Climate Change impacts on European crop production – Mitigation and adaptation opportunities by plant breeding

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Content

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1 Introduction

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 due to anthropogenic climate change. 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 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 weather extremes as the drought experienced in Germany and other European regions, will be more likely and longer in the future.

The quantity and quality of crop production depends on many factors such as the climate, weather, specific location, farmers' management, available inputs and the technologies used. One technology that can increase crop production without expanding agricultural land, and hence has the possibility to decrease land use change that has negative effects on the environment, is plant breeding. This technology can have several benefits for food security, particularly by increasing the yield potential and improving crop quality and bioavailability.

In this article, I first provide an overview of the already observed and projected climate change impacts in Germany and Europe (Chapter 2).[1] And then I elaborate on how plant breeding can help to adapt crop production to these changes and hence stabilize or increase food security (Chapter 3). The article will close with a conclusion and policy recommendations (Chapter 4).

[1] Please note, that this part of the article is based on Lüttringhaus et al. (2019).

2 Climate change impacts on crop production in Europe

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). Considering the same time period, land temperature increased by 1.6 to 1.7 °C in Europe (EEA, 2018). Along with rising temperatures, climate change increases the probability of occurrence and intensity of extreme weather events such as droughts and floods (Otto et al., 2012; 2018). In particular, high temperature climate-related extremes such as heat waves have become more frequent and intense (EEA, 2017a; Kovats et al., 2014). However, due to changes in global climate circulation patterns (e.g. blocked weather pattern due to a slower jet stream) low temperature extremes may also occur more often and for longer periods (Kornhuber et al., 2017; Rahmstorf and Coumou, 2011; Kretschmer et al., 2018, Pfleiderer et al. 2019).

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

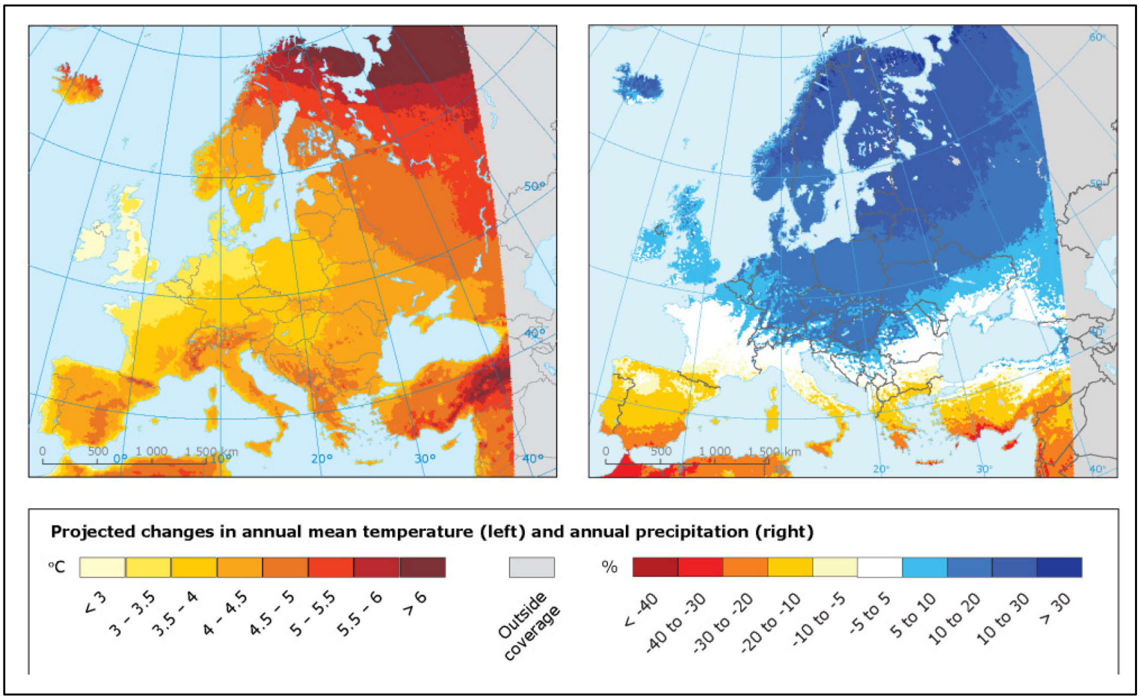
- Annual precipitation levels in Northern Europe have increased by up to 70 mm per decade since the 1960's, as winters have become wetter and also summer rains have increased by up to 18 mm per decade.
- In contrast, annual precipitation levels in Southern Europe have decreased by up to 90 mm per decade. 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[2].

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, 2017b). 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.

[2] 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



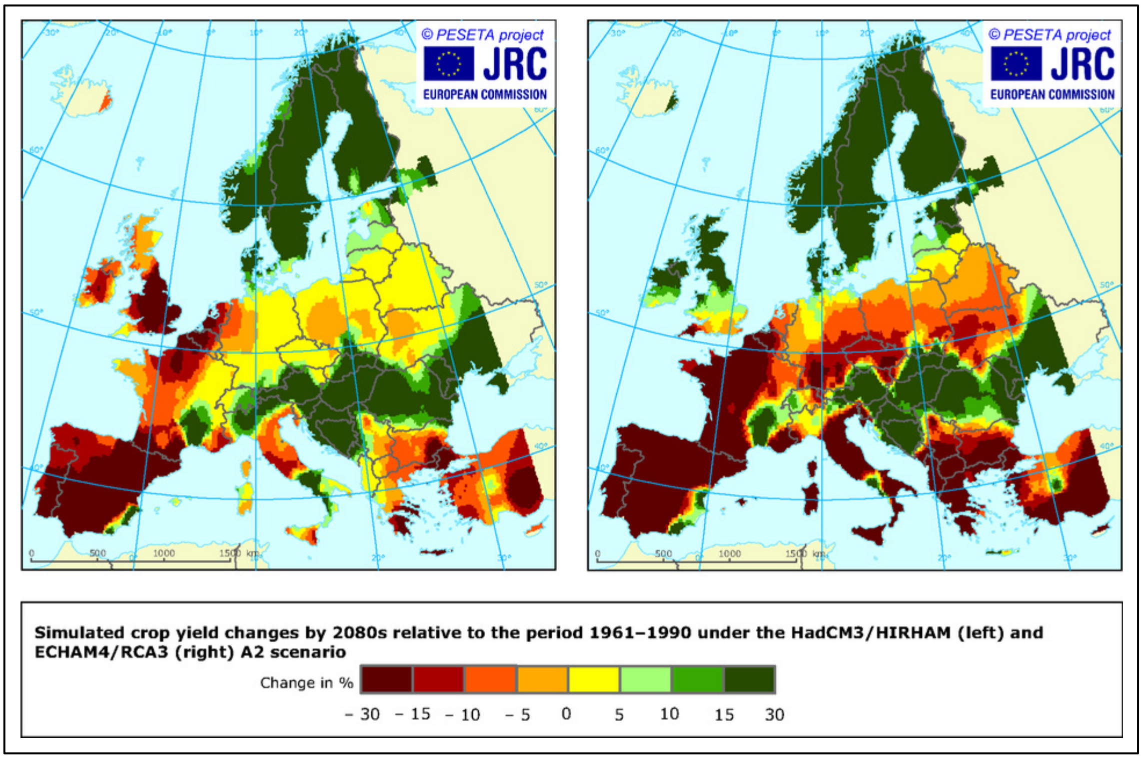
Source: EEA (2015).

Considering the above-mentioned wide range of changes, it is evident that climate change has large repercussions on agriculture. Figure 3.1 visualises climate change impacts on crop yields by the year 2080, as compared to the period from 1961 until 1990, and shows their heterogeneity within Europe. It 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.[3] Depending on the climate model[4], 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.

[3] 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 of Luettringhaus et al. (2019).

[4] Depending on the climate model used, climate change and subsequent impact findings may differ. See also chapter 4 in Luettringhaus et al. (2019), which provides insights concerning this still given "uncertainty".

Figure 3.1: Simulated crop yield changes by 2080



Source: EEA (2017a).

In the following I will explain the climate change impacts on agricultural crop production systems according to their practical relevance for farmers and other sectoral stakeholders.

a) 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 CO2 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, 2017a). 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, 2017a). 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., Powell and Reinhard, 2016; Rahmstorf and Coumou, 2011; Rosenzweig et al., 2001; Rötter and van de Geijn, 1999).

Another aspect of climate change 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, 2017a). 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.

These phenomena are also observed in pests and diseases, which in turn has large repercussions on the interaction between crops as well as pests and diseases. 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). As crops as well as pests and diseases change under climate change, the damage niche also changes. The damage niche describes the area where both, crops and affecting pests and diseases, prevail and pests and diseases also damage crop production. So, farmers must adopt new management strategies and technologies to plant the best suited crops or varieties and also pursue integrated plant protection[5] according to the most recent developments.

[5] Integrated plant protection describes a holistic approach that includes preventive measures as well as various non-chemical (e.g. mechanic procedures), and chemical plant protection measures (Freier et al., 2017).

b) 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)6. 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 crop production, 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.

A further important aspect is the spatiotemporal 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. Hence water scarcity is likely to persist longer and with higher intensity in more arid 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 lifecycle 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 develop-

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

ment, 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.

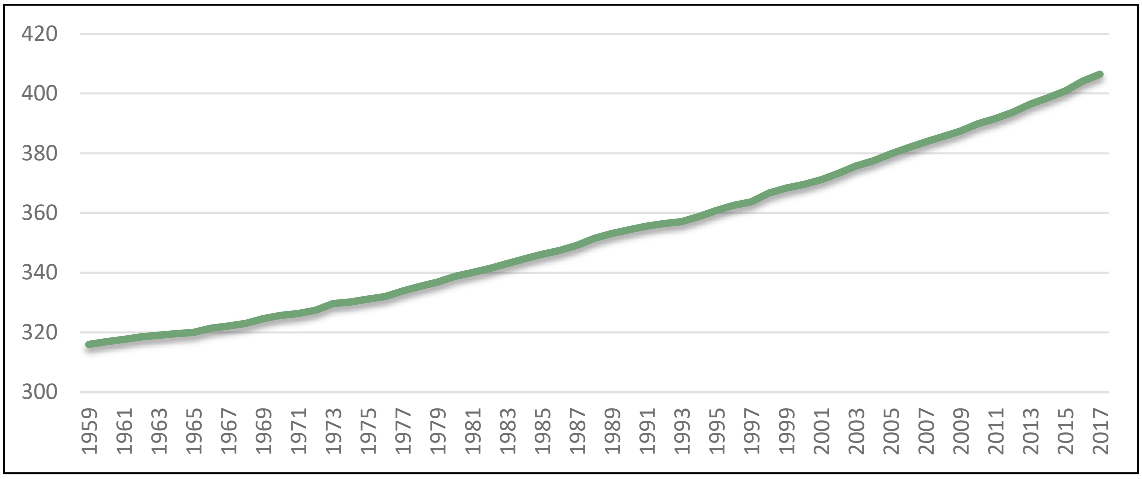
- If aridity coincides with an early start of vegetation in spring, weakened crops cannot recover very well as weeds will also start to compete for water resources.
- Early summer aridity, especially during the months of April and May, are of particular importance for crops' yield development, which is largely determined during the early crop development phase.

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.

c) 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[7] (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), which can translate into less water demand. 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 CO2 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. 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 might be negative.

d) Erosion

Following an increased occurrence and intensity of weather 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-Eastern 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, 2017a).

[7] 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).

3 Possible adaptation and mitigation pathways created by plant breeding

According to the IPCC (2019), one option to make more productive use of land, water, nutrients and other resources is the genetic improvement of crops for high yield, tolerances and adaptation to climate change. Hence plant breeding and the new technologies implemented in the sector can contribute to reduce the pressure on land and also contribute to climate change mitigation (IPCC, 2019; WRR, 2019).

The following are possible pathways for plant breeders to contribute to climate adaptation and mitigation. Please note that all these pathways are highly interconnected and influence each other. Furthermore, it depends on the overall crop management and local conditions to what extent these breeding induced benefits can be reaped.

Closing the yield gap – this means to decrease the differences between attainable yields under perfect management and actual farm yields achieved by an average farmer. On the one hand side plant breeding has increased – and still has the potential to further increase – the genetic yield maximum of plants. On the other hand plant breeding can create varieties that produce high yields under various environments and under limited input use (Voss-Fels et al. 2019). Furthermore, new traits that facilitate crop production (e.g. dwarf varieties or synchronization of ripening times) have helped farmers to achieve higher yields. For example Ahlemeyer and Friedt (2011) analyzed that German wheat breeding increased attainable yields by 0.34 to 0.38 dt/ha/y between 1966 and 2007. This is equivalent to about 0.5% of the average yield attained in 2010 in Germany (Statista 2018). Increasing land productivity by improved yields, can reduce worldwide land use changes and hence contributes to climate change mitigation.

Breeding for crop production under climate change conditions – as explained in Chapter 1 climate change will alter crop production systems. Plant breeding contributes to adapt crop plants to these changes. Increased drought and heat tolerance is for example achieved by creating crops with larger root systems (IPCC 2019). This improves the crops' water uptake as they can reach lower water reservoirs and access water from an increased area. Thereby also more nutrients might be absorbed. But plant breeding is not only helpful under adverse climate conditions. Another area of work is the selection and creation of varieties that are well adapted to new environments. Such as maize varieties that produce well in areas that were formerly too cold for the crop (see Chapter 2a). Moreover, plant breeding can optimize the crop life cycle under new climate conditions which ultimately translates into higher and more stable yields. Depending on a region's climate a variety's growing period can also be shortened to avoid water stress events during crucial stages of plant growth or a variety could even be bred to allow for several harvests per year.

Improving nutrient and water use efficiency – These breeding goals contribute to both, adaptation to and mitigation of climate change. For example genetic improvements pursued in Germany since the 1960's on winter wheat achieved a reduced demand for fertilizer and water (Voss-Fels et al. 2019). Also, fertilizer emissions into the environment can be reduced by increasing nitrogen use efficiency.

Enhancing nutrition and food security - Breeding has improved the quantity and quality of crop production. With increased yields food security is improved by higher food availability. Furthermore, plant breeding can stabilize or even enhance crops' micronutrient content under adverse climate change conditions. This is for example done by decreasing crops' sensitivity to atmospheric CO2 as research has shown that an elevated CO2 - level decreases crops micronutrient content (IPCC, 2019). Consequently, breeding can improve food security and global health by providing inputs that ensure a high-quality food production under climate change conditions. Another aspect is the proliferation of local protein crops, a strategy that is supported by the German government. To reduce protein imports and negative climate change effects from land clearing, for e.g. for soy plantations, plant breeding can enhance the agronomic qualities of protein crops such as legumes.

To maximize these possible breeding-induced benefits for climate change mitigation and adaptation, it is necessary to take advantage of the vast global genetic material available and further include landraces, crops' wild relatives, orphan and neglected crops (e.g. millet, beans, cassava) into breeding programs (WRR, 2019; Searchinger, 2014) in search for desired traits such as increased resistances to biotic stresses or heat tolerance.

The speed and quality of future genetic improvements also depends on the breeding technologies at hand. For example, the application of hybrid and CRISPR/Cas breeding in wheat, produced wheat varieties that are resistant to powdery mildew and also have higher and more stable yields (Zhao et al. 2015). The CRISPR/Cas technique made it possible to introduce the powdery mildew resistance found in barley to wheat. Without the new technique, thus with conventional breeding, this would probably have taken 10-20 years longer (Wang et al. 2014; Acevedo-Garcia et al. 2017).

As climate change is a rapidly evolving phenomenon, also plant breeding needs to speed up, but due to its complexity and the need to test new varieties in real field conditions, this is a difficult endeavor. So far other technologies such as high-throughput phenotyping and genomic markers have already decreased breeding time and costs.

4 Conclusion

Current and future climate change impacts make it clear that agricultural systems must adapt and reduce emissions. 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 must be considered when projecting climate change impacts on crop production. Regardless of the region- and crop specific projections of climate change impacts it becomes clear that crop production will face much more extreme weather events in the future. Such extremes as the rainfall deficit in Germany in 2018 and 2019 are more likely to appear more often and with higher impacts. Furthermore, the persistence of these events will increase. This means that crop production will be more volatile in the future. 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, habitat shifts, or habitat expansions occur as thermophile crops move northwards. One example is the expansion of the ecological niche of maize due to increasing average temperatures.

It is also important to consider farmers' management, political regulations and the quality and quantity of input factors (such as fertilizer and seeds) when analyzing the future of crop production. Plant breeding positively influences the phenotypic traits of varieties and crops used. Therefore, this sector plays a crucial role for climate change adaptation and mitigation by improving primary crop production, food security and resource efficiency. Increasing yields under various environments is still the main priority of plant breeders. With the right policies, yield boosts can reduce agricultural land extension and hence protect natural ecosystems. Nevertheless, it is a challenge to adapt to the rapidly changing climate and anticipate not only climatic conditions but also consumer preferences and international trade flows. Such a globalized challenge calls for international cooperation to exchange genetic material and experiences with different varieties or crops within different climatic zones and cropping systems. Also, national or international funding for research and development within the sector should be sustained. This way the breeding-induced benefits for climate change adaptation and mitigation can be optimized.

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