Climate change impacts on European crop production

A literature review

Sophia Lüttringhaus, Steffen Noleppa,
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Sophia Lüttringhaus, Steffen Noleppa
(HFFA Research)

and

Christoph Gornott, Hermann Lotze-Campen
(Potsdam Institute for Climate Impact Research)

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List of abbreviations

CMIP – Coupled Model Intercomparison Project

EEA – European Environment Agency

FAO – Food and Agriculture Organization

GCM – General Circulation Models

GISS – Goddard Institute for Space Studies

IPCC – Intergovernmental Panel on Climate Change

NASA – National Aeronautics and Space Administration

PIK – Potsdam Institute for Climate Impact Research

PPP – Plant Protection Product

RCP – Representative Concentration Pathways

UK – United Kingdom

UN – United Nations

WMO – World Meteorological Organization

Executive summary

The global and European agriculture faces multiple challenges. A growing world population in combination with a significant rise in per capita consumption of agricultural goods force farmers to produce ever more with less inputs. Consequently, agricultural supply will have to increase substantially. Increasing agricultural production through yield enhancements, however, is a challenging effort, especially because of adverse climate change impacts.

Recent extreme weather events such as extreme heat, dry spells or massive rains during summer months have made climate change and its impacts to be among the top headlines in the news. This has increased peoples' consciousness regarding the topic, but people working with and within the agricultural sector have already established it for a long time, as they have been facing climate impacts for decades. The above-mentioned extremes are in line with the latest report of the Intergovernmental Panel on Climate Change (IPCC) projecting that extreme weather events such as high temperature extremes, meteorological droughts and heavy precipitation will increase substantially in frequency and intensity in the future. Thus, it will be crucial for the agricultural sector to adapt to these fast changes and also to mitigate its own effects on the climate.

As climate change is a very fast changing and complex phenomenon, it is vital for farmers and all stakeholders along the food value chain to have up to date knowledge on how climate change is affecting their production systems and management strategies. Therefore, this study provides a broad overview of current and future climate change conditions as well as their impacts on European crop production. We describe the spatially and temporarily heterogeneous effects on this region and highlight areas which are particularly vulnerable to climate change. As weed management is of special interest in plant production, we analyse in detail how the crop-weed interaction changed and will continue to change in the future. For this purpose, we analysed current literature to condense the most important patterns of climate change impacts.

Climate change manifests itself in rising temperatures as well as structural changes in precipitation patterns and overall water availability. The climate has already changed in Europe and worldwide and the consequences are diverse impacts over time and space. Global annual near-surface temperature has increased by nearly 1 °C during the recent decades as compared to preindustrial levels. The latest decade has been the warmest on record. An approach to describe these climate shifts is the concept of climate analogues, which compares the projected future climate of a city to the current climate of another city. For example, with unabated climate change in 2071-2100 Berlin is likely to have the present climate of Saragossa. And as a general rule one can say that precipitation levels will increase in Northern Europe and decrease

in the South. Another effect of climate change is that the probability of occurrence and intensity of extreme weather events increases. Thus, such extreme summers as the one in 2018 will be more likely and longer in the future.

Climate change also considerably impacts water availability and irrigation demand. Despite the temporal and spatial shifts of rain fall patterns and a higher likelihood of extreme rainfall or drought events, another straightforward condition is important to note. As global and local temperatures rise, plants' evapotranspiration also increases which means that plants lose more water which will have to be compensated for by rainfall. And if precipitation decreases plants' will sooner face water stress.

These current and future effects make it clear that agricultural systems have to change. Climate change has led and will further lead to systematic problems such as irreversible environmental degradation. The impacts vary regionally and are very complex as many climate systems are interlinked and feed back into one another. Thus, the overall climate system has to be taken into account when projecting climate change impacts on agricultural production. Depending on the climate model, yield decreases are projected to be very high in the far West of the continent, on the Iberian Peninsula, in Italy and in the Balkans, whereas yield increases are forecasted mainly for Scandinavia and some parts of Central and Eastern Europe. Furthermore, climate change will affect the growing season length and crop life cycle. Since 1992 the thermal growing season has already expanded by 10 days and this trend continues. Also, crops' phenology has changed, visible by e.g. earlier flowering dates. Additionally, a habitat shift or habitat expansion occurs as thermophile crops move northwards. One example is the expansion of the ecological niche of maize due to increasing average temperatures.

Not only crops, but also weed plants shift their habitat and expand their seasonal activity. Consequently, the damage to specific cropping systems by weeds will change over time and across space. The shift of weeds' geographic niche, the overall area suitable for the specific weed species, and the damage niche, where the weed can grow and also possibly damage a crop, is also affected by climate change. Climate change effects can cause morpho-physiological and anatomical changes in plants (e.g. waxy leaf surface), which can alter nutrient and plant protection uptake. Hence, herbicide application is difficult under arid conditions as moisture is needed for product uptake by weed plants and soil incorporation. Moreover, dry conditions decrease microbial processes and often reduce plant health of the weed and also main crop, which increases the risk for crop injury.

Another aspect of climate change is the increasing level of CO_2 which can have positive yield effects due to CO_2 fertilization. Nevertheless, it is difficult to quantify the exact net effect taking into account other climate change effects on yields.

Following an increased occurrence and intensity of extremes, climate change impacts will increase soil erosion and reduce soil fertility, too. In particular rainfall induced soil erosion will occur more often and wind erosion will enhance around the Baltic sea and in arid regions such as the Mediterranean and Central-East Europe.

Based on this meta-analysis of climate change impacts, the report comes to the following recommendations for action. It is crucial to adapt to and mitigate climate change to uphold agricultural activity and thus farmers' livelihoods, but also to sustain consumer welfare. Concrete measures should be site-specific, cost-efficient and scalable. To help farmers cope with the risks posed by climate change, the information and knowledge loop between farmers, input suppliers (incl. breeders, plant protection), consulting and extension services as well as science has to be constantly updated to ensure timely, efficient and optimal knowledge transfer and thus practical implementation of suitable climate-resilient measures. In addition, more public funding should be provided for analysing climate change impacts on agriculture and creating innovations in climate-resilient agriculture (e.g. plant breeding, resilient cropping systems) as well as mitigating the negative effects for farmers. Farmers should be able to choose from a pool of measures and pick those that are most effective for their farm.

Our synthesis shows that climate change has already affected agricultural production systems and that overall negative effects will aggravate in the future, if climate change continues unabated. Thus, all agricultural stakeholders need to be prepared so that future supply of agricultural goods is ensured.

1 Introduction: Purpose and structure of this study

The global and European agriculture faces multiple challenges. A growing world population – by 2050 mankind is expected to have risen to about 10 billion (UN, 2015) – in combination with a significant rise in per capita consumption of food, feed, fibre, bio-energy, and other goods of the bio-economy force farmers to produce ever more with less inputs. Consequently, agricultural supply will have to increase at least by the same pace as demand. This is a major challenge as food demand is expected to increase by approximately 60 to 100 percent until the mid of the 21st century (Valin et al., 2014). Increasing agricultural production through yield enhancements, however, is a challenging effort, especially because of increasing climate change impacts.

Crop farming produces a manifold of primary resources used further up the agricultural value chain. Therefore, in this study we will analyse the impacts climate change has had – and will have in the future – on crop production in Europe which is an important region for global agricultural production. As proper weed management is one important challenge for maintaining and increasing yields in crop production, we decided to particularly present some more insights on weed-crop interactions in this study.

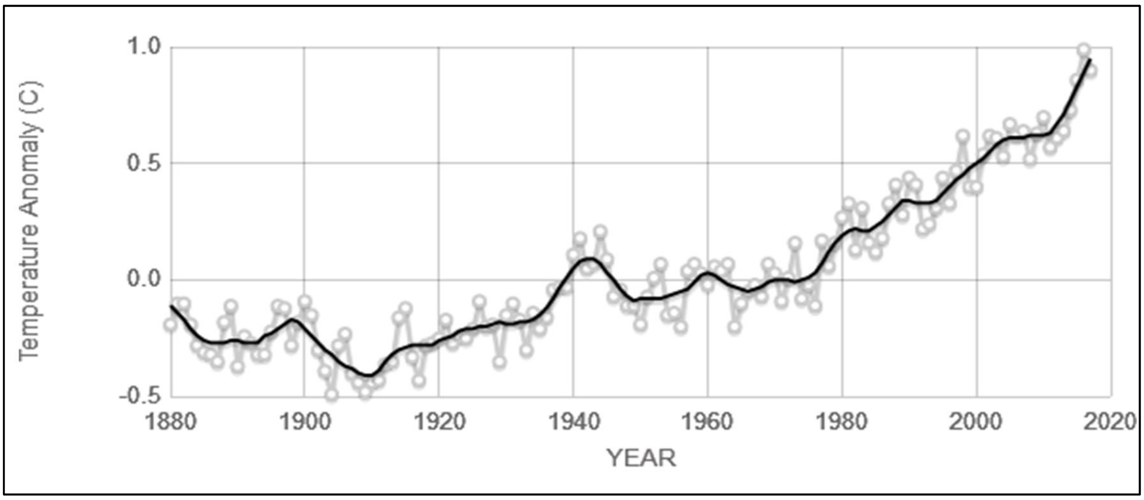
The study is structured as follows. First, we present an overview of climatic changes which have already been observed in Europe, as well as those that are projected to happen in the future (chapter 2). Therefore, we first describe the changes regarding temperature and precipitation patterns (sub-chapter 2.1) and then discuss the heterogenous regional patterns of future climate change effects in Europe (sub-chapter 2.2). Chapter 3 explains in more detail how different climate change impact pathways may affect crop production. After describing the general impacts (3.1), the alternation in growing season length, crop life cycle timing and habitat shift are explained in more detail (3.2), then impacts of increased CO_2 levels are discussed (3.3), followed by a description of climate change induced changes in weed-crop interactions (3.4), water availability (3.5), and erosion effects (3.6). Chapter 4 provides insights into different climate models applied in the literature, as well as their agreements and limitations. Chapter 5 concludes the study and introduces strategies for holistically tackling climate change impacts related to European crop production.

2 Observed and projected change impacts in Europe

2.1 Changes in temperature and precipitation patterns

On average, the global annual near-surface (land and ocean) temperature has increased by about 0.9 °C during the decade from 2008 to 2017 as compared to pre-industrial levels in the middle of the 19th to early 20th century (NASA GISS, 2018). Figure 2.1 shows this steep increase of global near-surface temperature.

Figure 2.1: Change in global near-surface temperature relative to 1951-1980, average temperature anomalies



Source: NASA GISS (2018).

Considering the same time period, land temperature increased by 1.6 to 1.7 °C in Europe (EEA, 2018). Not only here, the latest decade has been the warmest decade on record. This is particularly underlined by the fact that 17 of the 18 warmest years were recorded since 2001. 1998 is the only record year which was registered before the turn of the millennium. So far, 2016 was the warmest year ever recorded (NASA GISS, 2018b). This overall warming is pronounced in winter at high latitudes in Northern Europe (i.e. in Scandinavia) and in summer on the Iberian Peninsula (EEA, 2018).

Along with raising temperatures, climate change increases the probability of occurrence and intensity of extreme weather events such as droughts and floods. In particular, high temperature climate-related extremes such as heat waves have become more frequent and intense (EEA, 2017b; Kovats et al., 2014). However, due to changes in global climate circulation patterns (e.g. of the jet stream) low temperature extremes may also occur more often and for longer periods (Rahmstorf and Coumou, 2011; Kretschmer et al., 2018).

Otto et al. (2012) also showed that climate change has already altered the likelihood of extreme weather events in several regions around the world. Based on these findings, van Oldenborgh et al. (2015) compare how the likelihood of past extreme weather events would have changed without climate change. As a result, they show that, for instance, the probability of heavy precipitation has increased by 5 to 80 percent in the United Kingdom (UK). In other words: The likelihood for such events has substantially increased due to climate change. Latest research by Otto et al. (2018) provides more insights regarding the attribution of weather extremes to climate change. Their particular research allows to assign concrete likelihoods to certain events given climate change. For example, the likelihood of a dry summer, as we experienced in 2018, is much higher today than under previous "normal" climate conditions. According to Otto et al. (2018), an extreme summer such as in 2018 may become an average summer by the mid of the century.

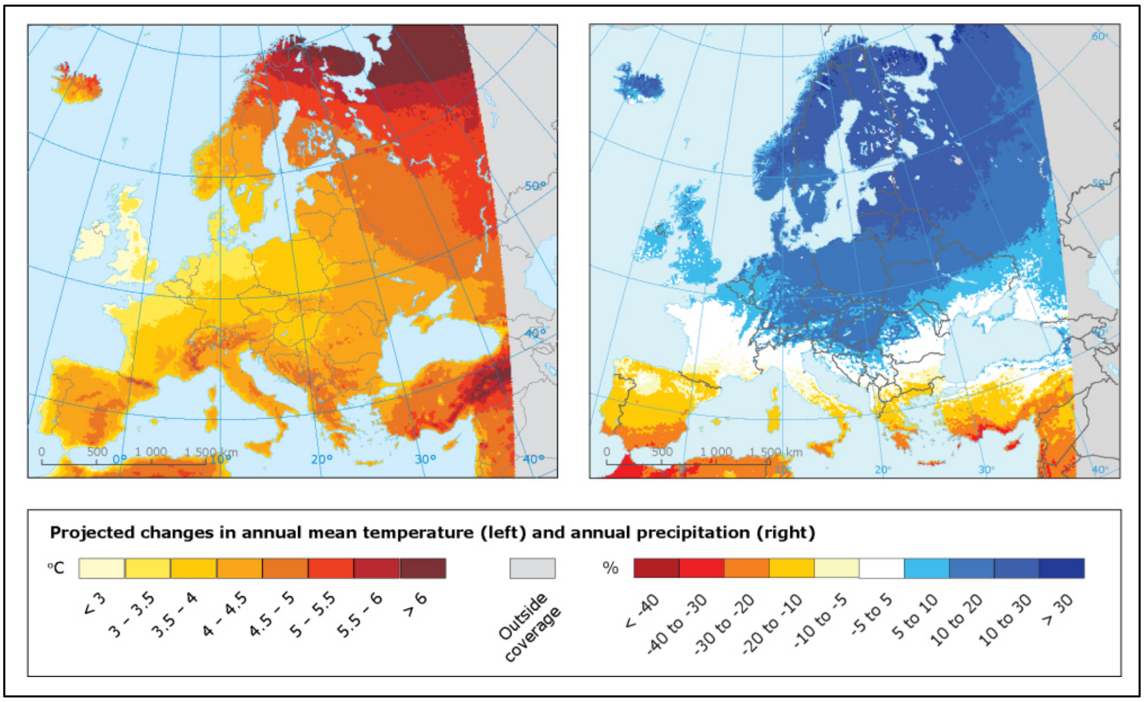
Precipitation patterns have also changed due to climate change. Again, effects are very heterogenous across space (EEA, 2017b). For Europe, these are the most striking points:

- Annual precipitation levels in Northern Europe have increased by up to 70 mm per decade since the 1960’s, as winters have become wetter and also summer rains have increased by up to 18 mm per decade.
- In contrast, annual precipitation levels in Southern Europe have decreased by up to 90 mm per decade. In this region, the mean precipitation during the summer months has decreased by up to 20 mm per decade.

Moreover, it is projected that, without effective emission mitigation measures, climate change will continue and that already observed changes will go on. Figure 2.2 gives an overview of how annual temperatures and precipitation patterns will most likely change in Europe. It displays the projected changes for the years from 2071 to 2100, compared to the time period one hundred years before[1].

[1] These projections are a model ensemble: They depict the average of multiple models under a high emission scenario using the so-called Representative Concentration Pathway (RCP) 8.5 high emissions scenario. During the timespan between 2046 and 2065 this scenario projects an increase in global mean temperature by 1.4 to 2.6 °C (mean 2.0 °C) (see EEA, 2015).

Figure 2.2: Projected changes in annual mean temperature (left) and annual precipitation (right) for 2071-2100 (assuming RCP8.5) compared to 1971-2000



Source: EEA (2015).

Apart from that, a particular climate phenomenon needs to be considered: Due to higher levels of warming in the Arctic compared to temperate regions, the jet stream will most likely weaken in its movement around the globe. Indeed, latest research shows that the jet stream will start to meander and form waves that may either bend to the North or the South, and that it will only move slowly. Depending on their specific extent, these movements may lead to long periods of cold air flowing in from the Arctic region (North), creating extended cold spells. On the other hand, these movements can also lead to warm air flowing in from Southern regions, provoking extended heat waves and drought periods. The so-called blocked weather patterns, such as the extreme rainfalls observed in 2017 or the extreme dry spells experienced in parts of Europe – but also in other regions of the Northern Hemisphere – in 2018 can be attributed to these jet stream changes (Kornhuber et al., 2017). These weather patterns certainly will impact agricultural production at a large regional scale.

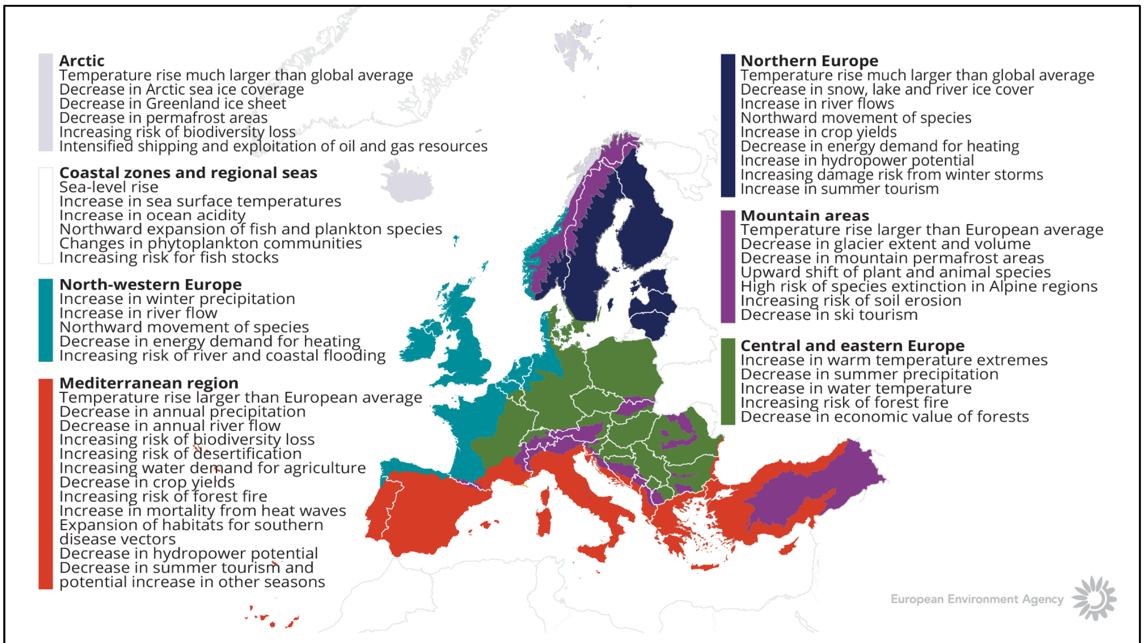
It becomes obvious: The annual mean temperature will increase everywhere in Europe; and regarding precipitation, one can say as a rule of thumb that the North will become wetter, while the South will become drier. In general, longer dry periods are projected in Europe, too (EEA, 2017c). Heat waves will particularly impact Southern Europe, increasing the likelihood of systemic failures as multiple sectors will be affected (e.g., health and agriculture). Thus, economic activity will be more adversely impacted in these regions than in other parts of Europe. Furthermore, there is a high confidence in model projections that the decline of all ecosystem services will be especially marked in Southern Europe.

As climate change is a complex event with many unknowns only future observations and further modelling can complement the picture (e.g. tipping points of climate processes).

2.2 Regional patterns of projected climate change across Europe

The regional pattern of projected climate change impacts across Europe are further differentiated in figure 2.3 focussing on bio-geographical regions of the continent.

Figure 2.3: Observed and projected climate change impacts in Europe's bio-geographical regions



Source: EEA (2017a).

As already stated above, and as already shown in figure 2.2, climate change is affecting all parts of Europe mainly in a negative way (EEA, 2017b; IPCC, 2014). Its impacts will continue to be very diverse between regions and over time. This heterogeneous nature of climate change effects in Europe also becomes apparent when using a regionalisation provided by EEA (2017a). In the following, regional impacts which are and will be particularly important for agriculture are highlighted:

- In the far North, the Arctic region (coloured in grey) will experience a temperature increase above global average, which will lead to a decreasing sea ice coverage and to a decrease of other ice formations. Rising sea surface temperatures will have a large effect on plant and animal species in this region.
- In North-Western Europe (coloured in turquoise), winter precipitation will increase, and species will move northwards due to higher temperatures.
- The Northern regions (coloured in dark blue) temperature increases above the global average, along with a northward expansion of certain species and increased crop yields.
- In Europe's mountainous regions (coloured in purple) temperature increases are above the European average. Species living in these areas will move to higher elevations, and soil erosion will increase.
- In Central and Eastern Europe (coloured in green), more heat extremes will be noted and summer rainfall will decrease.
- The Mediterranean region (coloured in red) is marked by above European average temperature rises and decreasing annual precipitation. This will lead to reduced crops yields and to increased water demand for the agricultural sector.

All these trends will continue and aggravate in the future since climate change is ongoing. It will lead to a further rise in temperatures as well as to structural changes in precipitation patterns and in overall water availability if climate change is not halted by a joint effort of the global community.

One approach to exemplify all the above-mentioned climate change impacts and projections is the calculation of so-called climate twins or analogues (Hallegatte et al., 2007; Ungar et al., 2011; Rohat et al., 2016). The climate analogue of one city A is another city B which currently has the climate that is projected under climate change for city A at a certain point of time in the future. To exemplify this approach, some climate twins according to Rohat et al., 2016 are shown hereafter. Hereby the IPCC emission scenario A2 is assumed, describing a heterogeneous world with strong self-reliance and local identities while the world population increases (see IPCC, 2000). Here, the climate analogues (right) represent the current location of the following cities' future climate in 2071–2100:

- The future climate of Berlin will be similar to the current climate of Saragossa,
- Brussels → Bordeaux,
- Hamburg → Toulouse,
- Nice → Naples, and
- Stockholm → Berlin.

3 Climate change impacts on crop production

3.1 General impacts

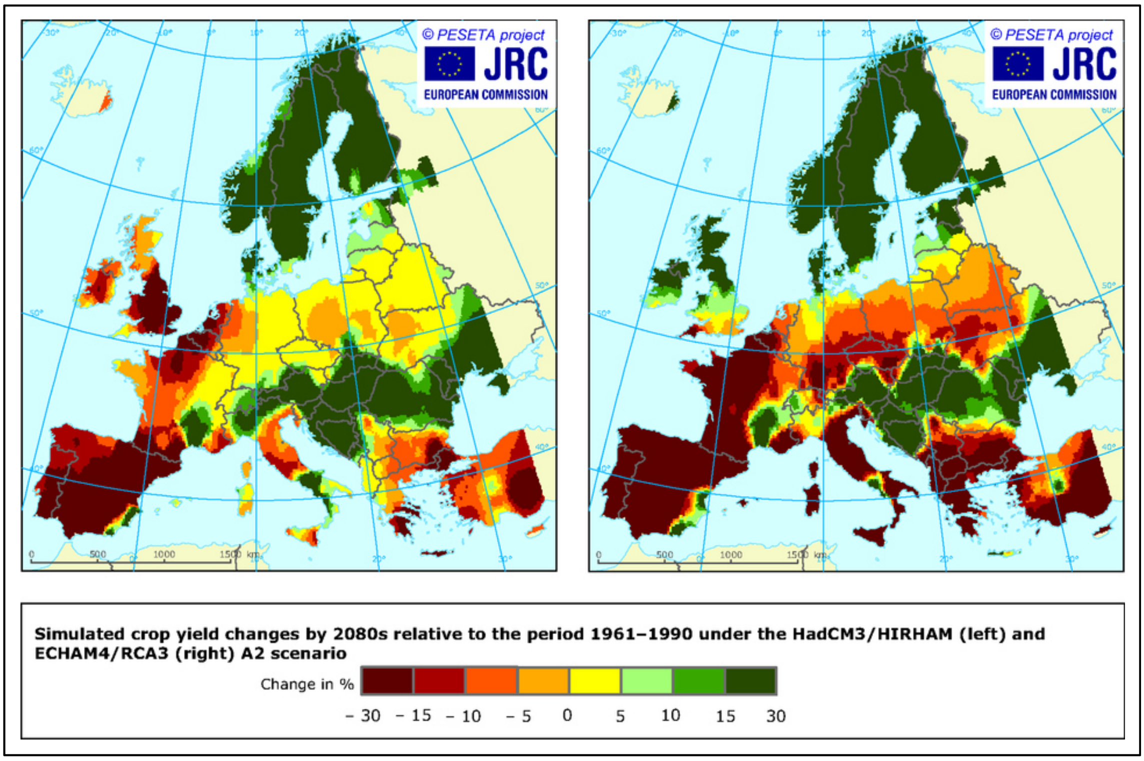
Climate change impacts on European crop production have already been experienced. For example, France had unforeseen and large yield losses in 2016 in its main wheat growing area. Such extreme yield losses had not occurred in this region for more than 50 years (Ben-Ari et al., 2018). The authors conclude that these were due to a combination of warmer temperatures in late autumn and abnormally wet conditions in the subsequent spring.

Olesen et al. (2011) summarise altogether six direct and indirect impact pathways of climate change on agriculture. The three direct effects are caused by (1) increased atmospheric CO_2 levels, which influence overall crop productivity and resource use efficiencies, (2) changes in temperature, rainfall, radiation, humidity, and other meteorological factors that influence crop development and growth and (3) damages caused by extreme events such as heat waves or flooding. In addition, agriculture is indirectly affected by (4) altered crop suitability meaning a northwards expansion of thermophile crops, (5) alternations in crop nutrition and occurrence of weeds, pests and diseases, as well as (6) climate-related environmental pollution or resource degradation (e.g., soil erosion).

Considering the above-mentioned wide range of changes, it is evident that climate change has large repercussions on agriculture, and mostly influences it in a negative way. This is particularly the case, when temperature increases are higher and at low latitudes (Rosenzweig et al., 2014). Having that in mind, figure 3.1 visualises climate change impacts on crop yields by the year 2080, as compared to the period from 1961 until 1990, and also shows their heterogeneity within Europe. It particularly compares two climate simulation models, which drive one crop model. The crop model predicts yield increases in the green shaded areas whereas red and orange coloured areas symbolise expected yield decreases.[2]

[2] For a more detailed view on how projected wheat yields under climate change vary between different combinations of specific climate and crop models, please see Chapter 4.

Figure 3.1: Simulated crop yield changes by 2080



Source: EEA (2017b).

Depending on the climate model[3], yield decreases are projected to be very high in the far West of the continent, the Iberian Peninsula, Italy, and the Balkan, whereas yield increases are forecasted mainly for Scandinavia and some parts of Central and Eastern Europe. Thereby, one has to take into consideration that the real effects “in the field” will further depend on the specific crop, soil type, farm management approach, etc., and will also change over time (EEA, 2017b).

Another important aspect which influences crop production more generally is land degradation caused by climate change. It is very likely that climate change will exacerbate degradation effects from farm management failure and other causes. EEA (2010), for instance, estimates that the current costs of different dimensions of land degradation such as soil erosion, salinization and decreasing organic matter are large in Europe and caused by, for example, a depreciation of land and corresponding

[3] Depending on the climate model used, climate change and subsequent impact findings may differ. See also chapter 4, which provides insights concerning this still given “uncertainty”.

ecosystem functions. Hotspot areas in Europe are the Mediterranean countries, where soil moisture has already decreased, and Central Eastern Europe.

It becomes apparent: Impacts of climate change are highly interconnected and influenced by each other. There are no monocausal interrelations. Thus, the subsequent paragraphs, each describing a specific climate change effect on crop production, cannot be seen as independent but rather as strongly interconnected with the other effects. In fact, due to certain (sometimes still unknown) thresholds and tipping points, modelling these interconnections is a scientific challenge.

As it is difficult to disentangle different direct and indirect climate change impacts, we chose to explain the climate change impacts on agricultural systems according to their practical relevance for farmers and other sectoral stakeholders. Each subsequent subchapter will provide an overview of climate change effects on mainly crop production: Chapter 3.2 explains the effects on growing season length, crop phenology and habitat shift; then the effects of CO_2 fertilization (chapter 3.3), weed-crop interaction (chapter 3.4), water availability (chapter 3.5), and erosion (chapter 3.6) are discussed.

3.2 Effects on growing season length, crop life cycle timing and habitat shift

An important aspect already altered by climate change – and which will continue to change – is the length of the growing season, which is a limiting factor particularly in Northern Europe. Recent developments show that crops' thermal growing season is widening with increasing temperatures and less frost days due to global warming. Since 1992, this period has become longer by more than 10 days, while the delay of the senescence has been more pronounced than the advancement of its start (Jeong et al., 2011). This expansion will continue and by 2050 the date of the last spring frost is projected to have advanced by 5 to 10 days (Trnka et al., 2011). This so-called spring advancement is more present in parts of Northern and Eastern Europe. Olesen et al. (2007) predict that net primary plant production may steeply increase by 35 to 54 percent in Europe's Northern regions due to a longer vegetative period (and also due to higher CO_2 concentration).

An altered growing season changes crops' phenology, i.e. timing of crops' life cycle, which shows, by, for instance, earlier flowering dates. During the past 50 years, the flowering of several crops has advanced by about 10 days (EEA, 2017b). This development is counteracted, however, by an earlier maturation of crops due to increased temperatures. Thus, growth phases (e.g. grain-filling phase) are shortened and possible yield enhancing effects of earlier planting dates are jeopardised. This results in lower biomass production and/or harvest indices (EEA, 2017b). To reap the possible benefits of those changes, farmers could plant other crops or varieties with higher thermal requirements or shift planting dates to create overall longer growth periods.

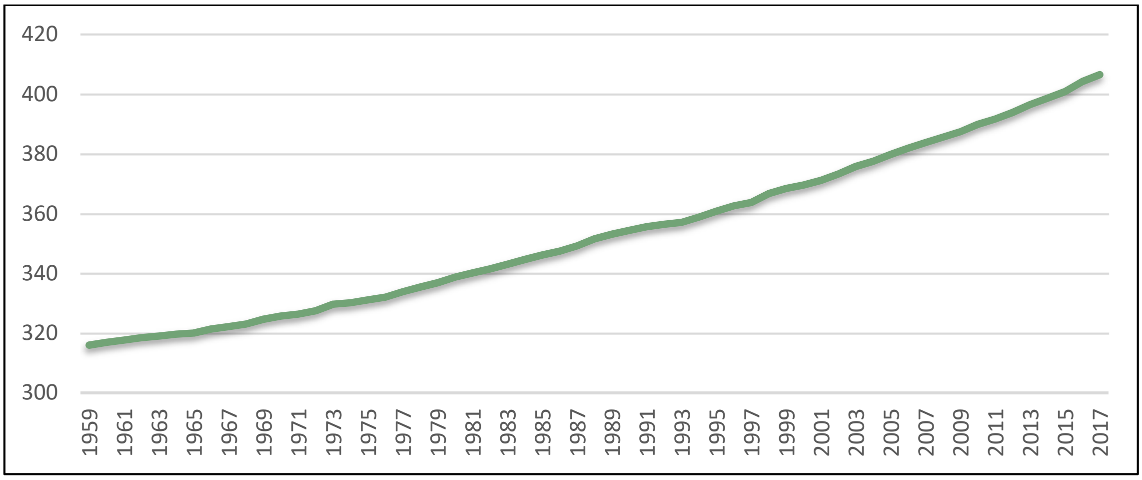
A further negative effect of climate change on plant growth and health is the higher probability of weather extremes, particularly during critical growing stages of a crop such as the flowering stage. This trend is expected to continue particularly in Central and Southern Europe (see, e.g., Rahmstorf and Coumou, 2011; Rosenzweig et al., 2001; Rötter and van de Geijn, 1999).

Another aspect of climate change to be listed here is the so-called habitat shift or habitat expansion of crops. This means that warmer temperatures and less frost days will allow thermophile crops to expand northwards or to higher altitudes. Hence, farmers will potentially be able to grow e.g. maize in Northern parts of Europe, where the growing period is currently still too short and temperatures are too low for these thermophile crops. A similar agronomic change induced by climate change is that, for instance, farmers in parts of Southern Europe will be partly able to shift their cultivation activities into winter months to avoid heat waves and droughts during summer (EEA, 2017b). In other European regions, however, such as Western France and parts of South-Eastern Europe, this shift will be difficult as the time horizon when plants can be ideally planted is more limited. In consequence, these regions' vulnerability is predicted to increase. Moreover, negative effects of climate change cannot be overcome by this adaptation option in cases where farmers plant two crops per year on a field.

3.3 Effects of elevated CO_2 levels

Despite the predominantly negative effects of global warming (particularly in the long term), some changes could be favourable for crop production. One of these is an increasing level of atmospheric CO_2 which can increase yields due to the CO_2 fertilisation effect under certain conditions. Figure 3.2 depicts the steadily increasing concentration of this greenhouse gas.

Figure 3.2: Annual mean CO_2 concentration (in parts per million)



Source: Own figure based on Tans and Keeling (2018).

More particularly, there exists much evidence that higher levels of CO_2 increase photosynthetic processes in C3 plants but less in C4 plants[4] (van Meijl et al., 2017; Ramesh et al., 2017; Fuhrer, 2003). In C3 crops higher CO_2 levels improve water use efficiency and cause plants to transpire less (Kruijt et al., 2008). Other authors conclude that water use efficiency is increased in both carbon pathways but not necessarily photosynthesis (Keenan et al., 2013).

This alone already shows that there is still much uncertainty concerning the yield effects of CO_2 fertilization. One reason for that is the limited understanding of how plants will respond in the long run. CO_2 concentration influences multiple – possibly counteracting – plant physiological processes (van Meijl et al., 2017). Nevertheless, Tubiello et al. (2007) summarise that compared to the CO_2 concentration levels in 2007, crop yields will increase by 10 to 20 percent for C3 and by up to 10 percent for C4 plants until 2100. Ribeiro et al. (2012) conclude that under augmented CO_2 levels even desired traits such as dwarfing varieties for better agronomic properties might be reversed, because of changed hormonal growth control.

[4] C3 and C4 plants have different paths of photosynthesis. C3 plants are the most common and have a very efficient photosynthesis under cool and wet climates. Examples for this group are wheat, rice, soya, sunflower, oilseed rape, potato, sugar beet, and dry bean. In opposite to that, C4 plants such as maize, sugar cane and sorghum are most efficient under hot and sunny climates (see van Meijl et al., 2017; Jaggard et al., 2010).

As stated above it is difficult to disentangle the different effects on plant growth and interactions from other climate change impacts. For example, the possible positive effects of CO_2 fertilisation can be significantly hampered if adverse weather conditions such as heat impede proper plant development (Tubiello et al., 2007) and thus net effects are uncertain or negative.

3.4 Changes in weed-crop interactions and management options

When analysing the climate change effects on crop production, one also has to take into consideration further effects of climate change through alternations at the system level, such as changes in competing weeds (Fuhrer, 2003). According to Ramesh et al. (2017) weed-crop competition is influenced through four channels, which are related to climate change: (1) elevated CO_2 concentration, (2) increased temperatures, (3) changed rainfall patterns, and (4) their interactive effects. Another influencing factor is – if applied – chemical plant protection, in particular herbicide efficacy under climate change (McDonald et al., 2009; Ziska and McConnell, 2016; Tubiello et al., 2007; Tungate et al., 2007).

However, it is impossible to postulate the exact impacts of these triggers as they highly depend on the geographic region, planted crops, surrounding ecosystems, management approaches, and their interactions. Below we will discuss the first three aforementioned climate change induced impacts on weed in more depth: elevated CO_2 concentration, temperature increase and changed precipitation patterns.

- To determine the effect of an elevated CO_2 concentration on weed populations, we have to consider the same conditions and uncertainties as explained above. Most food crops are C3 plants, which means that under certain conditions they could benefit from higher CO_2 concentrations, while many competing weeds are C4 plants (e.g. blackgrass, cleavers, green foxtail, kochia, and barnyard grass). And these, in turn, could profit from higher global temperatures. So far, these processes are understood in a qualitative but not in a quantitative way (Tubiello et al., 2007). In addition, a high degree of uncertainty remains whether the net effect will be positive or negative (van Meijl et al., 2017).

- As with crops, one important alteration caused by climate change is the shift of weeds' geographic niche (habitat shift), which is significantly altered by the second channel of climate impact on weeds: elevated temperatures. Studies suggest that the regional composition, distribution, density, phenology, and plant structure (e.g. increasing plant height) of damaging weeds will change greatly due to climate change (McDonald et al., 2009; Peters et al., 2014; Kovats et al., 2014).

McDonald et al. (2009) analyse climate change impacts on weeds in maize systems. They project a significant transformation in the geographic range of damaging endemic weed species as well as neophytes or invasive species. Thereby, the geographic range or bioclimatic niche of a specific weed species describes its potential distribution and is determined by the climate, topography, land use, and soil conditions that permit them to grow in specific places. The authors also define the term "damage niche". It is an expansion of the term bioclimatic niche. The "damage niche" further breaks down this concept and reduces the area, as it only refers to the bioclimatic niche, where a specific weed could grow and also cause damage to a cash crop. Hence, this specific niche is determined by the weeds' dispersal, disturbances such as extreme events, as well as competition with other weeds and food crops. Ecosystems which experience disturbances are more likely to be colonised by neophytes or invasive species (McDonald et al., 2009).

Having this in mind and similar to the northward expansion of the bioclimatic niche for thermophile crops (e.g. maize), milder and wetter winters will permit that also pests and diseases extend their seasonal activity and move to Northern regions (Kovats et al., 2014). Climate change can, thus, foster positive (if pests and diseases migrate from a region) or negative (if new pests and diseases are introduced to a region) effects on weeds (Ziska and McConnell, 2016). Additionally, the magnitude of weeds' damage to specific cropping systems will change over time and across space. Apart from that, higher temperatures and wetter winters certainly decrease the share of weeds which die off during winter dormancy. Increasing rainfall in Northern Europe will further enhance weed pressure.

- In this analysis, the third channel postulated by Ramesh et al. (2017), changes in rainfall, is expanded to overall water availability. A change in rainfall patterns and a higher likelihood for drought spells, heavy precipitation or water logging impacts the distribution and prevalence of weeds (Ramesh et al., 2017). While hydromorphic weeds such as common purslane, nutsedges and spurges could benefit from excess water availability, C4 weeds like blackgrass, cleavers, green foxtail, and barnyard grass will be more capable of coping with drought spells (Ramesh et al., 2017). In addition, it is more likely that more "general" weeds will expand or recover faster after extreme events such as heavy precipitation, waterlogging or droughts than more "specialised" cash crops.

With respect to aridity, Hanson (2015) elaborates that dry or periodically dry conditions alter weed pressure. One reason for this is that there will be fewer weeds under dry conditions, because weed germination is reduced, particularly for small-seeded weeds which usually establish on or near the soil surface. Even if weeds germinate, seedlings might not establish successfully under worsening water pressure. Nevertheless, this is not only good news for farming: The weeds which establish are very likely to be more competitive as they have less competition from other weeds and are more tolerant to the particular conditions. Furthermore, deep-rooted perennial weeds or larger weeds are less affected by temporary drought conditions thus adding additional pressure on farming systems. Regardless of these possible implications, the effects of drought conditions on the weed-crop interaction depend of course on the timing of weed and crop germination and their specific location. These effects also alter the proportions of weeds within a field.

Integrated weed management

The described weed-crop interactions are very similar to the climate change induced impacts on crops discussed above. We can assume that weed problems will partly increase with climate change and that farmers, and input suppliers need to adapt more quickly. Indeed, studies suggest that the need for plant protection applications in general and herbicides in particular will increase with climate change (see, e.g., Koleva et al., 2009). Managing the associated changes becomes a challenging task. Particularly concerned is the herbicide management since the effectiveness of herbicides highly depends on the local climate.

As discussed above, plants will change morpho-physiologically and anatomically with higher CO_2 levels, temperature increases and other climate change impacts. Consequently, plants' uptake rate and translocation of herbicides will also change (Ramesh et al., 2017). Observations by Ramesh et al. (2017) as well as Ziska and Teasdale (2000) suggest that the tolerance of C3 weeds to herbicides increases with elevated CO_2 levels.

Herbicide application is more difficult under aridity, because then the environmental conditions for herbicide uptake are not met. Soil moisture, in general, moves soil-applied herbicides from the surface to lower parts of the soil and thus influences the availability of it to weeds. Consequently, less soil moisture means reduced availability. Drier conditions can further inhibit herbicide degradation as microbial activity, essential for breaking down the active ingredients in the soil, are slowed (Hanson, 2015). Most important, however, is that good plant health is necessary for target weeds to sufficiently incorporate the active ingredients into their metabolism and that crops are not damaged by herbicide applications. Herbicide efficacy is thus greater and quicker if weeds are healthier; but dry conditions tend to generate more stress and thus decrease plant health. In other worlds plants' biosynthetic processes are functioning at normal (water) levels, but these are slowed under drier conditions.

Plant physiology might even be changed if adverse conditions such as a drought are present.

One example for this is that weeds develop a thicker cuticle under hot or dry conditions, which creates a barrier for the active ingredients (Hanson, 2015). Under very dry conditions, herbicide droplets could dry before reaching the destined spots, and depending on the specific herbicide ingredients it could crystallise, vaporise, volatilise or photodegrade before being up taken by the weeds. Johnson and Ikley (2018) consequently summarise that it depends on many factors, how much rainfall it takes to sufficiently activate a soil-applied, residual herbicide.

Regarding pre-emergence herbicides, a lack or delay of herbicide incorporation into the soil, due to aridity or other adverse conditions, may also reduce the herbicide efficacy, because the majority of these herbicide is designed to impact germinating seeds or small seedlings (Hanson, 2015). Soil moisture is particularly important when it comes to pre-emergence herbicides as these are applied to the soil (Hanson, 2015). It is critical if herbicides are not applied before it rains or rains will not come after their application. As a consequence, erratic weather and climate change (e.g. less winter rains) also turn herbicide efficacy erratic. Furthermore, farmers have to consider possible carry over effects which might harm subsequent rotational crops if conditions impede herbicide incorporation. To avoid these residue problems farmers could use tillage as it will dilute the herbicide (Zollinger, 2017b).

Apart from soil moisture, other indicators for an efficient herbicide application are temperature and plants' growth stage, as well as crops' herbicide tolerance. Zollinger (2017a) states that herbicide applications are usually best when temperatures are between 21 and 29 °C and when applied to a vigorously growing crop. Treatment of stressed plants (e.g. caused by extreme weather conditions) might result in higher crop injury and/or decreased weed control. This is because weeds growing in such conditions have a higher tolerance to herbicides as they adapt their physiology. Under heat the uptake and translocation within the target plant are reduced. Generally, plants close their stomata during heat periods.

Another barrier developed by weeds in hot climates is a waxy leaf surface (Zollinger, 2017a). Thus, weed control under hot and dry weather is the largest concern with the usage of systemic and contact or foliar applied herbicides. Farmers need to adapt applications' timing when using systemic herbicides under dry conditions. For example, it is better to apply herbicides in the morning when plants have recovered from the heat of the previous day. The majority of contact herbicides increases its activity with higher temperatures, which helps with weed control but might also increase crop injury; and if temperatures are too high, the application has to be postponed (Zollinger, 2017a). Such a postponement, however, might cause problems as farmers can miss the optimum treatment time and stage, which is generally when weed seedlings are small (Zollinger, 2017a). So, it can be a difficult trade-off when temperatures are very high early in the growing period.

Weed management adaptation options

As a matter of course, proper farm management of climate change induced crop-weed interactions goes beyond the adaptation of herbicide applications. Indeed, farmers are constantly adapting to climate change, but the unprecedented fast changing pace of climate change makes it more and more difficult for them. Holistic on-demand and site-specific capacitation services and other consulting services are vital to help them adapt and thus improve food security and increase the sustainability of the overall production system for food, feed, fuel, and fibre. Olesen et al. (2011) synthesised from expert interviews across Europe that the adaptation methods farmers most resort to are the selection of better suited crop species and shifting the planting date.

There are many adaptation options to mitigate climate change effects and they highly depend on a region's climate, soil conditions, political and economic conditions, as well as land use systems. More diverse crop rotations including winter and spring crops with different growing and harvest periods over the year are more resilient to more frequent weather extremes and the development of herbicide resistances than highly specialised rotations with a few similar crops. Furthermore, planting different crop varieties or cultivar mixtures, (i.e. two or more wheat varieties with different key traits such as resistances) in one field can contain certain pests and diseases. Adapted soil management and tilling will also become increasingly important in order to improve soil water holding capacity and reduce erosion potential.

It becomes obvious: Farmers need sufficient adaptation mechanisms for risk reduction and climate change mitigation, otherwise it is likely that they experience high yield penalties under climate change (Ramesh et al., 2017). Climate scientists agree that we already experience and will continue to experience greater interannual differences in growing and weather conditions (e.g. the wet year 2017 vs. the dry and hot year 2018 in Central Europe). This is particularly important when looking at increasing weed resistances to common herbicides. If adaptation fails, the worst climate change projections concerning agricultural production can be expected in the Pannonia region (including states such as Hungary, Bulgaria and Romania). Particularly there, the likelihood for heat waves and droughts increases and farmers cannot simply shift to other planting time slots and additional measures to diminish the risk (Olesen et al., 2011).

3.5 Effects on overall water availability and irrigation demand

Globally, climate change will put further pressure on agricultural water management, which is already under pressure due to population growth, economic development and environmental concerns (Iglesias and Garrote, 2015; IPCC, 2014; Jeong et al., 2011). Kovats et al. (2014) estimate that by mid-century irrigation in some European regions will not suffice to out-level the damages of water stress to crops. However, too much water – induced regionally by extreme events (such as heavy precipitation) and, in addition, locally by sea-level rise – also tends to threaten agricultural production. In particular, these impacts cause water logging and salinization which are often very site-specific (Iglesias and Garrote, 2015)[5]. Due to changes in overall water availability in the soil, there is a high probability that irrigation demand will increase, too.

When talking about climate change impacts on agriculture, it is of special interest to understand how precipitation patterns, i.e. the timely and regional distribution of rainfall, change throughout the year. The same can be said for the occurrence of extreme events. In this regard, it is necessary to look at the overall water availability, consisting of precipitation, evapotranspiration and soil moisture. As scientists agree that the global mean temperature has risen, and will continue to rise, evapotranspiration is also expected to increase. This, in turn, acts to reduce the overall water availability near surface (i.e. the hydrological balance) for crops (Solomon et al. 2007); and this water balance will further worsen if overall precipitation decreases in certain regions. Again, this interrelation underlines the dramatic consequences climate change will have on water availability, even though it is very difficult to exactly predict single precipitation events.

Nevertheless, it can be stated that extreme climatic events such as droughts and heat waves have already impacted European agriculture during the first decade of this century. It is no surprise that rainfed agriculture will face more climate change related problems then irrigated agriculture (Trnka et al., 2011). More generally, Iglesias and Garrote (2015) conclude five major changes in water resources for agriculture:

- Water demand will increase due to increased evapotranspiration in all regions.
- More water shortages – pronounced in regions which already experience water stress – will occur particularly during spring and summer.

[5] Another important point is water quality, which might diminish due to rising temperatures and environmental degradation.

- Due to higher water temperatures and less runoff in some regions water quality will diminish.
- The risk of floods will increase caused by predicted higher winter rainfalls.
- In low-lying areas, increased sea levels will make the land more vulnerable to flooding and salinization.

Having this in mind, Iglesias and Garrote (2015) particularly analyse the climate-induced changes in water-limited or rainfed crop yields in Europe. Accordingly, yields on the Iberian Peninsula, in South-West France, Italy, and the Balkans will decrease if crop production is water-limited, whereas yields are expected to increase in Northern and Eastern parts of Europe. Consequently, irrigation demand will increase with climate change, particularly in Southern and Eastern Europe, as most irrigation in Europe will have to take place in the Mediterranean countries in order to keep yield levels high. On the contrary, irrigation demand might partly decrease in Northwest Europe (EEA, 2017b).

Indeed, the Mediterranean area can be considered a hot spot area within Europe regarding aridity. In this region, it is likely that the threshold for the functioning of the ecosystem service of water provision will be reached (EEA, 2017b). If overall precipitation falls below a level where groundwater reservoirs can recharge and the vegetation cover is minimised, to a level where moisture recycling from land surface to the atmosphere is inhibited, this threshold is reached. This is supported by Konzmann et al. (2013). Although the authors argue that global irrigation demand will decrease by about 17 percent caused by shorter growing periods due to temperature increases, higher precipitation in certain world regions and the (possible) beneficial effects of CO_2 fertilization, they also state that in some regions such as Southern Europe irrigation water demand will increase by more than 20 percent.

A further important aspect is the spatio-temporal interactions between groundwater and climate. The hydraulic memory of groundwater systems differs and thus it is difficult to estimate the effects of climate change on these (Cuthbert et al., 2019). Furthermore, it is challenging to measure the effectiveness of certain mitigation activities as the response time might be longer than a human lifespan (i.e. about 100 years). The authors conclude that in arid regions groundwater systems are less responsive than in humid regions.

To accentuate this aspect, the following case study findings shall be added. Deike (2018) explains the impacts of climate change on water availability in the agricultural life-cycle while focussing on Germany. According to the author, precipitation in the first half of the year will decrease on average in many German regions:

- More persistent aridity from January to March rarely impacts yield development, as crops do not need much water at this time because of their low evapotranspiration and growth stage. Nevertheless, water reservoirs cannot be filled, so that future droughts or aridity cannot be compensated so well.
- If aridity coincides with an early start of vegetation in spring, weakened crops cannot recover very well as weeds will also start to compete for water resources.
- Early summer aridity, especially during the months of April and May, are of particular importance for crops' yield development.

On the contrary – and again on average – the second half of the year receives more precipitation. It hampers, for instance, oilseed rape harvests, but crops that are harvested later (e.g. maize) may benefit.

All this has implications for plant health and its protection. When spring drought occurs, it is particularly useful to achieve or maintain healthy crop stem bases as these are responsible for an efficient nutrient and water transport, furthermore more shoots will be produced if these are in good health. The aim of plant protection under aridity should, thus, be to reduce plant stress. Plant protection could also be applied below the damage threshold to help crops to stay vital.

Excursus

Case Study: Potsdam, Germany

As the weather station Potsdam hosts one of the longest uninterrupted weather data time series, we will briefly describe here, how climate change impacts can be seen in this part of Eastern Germany.

Climate change is already taking place. According to the World Meteorological Organizantion (WMO, 2019), 17 of the 18 warmest years on record have all been during the 21st century. In particular, the years 2015, 2016, 2017 were exceptionally warm in comparison to the past 100 years. This trend is visible at the global level as described by the WMO, as well as at single individual weather stations. For instance, the weather station in Potsdam shows that already by mid-October the year 2018 was warmer than overall records for 2017 and the "heat wave year" 2003 (Gutsch et al., 2018a).

In addition to the increasing temperature, plant water supply was exceptionally low in the year 2018. Lower precipitation together with higher temperatures have substantially decreased plant water supply. This was observed with low records for soil water condition and climatic water balance. Soil water conditions reached several times the threshold (permanent wilting point) and the climatic water balance shows extremely low values in the second half of the year (Gutsch et al., 2018b; 2018c).

3.6 Erosion effects

Following an increased occurrence and intensity of extremes, climate change impacts (e.g. heavy rains and/or droughts) may also increase soil erosion and reduce soil fertility (Kovats et al., 2014). In fact, model results of Panagos et al. (2017) show that overall rainfall induced soil erosivity in Europe will increase by 18 percent until 2050, and that 81 percent of the European territory will experience an increased erosivity. In particular the Western Alps, parts of the French Atlantic coast, East Croatia, parts of Slovakia, and Southern Germany are projected to have such an increase due to higher rainfall intensity and other erosive events. When looking at wind erosion, Mediterranean countries are projected to have the smallest impacts, while areas around the North Sea will experience more wind erosion (Borrelli et al. 2014); and in regions such as the Mediterranean and Central-East Europe, which are already – at present – desertification hot spots, extreme weather conditions such as droughts and forest fires will continue to increase the risk of desertification (EEA, 2017b).

4 Climate models, model agreements and limitations

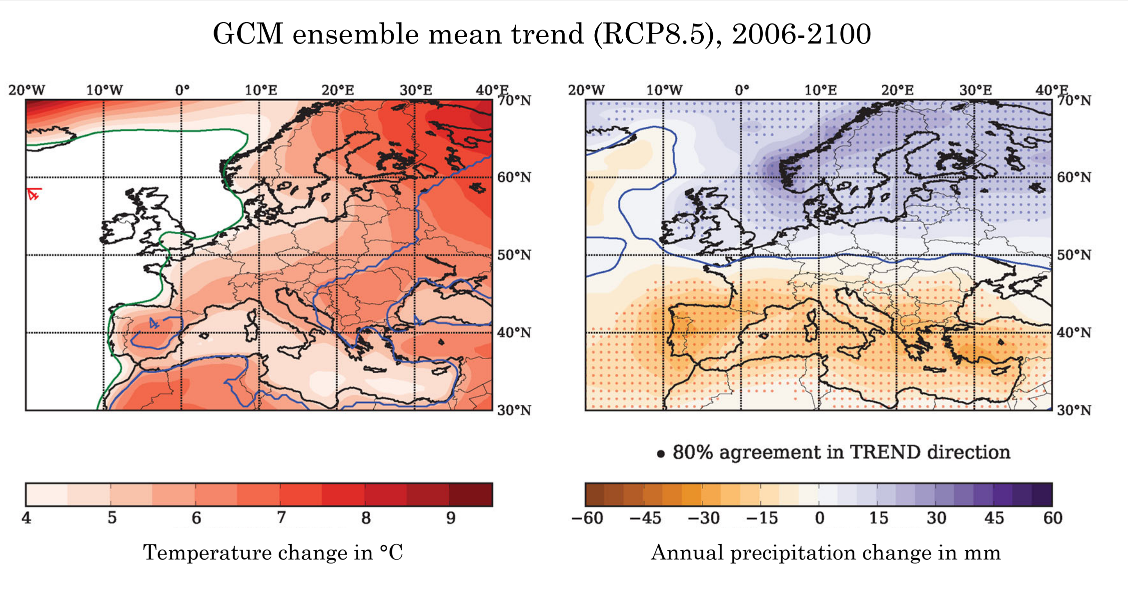
As stated above, modelling climate change and its impacts is a scientific challenge as it involves several interdependent systems feeding back into each other. Today climate and climate impact models are important analytical tools and due to scientific as well as computational advancements these are constantly being updated and improved.

When talking about projections of climate change impacts, it is important to discuss the degree of uncertainty in underlying climate models. In Europe, these models agree on increasing temperatures, but project different trends and magnitudes of precipitation changes. This means that each model may project, for instance, different degrees of warming. The modelling output depends on several factors such as the model assumptions, the data used, the level of applied spatial aggregation, the defined scenarios, and others. This means that all model projections have to be interpreted in the light of their specific model characteristics. General Circulation Models (GCMs), for example, simulate physical processes in the atmosphere, oceans, cryosphere, and land surface. Although they are at the present the most advanced tools available for simulating the response of the global climate system to increasing greenhouse gas concentrations (IPCC 2013), the agreement across GCMs on temperature increases is higher than on precipitation changes.

Let us consider a GCM ensemble[6] (altogether 18 GCMs) employing the so-called RCP8.5 scenario (see footnote 1 on page 6) as an example to illustrate this aspect. The maps in figure 4.1 display the mean change of temperature (left-hand side) and precipitation (right-hand side) of this global model ensemble for the years 2006 to 2100. In the map on the left-hand side all models agree on the temperature trend. It shows that temperatures are projected to increase more in the North-East (darker red shade) than in Great-Britain or Northern France (white or lighter red shade). As stated above the model agreement on the precipitation trend is lower. In the right map of figure 4.1 the dotted areas show where more than 80 percent of the 18 models agree on the trend direction concerning annual precipitation changes in Europe (Hoffmann, 2013). It becomes obvious: There is currently no strong model agreement for Central Europe including the Benelux countries, Northern France, Germany, and Poland.

[6] The global model ensemble shown here is CMIP5, which is the fifth phase of the Coupled Model Intercomparison Project (CMIP) promoted by the World Climate Research Programme's Working Group on Coupled Modelling.

Figure 4.1: Mean trends of a global model ensemble for temperature and precipitation



Source: according to Hoffmann (2013).

As models differ in process coverage and frequently use different scenario assumptions and/or different combinations of input parameters, they can derive diverging results. As a standard approach, the results of individual models can be checked for robustness with extensive sensitivity analyses, where each model is run with a range of input parameter sets. But even more importantly, shortcomings of individual models can be overcome by systematic model inter-comparison exercises, where a range of models is harmonised using the same set of input parameters, e.g. on climate projections and socio-economic trends. Accordingly, it is now standard to feed, for instance, crop yield impact models not only with one climate projection, but with an ensemble from the GCMs or other databases at the regional scale.

In addition, several crop models as well as a range of economic models have been used to assess the economic effects of climate change on agriculture (van Meijl et al., 2017). While this overall approach requires much more analytical effort and computing power, it is necessary to account for strengths and weaknesses of specific models at each step of the overall impact assessment. Assessments across models show that in many cases the ensemble mean results represent observed data better than any single model (Asseng et al., 2013; Nelson et al., 2014). Indeed, with these approaches climate impact projections have become more robust over time.

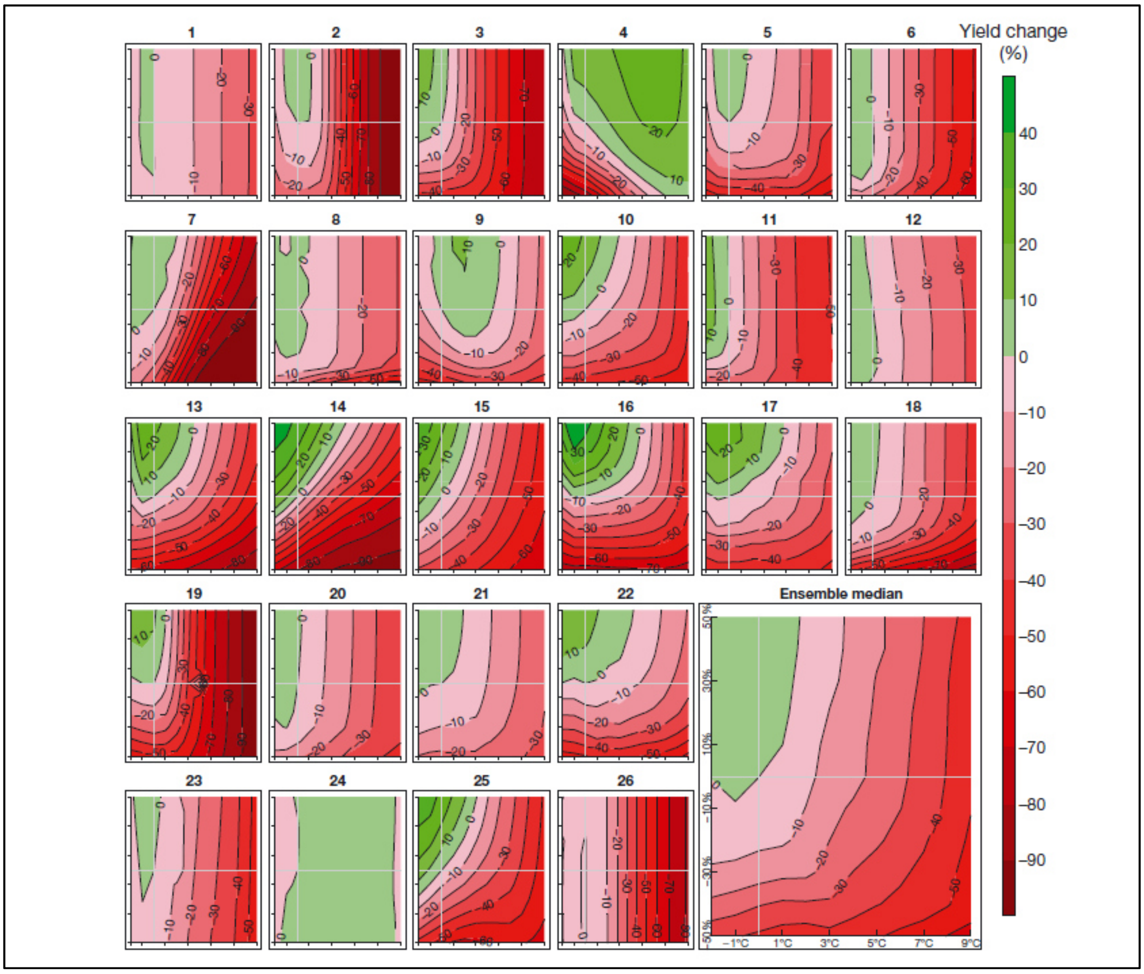
One additional limitation that has to be taken into consideration when interpreting model results is that models cannot include all planted crops, management options or the overall spatial extent of crops (Trnka et al., 2011) due to computing capacities and interpretability. Thus, some interactions (e.g. crop rotations) or rarely planted crops are not covered by the literature. So far little knowledge of interactive effects of, for instance, temperature and increased CO_2 levels and the subsequent impact on weed-crop competition exists (Fuhrer, 2003). In the future, models should analyse these more deeply. One obstacle for such analyses are a lack of empirical data or poor data quality for some regions and crops.

Furthermore, it is important to consider the degree of model uncertainty because each model is particularly well suited for specific crops, climatic regions etc., but less suitable for other regions (Vogel, 2015). Olesen et al. (2011) criticise that most models and studies assessing climate change impacts on agriculture only consider three out of six impact pathways. These three are the direct effects (1) increasing levels of atmospheric CO_2 and (2) changes in temperature, rainfall, radiation, and humidity, as well as indirectly (3) impact shifts in crop suitability (e.g. northward expansion of thermophile crops. This leads to a bias towards mostly direct climate change effects while acknowledging the indirect effects (damages caused by extreme weather events; alternations in crop nutrition and occurrence of weeds, pests and diseases; climate-related environmental pollution or resource degradation) to a lesser extent.

Against this background, EEA (2017b) underlines the fact that climate change projections stem from historical data and processes: The observed trends are expected to continue into the future, but extrapolations of current phenological trends may be misleading as the observed relationship between temperature and phenological events may change in the future. Moreover, new evidence suggests that agricultural yields may be more vulnerable to climate change than thought before as for example genetic limits to adaptation are reported (Kovats et al., 2014).

The following figure 4.2 displays how winter wheat yield projections partly vary according to the model applied. Here, the projections were done for the location Dikopshof in Western Germany and for the period 2070-2099 compared to the baseline climate in 1981-2010. Each small sub-plot of the figure represents one of 26 models projecting yield changes under climate change. The larger sub-plot at the right bottom gives the median of all these models (i.e. the median of all 26 models). In each plot the horizontal axis gives the change in average temperatures ranging from less than -1 °C to +9 °C. The vertical axis shows the changes in yield ranging from -50% to +50%. Hence, the differently coloured plot areas or bands show how yields change given a certain temperature. The wider a coloured band is given a certain temperature, the higher the probability for this projection is. The bands' hue provides information on the projected yield change. The deeper the green in a band, the higher are the projected yield increases and the deeper the red, the higher the projected yield decreases (see colour scale on the figure's right-hand side). It becomes apparent that model projections vary from model to model, but mostly the trend direction is similar. It is striking that the green areas (i.e. projecting yield increases) are mostly located at the left-hand side of the small sub-plots, while the right-hand part of each plot is red. Thus, it can be concluded that increasing temperatures (displayed at the right-hand side of each sub-plot) significantly decrease yields. Looking for example at the larger sub-plot, the model ensemble projects yield decreases in the range from 0% to -45% in Dikopshof if the temperature increases by 1.5°C. As the light red band displaying yield changes from 0% to -10% is the widest given this temperature, it is most likely that yield changes will be within this range according to the model ensemble. For more information and projections for other locations in Europe please see Pirttioja et al. (2015).

Figure 4.2: Projected yield changes under different degrees of global warming in Dikopshof, Germany



Source: Pirttioja et al., 2015.

5 Conclusion and recommendations

In a world of growing resource scarcity and at the same time increasing population, understanding the impacts of climate change is of utmost importance for all stakeholders in the agricultural sector ranging from the farmers to extension services, input suppliers, and policy makers. Therefore, this study offers a condensed overview and provides a valuable summary at hand to better understand the link between climate change and crop production in Europe. While climate change is often portrayed as an abstract, far away and complex occurrence, here we try to provide a comprehensive and yet comprehensible overview of its major impacts (today and in the future) on the agricultural sector.

As observed and projected climate change trends and impacts show, agricultural systems worldwide and also in Europe are massively changing due to climatic changes. These changes in precipitation levels and patterns, seasonal temperatures and thus evapotranspiration also alter the growing conditions of crops in every part of Europe. Our analysis has particularly shown that within Europe there are certain hotspots where climate change has considerable negative impacts and others, which may benefit from increased temperatures and rains. Altogether, these climatic changes will affect many aspects of farming including shifting growing season length, crop life cycle timing and habitat shift as well as crop-weed interaction.

Apart from a joint and sustained effort of the global community to halt future climate change, each sector and thus also the agricultural sector can do its part to mitigate climate change. In fact, the application of mitigation but also adaptation measures will be necessary to sustain farmers' livelihoods and to secure the quantity, as well as quality of their produce. Therefore, while the first step is to acknowledge climate change and its effects in the first place, the second step consists in seeking efficient (i.e. sustainable and cost-efficient) and climate-resilient measures, and implement them. These can, for instance, include a re-scheduling of seasonal activities such as planting and harvest, the use of different crop species or varieties that better match the climatic and agronomic conditions at site. Another important measure is making use of integrated plant protection through disease and pest minimizing cropping cycles or variety mixtures and also the proper application of plant protection. Precision farming tools might help herein.

Recommendations

Based on this literature survey of climate change impacts the report comes to the following recommendations for action. It is crucial to adapt to and mitigate climate change to stabilize agricultural production and thus farmers' livelihoods but also consumer food prices. These measures should be site-specific but also cost efficient and scalable. To help farmers cope with the risks posed by climate change, the reciprocal knowledge loop between farmers, input suppliers (incl. breeders, plant protection etc.), consulting and extension services as well as science has to be constantly updated to ensure timely, efficient and optimal knowledge transfer and thus practical implementation of suitable climate-resilient measures. Also, the general public has to become more aware of their behavioral impacts on the global climate and reduce food waste and CO_2 -intensive diets, as we can only halt climate change if we join forces globally and include all parts of the agricultural value chain "from farm to fork".

So far, the most common adaptation options in Europe are shifting to better suited crop species and shifting the planting date. Farmers should be further enabled to plant other crops or varieties which are more suitable to their locations and its specific climatic conditions (e.g. by picking a crop with higher thermal requirements). They should also be enabled to shift planting dates to take advantage of a longer growing period or time periods where water availability is sufficient. Moreover, diverse crop rotations including winter and spring crops with different growing and harvesting periods over the year are more resilient to weather extremes than highly specialised rotations with a few similar crops. Also, planting different crop varieties in one field can contain certain pests and diseases.

Adapted soil management and tilling will also become increasingly important for improving soils' water holding capacity and reducing the erosion potential. Healthy soils are key to mitigating and adapting to climate change. The ideal soil should be able to contain and take up water. Its health can be enhanced with green manuring and appropriate humus management. Furthermore, water efficient irrigation such as drip irrigation can help to overcome drier periods without using too much water. Precision or smart farming provides important tools for climate-resilient agriculture. Integrating plant management techniques with modern satellite data and image recognition will render monitoring and integrated plant protection much easier. In addition, more public funding should be provided for analysing climate change impacts on agriculture and creating innovations in climate-resilient agriculture (plant breeding, resilient cropping systems, etc.) as well as reducing the negative effects for farmers. Measures of climate-resilient agriculture should also be analysed from a cost-benefit point of view such that farmers can choose from a pool of measures and pick those that are most effective for their farm.

Our synthesis shows that climate change has already affected agricultural production systems and that these impacts will aggravate in the future, if climate change remains unabated. Thus, all agricultural stakeholders need to be prepared, to ensure future supply of agricultural goods.

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A literature review

Authors:
Sophia Lüttringhaus, Steffen Noleppa, Christoph Gornott, Hermann Lotze-Campen

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HFFA Research GmbH
Bülowstraße 66/D2
10783 Berlin, Germany

E-Mail: office@hffa-research.com

Web: www.hffa-research.com

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HFFA Research GmbH
Bülowstraße 66
10783 Berlin, Germany
Phone / Telefon: +49 (0)30 21 96 16 61
E-Mail: office@hffa-research.com