crop data simulated by crop-based models. This work is currently being developed by using crop yield and potential irrigation water withdrawals datasets, provided by the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP).

4. Any increase in irrigation demand will affect energy consumption since energy is required to withdrawal water and to distribute it for crop irrigation. Thus, one may ask how much energy is needed for crop irrigation during droughts and heatwaves. The Food and Agriculture Organization from the United Nations makes available annual records of the energy used in crop irrigation, at the country level (FAO, 2019b). However, those records are only reported per country, on every five or 10 years, and are repeated until the next reporting. Thus, such data lacks variability, in addition to missing records from a significant number of countries. The energy demand for crop irrigation has therefore to be modelled. One possible approach is to follow an already published methodology developed for the Mediterranean region (Daccache *et al.*, 2014), while taking advantage of more recent datasets (i.e. historical crop yield and irrigation water withdrawals, as well as, the share of irrigation system and its efficiency per system and crop type, the global shares of irrigation water sources, and the global data set of water table depth).

5. Finally, two very important open questions: (1) How EWD will potentially impact European crop yields in the future?, and (2) How much water and energy may be invested to attenuate such impact? Answering to these questions implies an understanding of the explanatory power of predictors – i.e. climate variables (e.g. temperature and precipitation) and energy demand – to crop yield anomalies. Evaluating the link of EWD with statistical meteorological definitions will also enable a forecasting of future impacts under climate change scenarios (Lesk et al., 2016). One could also take advantage of a selected number of remote sensing vegetation indexes used for crop yield predictions (such as (Burke and Lobell, 2017; Panda *et al.*, 2020)). Quantifying crop anomalies, and understanding their climate drivers is a prerequisite to assess vulnerabilities and design adaptation measures and corresponding costs – for example through an investment in irrigation - to increase the resilience of food systems.

5.4 Outputs

This section includes a list of the main outputs of this work.

Peer-reviewed publications

The first author of the papers was the leading responsible for the development of the investigation, that was supported by the co-authors, mainly regarding the design of the research, discussion of the results and revision of the manuscripts.

1. Brás, T.A., Seixas, J. Review on the climate change impacts on food availability and access. *Under Review* in *Global and Planetary Change*
2. Brás, T.A., Jägermeyr, J., Seixas, J., 2019. Exposure of the EU-28 food imports to extreme weather disasters in exporting countries. *Food Security*. https://doi.org/10.1007/s12571-019-00975-2
3. Brás, T.A., Seixas, J., Carvalhais, N., Jägermeyr, J., Drought and heatwave crop losses tripled over the last five decades in Europe. *Under Review* in *Environmental Research Letters*

Presentations in scientific conferences, workshops, and projects

- Oral Communication, Brás, T.A.; Seixas J.; Assessing the impact of climate extremes and energy use in crop production – EU28 agri-food suppliers, 18-20 Sep.. Fifth Annual International Conference on Sustainable Development., New York, USA, Columbia University, 2017
- Oral Communication, Brás, T.A.; Jägermeyr, J.; Carvalhais N.; Seixas, J.; How extreme weather disasters affect Food Security - Seeking an Integrated Approach with EO, AIR Centre Workshop on Discovering Exploratory EO Use-Cases in the Atlantic, December at TERINOV, Terceira Island, Azores, Portugal, 2019
- Project participation: ERA4CS Joint Call on Researching and Advancing Climate Services Development project entitled "CLIM2POWER - Translating climate data into power plants operational guidance". My participation included the estimation of future irrigation water demand in Europe and in the larger Portuguese and Spanish watersheds, by considering the representative concentration pathways (RCP) 8.5, and by taking advantage of the ISIMIP global data set on potential irrigation water withdrawals.
- Project participation: EU Climate KIC Pioneers programme, in Bulgaria during October-November 2018. Under this project, I selected Bulgaria as a case study to access historical irrigation water and energy

requirements. This project counted with the collaboration of the Faculty of Mathematics and Informatics, and the Faculty of Hydraulic Engineering at UACEG, in Sofia.

- European Space Agency Phi-Week Bootcamp 2019: Solving a Big Energy Challenge Using EO Data, Italy, December 2019, in which my team won the first prize.

- Short-term course: Climate KIC course on Earth observation - Big data for climate change, Poland, Warsaw, May 2019

- MATLAB course at Instituto Superior Técnico, Lisbon, 2016 and 2017

- ArcGIS online tutorials, 2018

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6 Appendix

6.1 Appendix A

Review on the climate change impacts on food availability and access

Table A1 Observed impacts of climate drivers on food availability indicators by crops and by region

Notes: Data is organised as follows: “Crop, Region: [location *(if appropriate)*, (time scale); Climate driver specification: impact specification] Literature reference”. “Region” includes: Naf – Northern Africa, SSA – Sub-Saharan Africa, WSSE – Western & Southern & Southeast Asia, CEA – Central & Eastern Asia, NCA – Northern & Central America, CSA – Caribbean & South America, EU – European Union, WSE - Western & Southern Europe, ENE – Eastern & Northern Europe. “Climate driver specification” refers to changes on P – precipitation, T – temperature, CO_2 – carbon dioxide, O_3 – ozone and Climate variability. “Impact specification” describes the impact of the climate driver on crop yield or production (green, red, or orange text indicates positive, negative or no impact, respectively). IT – Italy, PT – Portugal, ES – Spain, FR – France, NL – Netherlands, DE – Germany, GR – Greece, BE – Belgium, LU – Luxembourg, IE - Ireland.

AFRICA	EUROPE	ASIA	AMERICA	GLOBAL
Wheat; **Naf:** (1974-2008); **T & P**: **yield 12.0%** (Ray et al., 2019) Wheat; **SSA:** (1974-2008); **T & P**: **yield -2.3%** (Ray et al., 2019) Maize; **Naf:** (1974-2008); **T & P**: **yield -4.3%** (Ray et al., 2019) Maize; **SSA:** (1974-2008); **T & P**: **yield -5.8%** (Ray et al., 2019) Rice; **Naf:** (1974-2008); **T & P**: **yield -1.3%** (Ray et al., 2019) Rice; **SSA:** (1974-2008); **T & P**: **yield -3.1%** (Ray et al., 2019) Barley; **Naf:** (1974-2008); **T & P**: **yield -6.8%** (Ray et al., 2019) Barley; **SSA:** (1974-2008); **T & P**: **yield -0.6%** (Ray et al., 2019) Sorghum; **Naf:** (1974-2008); **T & P**: **yield 17.9%** (Ray et al., 2019)	Wheat; **EU:** [**O_3: yield -15% to -30%**] (Broberg, Feng, Xin, & Pleijel, 2015) Wheat; **EU:** [IT, LU, GR, BE, FR, ES, NL, PT, DE, UK, IE, (1989-2009); **T & P**: **yield** (median) **~-15%, -7%, -6%, -4%, -3%, -2.5%, -2.5%, -2%, 0%, +4%, +9%**] (Moore & Lobell, 2015) Wheat; **WSE:** (1974-2008); **T & P**: **yield -8.7%** (Ray et al., 2019) Wheat; **ENE:** (1974-2008); **T & P**: **yield -2.1%** (Ray et al., 2019) Maize; **EU:** [IT, PT, ES, FR, NL, DE, GR, BE (1989-2009); **T & P**: **yield** (median) **~-8%, -6%, -2.5%, +1%, +4%, +5%, +9%, +12%**] (Moore & Lobell, 2015)	Wheat; **CEA:** [China, (1961-2010), winter wheat; **Average T increase: production -5 to -8%; T range decrease: production -2 to -9%; P change**: contributes to **+1 to +6%** in production at national scale] (Chen, Zhou, & Zhou, 2014) Wheat; **CEA:** [China, (1980–2008); **T: yield +1.3%; P: yield -0.34%**] (Wei, Cherry, Glomrød, & Zhang, 2014) Wheat; **CEA:** [China ; **O3: yield -15% to -30%**] (Broberg et al., 2015) Wheat; **CEA:** (1974-2008); **T & P**: **yield 4.5%** (Ray et al., 2019) Wheat; **WSEA:** (1974-2008); **T & P**: **yield -0.9%** (Ray et al., 2019) Maize; **CEA:** [China, (1980–2008); **P: yield -0.14%**] (Wei et al., 2014)	Wheat; **NCA:** [**O3: yield -15% to -30%**] (Broberg et al., 2015) Wheat; **NCA:** [México; **T variability** (season-to-season T and radiation variability): influence on **yield inter-annual variability**] (Rosenzweig et al., 2014) Wheat; **NCA:** [México ; **CO_2 increase** [550 ppm]: **yield +19.6%** (±2.8%STD)] (Rosenzweig et al., 2014) Wheat; **NCA:** (1974-2008); **T & P**: **yield -1.3%** (Ray et al., 2019) Wheat; **CSA:** (1974-2008); **T & P**: **yield -1.6%** (Ray et al., 2019) Maize; **NCA:** (1974-2008); **T & P**: **yield 0.5%** (Ray et al., 2019)	Wheat; **Glob:** [(1979–2008); **Climate variability**: explained **production fluctuations** of **9 MT/y**] (Ray, Gerber, MacDonald, & West, 2015) Wheat; **Global:** [(1981–2010); **T increase** (warming)**: yield -6% per degree of warming** (with a 50% probability of between −4.2% and −8.2% loss)] (Asseng et al., 2015) Wheat; **Glob:** (1974-2008); **T & P**: **yield -0.9%** (Ray et al., 2019) Maize; **Glob:** [(1979–2009); **Climate variability**: explained **production fluctuations** of **22 MT/y**] (Ray et al., 2015)

AFRICA	EUROPE	ASIA	AMERICA	GLOBAL
Sorghum; **SSA:** (1974-2008); **T & P: yield 0.7%** (Ray et al., 2019) Soybean; **Naf:** (1974-2008); **T & P: yield 10.9%** (Ray et al., 2019) Soybean; **SSA:** (1974-2008); **T & P: yield -1.6%** (Ray et al., 2019) Rapeseed; **SSA:** (1974-2008); **T & P: yield 24.9%** (Ray et al., 2019) Oil palm; **SSA:** (1974-2008); **T & P: yield 0.0%** (Ray et al., 2019) Cassava; **Naf:** (1974-2008); **T & P: yield 18.0%** (Ray et al., 2019) Cassava; **SSA:** (1974-2008); **T & P: yield 1.7%** (Ray et al., 2019) Sugarcane; **Naf:** (1974-2008); **T & P: yield -5.1%** (Ray et al., 2019) Sugarcane; **SSA:** (1974-2008); **T & P: yield -3.9%** (Ray et al., 2019)	Maize; **WSE:** (1974-2008); **T & P: yield -6.3%** (Ray et al., 2019) Maize; **ENE:** (1974-2008); **T & P: yield -24.5%** (Ray et al., 2019) Rice; **WSE:** (1974-2008); **T & P: yield -3.2%** (Ray et al., 2019) Rice; **ENE:** (1974-2008); **T & P: yield -0.4%** (Ray et al., 2019) Barley; **EU:** [GR, IT, LU, BE, DE, FR, NL, PT, UK, IE, (1989-2009); **T & P: yield** (median) **~-8%, -6%, -5%, -5%, -4.5%, -2.5%, -2.5%, -2%, -2% ,-1%**] (Moore & Lobell, 2015) Barley; **ENE:** (1974-2008); **T & P: yield -9.1%** (Ray et al., 2019) Sorghum; **WSE:** (1974-2008); **T & P: yield -18.2%** (Ray et al., 2019) Sorghum; **ENE:** (1974-2008); **T & P: yield -9.5%** (Ray et al., 2019) Soybean; **WSE:** (1974-2008); **T & P: yield -21.2%** (Ray et al., 2019) Soybean; **ENE:** (1974-2008); **T & P: yield -3.8%** (Ray et al., 2019) Rapeseed; **WSE:** (1974-2008); **T & P: yield -11.4%** (Ray et al., 2019) Rapeseed; **ENE:** (1974-2008); **T & P: yield 3.1%** (Ray et al., 2019) Sugar beet; **EU:** [IT, GR, ES,NL, FR,BE,DE,UK (1989-2009); **T & P: yield ~-12.5%, -10%, 0%, +1%,+1.5%, +2.5%,+3%, +4%**] (Moore & Lobell, 2015) Sugarcane; **WSE:** (1974-2008); **T & P: yield 2.7%** (Ray et al., 2019)	Maize; **CEA:** [China, (1961-2010); **P: no significant** effect in production at a national scale] (Chen et al., 2014) Maize; **CEA:** [China (Liaoning province), (1961-2010), spring maize; **T increase** (climate warming): **production decreased**] (Zhao, Guo, Mu, & Xu, 2015) Maize; **CEA:** [China, (1961-2010); **Average T increase/ T range decrease**: **production -3 to -4%** at national scale / **production from 0 to +6%** at national scale (however reduced yield in the west and central regions)] (Chen et al., 2014) Maize; **CEA:** [China (Loess Plateau, north-western China), (1980s-2010); **T increase** (warming trend): **yield** potential averaged **-0.067 t ha−1 per year** (p < 0.01)] (Bu et al., 2015) Maize; **CEA:** [China, (1980–2008); **T: yield -12%**] (Wei et al., 2014) Maize; **CEA:** (1974-2008); **T & P: yield 5.1%** (Ray et al., 2019) Maize; **WSEA:** (1974-2008); **T & P: yield 1%** (Ray et al., 2019) Rice; **CEA:** [China, Yellow River Basin, (1961-2010); **T increase** (warming trend): shortened rice growth duration (0.15 - 0.27 day/y) and **yield decline (32.0- 49.3 kg/ha)**] (W. Wang et al., 2014) Rice; **CEA:** [north-east China, (1980s-1990s); **Minimum daily T increase: yield +3.6% /1◦C rise** during growing season] (Zhou, Li, Dong, & Wu, 2013) Rice; **CEA:** [southeast China, (2010–2014); **T increase: yield -4.8%** (J. Wang et al., 2016) Rice; **CEA:** [China, (1980–2008); **T: yield +0.4%**] (Wei et al., 2014)	Maize; **CSA:** (1974-2008); **T & P: yield 2.7%** (Ray et al., 2019) Rice; **NCA:** (1974-2008); **T & P: yield -0.1%** (Ray et al., 2019) Rice; **CSA:** (1974-2008); **T & P: yield -0.7%** (Ray et al., 2019) Barley; **NCA:** (1974-2008); **T & P: yield -2.5%** (Ray et al., 2019) Barley; **CSA:** (1974-2008); **T & P: yield 4.0%** (Ray et al., 2019) Sorghum; **NCA:** (1974-2008); **T & P: yield 4.3%** (Ray et al., 2019) Sorghum; **CSA:** (1974-2008); **T & P: yield 0.0%** (Ray et al., 2019) Soybean; **NCA:** (1974-2008); **T & P: yield 3.3%** (Ray et al., 2019) Soybean; **CSA:** (1974-2008); **T & P: yield 5.4%** (Ray et al., 2019) Rapeseed; **NCA:** (1974-2008); **T & P: yield -0.4%** (Ray et al., 2019) Rapeseed; **CSA:** (1974-2008); **T & P: yield 6.8%** (Ray et al., 2019) Oil palm; **NCA:** (1974-2008); **T & P: yield -7.2%** (Ray et al., 2019) Oil palm; **CSA:** (1974-2008); **T & P: yield -0.6%** (Ray et al., 2019) Sugarcane; **NCA:** (1974-2008); **T & P: yield 1.7%** (Ray et al., 2019) Sugarcane; **CSA:** (1974-2008); **T & P: yield 2.5%** (Ray et al., 2019) Cassava; **NCA:** (1974-2008); **T & P: yield -2.9%** (Ray et al., 2019) Cassava; **CSA:** (1974-2008); **T & P: yield 0.5%** (Ray et al., 2019) Coffee; **NCA:** [Central America, (2013 and 2014); **T range decrease**: averaged **production -16%** in 2013 (compared with 2011–12) and **-**	Rice; **Glob:** [(1979–2009); **Climate variability**: explained **production fluctuations** of **3 MT/y**] (Ray et al., 2015) Rice; **Glob:** (1974-2008); **T & P: yield -0.3%** (Ray et al., 2019) Barley; **Glob:** (1974-2008); **T & P: yield -7.9%** (Ray et al., 2019) Sorghum; **Glob:** (1974-2008); **T & P: yield 2.1%** (Ray et al., 2019) Soybean; **Glob:** [(1979–2009); **Climate variability**: explained soybean **production fluctuations** of **2 MT/y**] (Ray et al., 2015) Soybean; **Glob:** (1974-2008); **T & P: yield 3.5%** (Ray et al., 2019) Oil palm; **Glob:** (1974-2008); **T & P: yield -13.4%** (Ray et al., 2019) Rapeseed; **Glob:** (1974-2008); **T & P: yield 0.5%** (Ray et al., 2019) Cassava; **Glob:** (1974-2008); **T & P: yield -0.5%** (Ray et al., 2019) Sugarcane; **Glob:** (1974-2008); **T & P: yield 1.0%** (Ray et al., 2019)

AFRICA	EUROPE	ASIA	AMERICA	GLOBAL
		Rice; **CEA:** [China, (1980–2008); **P**: **yield ~0%**] (Wei et al., 2014) Rice; **CEA:** (1974-2008); **T & P**: **yield 0.9%** (Ray et al., 2019) Rice; **WSEA:** (1974-2008); **T & P**: **yield -0.8%** (Ray et al., 2019) Barley; **CEA:** (1974-2008); **T & P**: **yield 1.6%** (Ray et al., 2019) Barley; **WSEA:** (1974-2008); **T & P**: **yield -0.9%** (Ray et al., 2019) Sorghum; **CEA:** (1974-2008); **T & P**: **yield 4.9%** (Ray et al., 2019) Sorghum; **WSEA:** (1974-2008); **T & P**: **yield 0.9%** (Ray et al., 2019) Soybean; **CEA:** (1974-2008); **T & P**: **yield 0.2%** (Ray et al., 2019) Soybean; **WSEA:** (1974-2008); **T & P**: **yield -3.2%** (Ray et al., 2019) Rapeseed; **CEA:** (1974-2008); **T & P**: **yield 5.9%** (Ray et al., 2019) Rapeseed; **WSEA:** (1974-2008); **T & P**: **yield 1.9%** (Ray et al., 2019) Oil palm; **CEA:** (1974-2008); **T & P**: **yield -0.4%** (Ray et al., 2019) Oil palm; **WSEA:** (1974-2008); **T & P**: **yield -15.9%** (Ray et al., 2019) Sugarcane; **CEA:** (1974-2008); **T & P**: **yield 5.3%** (Ray et al., 2019) Sugarcane; **WSEA:** (1974-2008); **T & P**: **yield -0.6%** (Ray et al., 2019) Cassava; **CEA:** (1974-2008); **T & P**: **yield 1.2%** (Ray et al., 2019) Cassava; **WSEA:** (1974-2008); **T & P**: **yield -5.6%** (Ray et al., 2019)	**10%** in 2014 (compared with 2012–13)] (Avelino et al., 2015)	

Table A2 Future projected impacts of climate drivers on food availability indicators by crops and by region

Notes: Variations always refer to reference scenarios, which may differ from a study to another. Date is organised as follows: "Crop; Region: [food indicator; projection change; time scale; scenario; location; other *(when adequate)*] Literature reference". Food indicators (FI) are Y – Yield, P – Production, S - Suitable area and S_CD - Suitable area due crop disease. A projected change on FI is represented by (+) when the change is positive, (-) when it decreases and "cte" when there is no change. Three-time scales are considered: NF - near time future (with projections ranging from 2020s-2030s), MF - medium time future (from 2040s-2060s) and LF - longtime future (from 2070s-2100). IPCC Special Report Emissions Scenarios (SRES): A1, A1FI, A1T, A1B, A2, B1, B2; IPCC Representative Concentration Pathways (RCP): RCP2.6, RCP4.5, RCP6, RCP8.5; w CO_2 fert. or w/o CO_2 fert. - means with the effects of CO_2 fertilisation or without the effects of CO_2 fertilisation; w tech adaptation – by including technological adaptation measures; avg – average, CC – climate change, T –temperature; HCI – high climate index (high temperature increase, high sensitivity of crops to global warming, and a CO_2 fertilisation effect at the lower end of published estimates). "Region" includes: Naf – Northern Africa, SSA – Sub-Saharan Africa, WSSE – Western & Southern & Southeast Asia, CEA – Central & Eastern Asia, NCA – Northern & Central America, CSA – Caribbean & South America, EU – European Union, WSE - Western & Southern Europe, ENE – Eastern & Northern Europe.

FI	AFRICA	EUROPE	ASIA	AMERICA	GLOBAL
(+)	Maize; **SSA** [rainfed maize; P ; [5; 25]% ; MF ; avg[CSIRO (A1B, B1); MIROC(A1B, B1)]; South Africa] (Dube et al., 2013) Maize; **SSA** [Y ; (5.4; 4.6)% ; NF ; (RCP4.5, RCP8.5); Malawi] (Stevens & Madani, 2016) Maize; **SSA** [Y ; 8.9% ; MF ; RCP8.5; Guinea-Bissau] (Ahmed, Wang, Yu, Koo, & You, 2015) Maize; **SSA** [Y; 24%; MF; RCP8.5 w adapt. (drought tolerance)] (Islam et al., 2016) Maize; **SSA** [Y ; 84% ; MF ; (RCP4.5 & RCP8.5) w Nitrogen application; Ethiopia] (Kassie et al., 2015) Soybean; **SSA** [Y ; 20% ; MF ; avg[CSIRO (A1B, B1); MIROC(A1B, B1)]; South Africa] (Dube et al., 2013)	Wheat; **EU** [P ; ~5% ; MF ; RCP4.5 w O3 cont.] (Tai, Martin, & Heald, 2014) Wheat; **EU** [winter wheat; Y ; 0.2%/year ; (NF&MF) ; A1FI; Denmark] (Martín, Olesen, & Porter, 2014) Rice; **EU** [P ; ~7% ; MF ; RCP4.5 w O3 cont.] (Tai et al., 2014) Rice; **EU** [P ; ~12% ; MF ; RCP8.5 w O3 cont.] (Tai et al., 2014)	Wheat; **CEA** [P ; ~15% ; MF ; RCP4.5 w O3 cont.; China] (Tai et al., 2014) Wheat; **CEA** [Y ; (38, 19)% & (68, 23)% & (87, 34) % ; (NF) & (MF) & (LF) ; (A1FI w CO2 fert., A1FI w/o CO2 fert.); China] (Tao & Zhang, 2013) Wheat; **WSSE** [irrigated; P ; (2, 6)% ; MF ; (A1B, B1); Iran] (Emam, Kappas, & Hosseini, 2015) Maize; **CEA** [P ; ~5% ; MF ; RCP4.5 w O3 pollution; China] (Tai et al., 2014) Rice; **Asia** [Y ; ~[20, 26]% ; MF ; A2 w CO2 fert.] (Li et al., 2015) Soybean; **CEA** [P ; ~10% ; MF ; RCP4.5 w O3 pollution; China] (Tai et al., 2014) Potatoes; **Asia** [Y; ~[3;10]% ; MF ; RCP8.5 w adapt. (drought and heat tolerance)] (Islam et al., 2016)	Wheat; **NCA** [P ; 24% ; MF ; A1B; USA] (Dawson, Perryman, & Osborne, 2016) Wheat; **NCA** [P ; ~10% ; MF ; RCP4.5 w O3 cont.; USA] (Tai et al., 2014) Wheat; **NCA** [Y ; [20;60]% ; MF ; A2 w tech advances; USA] (Jiang & Koo, 2014) Rice; **NCA** [P ; ~5% ; MF ; RCP4.5 w O3 cont.; USA] (Tai et al., 2014) Rice; **NCA** [P ; ~2% ; MF ; RCP8.5 w O3 cont.; USA] (Tai et al., 2014)	Wheat; **Glob** [Y ; (9.8, 16.9)% & (9.0, 34.3)% ; (MF)&(LF) ; (RCP8.5, RCP2.6) w mean CC + extreme T around crop anthesis (HSA) + direct CO2 fert.] (Deryng, Conway, Ramankutty, Price, & Warren, 2014) Soybean; **Glob** [Y ; (9.5, 11.1)% & (7.1, 15.3)% ; (MF)&(LF) ; (RCP8.5, RCP2.6) w mean CC + extreme T around crop anthesis (HSA) + direct CO2 fert.] (Deryng et al., 2014)

FI	AFRICA	EUROPE	ASIA	AMERICA	GLOBAL
	Groundnuts; **SSA** [P; 73%; MF; avg [CSIRO (A1B, B1); MIROC (A1B, B1)]; South Africa] Yams; **SSA** [Y ; [7; 49]% ; MF ; A1B w adap.; Republic of Bénin] (Srivastava, Gaiser, & Ewert, 2015) Groundnuts; **SSA** [Y; ~ [-3;15]% ; MF; RCP 8.5 w adapt. (drought and heat tolerance)] (Islam et al., 2016)				
cte	Soybean; **SSA** [P ; 0% ; MF ; avg[CSIRO (A1B, B1); MIROC(A1B, B1)]; South Africa] (Dube et al., 2013)		Rice; **WSSE** [P ; 0% ; MF ; (RCP8.5&RCP4.5) w O3 pollution] (Tai et al., 2014) Soybean; **WSSE** [P ; 0% ; MF ; RCP4.5 w O3 pollution] (Tai et al., 2014)	Rice; **NCA** [P ; 0% ; MF ; (RCP8.5&RCP4.5) w O3 pollution] (Tai et al., 2014)	Rice; **Glob** [P ; 0% ; MF ; RCP8.5 w O3 pollution] (Tai et al., 2014)
(-)	Wheat; **NAf** [Y ; [-40; -22]% ; LF ; A1B; Algeria] (Chourghal, Lhomme, Huard, & Aidaoui, 2015) Maize; **SSA** [Y ; -20% ; MF ; (RCP4.5 & RCP8.5); Ethiopia] (Kassie et al., 2015) Maize; **SSA** [Y ; (-1.2; 1)% & (-3; 0.2; (MF) & (LF) ; (RCP4.5, RCP8.5); Malawi] (Stevens & Madani, 2016) Maize; **SSA** [Y ; [-20; 0]% ; MF ; A1B w 380 ppm CO2; Nigeria] (Mereu, Carboni, Gallo, Cervigni, & Spano, 2015) Maize; **SSA** [Y ; [-40.1; -0.4]% ; MF ; RCP8.5] ;	Wheat; **EU** [P ; -16% ; MF ; A1B; UK] (Dawson et al., 2016) Wheat; **EU** [P ; ~-12% ; MF ; RCP8.5 w O3 cont.] (Tai et al., 2014) Maize; **EU** [P ;(~-40%, -30%) ; MF ; (RCP8.5, RCP4.5) w O3 pollution] (Tai et al., 2014) Soybean; **EU** [P ; (~-20%, -10%) ; MF ; (RCP8.5, RCP4.5) w O3 pollution] (Tai et al., 2014) Oil seeds, Wheat, Rice; **EU** [Y ; ~-15% ; MF ; RCP8.5] (Nelson et al., 2014)	Wheat; **CEA** [P ; ~-15% ; MF ; RCP8.5 w O3 cont.; China] (Tai et al., 2014) Wheat; **CEA** [irrigated; Y ; (-6.7, -2.2)% ; MF ; (A2, B2); China] (Ju, van der Velde, Lin, Xiong, & Li, 2013) Wheat; **WSSE** [P ; ~-35%, -30% ; MF ; (RCP8.5, RCP4.4) w O3 cont.; South Asia] (Tai et al., 2014) Wheat; **WSSE** [P ; (~-10%, -5%) ; MF ; (RCP8.5, RCP4.4) w O3 cont.; Southeast Asia] (Tai et al., 2014) Wheat; **WSSE** [irrigated; P ; (-6,-1)% ; MF ; (A1B, B1); Iran] (Emam et al., 2015) Wheat; **WSSE** [Y ; -18% ; MF ; CSIRO-A1B; Pakistan] (Zhu, Ringler, Mohsin Iqbal, Sulser, & Arif Goheer, 2013) Wheat; **Asia** [Y; ~-7% ; MF ; RCP8.5; Bangladesh, India, Nepal, Pakistan] /[Y ; ~-2%	Wheat; **NCA** [P ; ~-5% ; MF ; RCP8.5 w O3 cont.; USA] (Tai et al., 2014) Wheat; **NCA** [Y ; <-30% ; MF ; A2; USA] (Jiang & Koo, 2014) Wheat; **NCA** [Y ; -10% ; MF ; A2&B1; Mexico] (Rosenzweig et al., 2014) Wheat; **CSA** [P ; ~-10%, -5% ; MF ; (RCP8.5, RCP4.5) w O3 cont.] (Tai et al., 2014) Maize; **NCA** [P ; (~-50%, -45%) ; MF ; (RCP4.5, RCP8.5) w O3 pollution; USA] (Tai et al., 2014) Maize; **CSA** [P ; (~-25%, -20%) ; MF ; (RCP8.5, RCP4.5) w O3 pollution] (Tai et al., 2014)	Wheat; **Glob** [Y ; [-50; -5]% ; LF ; A2] (Rosenzweig et al., 2014) Wheat; **Glob** [Y ; [-15; +5]% ; LF ; RCP8.5 w CO2fert.] (Müller et al., 2015) Wheat; **Glob** [P ; -40% ; MF ; A1B] (Dawson et al., 2016) Wheat; **Glob** [P ; ~-15%, -5% ; MF ; (RCP8.5, RCP4.4) w O3 cont.] (Tai et al., 2014) Wheat; **Glob** [Y ; -5.2%, -2.5% ; NF ; RCP8.5 (20, 10 year period)] (Lobell & Tebaldi, 2014) Wheat; **Glob** [Y ; [-15; +5]% ; LF ; RCP8.5 w CO2fert.] (Müller et al., 2015) Wheat; **Glob** [Y ; (−10.1, −4.5)% & (−24.1, −2.9)% ; (MF)&(LF) ; (RCP8.5, RCP2.6) w mean CC + extreme T

FI	AFRICA	EUROPE	ASIA	AMERICA	GLOBAL
	Gambia (Ahmed et al., 2015) Maize; **SSA** [Y ; <-8% ; MF ; (RCP4.5, RCP8.5); Burkina Faso] (Waongo, Laux, & Kunstmann, 2015) Maize; **SSA** [Y ; ~-6% ; MF ; RCP8.5] Angola, Benin, Ethiopia, Ghana, Kenya, Malawi, Mozambique, Uganda, United Republic of Tanzania, Zambia, Zimbabwe; (Islam et al., 2016) Rice; **SSA** [Y ; [-20; 0]% ; MF ; A1B w 380 ppm CO2; Nigeria] (Mereu et al., 2015) Millet; **Africa** [Y ; -6% ; LF ; (A1B & A2); Africa & India] (Berg, De Noblet-Ducoudré, Sultan, Lengaigne, & Guimberteau, 2013) Sorghum & Millet**; SSA** [Y ; [-30; 0]% ; MF ; A1B w 380 ppm CO2; Nigeria] (Mereu et al., 2015) Sorghum & Millet**; SSA** [Y ; [–41; 0]% ; LF ; CMIP3 (A2, A1B, B1), CMIP5(RCP 4.5, 6.0 and 8.5); Senegal, Mali, Burkina Faso and Niger] (Sultan et al., 2013) Sorghum & Millet**; SSA** [Y ; [-45.5; -4]% ; MF ; RCP8.5; Senegal, Gambia, Mali, Ivory Coast, Togo, Ghana, Sierra Leone, Guinea-Bissau] (Ahmed et al., 2015)		; MF ; RCP8.5 w adapt. (drought and heat tolerance)] (Islam et al., 2016) Maize; **CEA** [P ; (~-6%) ; MF ; (RCP8.5, RCP4.5) w O3 pollution; China] (Tai et al., 2014) Maize; **CEA** [irrigated; Y ; (-11.9, -0.4)% ; MF ; (A2, B2); China] (Ju et al., 2013) Maize; **WSSE** [P ; (~-8%, -5%); MF ; (RCP8.5, RCP4.5) w O3 pollution; South Asia] (Tai et al., 2014) Maize; **WSSE** [P ; ~-35% ; MF ; (RCP8.5&RCP4.5) w O3 pollution; Southeast Asia] (Tai et al., 2014) Maize; **WSSE** [Y ; -21% ; MF ; MIROC-A1B; Pakistan] (Zhu et al., 2013) Rice; **CEA** [P ; ~-2% ; MF ; RCP8.5 w O3 pollution; China] (Tai et al., 2014) Rice; **CEA** [irrigated; Y ; (-12.4, -4.3)% ; MF ; (A2, B2); China] (Ju et al., 2013) Rice; **CEA** [Y ; -18.9% ; LF ; (A2 & B2); China] (W. Wang et al., 2014) Rice; **WSSE** [P ; ~-1% ; MF ; RCP8.5 w O3 pollution] (Tai et al., 2014) Rice; **WSSE** [Y ; (<-20)% & (<-27.8)% ; (NF)&(MF) ; A2; India] (Banerjee, Das, & Mukherjee, 2014) Rice; **WSSE** [Y ; [-31;-18]% ; MF ; (MIROC-A1B,CSIRO-A1B); Pakistan] (Zhu et al., 2013) Rice; **Asia** [Y ; ~[-55, -5]% ; MF ; A2] (Li et al., 2015) Soybean; **CEA** [P ; ~-5% ; MF ; RCP8.5 w O3 pollution; China] (Tai et al., 2014) Soybean; **WSSE** [P ; ~-5%,-2% ; MF ; RCP8.5 w O3 pollution; South Asia, Southeast Asia] (Tai et al., 2014) Oil seeds, Wheat, Rice; **CEA** [Y ; ~-10% ; MF ; RCP8.5; China] (Nelson et al., 2014) Oil seeds, Wheat, Rice; **WSSE** [Y ; ~-20% ; MF ; RCP8.5; India] (Nelson et al., 2014)	Soybean; **NCA** [P ; (~-10%, -5%) ; MF ; (RCP8.5, RCP4.5) w O3 pollution; USA] (Tai et al., 2014) Soybean; **CSA** [P ; (~-25%, -20%) ; MF ; (RCP8.5, RCP4.5) w O3 pollution] (Tai et al., 2014) Oil seeds, Wheat, Rice; **NCA** [Y ; ~-20% ; MF ; RCP8.5; USA] (Nelson et al., 2014) Oil seeds, Wheat, Rice; **CSA** [Y ; ~-20% ; MF ; RCP8.5; Brazil] (Nelson et al., 2014)	around crop anthesis (HSA) w/o direct CO2 fert.] (Deryng et al., 2014) Maize; **Glob** [Y ; [-45; -20]% ; LF ; A2] (Rosenzweig et al., 2014) Maize; **Glob** [P ; -50% ; MF ; A1B] (Dawson et al., 2016) Maize; **Glob** [P ; (~-30%,-20%) ; MF ; (RCP8.5, RCP4.5) w O3 pollution] (Tai et al., 2014) Maize; **Glob** [Y ; [-5.3; -2.6]% ; NF ; RCP8.5] (Lobell & Tebaldi, 2014) Maize; **Glob** [Y ; [-35; -10]% ; LF ; RCP8.5 w CO2fert.] (Müller et al., 2015) Maize; **Glob** [Y ; (-7.4, -3.1)% & (-12.8, -2.9)% ; (MF)&(LF) ; (RCP8.5, RCP2.6)] (Deryng et al., 2014) Maize; **Glob** [Y ; (-10.5, -4.7)% & (-22.0, -4.4)% ; (MF)&(LF) ; (RCP8.5, RCP2.6) w mean CC + extreme T around crop anthesis (HSA) w/o direct CO2 fert.] / [Y ; (-7.4, -3.1)% & (-12.8, -2.9)% ; (MF)&(LF) ; (RCP8.5, RCP2.6) w mean CC + extreme T around crop anthesis (HSA) + direct CO2 fert.] (Deryng et al., 2014) Rice; **Glob** [Y ; [-30; -20]% ; LF ; A2] (Rosenzweig et al., 2014) Rice; **Glob** [Y ; [-20; -5]% ; LF ; RCP8.5 w CO2fert.] (Müller et al., 2015) Soybean; **Glob** [Y ; [-60; -30]% ; LF ; A2] (Rosenzweig et al., 2014) Soybean; **Glob** [P ; -50% ; MF ; A1B] (Dawson et al., 2016) Soybean; **Glob** [P ; ~-15%, -8% ; MF ; (RCP8.5, RCP4.5) w O3 pollution] (Tai et al., 2014)

FI	AFRICA	EUROPE	ASIA	AMERICA	GLOBAL
	Sorghum & Millet**; SSA** [Y ; ~-5% ; MF ; RCP8.5 w adapt. (drought and heat tolerance); Burkina Faso, Eritrea, Ethiopia, Mali, Nigeria, Sudan, United Republic of Tanzania] (Islam et al., 2016) Oil seeds, Wheat, Rice; **SSA** [Y ; ~-20% ; MF ; RCP8.5] (Nelson et al., 2014) Cassava**; SSA** [Y ; ~[-15; -5]% ; MF ; A1B w 380 ppm CO2; Nigeria] (Mereu et al., 2015) Yams; **SSA** [Y ; (-33; -27)% ; MF ; A1B, B1; Republic of Bénin] (Srivastava et al., 2015) Groundnuts; **SSA** [Y ; ~-9% ; MF ; RCP8.5] (Islam et al., 2016) Various crops**; SSA** [Y ; [-37; -11]% ; MF ; RCP8.5] (Hertel & Baldos, 2016)		Oil seeds, Wheat, Rice; **WSSE** [Y ; ~-10% ; MF ; RCP8.5] (Nelson et al., 2014) Potatoes; **Asia** [Y ; ~-1% ; MF ; RCP8.5] (Islam et al., 2016)		Soybean; **Glob** [Y ; [-30; 0]% ; LF ; RCP8.5 w CO2fert.] (Müller et al., 2015) Soybean; **Glob** [Y ; (−6.9 , 1.9)% & (−26.0, 0.9)% ; (MF)&(LF) ; (RCP8.5, RCP2.6) w mean CC + extreme T around crop anthesis (HSA) w/o direct CO2 fert.] (Deryng et al., 2014)

Table A3 Projections of climate change and climate variability impacts on food access by considering all reviewed crops

Notes: Variations always refer to reference scenarios, which may differ from a study to another. Date is organised as follows: "Region: [food product *(when adequate);* food indicator; projection change; time scale; scenario; location; other *(when adequate)*] Literature reference". Food indicators (FI) are PC - Price; UND - Prevalence of undernourishment. A projected change on FI is represented by (+) when the change is positive, (-) when it decreases and "cte" when there is no change. Three time scales were considered: NF - near time future (with projections ranging from 2020s-2030s), MF - medium time future (from 2040s-2060s) and LF - longtime future (from 2070s-2100). IPCC Special Report Emissions Scenarios (SRES): A1, A1FI, A1T, A1B, A2, B1, B2; IPCC Representative Concentration Pathways (RCP): RCP2.6, RCP4.5, RCP6, RCP8.5; w CO_2 fert. or w/o CO_2 fert. - means with the effects of CO_2 fertilisation or without the effects of CO_2 fertilisation; w tech adaptation – by including technological adaptation measures; HCI – high climate index (high temperature increase, high sensitivity of crops to global warming, and a CO_2 fertilisation effect at the lower end of published estimates). "Regions" include: Naf – North Africa, SSA – Sub-Saharan Africa, NWC – North & West & Central Asia, WSSE – South & Southeast Asia, CEA – East Asia, NCA – North America, CSA – Caribbean & South America, EU – Europe.

FI	Africa	Europe	Asia	America	Global
(+)	Soybean; **SSA** [PC ; 60% ; MF ; avg[CSIRO (A1B, B1); MIROC(A1B, B1)]; South Africa] (Dube et al., 2013) Oil seeds, Wheat, Rice; **SSA** [PC; ~15%; MF; RCP8.5 & avg. Econ. models] (Nelson et al., 2014) **SSA** (various crops) [PC ; 22.9% ; MF ; RCP8.5] (Hertel & Baldos, 2016)	Oil seeds, Wheat, Rice; **EU** [PC; ~10%; MF; RCP8.5 & avg. Econ. models] (Nelson et al., 2014)	Oil seeds, Wheat, Rice; **Asia** [PC; ~15%, 25%; MF; RCP8.5 & avg. Econ. models ; China, India] (Nelson et al., 2014) Maize, Wheat, Rice; **WSSE** [PC ; [14;18]%, [18;27]%, [26;32]% ; MF ; (CSIRO-B1,MIROC-A1); Pakistan] (Zhu et al., 2013) Cereals, oil crops, sugar crops, tubers, fibers; **CEA** [PC ; [-1; 4]%, [1; 6]%, 38%; MF ; A2; South Korea, China, Mongolia] (Mosnier et al., 2014) Cereals, oil crops, sugar crops, tubers, fibers; **WSSE** [und ; 97% ; MF ; RCP8.5, South Asia] (Hertel & Baldos, 2016)	Oil seeds, Wheat, Rice; **America** [PC; ~10%, 15%; MF; RCP8.5 & avg. Econ. models ; Brazil, USA] (Nelson et al., 2014)	Cereals, oil crops, sugar crops, tubers, fibers; **Glob** [PC ; [0, 5]% ; MF ; A2] (Mosnier et al., 2014) Various crops; **Glob** (various crops) [PC ; 27.6% ; MF ; RCP8.5] / [und ; 45% ; MF ; RCP8.5] (Hertel & Baldos, 2016) Various food products; **Glob** [und ; 50% ; MF ; A1B; South America, Africa, Australia and central Asia and partially Europe, South-East Asia, USA and Russia] (Dawson et al., 2016)
(-)			Various crops; **CEA** [PC ; [-5; -3]% ; MF ; A2; Japan] (Mosnier et al., 2014)		

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6.2 Appendix B

Exposure of the EU food imports to extreme weather disasters in exporting countries

Table B1. Observed losses in European agriculture attributed to extreme weather disasters.

EWD	Region/ country	Period of occurrence	Negative impact	Reference
Drought and Heat wave	Italy, Germany, Austria, Spain, France and Portugal	2003	10 Mt of wheat and 9 Mt of maize	COPA-COGECA, 2003)
Drought	Slovenia	2003	100 M€ for agriculture sector	(EEA, 2010)
Drought	South and Central Europe	2003	20% on grain harvested	(Kovats et al., 2014)
Drought	Iberia Peninsula	2004-2005	40% on cereal production	(EEA, 2010)
Flood	England and Wales	2007	50M£ for agriculture sector	(Chatterton, Viavattene, Morris, Penning-Rowsell, & Tapsell, 2010)
Heat wave	France	2011	8% on wheat yield	(AGRESTE, 2011)

Table B2. List of the extreme weather disasters that happened per year in the exporting countries (ISO3 codes) supplying the EU with soybeans and banana. Data was aquired through (FAO, 2017).

Soybeans				Banana			
Floods (n=43)	**Droughts** (n=27)	**Heat waves** (n=14)	**Cold waves** (n=18)	**Floods** (n=71)	**Droughts** (n=29)	**Heat waves** (n=3)	**Cold waves** (n=6)
1964 BRA	1970 BRA	1968 BRA	1975 BRA	1979 BLZ	1970 BRA	1968 BRA	1990 BLZ
1969 BRA	1977 BRA	1975 BRA	1988 BRA	1990 BLZ	1977 BRA	1975 BRA	1975 BRA
1973 BRA	1983 BRA	2010 BRA	1994 BRA	1995 BLZ	1983 BRA	2010 BRA	1988 BRA
1977 BRA	1985 BRA	1966 USA	2000 BRA	2008 BLZ	1985 BRA		1994 BRA
1983 BRA	1987 BRA	1972 USA	2004 BRA	1964 BRA	1987 BRA		2000 BRA
1995 BRA	1994 BRA	1980 USA	1982 CAN	1969 BRA	1994 BRA		2004 BRA
1974 CAN	1998 BRA	1983 USA	1992 CAN	1973 BRA	1998 BRA		
1976 CAN	2001 BRA	1986 USA	2000 PRY	1977 BRA	2001 BRA		
1979 CAN	2004 BRA	1990 USA	2004 PRY	1983 BRA	2004 BRA		
1983 CAN	2007 BRA	1993 USA	2010 PRY	1995 BRA	2007 BRA		
1986 CAN	2010 BRA	1995 USA	2000 UKR	1989 CIV	2010 BRA		
1990 CAN	2012 BRA	1998 USA	2009 UKR	1996 CIV	2012 BRA		
1993 CAN	1977 CAN	2005 USA	2012 UKR	2007 CIV	1983 CIV		
1995 CAN	1984 CAN	2011 USA	1977 USA	2010 CIV	1971 CMR		
2002 CAN	1988 CAN		1989 USA	1988 CMR	1990 CMR		
2011 CAN	1983 PRY		1995 USA	1991 CMR	2001 CMR		
1965 PRY	1999 PRY		2004 USA	1994 CMR	2005 CMR		
1971 PRY	2005 PRY		2009 USA	1999 CMR	2012 CMR		
1979 PRY	2008 PRY			2005 CMR	1998 COL		
1982 PRY	2012 PRY			2007 CMR	1973 CRI		
1988 PRY	2012 UKR			2010 CMR	1994 CRI		
1990 PRY	1988 USA			2012 CMR	1998 CRI		
1992 PRY	1991 USA			1969 COL	1968 DOM		
1995 PRY	1999 USA			1973 COL	1964 ECU		
1997 PRY	2002 USA			1976 COL	1997 ECU		
2002 PRY	2007 USA			1979 COL	2009 ECU		
2009 PRY	2011 USA			1984 COL	2013 ECU		
2012 PRY				1986 COL	1983 PAN		
1995 UKR				1993 COL	2013 PAN		
2001 UKR				1999 COL			
2003 UKR				1969 CRI			
2005 UKR				1980 CRI			
2008 UKR				1988 CRI			
2010 UKR				1991 CRI			
2013 UKR				1993 CRI			
1964 USA				1996 CRI			
1969 USA				1999 CRI			
1972 USA				2001 CRI			
1976 USA				2007 CRI			
1980 USA				2010 CRI			
1988 USA				1979 DOM			
1990 USA				1981 DOM			
1993 USA				1985 DOM			
				1988 DOM			
				1991 DOM			
				1993 DOM			
				1996 DOM			
				2002 DOM			
				2007 DOM			
				2009 DOM			
				1965 ECU			
				1967 ECU			

Soybeans				Banana			
Floods (n=43)	Droughts (n=27)	Heat waves (n=14)	Cold waves (n=18)	Floods (n=71)	Droughts (n=29)	Heat waves (n=3)	Cold waves (n=6)
				1970 ECU			
				1973 ECU			
				1982 ECU			
				1987 ECU			
				1989 ECU			
				1992 ECU			
				1997 ECU			
				2000 ECU			
				2006 ECU			
				2008 ECU			
				1966 PAN			
				1970 PAN			
				1972 PAN			
				1978 PAN			
				1984 PAN			
				1986 PAN			
				1991 PAN			
				1995 PAN			
				1999 PAN			

Table B3. List of the extreme weather disasters that happened per year in the exporting countries (ISO3 codes) supplying the EU with tropical fruits and coffee. Data was aquired through (FAO, 2017).
Note: Data on tropical fruits from Panama and on coffee from Ethiopia, were excluded from the analysis once yield values were not correctly reported or there is missing data at FAOSTAT. Those countries are, therefore, not indicated in this table.

Tropical Fruits				Coffee			
Floods (n=143)	Droughts (n=70)	Heat waves (n=17)	Cold waves (n=28)	Floods (n=141)	Droughts (n=109)	Heat waves (n=16)	Cold waves (n=28)
1964 BRA	1970 BRA	1968 BRA	1975 BRA	1964 BRA	1970 BRA	1968 BRA	1975 BRA
1969 BRA	1977 BRA	1975 BRA	1988 BRA	1969 BRA	1977 BRA	1975 BRA	1988 BRA
1973 BRA	1983 BRA	2010 BRA	1994 BRA	1973 BRA	1983 BRA	2010 BRA	1994 BRA
1977 BRA	1985 BRA	2003 DZA	2000 BRA	1977 BRA	1985 BRA	1965 IND	2000 BRA
1983 BRA	1987 BRA	2000 ISR	2004 BRA	1983 BRA	1987 BRA	1978 IND	2004 BRA
1995 BRA	1994 BRA	1968 MEX	1995 CHL	1995 BRA	1994 BRA	1985 IND	2001 GTM
1965 CHL	1998 BRA	1990 MEX	2000 CHL	1989 CIV	1998 BRA	1987 IND	2006 GTM
1974 CHL	2001 BRA	1975 PAK	2002 CHL	1996 CIV	2001 BRA	1994 IND	2011 GTM
1978 CHL	2004 BRA	1979 PAK	2004 CHL	2007 CIV	2004 BRA	1998 IND	1973 IND
1982 CHL	2007 BRA	1991 PAK	2010 CHL	2010 CIV	2007 BRA	2002 IND	1980 IND
1986 CHL	2010 BRA	1996 PAK	1992 ISR	1988 CMR	2010 BRA	2005 IND	1984 IND
1989 CHL	2012 BRA	1999 PAK	1988 MEX	1994 CMR	2012 BRA	2009 IND	1989 IND
1993 CHL	1968 CHL	2002 PAK	1992 MEX	1999 CMR	1983 CIV	2013 IND	1992 IND
1995 CHL	1991 CHL	2005 PAK	1995 MEX	2005 CMR	1971 CMR	1968 MEX	1998 IND
1997 CHL	1983 CIV	1983 PER	1997 MEX	2007 CMR	2001 CMR	1990 MEX	2000 IND
2000 CHL	1973 CRI	2000 TUR	2002 MEX	2010 CMR	2005 CMR	1983 PER	2007 IND
2004 CHL	1994 CRI	2007 TUR	2006 MEX	2012 CMR	2012 CMR		2010 IND
2008 CHL	1998 CRI		2011 MEX	1969 COL	1998 COL		1988 MEX
2012 CHL	1981 DZA		1990 PAK	1973 COL	1973 CRI		1992 MEX
1989 CIV	1964 ECU		2001 PAK	1976 COL	1994 CRI		1995 MEX
1996 CIV	1997 ECU		1991 PER	1979 COL	1998 CRI		1997 MEX

Tropical Fruits				Coffee			
Floods (n=143)	**Droughts** (n=70)	**Heat waves** (n=17)	**Cold waves** (n=28)	**Floods** (n=141)	**Droughts** (n=109)	**Heat waves** (n=16)	**Cold waves** (n=28)
2007 CIV	2009 ECU		2003 PER	1984 COL	1987 GTM		2002 MEX
2010 CIV	2013 ECU		2009 PER	1986 COL	1994 GTM		2006 MEX
1969 CRI	1965 HND		1987 TUR	1993 COL	2001 GTM		2011 MEX
1980 CRI	1972 HND		2001 TUR	1999 COL	2009 GTM		1991 PER
1988 CRI	1994 HND		2004 TUR	1969 CRI	2012 GTM		2003 PER
1991 CRI	1997 HND		1996 ZAF	1980 CRI	1965 HND		2009 PER
1993 CRI	2000 HND		2007 ZAF	1988 CRI	1972 HND		2006 SLV
1996 CRI	2004 HND			1991 CRI	1994 HND		
1999 CRI	2009 HND			1993 CRI	1997 HND		
2001 CRI	2012 HND			1996 CRI	2000 HND		
2007 CRI	1964 IRN			1999 CRI	2004 HND		
2010 CRI	1999 IRN			2001 CRI	2009 HND		
1966 DZA	1999 ISR			2007 CRI	2012 HND		
1969 DZA	1965 KEN			2010 CRI	1966 IDN		
1973 DZA	1971 KEN			1973 GTM	1972 IDN		
1979 DZA	1979 KEN			1982 GTM	1978 IDN		
1981 DZA	1984 KEN			1987 GTM	1982 IDN		
1984 DZA	1991 KEN			1994 GTM	1984 IDN		
1992 DZA	1994 KEN			1999 GTM	1986 IDN		
1996 DZA	1997 KEN			2002 GTM	1997 IDN		
1999 DZA	1999 KEN			2005 GTM	2003 IDN		
2011 DZA	2004 KEN			2007 GTM	1964 IND		
1965 ECU	2008 KEN			1965 HND	1972 IND		
1967 ECU	2011 KEN			1976 HND	1979 IND		
1970 ECU	1978 MEX			1979 HND	1982 IND		
1973 ECU	1988 MEX			1981 HND	1987 IND		
1982 ECU	1995 MEX			1984 HND	1993 IND		
1987 ECU	1999 MEX			1986 HND	1996 IND		
1989 ECU	2002 MEX			1988 HND	2000 IND		
1992 ECU	2011 MEX			1990 HND	2002 IND		
1997 ECU	1999 PAK			1993 HND	2009 IND		
2000 ECU	1966 PER			1999 HND	1965 KEN		
2006 ECU	1969 PER			2002 HND	1971 KEN		
2008 ECU	1983 PER			2005 HND	1979 KEN		
1965 HND	1990 PER			2010 HND	1984 KEN		
1976 HND	1992 PER			1966 IDN	1991 KEN		
1979 HND	2002 PER			1970 IDN	1994 KEN		
1981 HND	2004 PER			1976 IDN	1997 KEN		
1984 HND	2006 PER			1998 IDN	1999 KEN		
1986 HND	1977 TUN			1964 IND	2004 KEN		
1988 HND	1988 TUN			1966 IND	2008 KEN		
1990 HND	1964 ZAF			1970 IND	2011 KEN		
1993 HND	1980 ZAF			1974 IND	1978 MEX		
1999 HND	1982 ZAF			1977 IND	1988 MEX		
2002 HND	1986 ZAF			1964 KEN	1995 MEX		
2005 HND	1988 ZAF			1968 KEN	1999 MEX		
2010 HND	1991 ZAF			1975 KEN	2002 MEX		
1966 IRN	1995 ZAF			1977 KEN	2011 MEX		

Tropical Fruits				Coffee			
Floods (n=143)	Droughts (n=70)	Heat waves (n=17)	Cold waves (n=28)	Floods (n=141)	Droughts (n=109)	Heat waves (n=16)	Cold waves (n=28)
1968 IRN	2004 ZAF			1982 KEN	1994 NIC		
1980 IRN				1990 KEN	1997 NIC		
1986 IRN				1996 KEN	2000 NIC		
2012 IRN				2001 KEN	1966 PER		
1997 ISR				1965 MEX	1969 PER		
2010 ISR				1967 MEX	1983 PER		
1964 KEN				1970 MEX	1990 PER		
1968 KEN				1972 MEX	1992 PER		
1975 KEN				1978 MEX	2002 PER		
1977 KEN				1982 MEX	2004 PER		
1982 KEN				1984 MEX	2006 PER		
1990 KEN				1986 MEX	1980 PNG		
1996 KEN				1989 MEX	1997 PNG		
2001 KEN				1993 MEX	1982 SLV		
1965 MEX				1996 MEX	1994 SLV		
1967 MEX				1998 MEX	1998 SLV		
1970 MEX				2013 MEX	2001 SLV		
1972 MEX				1968 NIC	2009 SLV		
1978 MEX				1976 NIC	1967 TZA		
1982 MEX				1979 NIC	1977 TZA		
1984 MEX				1990 NIC	1984 TZA		
1986 MEX				1999 NIC	1988 TZA		
1989 MEX				2002 NIC	1991 TZA		
1993 MEX				2007 NIC	1996 TZA		
1996 MEX				1965 PER	2003 TZA		
1998 MEX				1967 PER	2006 TZA		
2013 MEX				1970 PER	2011 TZA		
1964 PAK				1977 PER	1967 UGA		
1967 PAK				1980 PER	1979 UGA		
1973 PAK				1986 PER	1987 UGA		
1976 PAK				1992 PER	1998 UGA		
1988 PAK				1999 PER	2002 UGA		
1991 PAK				2006 PER	2005 UGA		
2001 PAK				1983 PNG	2008 UGA		
1965 PER				1992 PNG	2011 UGA		
1967 PER				1999 PNG	1987 VNM		
1970 PER				2004 PNG	1997 VNM		
1977 PER				2008 PNG	1999 VNM		
1980 PER				2012 PNG	2002 VNM		
1986 PER				1982 SLV	2005 VNM		
1992 PER				1988 SLV			
1999 PER				1992 SLV			
2006 PER				1995 SLV			
1964 TUN				1999 SLV			
1969 TUN				2005 SLV			
1973 TUN				2007 SLV			
1979 TUN				2011 SLV			
1982 TUN				1964 TZA			

Tropical Fruits				Coffee			
Floods (n=143)	**Droughts** (n=70)	**Heat waves** (n=17)	**Cold waves** (n=28)	**Floods** (n=141)	**Droughts** (n=109)	**Heat waves** (n=16)	**Cold waves** (n=28)
1986 TUN				1968 TZA			
1990 TUN				1974 TZA			
2003 TUN				1978 TZA			
2007 TUN				1982 TZA			
2009 TUN				1986 TZA			
1964 TUR				1988 TZA			
1968 TUR				1993 TZA			
1974 TUR				1997 TZA			
1980 TUR				2000 TZA			
1984 TUR				2005 TZA			
1988 TUR				2008 TZA			
1990 TUR				2011 TZA			
1995 TUR				1997 UGA			
1998 TUR				2001 UGA			
2000 TUR				2006 UGA			
2009 TUR				2011 UGA			
2011 TUR				1964 VNM			
1968 ZAF				1966 VNM			
1974 ZAF				1970 VNM			
1977 ZAF				1978 VNM			
1981 ZAF				1980 VNM			
1987 ZAF				1984 VNM			
1993 ZAF				1990 VNM			
1999 ZAF				1998 VNM			
2006 ZAF							
2011 ZAF							

Table B4. List of the extreme weather disasters that happened per year in the exporting countries (ISO3 codes) supplying the EU with cocoa. Data was aquired through (FAO, 2017).

Cocoa			
Floods (n=51)	**Droughts** (n=15)	**Heat waves** (n=1)	**Cold waves** (n=1)
1989 CIV	1983 CIV	2002 NGA	1992 NGA
1996 CIV	1971 CMR		
2007 CIV	1990 CMR		
2010 CIV	2001 CMR		
1988 CMR	2005 CMR		
1991 CMR	2012 CMR		
1994 CMR	1968 DOM		
1999 CMR	1964 ECU		
2005 CMR	1997 ECU		
2007 CMR	2009 ECU		
2010 CMR	2013 ECU		
2012 CMR	1971 GHA		
1979 DOM	1977 GHA		
1981 DOM	1983 GHA		
1985 DOM	1983 NGA		
1988 DOM			
1991 DOM			
1993 DOM			

Cocoa			
Floods (n=51)	**Droughts** (n=15)	**Heat waves** (n=1)	**Cold waves** (n=1)
1996 DOM			
2002 DOM			
2007 DOM			
2009 DOM			
1965 ECU			
1967 ECU			
1970 ECU			
1973 ECU			
1982 ECU			
1987 ECU			
1989 ECU			
1992 ECU			
1997 ECU			
2000 ECU			
2006 ECU			
2008 ECU			
1968 GHA			
1989 GHA			
1991 GHA			
1995 GHA			
1999 GHA			
2001 GHA			
2007 GHA			
2013 GHA			
1985 NGA			
1988 NGA			
1994 NGA			
1998 NGA			
2009 NGA			
1996 SLE			
2004 SLE			
2007 SLE			
2009 SLE			

Table B5. Percentage of irrigated harvested area of the agrifood-product in each country and the dominant Koppen-Geiger climate classification per country. Notes: (1) Countries indicated in grey are the ones that are not considered for the analysis of the impact of droughts & heat waves in rainfed and non-tropical systems, i.e. without the interference of irrigation and/or wet tropical climate. (2) A wet tropical climate is considered for the classifications 'Tropical rainforest climate' (Af) and 'Tropical monsoon climate' (Am). (3) Only the countries with a percentage of irrigated harvest area higher than 40% are removed from the analysis. (4) Irrigation percentage of harvested area for 'Tropical Fruits' is not considered because at AQUASTAT there is not available data for crops on that specific category. (5) Data on tropical fruits from Panama and Ghana, on coffee from Ethiopia, on cocoa from Togo and Guinea and on banana from Suriname, are excluded from the analysis once yield, production and/or harvest area are not correctly reported or there is missing data at FAOSTAT. (6) '*' means that banana data from Cote d'Ivoire is removed while analysing the effect of DR&HW in rainfed and non-tropical systems. Even if data on irrigated area is not consistent (as irrigation area is indicated to be higher than harvested area), there is indication that the crop is irrigated.

Country	**Agri-food product**	**Dominant Koppen-Geiger classification** (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006)		**Irrigated area per agri-food product** (FAO, 2016) and (FAO, 2017)	
		Letter symbol	**Classification**	**Percentage**	**Reference year**
Algeria	Tropical Fruits	Csa	Hot-summer Mediterranean climate		
Belize	Banana	Am	Tropical monsoon climate	48%	2005
Brazil	Banana	Aw	Tropical savanna climate	5.4%	2006
Brazil	Coffee	Aw	Tropical savanna climate	11%	2006
Brazil	Soybeans	Aw	Tropical savanna climate	3%	2006
Brazil	Tropical Fruits	Aw	Tropical savanna climate		
Cameroon	Banana	Aw	Tropical savanna climate	6%	2000
Cameroon	Cocoa	Aw	Tropical savanna climate		
Cameroon	Coffee	Aw	Tropical savanna climate		
Canada	Soybeans	Dfb	Warm humid continental climate		
Chile	Tropical Fruits	Csb	Warm-summer Mediterranean climate		
Colombia	Banana	Af, Aw, Am	Tropical rainforest climate, Tropical savanna climate, Tropical monsoon climate	10%	1994
Colombia	Coffee	Af, Aw, Am	Tropical rainforest climate, Tropical savanna climate, Tropical monsoon climate	1%	2011
Costa Rica	Banana	Aw, Am, Af	Tropical savanna climate, Tropical monsoon climate, Tropical rainforest climate		
Costa Rica	Coffee	Aw, Am, Af	Tropical savanna climate, Tropical monsoon climate, Tropical rainforest climate		
Costa Rica	Tropical Fruits	Aw, Am, Af	Tropical savanna climate, Tropical monsoon climate, Tropical rainforest climate		
Cote d'Ivoire	Banana	Aw	Tropical savanna climate	242%	2008*
Cote d'Ivoire	Cocoa	Aw	Tropical savanna climate		
Cote d'Ivoire	Coffee	Aw	Tropical savanna climate		
Cote d'Ivoire	Tropical Fruits	Aw	Tropical savanna climate		
Dominica Republica	Banana	Aw, Af, Am	Tropical savanna climate, Tropical monsoon climate, Tropical rainforest climate		
Dominica Republica	Cocoa	Aw, Af, Am	Tropical savanna climate, Tropical monsoon climate, Tropical rainforest climate		
Ecuador	Banana	Aw	Tropical savanna climate	59%	2000
Ecuador	Cocoa	Aw	Tropical savanna climate	8%	2000

Country	**Agri-food product**	**Dominant Koppen-Geiger classification** (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006)		**Irrigated area per agri-food product** (FAO, 2016) and (FAO, 2017)	
		Letter symbol	**Classification**	**Percentage**	**Reference year**
Ecuador	Tropical Fruits	Aw	Tropical savanna climate		
El Salvador	Coffee	Aw	Tropical savanna climate	4%	
Ethiopia	Coffee	Cfb	Oceanic climate		
Ghana	Cocoa	Aw	Tropical savanna climate		
Ghana	Tropical Fruits	Aw	Tropical savanna climate		
Guatemala	Coffee	Aw	Tropical savanna climate	7%	2007
Guinea	Cocoa	Aw	Tropical savanna climate		
Honduras	Coffee	Aw	Tropical savanna climate		
Honduras	Tropical Fruits	Aw	Tropical savanna climate		
India	Coffee	BSh, Aw	Hot semi-arid climates, Tropical savanna climate		
Indonesia	Coffee	Af	Tropical rainforest climate		
Iran	Tropical Fruits	Csa, BSk, Dsa	Hot-summer Mediterranean climate, Cold semi-arid climates, Hot humid continental climate		
Israel	Tropical Fruits	Csa	Hot-summer Mediterranean climate		
Kenya	Coffee	Aw	Tropical savanna climate	13%	2010
Kenya	Tropical Fruits	Aw	Tropical savanna climate		
Mexico	Coffee	BSh, BWh	Hot semi-arid climates, Hot desert climates		
Mexico	Tropical Fruits	BSh, BWh	Hot semi-arid climates, Hot desert climates		
Nicaragua	Coffee	Aw	Tropical savanna climate		
Nigeria	Cocoa	Aw	Tropical savanna climate		
Pakistan	Tropical Fruits	BWh, Cfa	Hot desert climates, Humid subtropical climate		
Panama	Banana	Am, Af	Tropical monsoon climate, Tropical rainforest climate	93%	2009
Panama	Tropical Fruits	Am, Af	Tropical monsoon climate, Tropical rainforest climate		
Papua New Guinea	Coffee	Af	Tropical rainforest climate		
Paraguay	Soybeans	Cfa	Humid subtropical climate		
Peru	Coffee	Cfb	Oceanic climate	5.1%	1994
Peru	Tropical Fruits	Cfb	Oceanic climate		
Sierra Leone	Cocoa	Am	Tropical monsoon climate		
South Africa	Tropical Fruits	Cfb	Oceanic climate		
Suriname	Banana	Af	Tropical rainforest climate	98%	2011
Tanzania	Coffee	Aw	Tropical savanna climate	1%	2013
Togo	Cocoa	Aw	Tropical savanna climate		

Country	**Agri-food product**	**Dominant Koppen-Geiger classification** (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006)		**Irrigated area per agri-food product** (FAO, 2016) and (FAO, 2017)	
		Letter symbol	**Classification**	**Percentage**	**Reference year**
Tunisia	Tropical Fruits	Csa, BWh, BSh	Hot-summer Mediterranean climate, Hot desert climates, Hot semi-arid climates		
Turkey	Tropical Fruits	Csa, Dsb	Hot-summer Mediterranean climate, Warm humid continental climate		
Uganda	Coffee	Aw	Tropical savanna climate		
Ukraine	Soybeans	Dfb	Warm humid continental climate		
United States of America	Soybeans	Dfa	Hot humid continental climate	9%	2008
Vietnam	Coffee	Aw	Tropical savanna climate	54%	2005

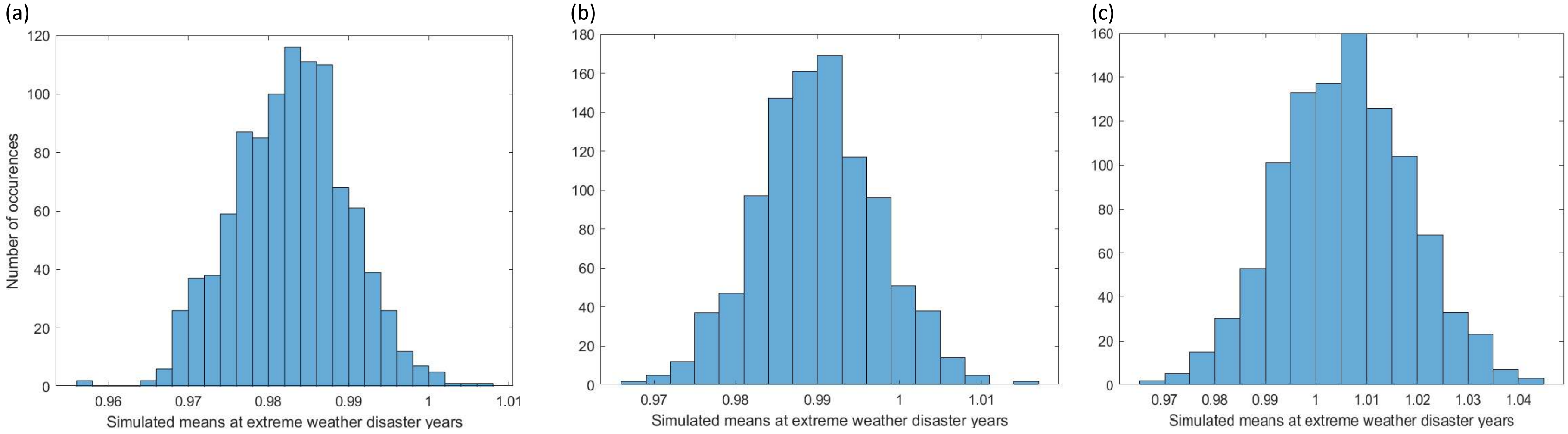

Figure B1. Histograms of the 1000 resampled normalised means of aggregated crop production at the EWD years, i.e., floods (a), droughts & heat waves (b) and cold waves (c). Histograms show that data follows a normal distribution. In this example, statistically significant impacts are obtained for floods and droughts & heats waves with the majority of resampled normalised means bellow ‘1’ (evidencing a negative impact). A non-significant impact is show in (c) where the majority of resampled normalised means is nearly distributed towards to ‘1’, meaning no change on aggregated crop production during years with cold waves.

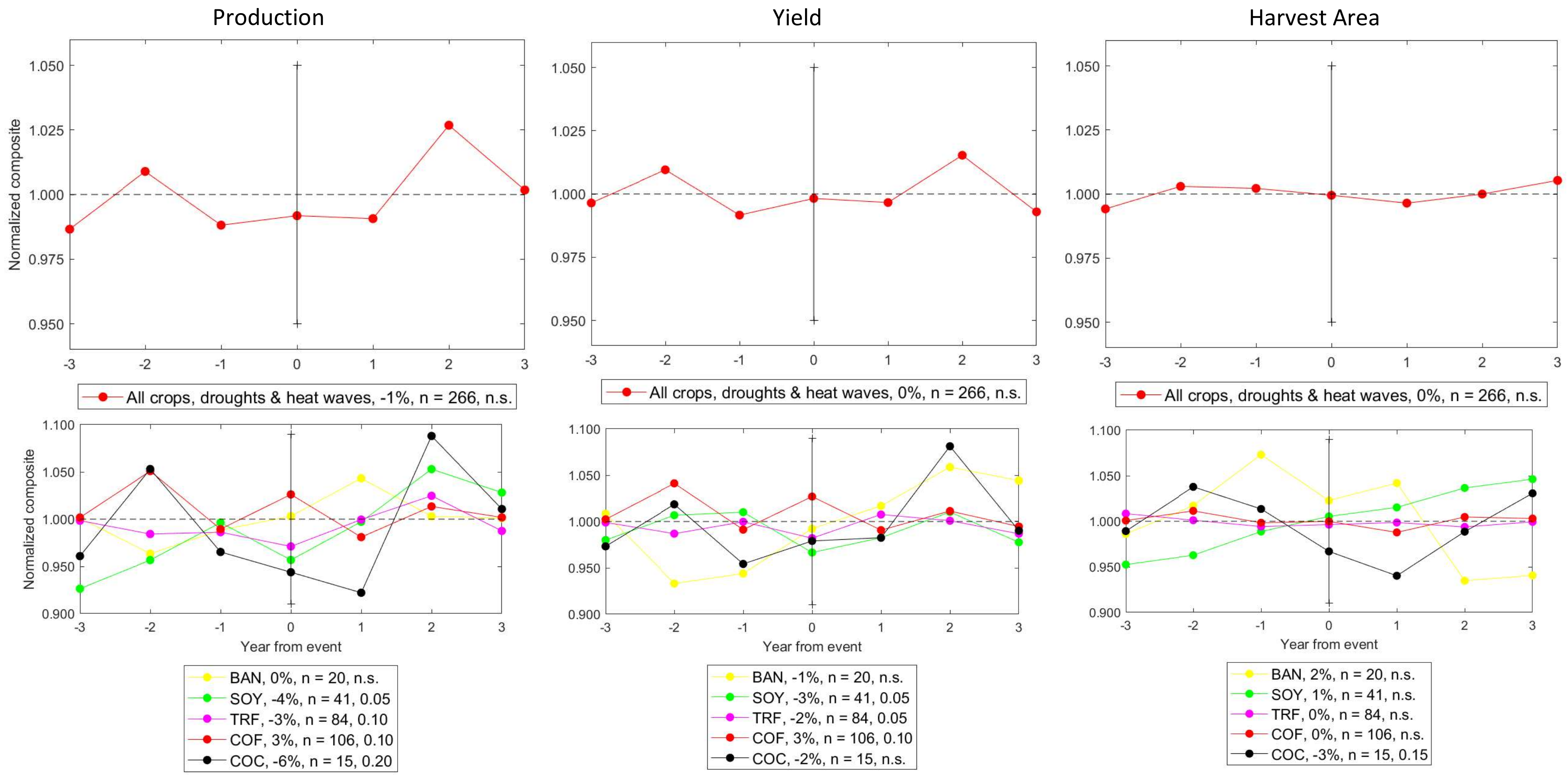

Figure B2. Observed influences of droughts and heat waves on crop production, yield and harvested area (columns) in rainfed and non-tropical systems. Results are shown for all crops aggregated (first row) and for soybeans, banana, tropical fruits, coffee and cocoa (second row). Mean event impact (%) is shown for the EWD years. “n” - number of droughts and heat waves considered in each normalised composite resampled 1000 times. The 1000 resampled normalised mean at the EWD is considered statistical significant for a level of significance up to 0.20 and not significant (n.s.) for higher than 0.20 (i.e., for confidence intervals below than 80%). For each EWD, the legend should read as: crop, mean event impact, number of selected events, level of significance.

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6.3 Appendix C

Drought and heatwave crop losses tripled over the last five decades in Europe

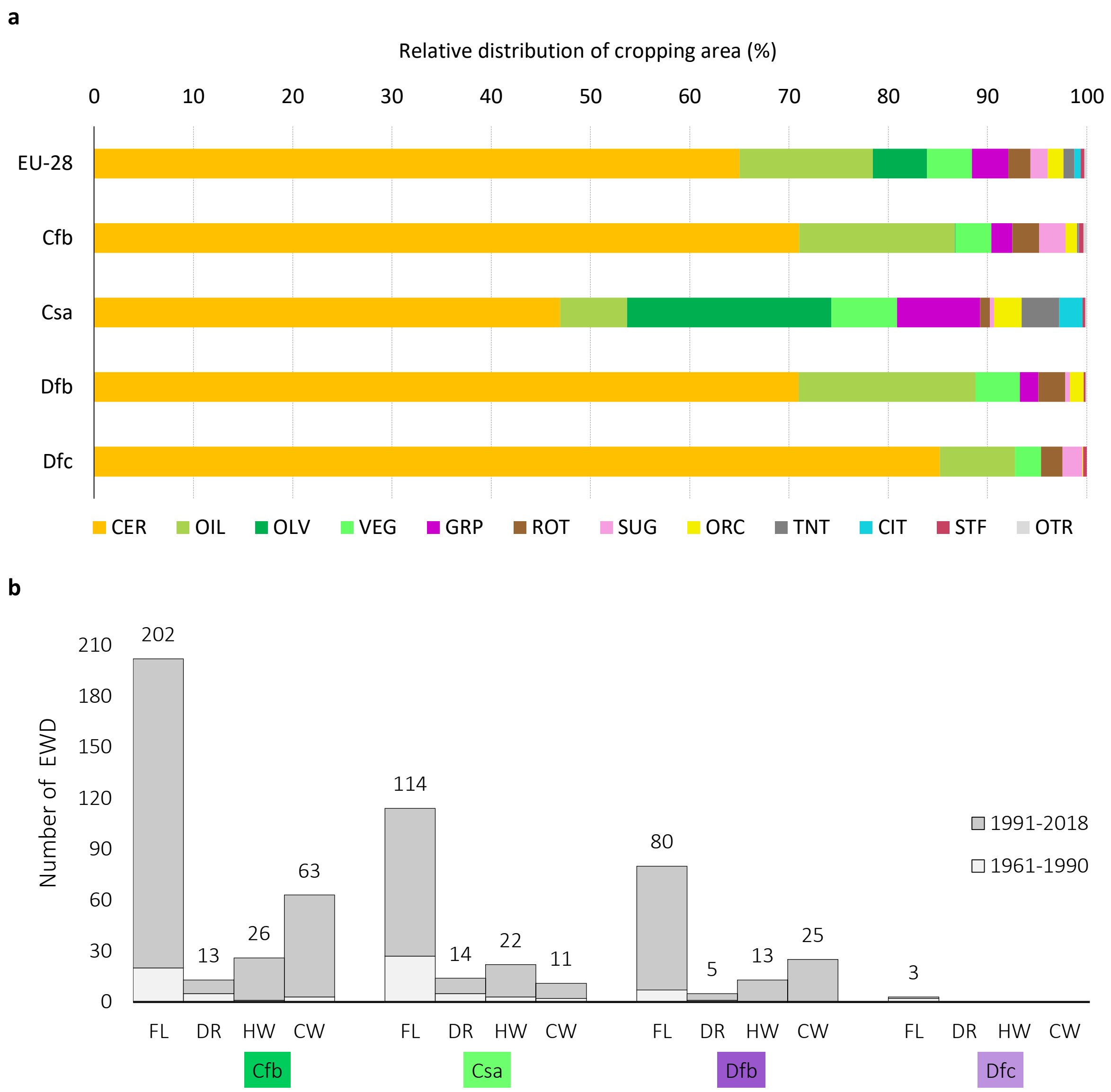


Figure C1. Relative distribution of cropping area by crops and climate region (a) Data is oriented from the highest to the lowest cropping area (%, averaged between 2008 and 2017) in the EU and in each dominant Koeppen-Geiger (KG) climate zones (Table C1, FAO, 2019 (FAO 2019)). Crop categories: cereals (CER), oil crops (OIL), olives (OLV), vegetables (VEG), grapes (GRP), roots and tubers (ROT), sugars (SUG), orchards (ORC), treenuts (TNT), citrus (CIT), soft fruits (STF) and other crops (OTR). **Number of extreme weather disasters (EWD) reported between 1961 and 2018 per climate region (b)** Data on EWD is taken from EM-DAT (EM-DAT 2018) and includes droughts (DR), heatwaves (HW), floods (FL), and cold waves (CW).

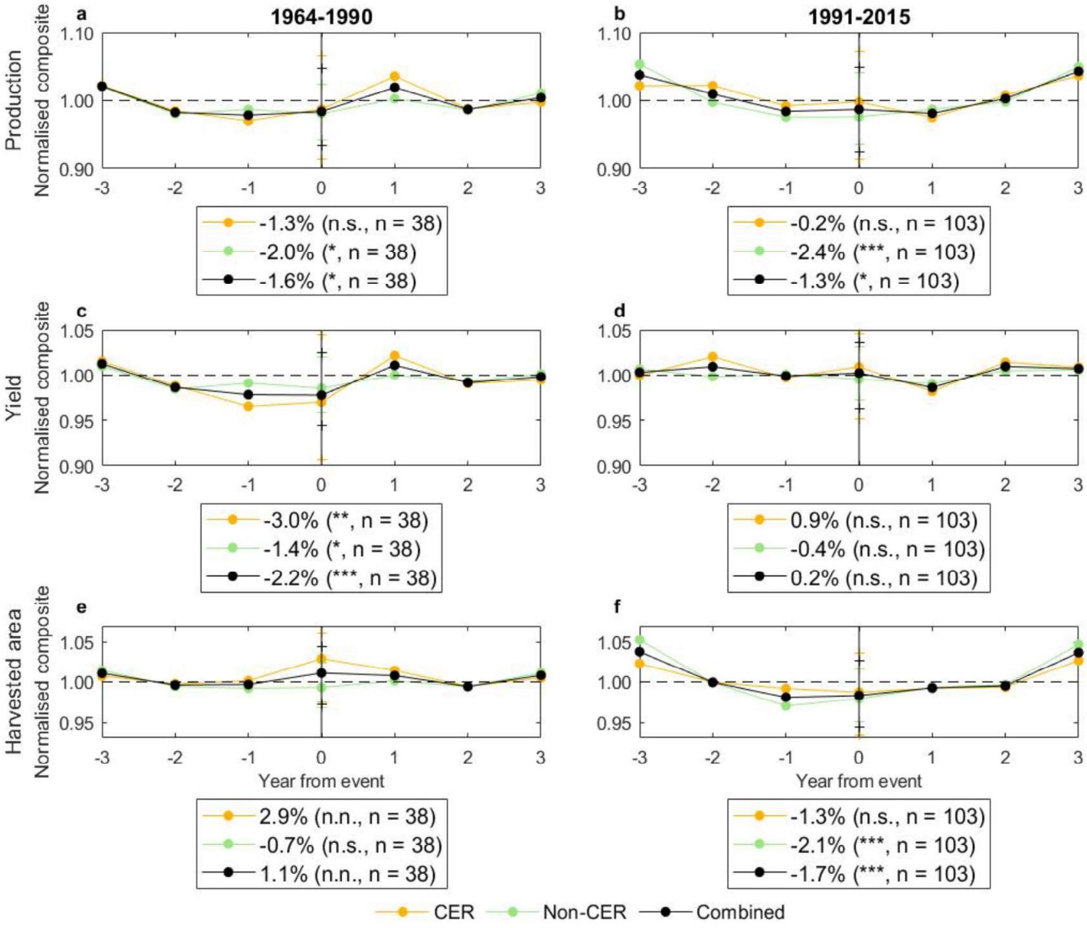


Figure C2. Flood crop responses in the first and second half of the observation record. The composite impact of cereal (CER), non-cereal (Non-CER) and both crop categories aggregated (Combined) is shown for production (1st row), yield (2nd row) and harvested area (3rd row), and is separated for the time slices 1964-1990 (1st column) and 1991-2015 (2nd column). Significance levels are as in Figure 4.1; n.n. if empirical bootstrapped distribution of the normalised mean is not normal (see Methods).

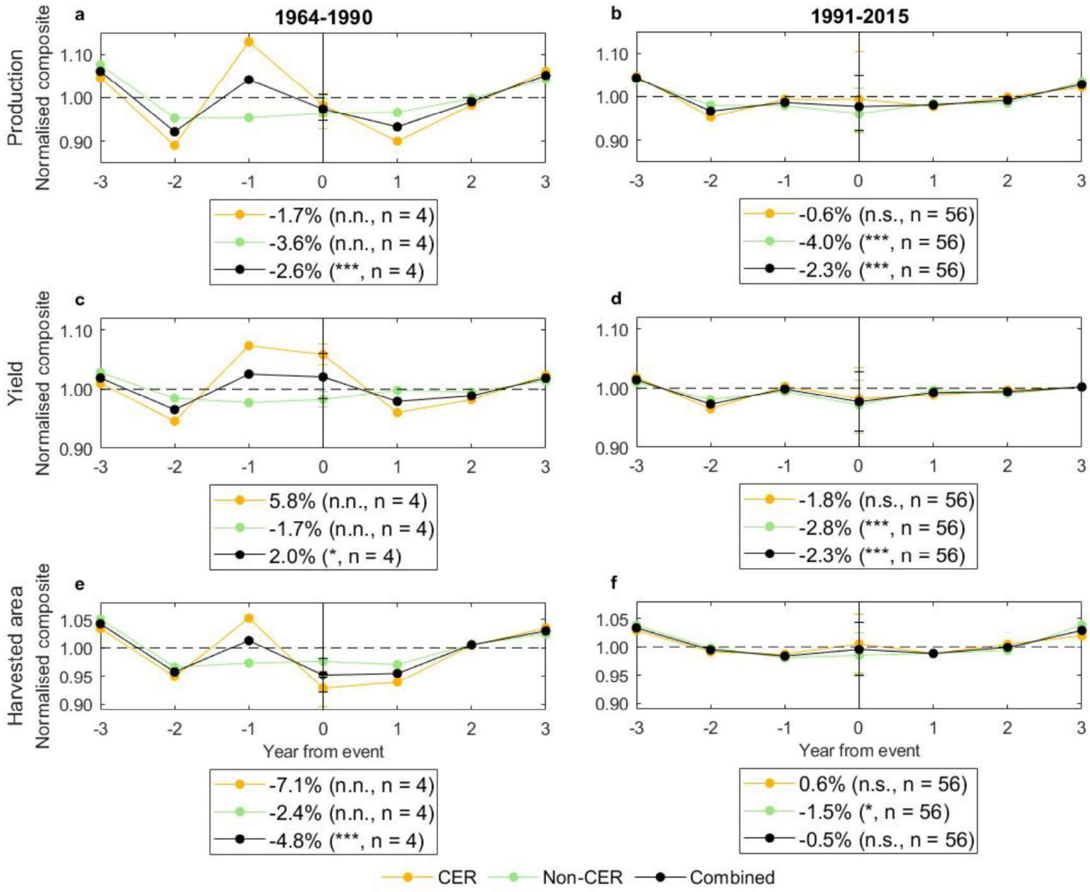


Figure C3. Cold wave crop responses in the first and second half of the observation record. The composite impact of cereal (CER), non-cereal (Non-CER) and both crop categories aggregated (Combined) is shown for production (1st row), yield (2nd row) and harvested area (3rd row), and is separated for the time slices 1964-1990 (1st column) and 1991-2015 (2nd column). Significance levels are the same as in Figure 4.1; n.n. if empirical bootstrapped distribution of the normalised mean is not normal (see Methods).

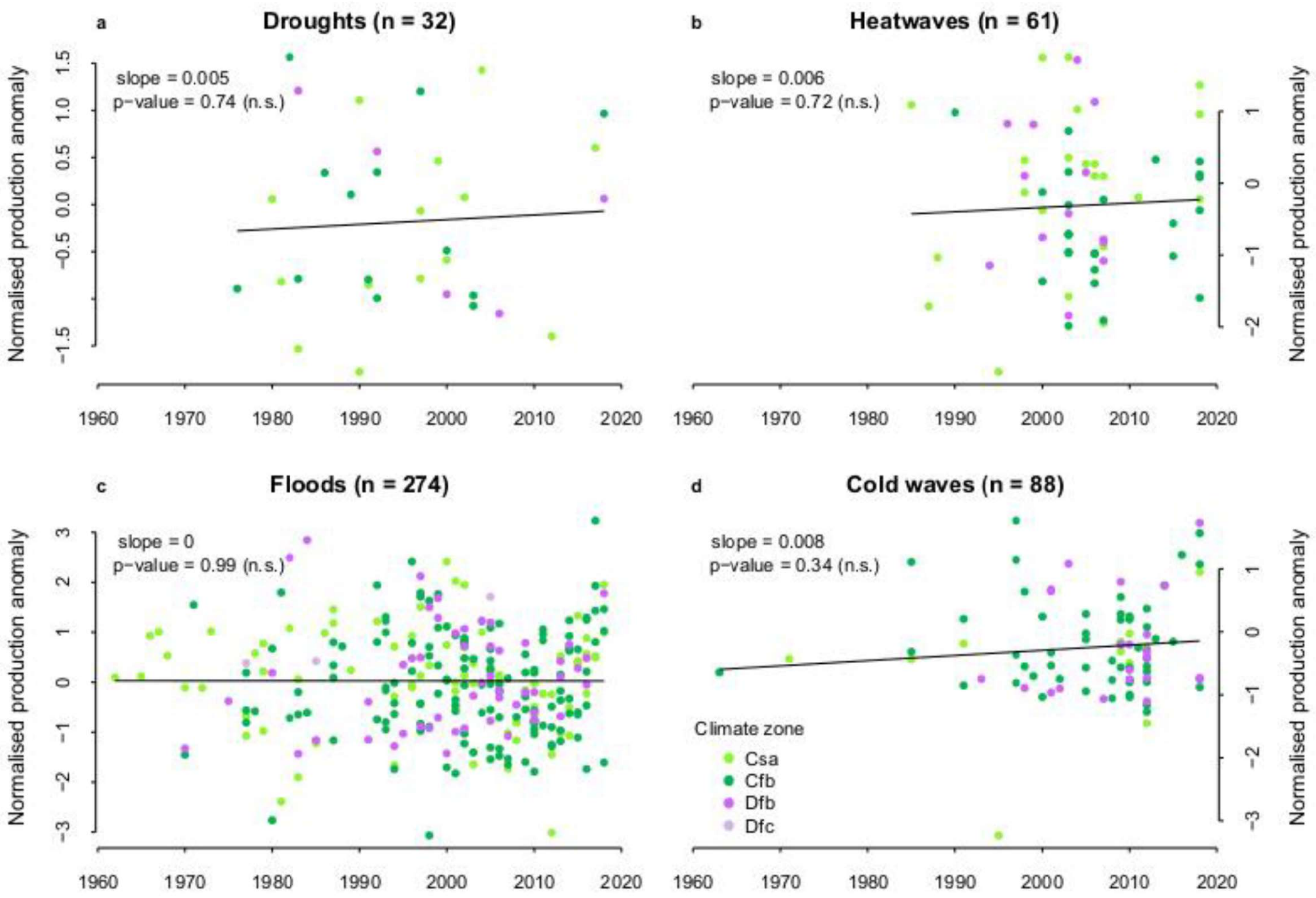
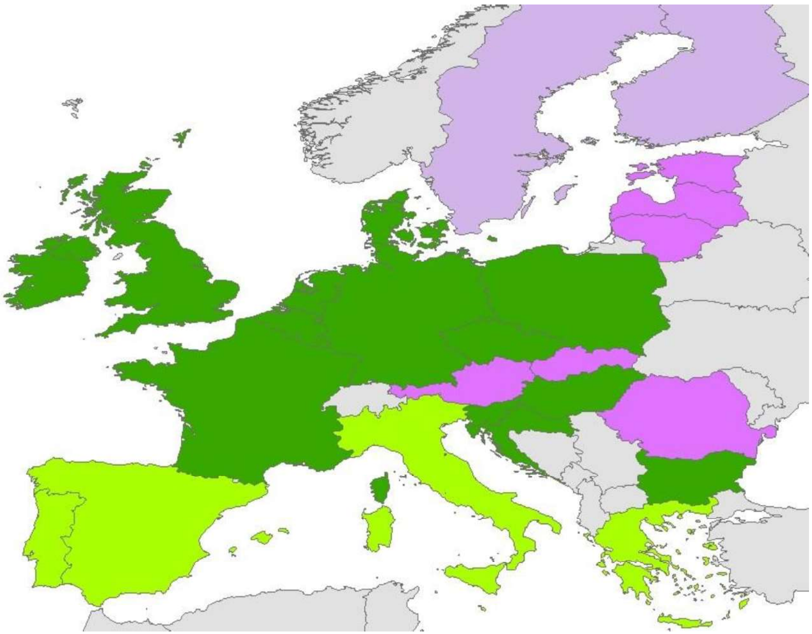


Figure C4. Non-cereal production anomalies during years of reported EWDs. Same as Figure 4.3 but for non-cereals.

Table C1. Dominant Koeppen-Geiger (KG) climate zones (Kottek *et al* 2006) considered for each EU Member State (ISO 3166 alpha-2). Cfb – Temperate oceanic climate; Csa – Hot-summer Mediterranean climate; Dfb – Warm-summer humid continental climate; and Dfc – Subarctic climate.



Country	ISO 3166 alpha 2	KG dominant classification	Country	ISO 3166 alpha 2	KG dominant classification
Austria	AT	Dfb	Italy	IT	Csa
Belgium	BE	Cfb	Latvia	LV	Dfb
Bulgaria	BG	Cfb	Lithuania	LT	Dfb
Croatia	HR	Cfb	Luxembourg	LU	Cfb
Cyprus	CY	Csa	Malta	MT	Csa
Czechia	CZ	Cfb	Netherlands	NL	Cfb
Denmark	DK	Cfb	Poland	PL	Cfb
Estonia	EE	Dfb	Portugal	PT	Csa
Finland	FI	Dfc	Romania	RO	Dfb
France	FR	Cfb	Slovakia	SK	Dfb
Germany	DE	Cfb	Slovenia	SI	Cfb
Greece	EL	Csa	Spain	ES	Csa
Hungary	HU	Cfb	Sweden	SE	Dfc
Ireland	IE	Cfb	United Kingdom	UK	Cfb

Table C2. Crop categories considered in this study based on the crops (129 in total) listed by FAOSTAT (FAO 2019).

Crop category	Category code	FAOSTAT designation
Cereals	CER	Barley
Cereals	CER	Buckwheat
Cereals	CER	Cereals nes
Cereals	CER	Grain, mixed
Cereals	CER	Maize
Cereals	CER	Millet
Cereals	CER	Oats
Cereals	CER	Rye
Cereals	CER	Sorghum
Cereals	CER	Triticale
Cereals	CER	Wheat
Cereals	CER	Rice, paddy
Cereals	CER	Canary seed
Cereals	CER	Quinoa
Citrus	CIT	Lemons and limes
Citrus	CIT	Oranges
Citrus	CIT	Tangerines, mandarins, clementines, satsumas
Citrus	CIT	Fruit, citrus nes
Citrus	CIT	Grapefruit (inc. pomelos)
Grapes	GRP	Grapes
Oil crops	OIL	Hemp tow waste
Oil crops	OIL	Linseed
Oil crops	OIL	Oil, palm
Oil crops	OIL	Oilseeds nes
Oil crops	OIL	Poppy seed
Oil crops	OIL	Rapeseed
Oil crops	OIL	Soybeans
Oil crops	OIL	Sunflower seed
Oil crops	OIL	Castor oil seed
Oil crops	OIL	Groundnuts, with shell
Oil crops	OIL	Hempseed
Oil crops	OIL	Melonseed
Oil crops	OIL	Mustard seed
Oil crops	OIL	Seed cotton
Oil crops	OIL	Sesame seed
Oil crops	OIL	Safflower seed
Olives	OLV	Olives
Orchards	ORC	Apples
Orchards	ORC	Apricots
Orchards	ORC	Cherries
Orchards	ORC	Cherries, sour
Orchards	ORC	Peaches and nectarines
Orchards	ORC	Pears
Orchards	ORC	Plums and sloes

Crop category	Category code	FAOSTAT designation
Orchards	ORC	Quinces
Orchards	ORC	Kiwi fruit
Orchards	ORC	Figs
Orchards	ORC	Avocados
Orchards	ORC	Bananas
Orchards	ORC	Fruit, tropical fresh nes
Orchards	ORC	Mangoes, mangosteens, guavas
Orchards	ORC	Persimmons
Orchards	ORC	Pineapples
Orchards	ORC	Dates
Other	OTR	Flax fibre and tow
Other	OTR	Hops
Other	OTR	Mushrooms and truffles
Other	OTR	Spices nes
Other	OTR	Vanilla
Other	OTR	Anise, badian, fennel, coriander
Other	OTR	Cotton lint
Other	OTR	Cottonneseed
Other	OTR	Pepper (piper spp.)
Other	OTR	Peppermint
Other	OTR	Carobs
Other	OTR	Agave fibres nes
Other	OTR	Pyrethrum, dried
Other	OTR	Tea
Other	OTR	Bastfibres, other
Other	OTR	Coffee, green
Roots and tubers	ROT	Carrots and turnips
Roots and tubers	ROT	Potatoes
Roots and tubers	ROT	Sweet potatoes
Roots and tubers	ROT	Roots and tubers nes
Roots and tubers	ROT	Taro (cocoyam)
Roots and tubers	ROT	Yams
Soft fruits	STF	Berries nes
Soft fruits	STF	Currants
Soft fruits	STF	Gooseberries
Soft fruits	STF	Raspberries
Soft fruits	STF	Strawberries
Soft fruits	STF	Blueberries
Soft fruits	STF	Cranberries
Soft fruits	STF	Fruit, fresh nes
Soft fruits	STF	Fruit, stone nes
Sugar	SUG	Sugar beet
Sugar	SUG	Sugar cane
Treenuts	TNT	Walnuts, with shell
Treenuts	TNT	Almonds, with shell

Crop category	Category code	FAOSTAT designation
Treenuts	TNT	Chestnut
Treenuts	TNT	Hazelnuts, with shell
Treenuts	TNT	Nuts nes
Treenuts	TNT	Pistachios
Treenuts	TNT	Coconuts
Vegetables	VEG	Asparagus
Vegetables	VEG	Beans, dry
Vegetables	VEG	Beans, green
Vegetables	VEG	Broad beans, horse beans, dry
Vegetables	VEG	Cabbages and other brassicas
Vegetables	VEG	Cauliflowers and broccoli
Vegetables	VEG	Chillies and peppers, green
Vegetables	VEG	Cucumbers and gherkins
Vegetables	VEG	Eggplants (aubergines)
Vegetables	VEG	Garlic
Vegetables	VEG	Leeks, other alliaceous vegetables
Vegetables	VEG	Lettuce and chicory
Vegetables	VEG	Lupins
Vegetables	VEG	Maize, green
Vegetables	VEG	Melons, other (inc.cantaloupes)
Vegetables	VEG	Onions, dry
Vegetables	VEG	Peas, dry
Vegetables	VEG	Peas, green
Vegetables	VEG	Pulses nes
Vegetables	VEG	Pumpkins, squash and gourds
Vegetables	VEG	Spinach
Vegetables	VEG	Tomatoes
Vegetables	VEG	Vegetables, fresh nes
Vegetables	VEG	Vegetables, leguminous nes
Vegetables	VEG	Vetches
Vegetables	VEG	Watermelons
Vegetables	VEG	Chicory roots
Vegetables	VEG	Onions, shallots, green
Vegetables	VEG	Chick peas
Vegetables	VEG	Chillies and peppers, dry
Vegetables	VEG	Lentils
Vegetables	VEG	Cow peas, dry
Vegetables	VEG	Artichokes
Vegetables	VEG	Okra
Vegetables	VEG	String beans

Table C3. List of the year, country (ISO2 code of the EU members) and type of extreme weather disasters reported by the EM-DAT (EM-DAT 2018) **data base between 1961 to 2018.** The EWD considered in the composite analysis (Fig. 4.1 and 4.2) are indicated in black, while the ones in grey are excluded (see Methods). The first and last 3 years of the data record are omitted for the compositing, but are included in the time series in Figures 4.3 and 4.4. Since there are years with more than one EWD of the same type in the same country, the total number of floods is 399(*) and cold waves 99 (**), which for simplicity are not listed in the table.

Droughts			**Heatwaves**				**Floods**																**Cold waves**					
(n=28 from 32)			(n=47 from 61)				(n=141 from 274*)																(n=60 from 88**)					
1	1976	BE	2003	AT	2011	IT	1980	AT	2018	BG	2007	EL	1983	FR	2002	HU	2015	IT	1970	RO	2005	SK	2009	AT	2012	HR	1998	RO
2	1983	BG	2007	AT	2018	IT	1982	AT	1996	CZ	2010	EL	1987	FR	2004	HU	2016	IT	1975	RO	2006	SK	2012	AT	2001	HU	2001	RO
3	2000	BG	2003	BE	1999	LT	1983	AT	1997	CZ	2012	EL	1988	FR	2005	HU	2017	IT	1984	RO	2010	SK	1963	BE	2008	HU	2002	RO
4	1991	CY	2006	BE	2003	LU	1985	AT	1998	CZ	2014	EL	1992	FR	2006	HU	2018	IT	1991	RO	2013	SK	1985	BE	2012	HU	2007	RO
5	2000	CY	2015	BE	2003	NL	1991	AT	2000	CZ	2015	EL	1993	FR	2010	HU	2005	LT	1994	RO	1977	UK	2005	BE	2009	IT	2009	RO
6	1992	DK	2018	BE	2006	NL	1995	AT	2002	CZ	2016	EL	1994	FR	2013	HU	2010	LT	1995	RO	1993	UK	2009	BE	2010	IT	2010	RO
7	1990	EL	2000	BG	2018	NL	1996	AT	2005	CZ	2017	EL	1996	FR	2014	HU	1983	LU	1997	RO	1994	UK	2012	BE	2012	IT	2012	RO
8	1980	ES	2007	BG	2003	PT	1997	AT	2006	CZ	1962	ES	1999	FR	2016	HU	1993	LU	1998	RO	1997	UK	1998	BG	2018	IT	2014	RO
9	1981	ES	1998	CY	2005	PT	1999	AT	2009	CZ	1972	ES	2000	FR	1987	IE	1992	NL	1999	RO	1998	UK	2000	BG	2001	LT	2018	RO
10	1990	ES	2000	CY	2006	PT	2002	AT	2010	CZ	1973	ES	2001	FR	1993	IE	1993	NL	2000	RO	1999	UK	2008	BG	2010	LT	2010	SK
11	1999	ES	2007	CY	2018	PT	2005	AT	2013	CZ	1978	ES	2002	FR	2002	IE	1998	NL	2001	RO	2000	UK	2010	BG	2012	LT	2012	SK
12	1982	FR	2003	CZ	1994	RO	2006	AT	1992	DE	1979	ES	2003	FR	2009	IE	1977	PL	2002	RO	2001	UK	2012	BG	2018	LT	1991	UK
13	1989	FR	2003	DE	1996	RO	2009	AT	1993	DE	1982	ES	2005	FR	2011	IE	1980	PL	2003	RO	2002	UK	2010	CZ	2001	LV	1997	UK
14	1991	FR	2006	DE	1998	RO	2013	AT	1994	DE	1983	ES	2010	FR	2017	IE	1982	PL	2004	RO	2004	UK	2012	CZ	2003	LV	2005	UK
15	1997	FR	2018	DE	2000	RO	2016	AT	1997	DE	1987	ES	2011	FR	1965	IT	1987	PL	2005	RO	2007	UK	2018	CZ	2012	LV	2009	UK
16	2003	HR	1985	EL	2004	RO	1971	BE	1999	DE	1989	ES	2013	FR	1966	IT	1997	PL	2006	RO	2008	UK	1997	DE	2005	NL	2010	UK
17	1986	HU	1987	EL	2005	RO	1984	BE	2002	DE	1994	ES	2014	FR	1968	IT	1998	PL	2007	RO	2009	UK	2005	DE	2012	NL		
18	1992	HU	1988	EL	2006	RO	1987	BE	2005	DE	1996	ES	2015	FR	1970	IT	2001	PL	2008	RO	2012	UK	2009	DE	1997	PL		
19	2003	HU	2000	EL	2007	RO	1993	BE	2006	DE	1997	ES	2016	FR	1977	IT	2004	PL	2009	RO	2013	UK	2010	DE	1998	PL		
20	1997	IT	2007	EL	2003	SI	1994	BE	2007	DE	2000	ES	2017	FR	1985	IT	2005	PL	2010	RO	2014	UK	2012	DE	1999	PL		
21	2002	IT	1995	ES	2003	SK	1998	BE	2009	DE	2002	ES	2018	FR	1986	IT	2006	PL	2013	RO	2015	UK	2012	EE	2000	PL		
22	2012	IT	2003	ES	2007	SK	2002	BE	2010	DE	2004	ES	2000	HR	1987	IT	2009	PL	2014	RO	2017	UK	2018	EE	2001	PL		
23	2017	IT	2004	ES	2003	UK	2003	BE	2011	DE	2006	ES	2001	HR	1992	IT	2010	PL	2015	RO			1991	EL	2002	PL		
24	1992	LT	2006	ES	2013	UK	2005	BE	2013	DE	2007	ES	2005	HR	1994	IT	2016	PL	2016	RO			2012	EL	2008	PL		
25	2006	LT	2018	ES	2018	UK	2010	BE	2016	DE	2010	ES	2006	HR	1996	IT	1967	PT	2018	RO			1971	ES	2009	PL		
26	2018	LT	1990	FR			2011	BE	2017	DE	2011	ES	2010	HR	2000	IT	1979	PT	1977	SE			1985	ES	2010	PL		
27	2018	PL	2003	FR			2016	BE	1977	EL	2012	ES	2012	HR	2001	IT	1981	PT	1985	SE			1995	ES	2011	PL		
28	1983	PT	2006	FR			1997	BG	1979	EL	2013	ES	2014	HR	2002	IT	1983	PT	2005	SI			1985	FR	2012	PL		
29	1997	PT	2015	FR			2002	BG	1994	EL	2015	ES	2015	HR	2003	IT	1996	PT	2012	SI			1991	FR	2013	PL		
30	2004	PT	2018	FR			2005	BG	1997	EL	2016	ES	2018	HR	2008	IT	2001	PT	2014	SI			1997	FR	2014	PL		
31	1983	RO	2000	HR			2006	BG	1998	EL	2018	ES	1970	HU	2009	IT	2002	PT	1997	SK			2005	FR	2015	PL		
32	2000	RO	2003	HR			2007	BG	2000	EL	2005	FI	1996	HU	2010	IT	2003	PT	1998	SK			2009	FR	2016	PL		
33			2007	HU			2010	BG	2001	EL	1977	FR	1997	HU	2011	IT	2006	PT	1999	SK			2010	FR	2018	PL		
34			1998	IT			2012	BG	2002	EL	1978	FR	1999	HU	2012	IT	2008	PT	2001	SK			2012	FR	2009	PT		
35			2003	IT			2014	BG	2003	EL	1980	FR	2000	HU	2013	IT	2010	PT	2002	SK			2018	FR	2010	PT		
36			2007	IT			2015	BG	2006	EL	1981	FR	2001	HU	2014	IT	2015	PT	2004	SK			2010	HR	1993	RO		

Table C4. Composite floods impact by crops and climate region. Observed production, yield and harvested area (H. area) impacts (%) associated with floods are separated for the EU level and for each Koeppen-Geiger (KG) region (Kottek *et al* 2006) between 1964 and 2015. Results are shown for major crop categories, ordered by the respective fraction of the total EU cropping area. Average event impacts are shown (red if negative, green if positive) if statistically significant (*** if *alpha* < 0.05, ** if *alpha* < 0.10, * if *alpha* < 0.2, n.s. for not significant if *alpha* ≥ 0.2) ; n.n. if empirical bootstrapped distribution of the normalised mean is not normal. Statistical significance is based on 1000 bootstrap samples (see Methods). Column n indicates the number of events. Blank cells mean that a crop is not grown in the respective KG region.

Crops	European Union-28				Cfb - Temperate oceanic climate				Csa - Hot-summer Mediterranean climate				Dfb - Warm-summer humid continental climate				Dfc - Subarctic climate			
	Production	Yield	H.area	n	Production	Yield	H.area	n	Production	Yield	H.area	n	Production	Yield	H.area	n	Production	Yield	H.area	n
CEREALS	**-0.4 n.s.**	**0 n.s.**	**-0.2 n.s.**	**141**	**-0.9 n.s.**	**-0.3 n.s.**	**-0.6 n.s.**	**72**	**1.6 n.s.**	**1.2 ***	**-0.1 n.s.**	**42**	**-1.8 n.s.**	**-0.8 n.s.**	**0.6 n.n.**	**24**	**-7.1 ***	**-6.7 n.n.**	**-0.3 n.s.**	**3**
Wheat	1 n.s.	0 n.s.	0.6 n.s.	141	-1 n.s.	-1.5 **	0.5 n.s.	72	4.1 n.s.	2.8 n.s.	0 n.s.	42	1.2 n.s.	-0.1 n.s.	1.1 n.s.	24	1.1 n.n.	-4.8 n.n.	6.6 n.n.	3
Barley	-1.1 n.s.	-0.4 n.s.	-1.1 n.s.	141	-3.4 ***	-2.1 ***	-1.7 **	72	2.4 n.s.	2.8 n.s.	-0.7 n.s.	42	-0.9 n.s.	-0.7 n.s.	-0.4 n.s.	24	2.4 n.n.	-2.2 n.n.	4.8 n.n.	3
Maize	1.7 n.s.	2.5 ***	-0.3 n.s.	128	5.3 ***	4.6 ***	1.3 n.s.	62	-1.8 n.s.	-1.6 **	-0.3 n.s.	42	-1.4 n.s.	4 n.s.	-4.3 ***	24				
Other cereals	-0.8 n.s.	-0.3 n.s.	-0.3 n.s.	141	-1.4 n.s.	-0.5 n.s.	-0.9 n.s.	72	1.6 n.s.	1.2 n.s.	0.1 n.s.	42	-2.7 n.s.	-1.8 n.s.	1.6 n.n.	24	-12.4 ***	-8.7 ***	-3.9 n.s.	3
NON-CEREALS	**-2.1 *****	**-0.4 ***	**-1.8 *****	**141**	**-3.3 *****	**-0.8 *****	**-2.4 *****	**72**	**-1 *****	**0.2 n.s.**	**-1.4 *****	**42**	**-2 ***	**-0.8 n.s.**	**-1.3 n.s.**	**24**	**8.1 *****	**3.4 ***	**4.7 ****	**3**
Oil crops	-2.1 *	0.7 n.s.	-2.3 *	141	3.3 *	-1.2 *	4.8 ***	72	-8.5 ***	1.4 n.s.	-9.4 ***	42	-4.6 *	4 **	-7.5 ***	24	0 n.n.	8.4 n.n.	-6.7 n.n.	3
Olives	2 n.s.	1.9 n.s.	-0.2 n.s.	52	0.5 n.s.	0.8 n.s.	-0.8 n.s.	18	2.8 n.s.	2.5 n.s.	0.2 n.s.	34								
Vegetables	-2.1 ***	-0.3 n.s.	-2.1 ***	141	-4 ***	0.1 n.s.	-4 ***	72	-0.1 n.s.	-0.5 *	-0.2 n.s.	42	-1.9 n.s.	-1.2 *	-1.4 n.s.	24	5 *	0.1 n.s.	5.9 *	3
Grapes	-1.5 n.s.	-0.7 n.s.	-1.4 *	122	-4.9 *	-3.5 **	-2.3 n.s.	58	4.4 **	4.9 ***	-0.5 n.n.	42	-4.2 n.s.	-4.2 n.s.	-1 n.s.	22				
Roots & tubers	-1.6 **	-1 *	-1 n.s.	141	-2.5 **	0 n.s.	-2.8 ***	72	-0.3 n.s.	-1.4 **	0.7 n.s.	42	-4.3 *	-3.7 **	-1.6 n.s.	24	9.5 n.n.	5.1 ***	3.8 n.n.	3
Sugar	-0.8 n.s.	0.1 n.s.	-1.7 n.s.	136	1.8 n.s.	-0.5 n.s.	1.3 n.s.	67	-7.5 ***	0 n.s.	-7.4 ***	42	8.1 ***	2.2 n.s.	3.9 *	24	12.9 n.n.	0.3 n.n.	11.5 n.n.	3
Orchards	-3 ***	-1.9 ***	-1.3 ***	131	-6.4 ***	-3.4 ***	-2.7 ***	68	-0.4 n.s.	0.2 n.s.	-0.9 **	42	-1.7 n.s.	-4.8 **	2.4 n.s.	19	9.8 n.n.	7.5 n.n.	2.4 n.n.	2
Treenuts	-1.9 n.s.	-0.4 n.s.	-2.2 **	97	-3.1 n.s.	-2.8 n.s.	-0.9 n.s.	48	0.6 n.s.	2 *	-2.2 ***	40	-21.4 ***	-8.7 *	-11.9 *	9				
Citrus	-1.1 n.s.	0 n.s.	-1.8 *	57	-12.7 ***	-1.8 n.s.	-11.2 ***	15	2.1 *	0.5 n.s.	0.8 n.s.	42								
Soft fruits	-1 n.s.	-0.8 n.s.	-0.1 n.s.	137	-2.9 **	-0.4 n.s.	-2.5 ***	71	-2.1 *	-2.2 ***	1.3 n.s.	42	4.9 n.s.	-1.3 n.s.	5 n.s.	21	23.4 n.n.	13.6 n.n.	4.7 *	3
Other crops	-3.6 ***	1.4 *	-3 **	138	-5.3 ***	-0.6 n.s.	-4.7 ***	72	-1.9 n.s.	3.1 *	-2.2 n.s.	42	-3.8 n.s.	2 n.s.	-0.7 n.s.	24				

Table C5. Composite cold waves impact by crops and climate region. Observed production, yield and harvested area (H. area) impacts (%) associated with cold waves are separated for the EU level and for each Koeppen-Geiger (KG) region (Kottek *et al* 2006) between 1964 and 2015. Results are shown for major crop categories, ordered by the respective fraction of the total EU cropping area. Average event impacts are shown (red if negative, green if positive) if statistically significant (*** if *alpha* < 0.05, ** if *alpha* < 0.10, * if *alpha* < 0.2, n.s. for not significant if *alpha* ≥ 0.2) ; n.n. if empirical bootstrapped distribution of the normalised mean is not normal. Statistical significance is based on 1000 bootstrap samples (see Methods). Column n indicates the number of events. Blank cells mean that a crop is not grown in the respective KG region.

Crops	European Union-28				Cfb - Temperate oceanic climate				Csa - Hot-summer Mediterranean climate				Dfb - Warm-summer humid continental climate			
	Production	Yield	Harvested area	n	Production	Yield	Harvested area	n	Production	Yield	Harvested area	n	Production	Yield	Harvested area	n
CEREALS	**-0.8 n.s.**	**-1.3 ****	**0.1 n.s.**	**60**	**3.6 *****	**2.2 *****	**1.3 n.s.**	**34**	**-7 ***	**-5.4 *****	**-2.6 n.s.**	**8**	**-6.4 ****	**-6.4 *****	**-1.2 n.s.**	**18**
Wheat	-2.3 *	-5 ***	0.8 n.s.	60	1.9 n.s.	1 n.s.	1 *	34	-0.3 n.n.	1 n.n.	-0.8 n.n.	8	-11.1 ***	-11.4 ***	1.1 n.s.	18
Barley	-3.5 *	-2.6 ***	-1.3 n.s.	60	3.2 *	2.2 *	0.5 n.s.	34	-4.9 n.n.	-0.5 n.n.	-3.6 n.n.	8	-15.4 ***	-12.7 ***	-3.7 *	18
Maize	-3.6 *	-4.5 ***	1.7 n.s.	52	-2.4 n.s.	-4.1 *	3 ***	30	-1 n.n.	-1.8 n.n.	1 n.n.	8	-7.8 *	-7 **	-0.8 n.s.	14
Other cereals	0.3 n.s.	-0.4 n.s.	-0.1 n.s.	60	4.8 ***	3.3 ***	1.2 n.s.	34	-9.3 *	-7.7 ***	-3.3 n.s.	8	-3.9 n.s.	-4.4 ***	-1.2 n.s.	18
NON-CEREALS	**-4.1 *****	**-2.6 *****	**-1.8 *****	**60**	**-3 *****	**-1.2 *****	**-1.7 *****	**34**	**-4.1 *****	**-1.6 *****	**-2.9 *****	**8**	**-6.4 *****	**-6 *****	**-1.2 n.s.**	**18**
Oil crops	-9.6 ***	-3.7 ***	-6.7 ***	60	-3.4 n.s.	0.3 n.s.	-4.1 *	34	-21.2 ***	-2.9 n.s.	-17.6 ***	8	-15.9 ***	-11.8 ***	-6.3 **	18
Olives	5.2 n.s.	5 n.s.	-0.2 n.s.	15	14.8 *	14.2 *	-0.2 n.s.	8	-5.8 n.n.	-5.5 n.n.	-0.2 n.n.	7				
Vegetables	-2 ***	-1.3 ***	-0.7 n.s.	60	-1.3 n.s.	0.2 n.s.	-1.5 *	34	-0.2 n.s.	0.3 n.s.	-0.5 n.s.	8	-4.6 ***	-5.2 ***	1 n.s.	18
Grapes	-6 ***	-6.2 ***	-1 n.s.	51	-4.7 n.s.	-5.2 ***	-1.2 n.s.	32	-7.1 n.n.	-6.4 n.n.	-1 n.s.	8	-9 *	-9.2 ***	-0.4 n.n.	11
Roots & tubers	0 n.s.	-0.1 n.s.	-0.6 n.s.	60	1.8 n.s.	1.2 n.s.	0.7 n.s.	34	-0.4 n.s.	-0.1 n.s.	-2.2 n.s.	8	-3.4 n.s.	-2.6 n.s.	-2 n.s.	18
Sugar	-4.2 **	-2.9 ***	-1.9 n.s.	55	-3.4 **	-1.6 n.s.	-1.7 n.s.	31	-10.3 *	-4.7 *	-8.5 n.n.	8	-1.5 n.s.	-4.1 **	2.6 n.s.	16
Orchards	-7 ***	-6.9 ***	-0.6 n.s.	60	-9.6 ***	-9.9 ***	0.8 n.s.	34	-3.9 ***	-3.1 **	-0.9 n.s.	8	-4 n.s.	-3.4 n.s.	-3.5 **	18
Treenuts	-9.2 ***	-5.9 ***	-2.5 n.s.	44	-7.6 **	-5.6 *	0.9 n.n.	27	-3.1 n.s.	-4.6 *	-0.1 n.s.	8	-26.6 ***	-9.1 **	-19.9 ***	9
Citrus	-5.4 ***	-2.3 n.s.	-5.4 ***	16	-7.6 **	0.4 n.s.	-13.1 ***	8	-3.6 **	-4.4 ***	0.7 n.s.	8				
Soft fruits	-4 ***	-2.7 ***	-1.7 *	60	-3.3 **	-1.5 n.s.	-1.8 *	34	-4.3 **	-2.3 *	-2.8 n.s.	8	-5 n.s.	-4.8 **	-1.3 n.s.	18
Other crops	-0.7 n.s.	1.8 n.s.	-2.8 n.s.	59	1.6 n.s.	7.6 ***	-5.4 ***	34	-6.5 n.s.	1.8 n.s.	-9 *	8	-0.8 n.s.	-8.2 **	5.7 n.s.	17

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