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Assessment of cropping risks in Austria under climate change

submitted by

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Affidavit

I hereby declare that I am the sole author of this work. No assistance other than that which is permitted has been used. Ideas and quotes taken directly or indirectly from other sources are identified as such. This written work has not yet been submitted in any part.

Gothenburg (Sweden), 13/9/22 Signature (handwritten)

Abstract

Among socio-economic and other factors, especially the impacts of climate change and extreme weather events can lead to increasing food risks. However, these impacts are uncertain and depend on regional factors, choice of crop and various adaptation options. The aim of the present study was to assess how the impact of climate change, expressed in the form of cropping risks, can differ for three Austrian study sites, characterized by different climates, such as the effects on local yields and yield variability. Furthermore, another aim was to assess the effect of irrigation as an important adaptation option, i.e. to differentiate between rainfed and irrigated agriculture and winter and summer crops, respectively. Agrometeorological indices, which represent key cropping risks for the three study sites as well as a crop model (AquaCrop) were applied to assess and correlate the potential impacts at each site and under different conditions (including two climate scenarios). It is shown that semi-arid areas such as Poysdorf are expected to experience more rainfed crop failures under the future climate scnearios applied and will benefit preferably from irrigation and water saving strategies. The warm-humid case study areas areas like Bad Gleichenberg in our case, can expect to be less impacted by rainfed crop failures in the future due to drought but be affected by other cropping risks and extreme events (for instance from heavy or to high precipitation which can make adaptation more complex). Humid areas can also experience less field working days, which makes timing for field operations (by machinery) more difficult in the future. The achieved results are more optimistic than earlier studies in the area, based on other global circulation models, whereas our scenarios show more precipitation especially in early summer for Central Europe. This highlights the need to use more precise data bases in future adaptation studies at the local level.

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Conventions and abbreviations in this study

WHC	Water holding capacity
EGD	Effective growing day
GCM	Global circulation model
GDD	Growing degree days
Obs.	Observed (weather data)
First climatic period	The years 2030-2059
Second climatic period	The years 2060-2089
Sowing days	early spring = March 1st to April 25th, late spring = April 26th to May 20th
Baseline	The years 1981-2010
Wheat	Always refers to winter wheat

All the baseline calculations are made with observed weather data for 1981-2010 for the three study sites apart from in the bias and trend analysis where also climate scenario data for the baseline years are used. This will be described under the relevant chapters as well.

The chosen agrometeorological indices were written in italics and with capital first letter to be able to distinguish them in the text.

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1. Introduction

1.1 Motivation and problem statement

One of the big questions regarding food production and food safety in the future is whether agricultural output can keep up with the increasing demand especially under climate change that could have a negative impact on crop yields.

There are indications that yields are stagnating for some of the most important crops such as wheat and rice. Even though there is a great uncertainty and debate on the relative effect of climate change and its impact on stagnating yields, there is a consensus that climate change will affect future yields, both positively and negatively depending on the region and time scale considered.

In light of stagnating yields, increasing global food demand, and the hint that climate is already now negatively affecting yields, it is relevant to assess how climate change could impact agriculture in the future. Even though food security is a global problem, there is a lot to be gained from zooming in and assessing more regional and local situations, since climate change is expected to have a spatial gradient.

This study was aimed to complement different studies that have already been conducted in the field and focused on the regional and local scales. Earlier studies have varied in their choice of time period assessed, methodology and scale. Many studies have used historical data to assess how climate change could impact crop yields in the future. Some studies have looked at the last decades (Finger, 2010; Lobell, Schlenker & Costa-Roberts, 2011) whereas others have gone back even further to assess the relationship between climate and agricultural yields before the warming trends started in the second half of the 20th century (Trnka et al., 2012, 2016a). One problem with these types of studies, especially the latter, has been the lack of available data (Trnka et al., 2012).

Related studies have used process-based crop models focusing on specific aspects such as different crops or single meteorological and climatic variables and how these will be affected under climate, for instance evapotranspiration (Trnka et al., 2011b). Another method that has been used is agrometeorological indices to understand some of the complex relationships between climate and crops (Eitzinger et al., 2013; Trnka et al., 2010a). They have the potential to incorporate aspects that often are not integrated in crop models such as extreme events (Lalić et al., 2014). These can also be used to assess the potential impacts of climate change on a greater scale and work as a great compliment to crop models.

Larger scale studies both on global level and across multiple countries are rare (Ray et al., 2012; Trnka et al., 2010a). Apart from the lack of data in larger scale studies, there are other good reasons to do more regional studies. As already said, climate change will have different impacts in different areas and regions, and therefore it can be useful for adaptation purposes to focus on single locations or smaller regions. The message and information from climate change studies are still not reached by all farmers due to too long time horizons and high complexity (Trnka et al., 2011b).

1.1.1. Yield trends

In developed areas of the world such as Austria and Europe a steady growth trend has been seen in the second part of the 20th century (Brisson et al., 2010; Ewert et al., 2005). The use of irrigation, chemical inputs, modern high-yielding crop varieties, higher level of plant protection, pest and disease management have all contributed to higher yields (Lobell & Gourdji, 2012a; Supit et al., 2010).

Many areas characterized by high yields are now experiencing decreasing yield growth (Lobell & Gourdji, 2012a). Yields have been stagnating, beginning in the 1990's, in many areas such as Europe and the US (Brisson et al., 2010; Ma et al., 2016; Ray et al., 2012; Supit et al., 2010; Trnka et al., 2016a; Zimmermann et al., 2017). There are also indications that interannual yield variabilities have increased, especially in absolute terms which is also a logical consequence of higher yields (Finger, 2010; Trnka et al., 2012).

1.1.2. Productivity

In light of population growth, dietary changes and the uncertainty of climate change there is a possibility of a food crisis and food scarcities if productivity is not increased (Ray et al., 2012; Sakschewski et al., 2014).

There are two general ways to increase agricultural production – increase in production per area, hence productivity, and expansion of agricultural lands (Sakschewski, Von Bloh, Huber, Müller, & Bondeau, 2014). Agricultural lands diminished by 13% in Europe in the last decades of the 20th century, and this trend is expected to continue due to a higher demand for other land uses such as urban expansion, bioenergy, and carbon sequestration (Ewert et al., 2005; D. B. Lobell & Gourdji, 2012). The needed increase in future supply will have to come mainly from an increase in productivity.

1.1.3 Other reasons for stagnating yields

In light of stagnating yields and future crop demand, there is a great interest in knowing what drivers have caused these stagnations and what the situation in the future will be. Due to the great increase in demand, global prices and food security are highly influenced by even small fluctuations in supply that could potentially be caused by climate change (Lobell & Gourdji, 2012b).

In spite of this, the relative importance of the different drivers have not been assessed thoroughly (Moore & Lobell, 2015). Observed yield trends are often seen solely as a result of technological growth and a logical explanation is that the high-input systems have reached their potential and the marginal yield improvement from more fertilizer and other intensification practices is decreasing.

Yield gap is a measurement of the difference between actual yields and the potential yields that can be obtained with an adapted crop variety grown under optimal conditions with no yield-limiting factors (Ma et al., 2016). The stagnating yields can be the result of two different things in relation to yield gaps. Either actual yields are approaching potential yields due to technical advancements or else, the potential yields have decreased as a result of other factors, for instance changing climate (Supit et al., 2010). Yield gaps were found to be smaller in advanced agricultural systems such as in

Western Europe, for instance in Germany and France, compared to in Eastern Europe (Ma et al., 2016). There are no substantial differences between the potential yields between Western and Eastern Europe, which indicates a higher potential for yield increases in Eastern Europe in the future (Ma et al., 2016).

Another explanation for stagnating yields is environmental regulations that have resulted in less areas under intensive agricultural practices with less use of fungicides, plant growth regulators, fertilizers etc. (Finger, 2010; Peltonen-sainio, Salo & Jauhiainen, 2015; Trnka et al., 2016b). This also happened in the European Union in the 1990's with the introduction of policies that for instance restricted fertilizer levels and also subsidy payments that were first coupled to the production level of the farm, and from 2004 decoupled form production levels (Moore & Lobell, 2015). If subsidies are not linked to agricultural output, it can reduce the incentive for intense production and lead to more areas under extensive production, and thus lead to lower yields.

Fluctuating prices can also result in lower yields if the crop prices decline thereby making it more economically sound to reduce inputs and not produce the highest possible output. The opening to the free-market economy and the increased competition has meant that the highest yields was not always the best option to obtain the highest possible profit (Trnka et al., 2012).

There might also be agronomic reasons for the yield trend, such as increasing disease frequency, nitrogen requirements and crop cycles (Brisson et al., 2010).

1.1.4 The role of climate change

There is now a growing awareness that climate change plays a part in stagnating yield trends but it is often only mentioned marginally and mainly responsible for year-to-year variability, while rarely seen as a cause for stagnating yields (Brisson et al., 2010). Many studies report that climate change is a plausible cause for stagnating yields (Brisson et al., 2010; Moore & Lobell, 2015; Trnka et al., 2016a).

Climate change impact studies are based on complex relationships and since the expected response to variabilities in climate forcings is based on a response function that is uncertain, the results have to be treated with caution. Secondly farmer may or may not be adapting to climate change thereby masking the effect it has (Moore & Lobell, 2015).

Climate change impact might be rather marginal compared to other drivers and also coupled with great uncertainties. Climate change could explain around 10% of the yield stagnation in the last couple of decades whereas agricultural and environmental policies were the main driver for the remainder (Moore & Lobell, 2015). It was estimated that climate change have resulted in yield decreases of about 0.02 – 0.05 t/ha/year in France compared to for instance genetic progress that has resulted in yield increases between 0.1 – 0.12 t/ha/year (Brisson et al., 2010).

Even though climate change may only have had a marginal effect on absolute yields, climate variability may have increased the variability of crop yields. Climatic factors were found to explain between 18 and 71% of wheat yield variability in Europe in the years 1991-2012 and it has been suggested that climate trends are becoming as important as technology for yield variability (Trnka et al., 2016a).

Climate change seems to still only have a marginal influence on yield trends. It is important to note that this is based on observed trends and coupled to many uncertainties as it is difficult to separate the relative importance of different factors on yield trends. Yields are stagnating, and climate change is one of different possible explanations for this.

As global food demand has increased rapidly in the last couple of decades, even small fluctuations in supply can influence food security and result in fluctuations in food prices (Lobell & Gourdji, 2012a). Areas under intensified agriculture tend to be more sensitive to weather and climate changes, for instance due to higher fertilization rates (Lobell, Schlenker & Costa-Roberts, 2011), and many of these high-yielding areas is exactly where most stagnating yields are being found (Lobell & Gourdji, 2012a).

Yield trends on a global scale will continue to be mainly shaped by technological and agronomic advancements, and it is not likely that climate change will result in a decline in global yields, but the question is to what degree climate change will counteract yield increases (Lobell & Gourdji, 2012a).

Even though some studies have found the relative role of climate change on yield levels to be relatively negligible in the last decades, there is a consensus that the adverse effects of climate change on crop risks and yields are expected to increase in the future (Eitzinger et al., 2013; Trnka et al., 2011c). Agriculture in Europe is highly sophisticated with a high level of inputs and therefore likely to be more sensitive to changing climate and weather in the future due to the complex relationships with technology (Lobell, Schlenker & Costa-Roberts, 2011; Trnka et al., 2012). Because of stagnating yields, it is important to assess future European yields under climate change.

1.2 Aims and objectives of the study

The aim of this study was to assess the potential impacts of climate change on cropping risks and how this could impact future crop yields in different Central European, more precisely Austrian climates. Two aspects should be assessed to fulfil the main aim:

- Assess what cropping risks are most likely to affect maize and wheat yields in Austria and how these will differ for three different climates/study sites
- Assess to what degree the risks will differ for rainfed and irrigated agriculture and for winter (winter wheat) and summer (maize) crops

Due to the shortcomings of single crop models that are not able to incorporate important processes, and with inspiration from earlier studies in the field, this study used both crop models to estimate maize and wheat yields and agrometeorological indices to make the assessments. The study stands between studies working on a bigger scale such as pan-European studies and single-location studies.

There are still many research gaps and uncertainties in this field since many processes are not sufficiently understood. By making a thorough regional study, using data from different study sites, located in different climates, this study could help to gain important insights to how climate change impacts will differ regionally. By considering the regional climates and using regional data, it could be easier to propose adaptation strategies that take the local conditions into account (Eitzinger et al., 2013).

1.3 Climate change and cropping risks

1.3.1 The complexity of climate change

It is difficult to assess how climate change will affect both global and regional crop production. The interaction between climate and crops is complex and based on many physical and physiological processes (Lalic et al., 2013). The suitability of a plant to grow in a specific region is dependent on climate and meteorological factors, physical and landscape factors and also economic factors, for instance nutrient inputs and farm size (Trnka et al., 2011b). How crops respond to climate change therefore also depends on non-meteorological factors such as production technique used, soil type and land use (Lalic et al., 2013). As pointed out in the beginning, it is difficult to assess the relative importance of climate change on productivity changes such as stagnating yields, since technological developments have had a profound impact on productivity. To assess the influence of climate change on global crop production is difficult since environmental conditions have a spatial gradient, and therefore changes will be felt different in different areas. It is therefore crucial to look holistically at the whole picture when assessing climate change effect for a specific location. This includes local soil conditions, changing meteorological variables, land use, and the production system used.

It is difficult to simulate the complex system of plant-environment interactions through crop models and therefore simplifications are necessary that increase the possibility of uncertainties. In other words, our ability to simulate the future influence of climate change on crop production and agriculture is limited by the precision of crop models (Lalic et al., 2013; Thaler et al., 2012).

1.3.2 Climates in Central Europe

Most of the climate change impact studies that have been carried out in Central Europe have been site-based with a limited spatial scope, and rarely consisting of more countries (Trnka et al., 2010a). That being said, some studies based on different methodologies, such as agrometeorological indices, have been carried out on a bigger scale (Trnka et al., 2010a, 2011c, 2011b). The limited availability and low density of climate, soil and management data, has been one of the reasons for the limited number of studies in multiple regions and countries in Central Europe (Trnka et al., 2010a).

Since Central Europe consists of a range of different environmental zones and a high vertical gradient (Trnka et al., 2011b), a high density of climate data is generally needed to make spatial studies. These different environmental zones with different agroclimatic conditions are expected to respond differently to climate change. The main zones characterizing our study sites and Central Europe is the Continental, Pannonian and Artic South zones (Trnka et al., 2011c, 2011a). The continental climate is characterized by big yearly differences in precipitation and temperature. The Pannonian is a dry zone in the East-southern part of Central Europe, from approximately Vienna in the west to Zagreb in the southwest (Lalic et al., 2013; Trnka et al., 2011a). The area is characterized by flat regions and highly influenced by the continental climate with a high climate variability. Compared to the Continental zone, the Pannonian experiences higher summer temperatures and more dry days, and therefore one of the limiting factors is lack of water in the summer (Lalic et al., 2013; Trnka et al., 2011c). Big differences in the precipitation during the growing season is problematic for crop growth in the region (Lalic et al., 2013) but still crop production in the area is dominated by arable production and typical crops such as maize and winter wheat (Trnka et al., 2011c).

On the other hand, Central Europe also encompasses the wet highlands and mountain regions that are characterized by a vastly different climate due to more precipitation and lower temperatures. One problem in these areas apart from a shorter growing season and poor soils is the terrain that cannot be reached due to the topography which limits the crop production (Trnka et al., 2011a). The intensively cultivated regions in these areas are generally located at elevations below 750 meters above sea level where the conditions for crop growth are better (Trnka et al., 2011b, 2011c).

As Austria is characterized by both oceanic and continental effects and also the orographic effects of the Alps that influences and changes the precipitation patterns and amounts, it is useful to assess the climate change effect in different regions of the country.

1.3.3 Cropping risks

Through simulated potential yields, Supit et al. (2010) assessed trends in the regional response to climate in Europe from 1976-2005. Central Europe, including Austria and Czech Republic, was one of the regions with the highest negative yield response to climatic changes for the period, only surpassed by Northern Italy.

Big parts of the crop growing regions in Central European countries as Czech Republic and Austria are characterized by dry conditions and big yearly amplitudes in temperatures which limits the number of crops that can be grown and their yields (Trnka et al., 2016a). In the future this situation is expected to be even more severe, and drought is one of the main cropping risks that could affect agriculture in the region. Studies have shown that major adverse drought events with traditionally long return times are more likely to occur in the near future, compared to the previous 130 year (Trnka et al., 2010a). The dry agricultural areas are expected to be even more dry with higher frequency of heat stress and drought periods (Lalic et al., 2013).

Warmer days will increase evapotranspiration levels in the future which may not be accompanied by an increase in precipitation levels or increase in water use efficiency. The increases in water deficit will especially be detrimental for rainfed yields in many agricultural regions and also areas under irrigation if the water resources are decreasing. The rainfed production potential of Central Europe as a whole was found to increase under climate change due to an increase in effective growing days, especially in the dry and warm zone (Trnka et al., 2010a, 2011a). Even though rainfed yields will in most years remain at an acceptable yield level, the projected increase in drought and water deficits will increase the risks and interannual variability.

Studies agree that droughts will generally occur in the summer which can make crop production in summer much more difficult and even impossible in some areas – especially since some of critical growth periods with high water stress sensitivity occur in this period (Thaler et al., 2012; Trnka et al., 2010a, 2011b, 2011a). This is especially problematic since Central Europe is a region that to a large degree depends on adequate and well-distributed precipitation for crop production (Trnka et al., 2010a).

Adapting to drought risks through expansion of areas under irrigation could be problematic due to the lack of access to irrigation in many areas in Central Europe. This could for instance be the case in

Czech Republic because of a low number of suitable water reservoirs and potentially decreasing water resources (Trnka et al., 2010a, 2011a). This can make it feasible to put a heavier emphasis on winter crops where the drought problem is less (Trnka et al., 2010a).

Not surprisingly, the Pannonian region will experience highest water deficit levels in Central Europe, especially in the spring and summer months due to a warmer and drier climate with high reference evapotranspiration rates (Eitzinger et al., 2013; Trnka et al., 2011c). The drought duration and variability in the Continental and Pannonian zones are both expected to increase (Trnka et al., 2011c). Even though a regional increase in production potential was found for Central Europe (Trnka et al., 2010a), this was not the case in Pannonian due to the water limitations and also declines in effective global radiation (Trnka et al., 2011c).

The rainfed potential is expected to increase in the alpine and mountain regions since the water deficits will be less here compared to dryer regions (Trnka et al., 2011c).

Other risks that are expected to increase in Central Europe are snow cover decrease, frost risk and pest and diseases. Eitzinger et al. (2013) found a reduction in snow cover in most of the assessed area, which covered Austria, Slovakia, and Czech Republic where one third of the domain will experience less than 25 days with snow cover. In spite of higher temperatures in winter, this can increase the crop sensitivity to frost risk which could be detrimental for winter crops grown in the area. It was also found that higher temperatures in winter can prevent vernalization for winter wheat but only in extreme cases, which is not expected to be the case in most future year, as well as an increase in pests and diseases such as the European Corn Borer and Colorado Potato Beetle due to higher temperatures (Eitzinger et al., 2013).

Crops can respond non-linearly to changes in their growing conditions and Trnka et al. (2012) found a sharp increase in yield response above a critical temperature threshold in Central Europe, indicating that higher temperature increases can result in much higher yield reductions, which was also found in IPCC (2018). Many agrometeorological studies made in Central Europe have tried to relate cropping risks and yield responses. (Lalic et al., 2013) found the number of days with water and temperature stress as well as precipitation levels and actual evapotranspiration to be the most important factors affecting winter wheat crop yields in a Serbian region of the Pannonian Lowlands. The ratio between actual and potential evapotranspiration from April to June was also important which can be expected to be lower under climate change as both water shortage and higher temperatures lead to a reduction in actual evapotranspiration, thus restricting crop yields (Lalic et al., 2013).

1.3.4 Crop responses to climate change

One of the fundamental axioms of agroclimatology is that different crops grow well in different climate regions, and that the success of the crop is dependent on both climate, physical and economic factors (Trnka et al., 2011b). Central Europe that is influenced by the continental climate has greater annual temperature fluctuations than in more maritime climates and is also a relatively dry region, and this limits the number of crops that can be grown (Trnka et al., 2016a).

Climate change will likely result in new agrometeorological zones, and it is important to assess the expected responses of different types of crops for future adaptation. Winter wheat and maize are some of the most important crops in different regions in Central Europe (Trnka et al., 2011a, 2011b), and included in many of the regional studies. Apart from their global as well as regional importance in Central Europe, the two crops also represent different key types since they are grown at different times of the year and have different carbon pathways.

1.3.5 Crop characteristics of the investigated crops (wheat and maize) and selected cropping risks related to climate change

Maize is a tropical plant that is grown best in warm climates at temperatures above 10 °C but is now common as a summer annual crop in more northern latitudes where it is planted in the spring and harvested in the fall (Sheaffer, C. C., & Moncada, 2012). Wheat, on the other hand, is a temperate, cool-season plant that can sustain big annual differences in temperature, as in Central Europe (Sheaffer, C. C., & Moncada, 2012).

Winter crops are normally planted in the early fall and have to undergo a cold vernalization period to induce flowering and growth in the spring. Spring and summer crops on the other hand are planted in the spring and do not depend on vernalization to flower (Sheaffer, C. C., & Moncada, 2012; Steduto et al., n.d.). Furthermore, maize is a C4-crop, whereas wheat is a C3-crop. The plants differ in their carbon fixation procedure, their response to rising CO_2 in the atmosphere and also their water use efficiency (Sheaffer, C. C., & Moncada, 2012; Steduto et al., n.d.). The photosynthetic pathway for C4-crops, such as maize, means that they only have strong responses at CO_2 levels well below the current ones, so CO_2 assimilation rates will not change much under increasing CO_2 levels in the future (Lobell & Gourdji, 2012a; Supit et al., 2012). C3- and C4-rops also differ in their optimum temperatures for photosynthesis. C4-crops such as maize originated in the tropics, and therefore they have higher optimum temperatures than wheat. This means that both the absolute minimum temperature, optimum temperatures and absolute maximum temperature differ for these crops (Hollinger & Angel, 2009).

These differences between the crops will mean that they will face different cropping risks. Generally, wheat will be sensitive to warmer temperatures, whereas maize is sensitive to cold temperatures. Still, maize-growing areas are already experiencing higher than optimum temperatures, and even C4-crops can experience reduction in assimilation rates under sharply increasing temperatures as expected in Southern Europe (Supit et al., 2010). High temperatures at night can raise respiration costs which is not beneficial for photosynthesis (Lobell & Gourdji, 2012a). Hatfield et al. (2011) identified optimal season average temperatures for major crops and found it to be 15 °C for wheat and 18 °C for maize, but several important high-producing countries are already above the optimal level which results in lower yields – especially for maize (Lobell & Gourdji, 2012a).

Still, some maize yields could increase under higher temperatures dependent on the circumstances. This could result in new areas opening up as maize areas and increase potential maize yields in others. Introducing maize in more northern regions, though, could increase risks from cold temperatures as freezing temperatures can kill tropical plants (Sheaffer, C. C., & Moncada, 2012).

Another cropping risk related to maize is its higher sensitivity to water stress compared to other crops which can also be accompanied by nitrogen deficiencies as nitrogen is applied to the top soil layer which dries up first and therefore becomes unavailable to the plant (Steduto et al., n.d.). The frequency of summer drought and heat waves are expected to increase in Central European areas such as Pannonian Lowland, which will have a negative effect on maize yields, especially under rainfed conditions (Trnka et al., 2011c).

1.3.6 Increase of ambient CO_2-level

The question is whether CO_2 is able to offset some of the negative effects of temperature increases and drought conditions, especially in C3-crops such as wheat. Higher atmospheric CO_2 concentration could increase the photosynthesis rate and water-use efficiency but the increase in CO_2 from 1870 to 2005 was assumed to not be enough to counteract the influence of higher temperatures on interannual yield variability in Central Europe (Trnka et al., 2012).

In Thaler et al. (2012) CO_2 enrichments lowered the simulated wheat yield losses caused by higher temperatures and crop water stress and even led to yield increases depending on choice of global circulation model (GCM) based climate scenario. Eitzinger et al. (2013) simulated the changes in winter wheat and spring barley yields in the Marchfeld region for 2035 and found that the effect of CO_2 fertilization could not offset the negative impacts of shortened growing season and precipitation reduction during critical growth stages. Supit et al. (2012) looked at the climate change effect at a European scale and found that winter wheat may benefit from higher temperature and the production potential could increase until 2050. After 2050, depending on choice of climate scenario, atmospheric CO2 and temperature increases may result in continued increase in production potential.

The general picture is that in most cases CO2 enrichments will not be able to offset the negative impacts of cropping risks and warming on yields but can ameliorate the situation to a certain degree.

Globally but also in Europe, studies have shown that wheat has suffered more yield depressions than maize (Moore & Lobell, 2015; Ray et al., 2012). Moore & Lobell (2015) found that long-term temperature and precipitation since 1989 reduced wheat yields by 2.5% over the European continent and during the same time maize yields increased around 0.3%. Especially temperature was one of the explanations behind these changes, and the temperature effects on maize yield was estimated to being very low (Moore & Lobell, 2015).

1.3.7 Impact of soil conditions

A profitable crop production does not only depend on climate and technology but also on soil conditions (Trnka et al., 2011b). Soils differ in their physical and chemical compositions, and some are more useful for agricultural production. Soil texture influences the amount of pore space and thereby the amount of water that can be held in the soil and is available to plants (Hollinger & Angel, 2009; Sheaffer, C. C., & Moncada, 2012). Sandy soils can hold less water than clayey soils, and therefore these are generally more sensitive to drought conditions. Soil moisture is important for plant growth and directly influences changes in temperature and precipitation but the changes will differ for different types of soils (Lobell & Gourdji, 2012b)

When assessing the future crop yields, soils with low WHC will be much more sensitive, and mean yields are likely going to be lower on sandy soils as shown in (Eitzinger et al., 2013). Thaler et al. (2012) used 4 soil classes with different water-holding capacities in their assessment of climate change impacts on winter wheat yields in Marchfeld, Austria. Different problems were found with the soils with lower WHC, such as a higher level of nitrogen leaching which could worsen the already bad nitrogen situation in the area (Strauss et al., 2012).

Extreme events like those that face Central Europe such as drought and heat impacts will likely be more severe on soils with lower WHC which was also found to be the case in (Trnka et al., 2014; Trnka, Hlavinka & Semenov, 2015).

High underground table could potentially mitigate and reduce the severity of some extreme events, especially drought that is one of the most common adverse events that will face Central Europe (Trnka, Hlavinka & Semenov, 2015).

1.3.8 Impact of crop management conditions

Soil moisture is a key aspect when calculating the number of suitable days for field work such as sowing and harvesting (Hollinger & Angel, 2009).

Sowing and harvest suitability have often been studied as agrometeorological indices where soil moisture thresholds are used to define suitable days (Trnka et al., 2010a, 2011c, 2011b). In case of wet soils, especially in spring, even small precipitation amounts can delay field work operations, namely on clayey and loamy soils (Hollinger & Angel, 2009). A wet soil profile can result in compaction due to traffic and tillage and lead to nitrogen leaching, and therefore planting should not be done on too wet soils. On the other hand too dry soils can also be problematic as it can be detrimental for stand establishment (Hollinger & Angel, 2009).

The literature is not conclusive when it comes to how sowing suitability will be affected under climate change in Central Europe. The earlier start to the growing season in the spring tends to increase the number of spring sowing days, especially early-spring sowing (Trnka et al., 2011b, 2011c). (Trnka et al., 2010a) found a substantial decrease in suitable sowing days in different areas in Central Europe, here under northern and eastern Austria due to precipitation increases but this was dependent on the choice of GCM.

Sowing conditions in the fall seem to benefit from climate change which especially was pronounced in areas where autumn sowing at the moment is generally not very suitable, due to decrease in autumn precipitation (Eitzinger et al., 2013; Trnka et al., 2010a). This is another reason why winter crops may be preferred in the future in many areas (Trnka et al., 2010a).

Suitable days for harvest could generally increase in Czech Republic and Austria under climate change. The growing season will move towards the beginning of the year under climate change, and a higher proportion of areas in Central Europe will likely be harvestable in June. June was projected to have fewer harvest days compared to the other typical harvest months due to wet soil profiles (Trnka et al., 2010a). So even though the harvest window may increase, it will not, in many cases, practically lead to better harvest conditions due to the timing of the growing season and harvest planning can be more challenging in the future (Trnka et al., 2010a).

Growing later ripening cultivars can offset some of these harvest problems (Eitzinger et al., 2013) but as already stated, these cultivars can be prone to more adverse events, especially in Austria and Central Europe.

2. Materials and methods

2.1 Data base

The data in this study consisted of observed and climate scenario data. The observed data was taken from The Austrian Meteorological Service (ZAMG) stations covering the years 1981-2010 (from now on called the baseline period of the study). The simulated data was taken from the ÖKS15 dataset with different climate scenarios or projections, based on the EURO-CORDEX climate models. These datasets were created due to the high demand for publicly available regional climate change data that could form the basis for developing climate change adaptation strategies (About - ÖKS15 - Groups | CCCA Data Server, 2022). The dataset consists of regional climate model output on a daily basis covering Austria (Chimani et al., 2020).

ÖKS15 scenarios first consisted of 13 regional-scale climate change projections that were created through the use of five GCM's and six regional models with a resolution of 12.5 km, covering the years from 1971-2100 and the variables temperature, precipitation and solar radiation (Chimani et al., 2018, 2020; Thaler et al., 2021). To further downscale to a grid size of 1 km, an observational grid of 1 km, the Spartacus dataset from ZAMG (SPARTACUS — English, 2022) was used to project the regional climate scenario data to also cover a grid size of 1 km. The reference period was 1961-2005. A statistical downscaling was performed with the help of bias-correction to diminish the errors between the simulated and observed gridded data (Chimani et al., 2018). The bias-correction method used was Scaled Distribution Mapping (SDM) (Thaler et al., 2021). Traditional quantile mapping (QM) makes an assumption of stationarity, meaning the function of error correction is independent of time, which was found to be flawed in Switanek et al. (2017). SDM was found to perform superior to QM and the correction is based on changes in the simulated data, thereby not making any stationary assumptions (Switanek et al., 2017). The final data in the ÖKS dataset represented the concentration pathways RCP4.5 and RCP8.5 (Thaler et al., 2021).

The global-regional model combination used in this study was the global model IPSL-CM5A-MR and the regional model WRF331F that both have French origin (Chimani et al., 2018). Ideally an ensemble of climate models should be used together with cross-validation to make the results more robust (Chimani et al., 2018; Thaler et al., 2021). This was deemed unrealistic for this study due to the already high number of different factors considered in the modelling such as soil characteristic and data representing different concentration pathways.

The years used in the study were the baseline period, 1981-2010 that primarily was used together with observed data apart from in the bias and trend analysis (see more under the relevant chapter) and 2030-2059 (first climatic period) and 2060-2089 (second climatic period) for the climate scenario data. Having two simulated normal periods covering 30 years each made it easier to generalize the results as opposed to only looking at one year that could represent an extreme year in some regard. The statistical value is much higher when looking at longer time periods (Chimani et al., 2018).

One should keep in mind that even though the data were bias-corrected, this was done on a monthly basis which could result in daily deviations that could have a strong impact on the modelled yields. Even if an error or trend analysis is performed on a monthly basis this may not show the whole picture (Thaler et al., 2021). Using dynamic and statistical downscaling to such a degree that the data is on a 1 km scale can result in big uncertainties, especially in areas with a complex topography and it is important to keep this in mind when using regional climate scenario data (Thaler et al., 2021).

2.2 The motivation behind the choice of emission scenarios

In the fifth IPCC assessment from 2014, Representative Concentration Pathways (RCP's) were used (Intergovernmental Panel on Climate Change, 2014). These describe different pathways of greenhouse gas emissions and atmospheric concentrations, and they are based on socio-economic and climatological factors such as population size, economic activity, land use changes, technology and climate policy (Intergovernmental Panel on Climate Change, 2014). Emission scenarios are used to illustrate different plausible climate outcomes based on human and climatological actions (Schwalm, Glendon & Duffy, 2020). These RCP's are used in global climate models and use historical emissions until 2005 and projected emissions in subsequent years (Schwalm, Glendon & Duffy, 2020).

In this study ÖKS datasets representing RCP4.5 (medium warming trend) and RCP8.5 (strong warming trend) emission scenarios were used (Intergovernmental Panel on Climate Change, 2014).

These two scenarios make sense to use since they represent two different pathways with different climate signal strength. RCP4.5 is an intermediate scenario where total radiative forcing will stabilize around 2050 and assume that different technologies and strategies for emission reductions have been employed (San José et al., 2016). The increases in global mean surface temperature at the end of the 21st century are projected to be between 1.1 °C and 2.6 °C (relative to the global mean surface temperature in 1986-2005) (Intergovernmental Panel on Climate Change, 2014).

RCP8.5 is the most extreme scenario with the highest signal in the fifth assessment report (Intergovernmental Panel on Climate Change, 2014). It resembles a "baseline scenario", as a situation without additional efforts to reduce emissions will lead to a pathway that lies between the RCP6.0 and the RCP8.5 scenarios (Intergovernmental Panel on Climate Change, 2014). This scenario is clearly based on a situation where efforts to reduce warming have not been successful and whereas the temperature increases in the RCP4.5 scenario stabilizes around 2050, the RCP8.5 is characterized by increasing greenhouse gas emissions over time (San José et al., 2016). It is characterized as a "non-mitigation business as usual scenario" (San José et al., 2016). The likely range of temperature increases relative to 1986-2005 is 2.6 °C 4.8 °C at the end of the century (Intergovernmental Panel on Climate Change, 2014).

Many studies have used RCP8.5 to describe a worst-case scenario but the scenario is rather controversial. It has received criticism for representing a highly unlikely future situation and the scenario has been described as "misleading" and "extreme" (Schwalm, Glendon & Duffy, 2020). Schwalm, Glendon & Duffy (2020) argues that this critique is misplaced for different reasons. First of all, scenarios should primarily show a wide range of possible future outcomes and guide decision makers to make informed decisions. Furthermore, RCP8.5 actually agreed most with observed CO_2 emissions in the years 2005-2020 of all the RCP's and the recent global warming trend. Looking into the future RCP8.5 makes sense to use, especially on the short term. According to Schwalm, Glendon & Duffy (2020) argues, it is not useful only to look at the longer time scale, also shorter time horizons such as 2030 and 2050 are important and at these time scales, RCP8.5 is highly relevant. And actually it has been found through forecasting of long-term economic growth that there is a 35% chance that CO_2 concentrations at the end of this century will exceed those in RCP8.5 (Christensen, Gillingham & Nordhaus, 2018). The final argument for using this scenario is the fact that there is still so much uncertainty surrounding climate research and possible future outcomes for instance due to climate feedbacks, that may enhance the effect from increasing greenhouse gas emissions (Schwalm, Glendon & Duffy, 2020).

2.3 Comparing climate scenario and observed weather data

As a starting point, bias and trend analyses were performed between the observed station-based data and the climate scenario data from the ÖKS dataset for the years 1981-2010, the baseline period. By assessing the bias and trends, an estimation could be made on how reliable the scenario data could be in the future climatic periods. This also included performing crop modellings for the baseline period with both scenario and observed data to see the deviations in crop yields. Naturally, many other uncertainties remain such as reliability of the emission scenarios in the future years and also uncertainties of the crop models. Both the RCP4.5 and the RCP8.5 simulated data were assessed.

Correlation and root mean square error (Correlation (Pearson, Kendall, Spearman) - Statistics Solutions, 2022; RMSE: Root Mean Square Error - Statistics How To, 2022) were used for the bias assessment in three steps – analysing all days, days in January and finally days in July. Looking at these months and comparing them with the overall results, made it possible to assess whether these results might mask some months where bias was higher. A significance level of 0.05 was chosen (as in the other statistical tests performed in this study), and low p-values of the correlation tests represented cases where the alternative hypothesis, that the correlation was significant, could not be rejected.

Trends were assessed with the use of Mann-Kendall trend-test (Mann Kendall Trend Test: Definition, Running the Test - Statistics How To, 2022) with low p-values representing cases where trend was found.

Both the bias and trend tests were performed for all the climate variables included in the data – max. temperature, min. temperature, precipitation, and solar radiation.

2.4 Study sites

Figure 1 shows the borders of Austria and the location of the three weather stations that were included in this study.

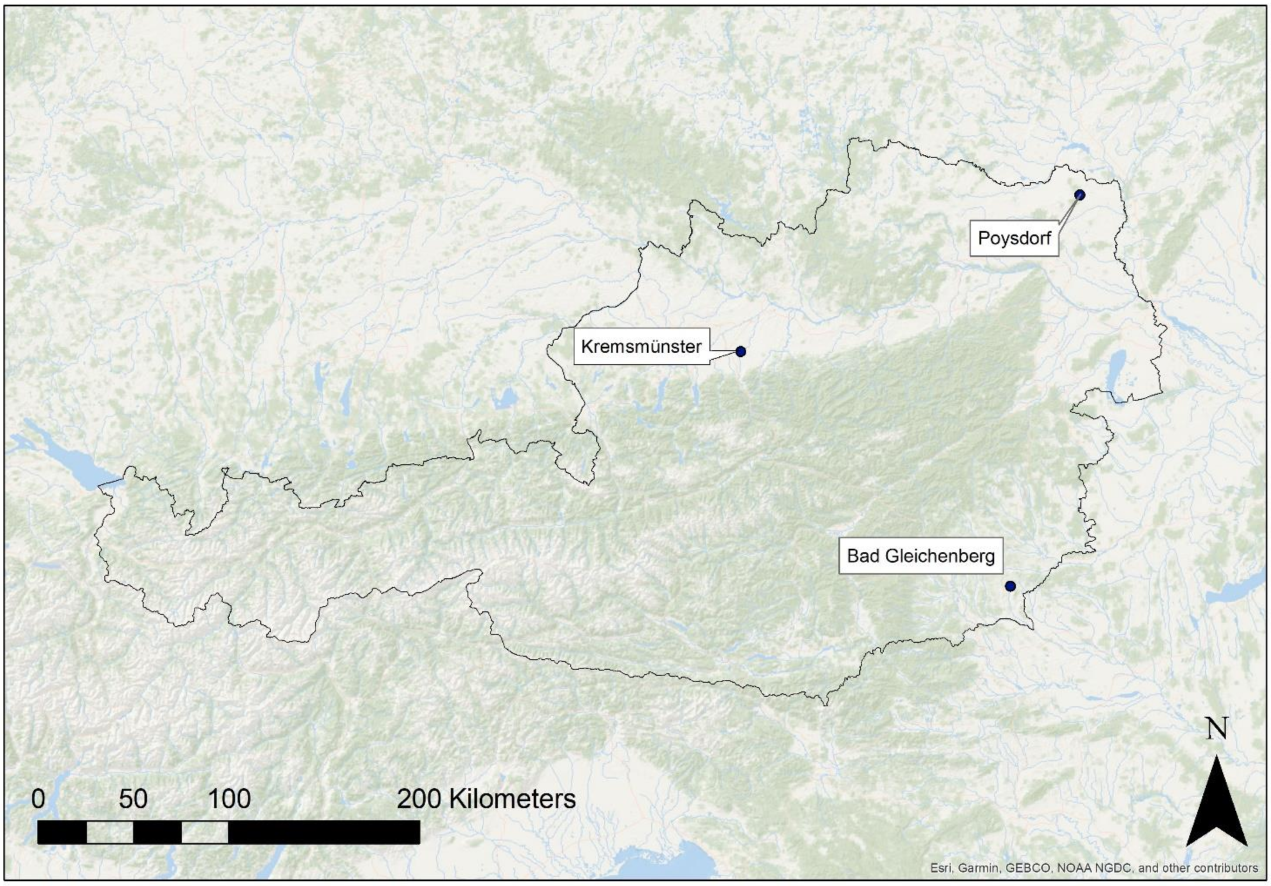

Figure 1. Map showing the weather stations and Austrian borders

Bad Gleichenberg is located at 46°5’ N, 15°5’ E, 317 meters above sea level, in the region of Styria in the south-eastern part of the country. This site is influenced by the continental and Mediterranean climate zones with warm summers and relatively high precipitation, especially in the summer months as indicated in the climate graph (Figure 3). The mean annual temperature for the observed years was 10.2 °C and mean annual precipitation sum 825 mm. In Figure 2, Bad Gleichenberg is located in the climate cluster 909, characterized by annual precipitation between 800 and 900 mm and mean annual temperature between 8.5 and 9.5 °C. This indicates a temperature increase from 1961-1990 to the baseline period used in this study.

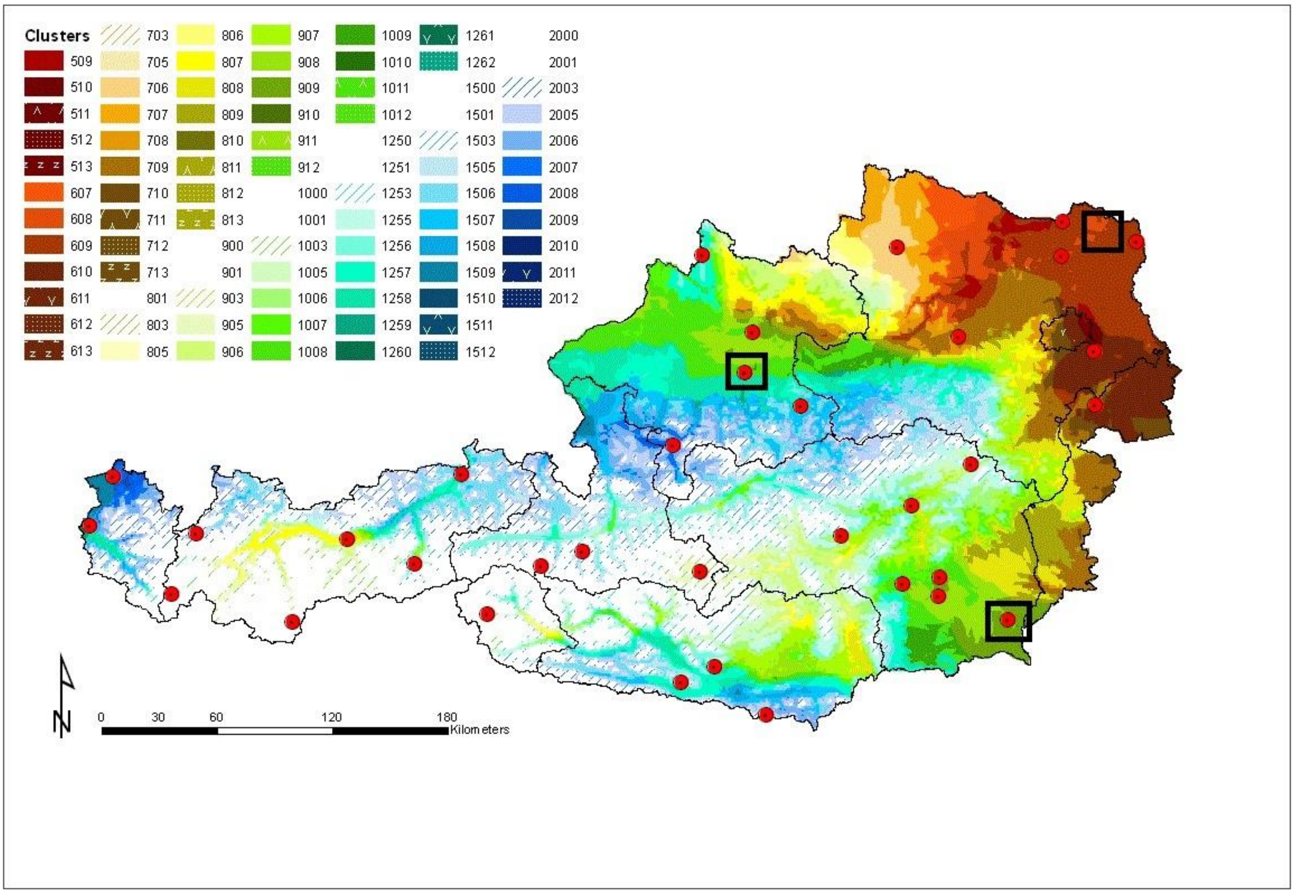

Figure 2. Climate clusters based on precipitation and temperature classes for Austria averaged over the period 1961-1990 adapted from (Strauss et al., 2010). *The map includes weather stations for the different climate clusters in Austria. The marked locations represent the three study sites (Poysdorf was not included in the previous study). The first part of the code (500-2000) is dependent on precipitation sums and the second (1-13) on average temperatures. The code descriptions for the three study sites are described in the text.*

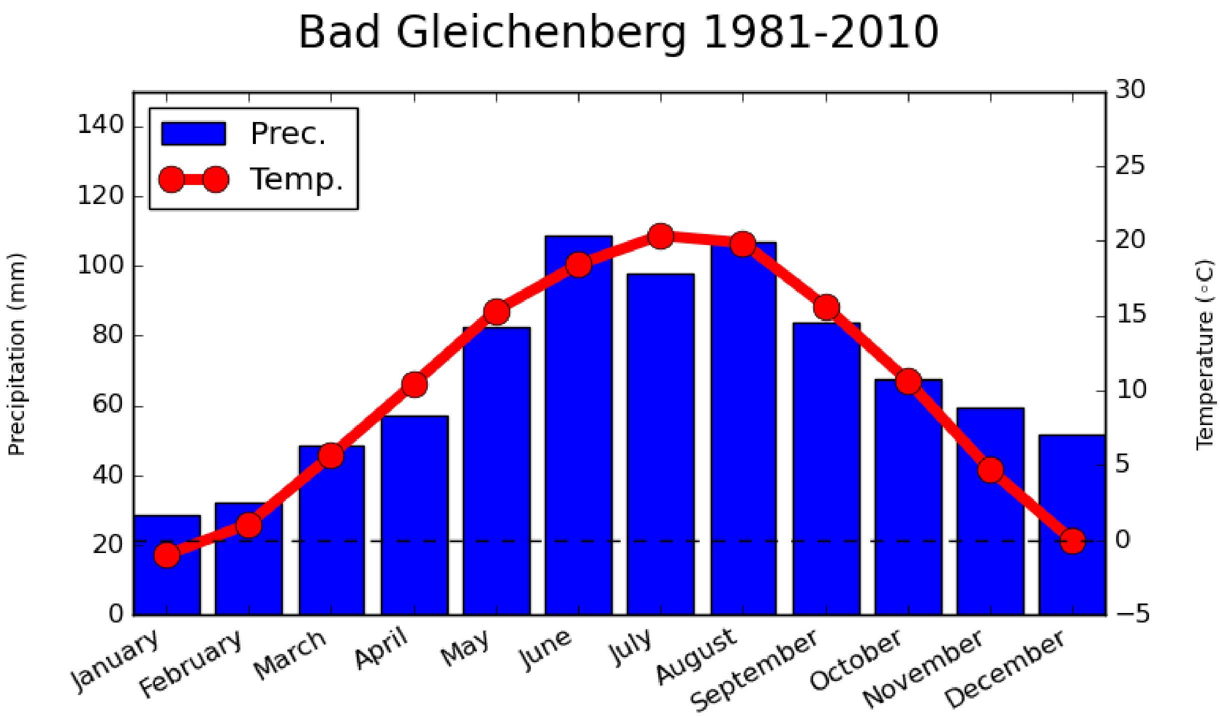

Figure 3. Baseline (obs.) climate graph, Bad Gleichenberg (1981-2010)

Poysdorf is located in the north-western part of the country, at 48°4’ N, 16°4’ E and 225 meters above sea level. This site is located in the dry Pannonian climate zone characterized by flat regions and a high climate variability (Figure 4). The climate is characterized by hot and dry summers and cold winters with heavy frosts (Thaler et al., 2021). Mean annual temperature was 9.6 °C in the observed years and mean annual precipitation sum was 553 mm. Poysdorf looks to be located in climate cluster 608 or 609 which indicates precipitation between 500 and 600 mm but with lower temperatures than found in our baseline, between >7.5 to ≤8.5 °C for class 8 and >8.5 to ≤9.5 °C for class 9.

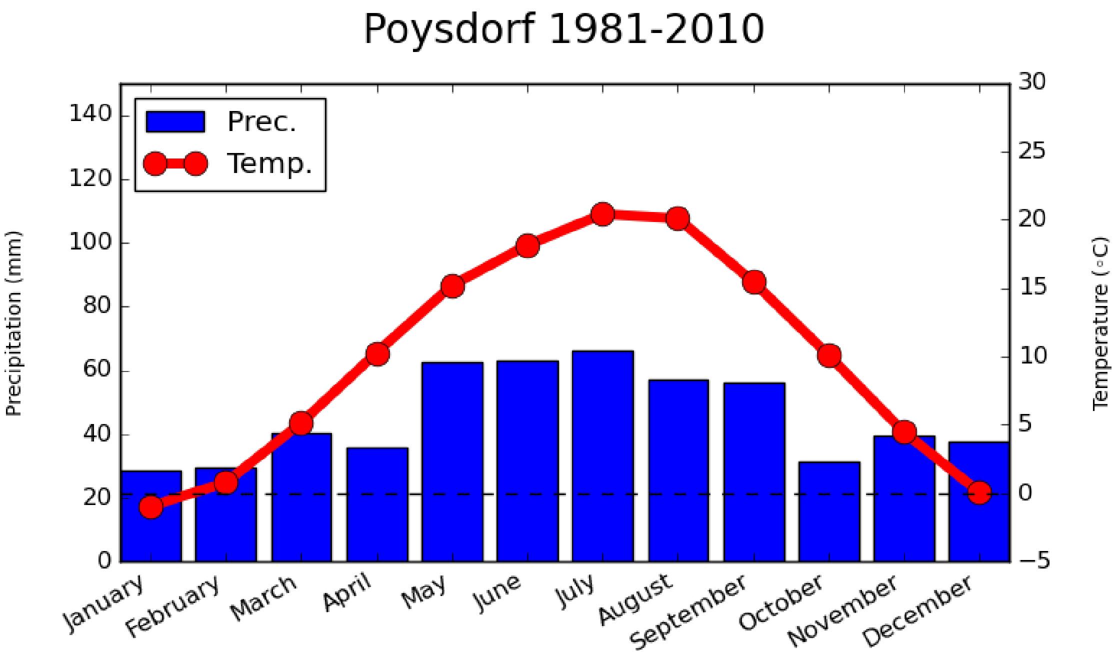

Figure 4. Baseline (obs.) climate graph, Poysdorf (1981-2010)

Kremsmünster, located at 48°3′ N, 14°8′ E, 384 meters above sea level, in the northern part of the country in the region Upper Austria is located in a humid, temperate climate (Thaler et al., 2021), thus colder and wetter than the two other regions, since it is to a higher degree influenced by the Atlantic climate. As at the two other sites, precipitation is highest in summer and generally lowest in the beginning of the year (Figure 5). The mean annual precipitation sum was 1016 mm and 9.2 °C in the baseline period and the site was located in the climate cluster 1009 in Figure 2 which corresponds to precipitation from >900 to ≤1000 and temperature from >8.5 to ≤9.5 °C. There was more or less agreement, apart from a slightly higher precipitation found in our baseline compared to the earlier normal period (1961-1990).

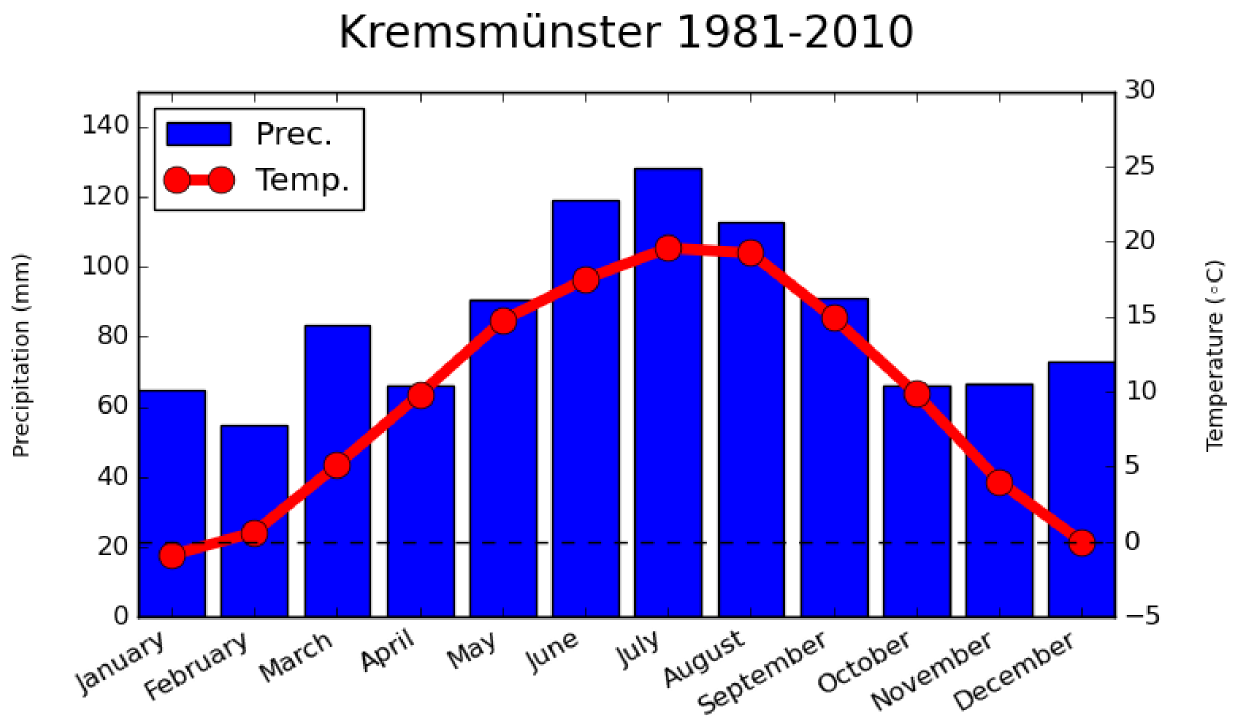

Figure 5. Baseline (obs.) climate graph, Kremsmünster (1981-2010)

2.5 Agrometeorological indices applied

This study used a combination of crop modelling and agrometeorological indices to fulfil the aim and make a holistic assessment of climate change impacts at the three Austrian study sites, representing different climatic regions.

Agroclimatic indices have been used in different studies in Europe and Central Europe such as (Jancic, 2017; Lalic et al., 2013; Lalić et al., 2014; Trnka et al., 2010a). These indices can help to describe some of the complex relationships that exist between climate and crop growth including cropping risks such as heat days and drought, sowing and harvesting windows as well as viticulture possibilities (Eitzinger et al., 2013; Trnka et al., 2010a). Agrometeorological indices is not an alternative to more traditional crop modelling approaches, on the other hand these two methodologies can complement each other (Eitzinger et al., 2013; Trnka et al., 2010a) in cropping risks analyses. The output from crop models can be compared and correlated with agroclimatic indices. Indices and crop model results can also be used together to formulate suited adaptation measures for a region (Jancic, 2017).

Indices may be able to describe factors that are not included in crop models – one of these could be the use of adverse weather indices to assess the impacts of extreme events on agricultural production (Lalić et al., 2014). Furthermore, indices are easy to use over large regions and require only limited data input (Eitzinger et al., 2013). Agroclimatic indices have therefore also been used on larger scales with climate data from a number of stations to assess agroclimatic conditions (Trnka et al., 2011a, 2011c).

2.5.1 AGRICLIM software

AGRICLIM was used in this study. This is a dedicated software solution to calculate agrometeorological indices and gives the user different parameter options to evaluate climate-related stress factors and cropping risks that influence agricultural production (Klein et al., 2017; Trnka et al., 2011b). The software was developed and tested at Mendel University of Agriculture and Forestry in Brno between 2005 and 2007 (Trnka et al., 2011b). It's a flexible software that can be used on different temporal and spatial scales – it can be used both on a station level and with gridded datasets (Olesen, n.d.; Trnka et al., 2011b).

The software uses daily values of meteorological elements such as maximum and minimum temperatures, solar radiation, mean wind speed, and humidity as inputs (Trnka, Hlavinka & Semenov, 2015). The software algorithms use these inputs to create a range of outputs with the help of the different modules. The evapotranspiration model calculates the potential evapotranspiration with the Penman-Monteithe or Prestley-Taylor equation dependent on which weather data is available.

The snow model calculates snow cover characteristics such as number of days with and without snow as well as volume of snowfall. The snow data also helps to calculate combined indices such as effective growing days, effective global radiation, and frost damage where no snow cover is one of the prerequisites. The next model, the FAO model (Allen et al., 1998) sets the parameters for calculating growth and actual evapotranspiration of a specific crop. The Agro model sets the parameters for calculating cropping risk indices such as tropical days, frost days, as well as field operation indices such as sowing and harvest days. Apart from these models, further indices are calculated such as vernalization for winter crops and Huglin index (Huglin & Schneider, 1998) to assess the viticulture potential based on the weather data.

The snow cover model has been validated at 105 climatological stations in Czech Republic and Austria and the soil water balance model has been calibrated and validated for the conditions in Central Europe (Trnka et al., 2010b, 2011b). The parameter boundary values were not changed in this study.

2.5.2 The chosen indices

The main part of this study was to assess how climate change could alter cropping risks in the future, so the focus was on these when deciding which indices to use. Furthermore, some of the indices that were found to be most important in similar studies from Central Europe were also included. An overview of chosen indices in AGRICLIM is included in Table 1.

The time between the last frost in spring and first frost in the fall defined the "general growing period" (Hollinger & Angel, 2009; Sheaffer, C. C., & Moncada, 2012) and was included to assess future growth period and potential at the three sites. The "number of effective growing days" was also calculated since these are dependent on effective global radiation and could indicate whether the change in growing season coincide with optimal growing conditions for the two crops. Definition of effective growing days is included in Table 1.

Cropping risks in the form of adverse weather events can be either single indices such as characteristic days or combined indices. These cropping risks might have a big negative influence on future crop production and therefore a number of indices were chosen to cover these.

Days with temperature characteristics such as “Number of tropical days in June” (max. temp above 30 °C) and “Number of summer days in May” (max. temp above 25 °C) where included, as high, negative correlations with yield were found for these indices in (Lalic et al., 2013).

Other adverse weather events included were “Maximum 1-day and 3-day rainfall events” to assess whether the intensity of extreme precipitation events was increasing. As already said, high-intensity rain events can have a negative influence on soil erosions and are less efficient at recharging the soil compared to less intense rain showers (Hollinger & Angel, 2009).

Drought is one of the cropping risks most likely to affect Central European agriculture in the future (Trnka et al., 2010a, 2011b). where water deficiency in April-June was found to be one of the most important indices with a negative impact on yields (Lalic et al., 2013). Intensive (ratio of actual to potential evapotranspiration was less than 0.4), extreme (less than 0.3) and very extreme (less than 0.2) dry days were calculated for the periods June-August, September-November, and March-May.

The last two categories of indices that were included were field-related indices and “Huglin index” (Huglin & Schneider, 1998) which have also been frequently used in other Central European studies (Lalic et al., 2013; Trnka et al., 2010a, 2011b). Since the timing of the growing season is likely to change due to changing weather patterns it is important to look at the proportion of suitable “sowing and harvest days” – this can also be an important assessment when considering winter versus summer crops. “Number of sowing days” were calculated both in fall and spring and were defined as days where precipitation is below 1 mm on the particular day and 5 mm on the previous day, with no snow cover, mean daily temperature above 5 ◦C and water content in the surface layer between 0.1 and 0.7 of the maximum soil water holding capacity (Trnka et al., 2010a). “Harvest days” were calculated as days with the same precipitation and temperature requirements as the “sowing days” and soil water content below 0.7 of WHC of the soil. AGRICLIM calculates “harvest days” in June, July, August, and September. As the growing season is expected to shift towards the beginning of the year, June harvesting will become more common, so especially the “harvest days” in June and July were assessed.

The “Huglin index” was included as an extra index, that is not directly related to cropping risks but can be included to assess the future productivity potential and also adaptation options at the three sites. The “Huglin index” measures the thermal suitability for viticulture based on a temperature threshold (Trnka et al., 2011c).

General temperature and precipitation indices based on mean values were also used in the subsequent analyses including “spring and summer temperature”, “spring and summer precipitation” as well as “potential water balance” (difference between precipitation and potential evapotranspiration) in spring and summer.

Group	Agroclimatic factor	Description of index
Growing season and days	General growing period	Days between the last frost in spring/winter and the first frost in fall/winter.
	Effective growing days	Number of days with effective global radiation. Days with an average temperature above 5 degrees Celsius, minimum temperature above 0 degrees Celsius, no snow cover, ratio of actual to potential evapotranspiration above 0.5 and radiation above 10 W/m2.
Cropping risks/extreme events	Number of tropical days	Number of days where daily maximum temperature is above 30 degrees Celsius. Especially important for June.
	Number of summer days	Number of days where daily maximum temperature is above 25 degrees Celsius. Especially important for May.
	Number of heat stress days	Days with a max temperature above 35 degrees Celsius and actual evapotranspiration ratio to potential below 0.5
	Heat stress periods	Number of episodes with extreme heat, daily maximum temperature above 35 degrees Celsius, and daily minimum temperature below 20 degrees Celsius for a period of 3 consecutive days.
	Maximum rainfall events	Maximum daily rainfall for April-June, June-August, and April-September, as well 3-day maximum.
	Drought conditions	Number of days with initial water deficits (ETa / ETr < 0.5), intensive water deficits (ETa / ETr < 0.4), extreme water deficits (ETa / ETr < 0.3), very extreme water deficits (ETa / ETr < 0.2), complete water deficits (ETa / ETr < 0.1). Calculated for the periods April-June, June-August, September-November, March-May.
Field related	Sowing days in fall and spring	days where precipitation is below 1 mm on the particular day and 5 mm on the previous day, no snow cover, mean daily temperature above 5 degrees Celsius and water content in the surface layer is between 0.10 and 0.70 of the maximum soil water holding capacity
	Harvest days	Harvest days were calculated as days with the same precipitation requirements as the sowing days and soil water content below 0.7 of water holding capacity of the soil. Agriclim calculates harvest days in June, July, August, and September.
Thermal suitability for viticulture	Huglin index	Temperature threshold over threshold (10 degrees Celsius) calculated from April to September

Table 1. Overview of agrometeorological indices calculated in AGRICLIM

2.5.3 Working steps in AGRICLIM

The first step was to prepare the data and calculate potential evapotranspiration. Both the observed and simulated climate data consisted of daily values of solar radiation, max., and min. temperature, as well as precipitation. AGRICLIM needs humidity data in the form of vapor pressure or relative humidity to calculate potential evapotranspiration. This data was lacking and therefore the potential evapotranspiration calculated in AQUACROP was used – the calculation of this is described under AQUACROP working steps.

AGRICLIM also needs information about the stations, which was organized in station list files containing information about the duration of the simulation period as well as the longitude, latitude, and altitude of the station.

Different runs were performed to take advantage of the software and make different useful outputs, and these were based on different soil, crop, emission, and CO_2-data. The crop and soil files were based on the ones created in AQUACROP, that are described below, to allow for comparison under the same conditions applied. CO_2-files were also taken from the AQUACROP software. The Mauna Loa CO_2-file was used for the runs with observed data. This CO_2 file is suitable for historical and near-future climate data but since it estimates a linear increase of 2.0 ppm CO_2 per year, it is only valid for the near-future. For the simulated data different runs were performed for the three stations, based on the emission scenarios RCP4.5 and RCP8.5.

2.6 Crop modelling

Crop models generally depict a simplified version of the complex soil-crop-atmosphere system (Thaler et al., 2012) and simulate, in a dominating process-oriented manner, crop growth development at mainly daily time steps, generating outputs of key parameters such as biomass and leaf area development, soil water balance parameters, stress indicators and ultimately harvestable yield. Crop models such as DAISY, CERES and EPIC have been used in earlier, similar studies (Eitzinger et al., 2013; Gobin et al., 2017; Strauss et al., 2012; Thaler et al., 2012). Inputs include crop characteristics, management, soil conditions, weather conditions and CO_2 with the aim to study how these aspects impact crop yields, growth conditions and cropping risks (Eitzinger et al., 2013; Thaler et al., 2012).

This simplification of the soil-crop-atmosphere system and the possibility to use different useful inputs make crop models generally easy to use and intuitive but at the same time prone to uncertainties (Thaler et al., 2012). One way to partly overcome the uncertainties in modelled yields is to use multiple crop models and measure the central tendency of the estimated yields, thus decreasing the error rate (Ma et al., 2016). Another way is to validate the models by doing field trials and compare those to the simulated results (Eitzinger et al., 2013).

Still some aspects may not be fully covered in these models such as extreme and adverse weather events. The effects of these on crop yields are still not well understood, and using crop models to predict how these will affect yields is very difficult (Lalić et al., 2014; Trnka et al., 2011c).

Another problem with crop models is their rather limited scope, both in respect to number of analysed crops but also spatial extension (Trnka et al., 2011c). Since inputs are often very local in nature, the output of a crop model will only have relevance on a local scale. Multiple crop modelling runs can be performed as well as the use of interpolation techniques but generally the results are local in nature.

2.6.1 The crop model – AQUACROP

The crop model used in this study was AQUACROP which is a water-driven model that was released by FAO in 2009 (AquaCrop | Food and Agriculture Organization of the United Nations, 2022; Vanuytrecht et al., 2014).

In light of growing water scarcities, uncertainties about the impact of future climate change on crop production, and the need to improve crop productivity to respond to future dietary demands, many crop models have been developed in the last decades (Vanuytrecht et al., 2014). They have different uses and applications. For instance, they can be used as an agronomic research tool and to pre-evaluate which field experiments could be most feasible, thereby lowering costs. They can also be used more first hand to decide on the most appropriate management system to increase yields (Steduto et al., 2009).

AQUACROP has been developed to overcome some of the limitations these models traditionally have posed, such as depending on a large number of inputs and parameters, thus being too scientific and therefore only applicable to experts and science personnel (Vanuytrecht et al., 2014). AQUACROP is a type of engineering model which is more mechanistic and helpful for end users such as farmers and policymakers. Scientific models on the other hand are mainly used in a research context to broaden our understanding of crop behaviour and physiology (Steduto et al., 2009).

The model is water-driven, meaning that the simulated crop growth, biomass and final yields are dependent on water availability due to the greater demand and scarcity of fresh water, its huge importance in crop production, and the level of uncertainty surrounding the impact of water deficiency on yields (Steduto et al., 2009; Vanuytrecht et al., 2014).

AQUACROP has been used in various studies to improve irrigation systems and schedules, to assess crop yields under specific management and adaptations and to assess the consequences of climate change on cropping risks and yields (Gobin et al., 2017; Iqbal et al., 2014; Kim & Kaluarachchi, 2015; Vanuytrecht et al., 2014).

2.6.1.1 The core equation in AQUACROP

At the core of the AQUACROP growth engine is the relationship between biomass and transpiration, defined as the product of the water productivity which is the biomass per unit of cumulative transpiration, and the cumulative transpiration. This is calculated in daily steps which is also an improvement to other water-driven crop models (Steduto et al., 2009). To calculate the transpiration, biomass and subsequently the crop yield, a soil-crop-atmosphere continuum is established combining aspects such as crop physiology, soil water balance, and atmospheric conditions, for instance carbon dioxide concentration and evaporative demand (Steduto et al., 2009; Vanuytrecht et al., 2014).

The first step in the calculation is to simulate the crop development which is expressed as the extension of the green canopy cover. This is one of the distinctive characteristics of the model, as normally leaf area index is considered here (Steduto et al., 2009; Vanuytrecht et al., 2014). One advantage of using canopy cover, is the possibility to validate the simulated canopy cover using remote sensing technique (Steduto et al., 2009). The daily canopy cover development determines the crop transpiration levels, and under optimal conditions it is approximately proportional to the canopy cover. The core equation of the software is then used to calculate the daily levels of biomass production. One note here is that the water productivity value is normalized to the current atmospheric CO_2-concentration, and the evaporative demand, thereby making it possible to use the model with climate scenarios and in different locations (Steduto et al., 2009). The final step is then to calculate the fraction of the biomass that will constitute final yield, and this is the product of the harvest index and the biomass (Raes et al., 2018a).

Another integral part of the calculation is the use of stresses that can affect anything from the development of the canopy cover to the final yield and each calculation step are dependent on these. Example of stresses are low temperature, measured as growing degree days (GDD) below a threshold and water shortage, measured as water depletion in the root zone (Vanuytrecht et al., 2014). Stress coefficients are used in the various calculation to assess the severity of the stress.

2.6.2 Preparation of data in AQUACROP

The first step was to create climate data files based on the observed and simulated weather data for the three weather stations. The required climate data in AQUACROP is potential evapotranspiration, minimum and maximum temperature, precipitation, and CO_2-data (Raes & van Gaelen, 2017). The first step was to calculate the potential evapotranspiration as no humidity data was present in the used data sets. It was calculated with the FAO Penman-Monteith method that requires air temperature, air humidity, radiation, and wind speed. Since both air humidity and wind speed data were lacking these were estimated in the program. Light to moderate winds were selected for each station. The vapour pressure was estimated through the assumption that dewpoint temperature is near the daily minimum air temperature. Poysdorf was characterized as arid, and therefore 2 °C were subtracted from the minimum temperature, as the air might not be saturated at minimum temperatures in arid locations (Raes & van Gaelen, 2017).

The CO_2 data used to create the climate files was based on the scenarios that are included in the AQUACROP package (RCP4.5 and RCP8.5).

2.6.3 Crop files in AQUACROP

The AUQACROP package includes crop files with validated and calibrated crop parameters. Typical crops such as maize and wheat that were used in this study are stored in the program (Raes, 2017).

Regarding the crop files, a distinction is made between conservative and non-conservative crop parameters. The first do not change much with location and management practices, whereas the latter do. Conservative crop parameters include threshold temperatures used in the calculation of GDD and canopy growth and decline coefficients (Raes et al., 2018b). These might require an adjustment, but they were not changed in this study.

2.6.3.1 Preparation of crop files

The initial idea was to use the default crop files from the AQUACROP software. These were validated for Valzano, Italy (wheat) and Davis, California (maize). The main aim of this study was not to make perfect predictions on absolute cropping yields for the different sites, but instead to assess how impacts from climate change on cropping risks and crop yields would differ between the three sites. Even though the crop files had not been validated in the three sites they were assumed to be sufficient, since no field measurements and calibration were performed in this study as they were not deemed necessary to fulfil the aim.

The maize file turned out to be problematic due to a too high GDD requirement to reach maturity under current climate conditions in Austria. This was especially problematic in the baseline period (obs.) in Kremsmünster and Poysdorf where the growing cycle was not completed until next year in many cases. Therefore, an updated maize file was made to better reflect the real cultivar characteristics used in practice, based on typical calendar days to reach the different stages. Bad Gleichenberg in 1981 was used as reference year. These calendar times were then converted to thermal times. Since Bad Gleichenberg is the warmest of the three sites, using typical growing times from here resulted in a higher GDD file (but still lower than the generic maize file in AQUACROP). This was assumed to be better as this could more realistically reflect the future situation with expected warming. The updated file was used for all the maize runs in all sites and under both scenarios. The generic wheat file from AQUACROP was used for all the wheat runs in all sites and under both scenarios as it provided acceptable results and did not expand over two years in any situations. The crop specifics are summarised in Table 2 and Table 3 including the GDD.

Growing stages	**Degree-days (°C)**
To emergence	150
To maximum canopy cover	1186
To maximum rooting depth	864
To start of canopy senescence	1700
To maturity	2400
To flowering	1250
Duration of flowering	200
Threshold temperatures for crop development	
Base temperature	0.0 °C
Upper temperature	26.0 °C
Production and development	
Crop water productivity	15.0 g/m^2
Harvest index	50%
Type of planting	Direct sowing
Plant density	450 plants/m^2
Initial canopy cover	Very high cover, 6.75% at 90% emergence
Max canopy cover	Almost entirely covered, 96%
Root deepening	Medium, deep rooted, 1.5 meter max. effective rooting depth
CO_2-effect	See Table F1 (appendix F)

Table 2. The wheat crop characteristics inputs

Growing stages	Degree-days (°C)
To emergence	56
To maximum canopy cover	536
To maximum rooting depth	582
To start of canopy senescence	1153
To maturity	1411
To flowering	660
Duration of flowering	146
Threshold temperatures for crop development	
Base temperature	8.0 °C
Upper temperature	30.0 degrees Celsius
Production and development	
Crop water productivity	33.7 g/m^2
Harvest index	50%
Type of planting	Direct sowing
Plant density	7.5 plants/m^2
Initial canopy cover	0.49% at 90% emergence
Max canopy cover	Almost entirely covered, 96%
Root deepening	Very deep rooted, 2.3 meter max. effective rooting depth
CO_2-effect	See Table F2 (appendix F)

Table 3. The maize crop characteristics inputs

2.6.4 Soil data inputs

To assess how different soils influence the impacts of climate change, three different soil types were used in the computations. In general, soils with lover WHC are expected be more affected by adverse events and cropping risks such as drought stress (Thaler et al., 2012; Trnka, Hlavinka & Semenov, 2015), and therefore the main differences considered with the soils in this study was their WHC. Uniform soil profiles with only one soil horizon of 4 meters were used. The soil profiles were based on the standard soil profiles, incorporated in the AQUACROP software package. The three soils chosen were sandy loam with lower WHC, loamy sand with medium WHC and a silt soil with a high WHC. Soil characteristics of the three soils are included in Table 4.

Loamy sand (low WHC)	
Number of soil horizons	1
Thickness	4 m
Field capacity	16% vol.
Permanent wilting point	8% vol.
Total available water	80 mm/m
Sandy loam (mid WHC)	
Number of soil horizons	1
Thickness	4 m
Field capacity	22% vol.
Permanent wilting point	10% vol.
Total available water	120 mm/m
Silt (high WHC)	
Number of soil horizons	1
Thickness	4 m
Field capacity	33% vol.
Permanent wilting point	9% vol.
Total available water	240 mm/m

Table 4. Soil characteristics

2.6.5 The high underground table and groundwater files in AQUACROP

AQUACROP offers the possibility to create groundwater table files to indicate whether the groundwater table is located at a constant or varying depth and also the water quality (Raes & van Gaelen, 2017). A high underground table could have both positive and negative effects. It could mitigate some of the impacts of cropping risks and adverse events, for instance drought risk but could at the same time prolong a stagnation situation (Trnka, Hlavinka & Semenov, 2015).

The groundwater table was not considered in this study as the groundwater table is generally located deep in the Marchfeld area close to Poysdorf. Groundwater is located around 6 meters below the surface and does not have an impact in the crop rooting zone (Thaler et al., 2012). If the groundwater table is not shallow (located more than 4 meter below rooting zone), capillary rise can be disregarded and a groundwater table file is not needed in AQUACROP (Raes & van Gaelen, 2017). To allow for a site-to-site comparison, the groundwater table was not considered at any of the sites.

2.6.6 Crop management

2.6.7 Irrigation

As already mentioned, rainfed agriculture in Europe will likely face higher cropping risks under climate change than irrigated, but this depends on climate and local conditions (Eitzinger et al., 2013; Trnka et al., 2010a, 2011c). Irrigation systems can lower the effects of warming on crop transpiration rates and water stress and help to cool crop canopies (Lobell & Gourdji, 2012a). One of the main applications of AQUACROP is to assess the usefulness of irrigation schedules or generate irrigation schedules based on other data. Soil and climate characteristics, soil moisture and choice of crop determines the irrigation water requirements (Riediger et al., 2014).

In this study, the net irrigation water requirements were determined and compared to allow for a comparison between the sites. This is done in AQUACROP through the addition of a small amount of water added to the soil profile, when root zone depletion is higher than a specified threshold (Raes, 2017). The threshold was set to 50% of root available water. AQUACROP also offers the possibility to create irrigation schedules that could be used for adaptation purposes and assessment. In the end the irrigation water requirement was seen as sufficient to assess how impacts would differ for rainfed and irrigated agriculture at the three sites.

2.6.8 Field management

The other type of management that can be specified in AQUACROP is field management. This was not considered to a high degree in this study. Nutrients were assumed to be optimal and no pests present. As an adaptation method, the use of mulches was considered for all three sites. The following characteristics was used for the mulch layer – soil covered by mulches set to 100% and the type of surface mulches was set to synthetic (plastic) mulches.

Irrigation was assessed for both RCP4.5 and RCP8.5 whereas mulch was only assessed for the latter, since the climate effect was expected to be highest here, and thus the effect of mulches could also be expected to be highest here. Table 6 shows a list of the performed simulations with climate projection data.

2.6.7 AQUACROP simulation runs

Project files were created in AQUACROP with the different characteristics to assess the relative importance of soil WHC, irrigation versus rainfed, type of crop, CO_2 (through the use of the scenarios) and different management (mulches). See Table 5 and Table 6 for an overview and characteristics of the runs.

For the observed years, six runs were performed for each site. For each of the three soils with different soil WHC, both a rainfed and an irrigated (net irrigation requirement) run was performed. For the scenario-based runs with climate change data, the same runs were performed as for the observed data, and additionally also management runs were performed here.

Both the simulation period and the initial conditions had to be specified in the project files. Initially the idea was to start the simulation period at January 1st in the first simulation year, set the initial soil water profile to field capacity which could be assumed (Raes et al., 2018b) and then link the simulation runs so the final water conditions of previous run were kept for the subsequent run. This worked for wheat but proved to be problematic for the maize, even with the updated GDD file, as some years in Kremsmünster and Poysdorf did not have enough GDD to reach maturity in one season. Therefore, the simulation runs could not be linked and to avoid further problems, each simulation run was started at January 1st with soil water content at field capacity for the maize runs. In the wheat runs, the simulation runs were linked with no problems. In the end, this should not have a big influence on the results since both approaches should work sufficiently well.

2.6.7.1 Missing years

The years that did not have enough GDD to reach maturity in one season were omitted to not obscure the results. This was deemed acceptable as the number of assessed years was relatively high.

2.6.7.2 Sowing dates/start of the growing cycle

Sowing days are based on temperature, precipitation, and water content in the surface layer in AGRICLIM. In AQUACROP on the other hand, suitable sowing days are based on either rainfall or temperature characteristics.

In this study consistent sowing days were chosen in AQUACROP: April 15th for maize, and October 20th for wheat. These were chosen since this ensured minimum problems with the runs especially for maize where later sowing days could be problematic due to the high GDD requirement. These dates represented realistic sowing times in Austria – especially under climate change where later sowing days could be expected in the fall for winter crops.

Crop	WHC	Irrigation	Linked/reset	Sowing day
Wheat	Low	Rainfed	Linked	Specified
Wheat	Medium	Rainfed	Linked	Specified
Wheat	High	Rainfed	Linked	Specified
Wheat	Low	NET	Linked	Specified
Wheat	Medium	NET	Linked	Specified
Wheat	High	NET	Linked	Specified
Maize	Low	Rainfed	Reset	Specified
Maize	Medium	Rainfed	Reset	Specified
Maize	High	Rainfed	Reset	Specified
Maize	Low	NET	Reset	Specified
Maize	Medium	NET	Reset	Specified
Maize	High	NET	Reset	Specified

Table 5. Baseline (obs.) AQUACROP runs made with observed weather data for the baseline period (1981-2010)

Crop	Scenario	WHC	Irrigation	Management	Linked/reset	Sowing day
Wheat	RCP4.5	Low	Rainfed	None	Linked	Specified
Wheat	RCP4.5	Medium	Rainfed	None	Linked	Specified
Wheat	RCP4.5	High	Rainfed	None	Linked	Specified
Wheat	RCP4.5	Low	NET	None	Linked	Specified
Wheat	RCP4.5	Medium	NET	None	Linked	Specified
Wheat	RCP4.5	High	NET	None	Linked	Specified
Wheat	RCP8.5	Low	Rainfed	None	Linked	Specified
Wheat	RCP8.5	Medium	Rainfed	None	Linked	Specified
Wheat	RCP8.5	High	Rainfed	None	Linked	Specified
Wheat	RCP8.5	Low	NET	None	Linked	Specified
Wheat	RCP8.5	Medium	NET	None	Linked	Specified
Wheat	RCP8.5	High	NET	None	Linked	Specified
Maize	RCP4.5	Low	Rainfed	None	Reset	Specified
Maize	RCP4.5	Medium	Rainfed	None	Reset	Specified
Maize	RCP4.5	High	Rainfed	None	Reset	Specified
Maize	RCP4.5	Low	NET	None	Reset	Specified
Maize	RCP4.5	Medium	NET	None	Reset	Specified
Maize	RCP4.5	High	NET	None	Reset	Specified
Maize	RCP8.5	Low	Rainfed	None	Reset	Specified
Maize	RCP8.5	Medium	Rainfed	None	Reset	Specified
Maize	RCP8.5	High	Rainfed	None	Reset	Specified
Maize	RCP8.5	Low	NET	None	Reset	Specified
Maize	RCP8.5	Medium	NET	None	Reset	Specified
Maize	RCP8.5	High	NET	None	Reset	Specified
Wheat	RCP8.5	Low	Rainfed	Mulch	Linked	Specified
Wheat	RCP8.5	Medium	Rainfed	Mulch	Linked	Specified
Wheat	RCP8.5	High	Rainfed	Mulch	Linked	Specified
Maize	RCP8.5	Low	Rainfed	Mulch	Reset	Specified
Maize	RCP8.5	Medium	Rainfed	Mulch	Reset	Specified
Maize	RCP8.5	High	Rainfed	Mulch	Reset	Specified
Wheat	RCP8.5	Low	NET	Mulch	Linked	Specified
Maize	RCP8.5	Low	NET	Mulch	Reset	Specified

Table 6. Future AQUACROP runs with climate projection data (2030-59) and (2060-2089). Soils include loamy sand (low WHC), sandy loam (mid WHC), silt (high WHC). NET = net irrigation requirement. Linked = the soil water profile is kept in subsequent run, Reset = the soil water profile is reset to field capacity at the beginning of simulation run (January 1st). Sowing data specified: April 15th for maize and October 20th for wheat.

2.6.8 Evaluation of simulations

To assess the suitability of using climate projection data to assess yields in AQUACROP, runs were performed using both observed data and climate projection data (RCP4.5 and RCP8.5) for the baseline years 1981-2010 and comparing the yields statistically. Two-sample t-tests were used to compare the means of the yields, and correlations were performed to compare them year-wise.

To compare baseline yields based on observed data (Table 5) with the future yields based on climate scenario data (Table 6), two sample t-tests and F-tests were used to compare the means and variance of the yields. Normality was assumed in the data. Looking at the variance is an important measure to assess whether climate change will lead to a change in interannual variability. Also irrigated and rainfed yields were compared to assess the change in yield levels and variability for both wheat and maize.

2.7 Why it makes sense to include both calculation approaches

Both AGRICLIM and AQUACROP were used in this study as they complement each other and make a more thorough assessment possible. AGRICLIM is more simplified, using algorithms to calculate impact indicators of single or few weather variables. The output is on an annual base whereas AQUACROP's output is daily time step with more detailed output on several process-based crop growth parameters. AQUACROP makes it possible to make more crop specific computations that take management into account for instance through irrigation schemes.

Correlation analyses were performed between agrometeorological indices and crop yields under different conditions. This is useful for instance when assessing adverse events that crop models have not been able to include fully (Lalić et al., 2014) – e.g. the timing of extreme weather in relation to crop sensitivities. Therefore, the combination of the two programs can be used to assess the validity of each and gather additional information on cropping risks.

2.8 Correlations and extreme events

The aim was to see which indices were significantly correlated to crop yield and under which situations.

Extreme years were also included in the correlations. Since outputs from AGRICLIM is on a yearly scale, it does not make sense to talk about extreme events in the traditional way. Instead, the number of indices that crossed an extreme threshold were calculated for each year. This threshold was defined as the 95th and 99th percentile of the baseline value (based on observed weather data) for a particular index.

The agrometeorological indices that were used for the extreme event and correlation analysis were the same as indicated in Table 1 but also included “mean spring temperatures”, “mean summer temperatures”, “mean spring precipitation”, “mean summer precipitation”, “potential water balance in spring” and “potential water balance in summer”. “Harvest days” in June and July were used for wheat, whereas “Harvest days” in July and August were used for maize. “Sowing days” were spring-early (March 1st to April 25th) for maize and fall for wheat. These were used to suit the typical growing season of the two crops. The dry days were “intensive dry days” from April to June for wheat and “extreme dry days” from March to August for maize since there were sufficient dry days in these situations. The growing season length used in the correlation was taken as the number of days from sowing to maturity in AQUACROP and not the frost-free growing season period calculated in AGRICLIM. The reason for this was the more direct relationship that could be expected between crop yields and growth period in the crop model. Finally, also the ambient CO_2-levels were used in the correlation analyses.

The direction of extreme events was based on the situation, meaning that temperature and precipitation events were assessed as extreme in both directions, since both too high and too low levels could have negative impacts. Number of "harvest and sowing days" and "effective growing days" were only considered extreme if they were significantly lower than the observed value, more specifically lower than the 5th percentile for the observed weather data in the baseline period. All the other indices where only considered extreme if significantly higher (higher than the 95th percentile).

Since soils with low WHC are expected to be more sensitive to adverse events (Trnka, Hlavinka & Semenov, 2015), the calculations were only made for these soils.

3. Results

3.1 Climate change at the three study sites

The climate graphs (Figure 7, Figure 8 and Figure 8) show the precipitation sums and mean temperatures in the baseline period (obs.) and the two future climatic periods, 2030-2059 and 2060-2089. As already said, Bad Gleichenberg is characterized by a humid-warm climate, Kremsmünster by a temperate-humid climate and Poysdorf by an arid-warm climate. Generally, the summer period is the wettest at all the study sites – in Kremsmünster and Poysdorf the wettest month is July, whereas June and August are wetter than July in Bad Gleichenberg. April is relatively dry at all the sites, especially in Poysdorf where it is one of the driest months. This could have negative implications for crop growth and potentially also the number of suitable sowing days which depends on precipitation.

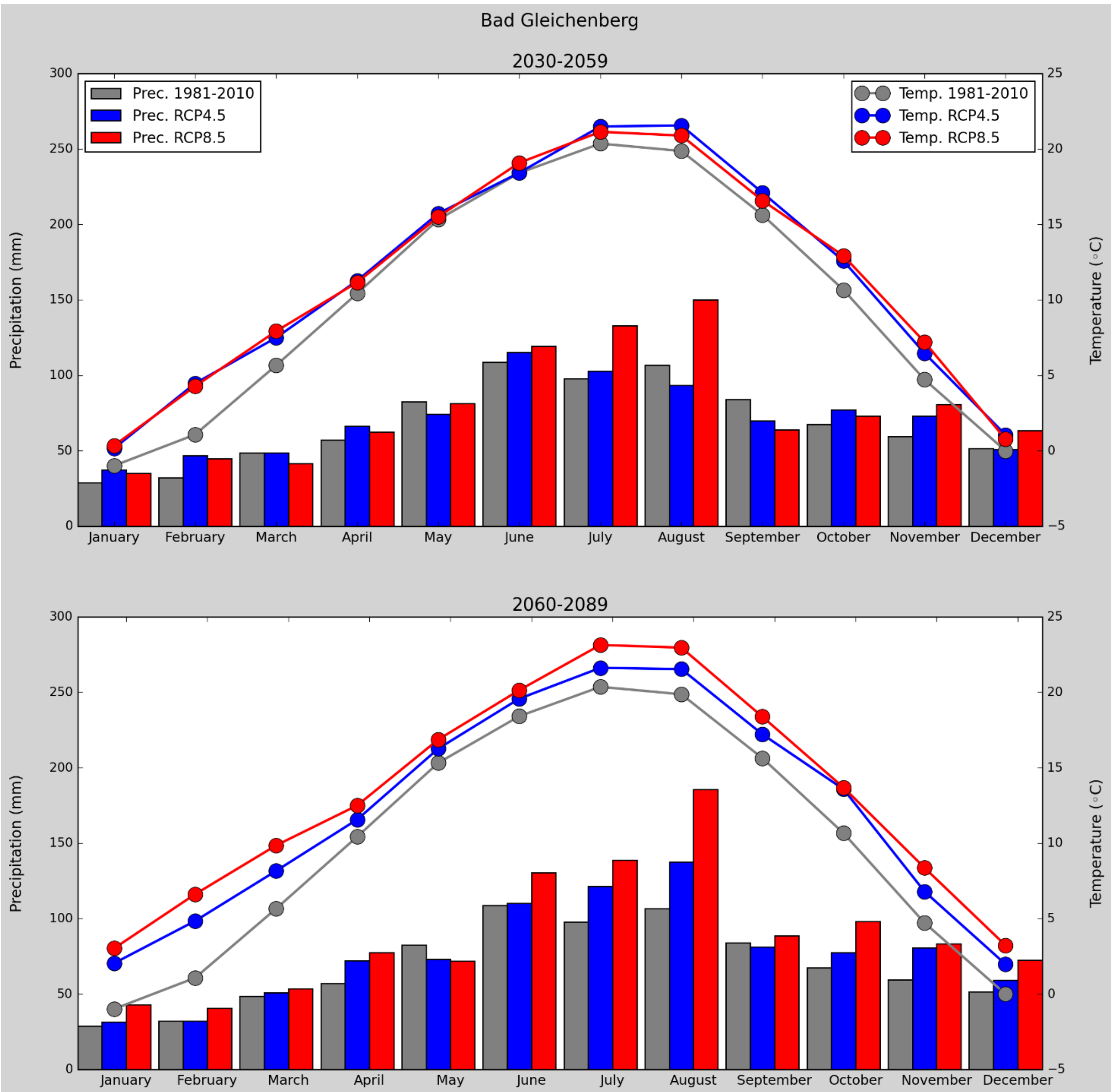

Figure 6. Climate graphs, Bad Gleichenberg

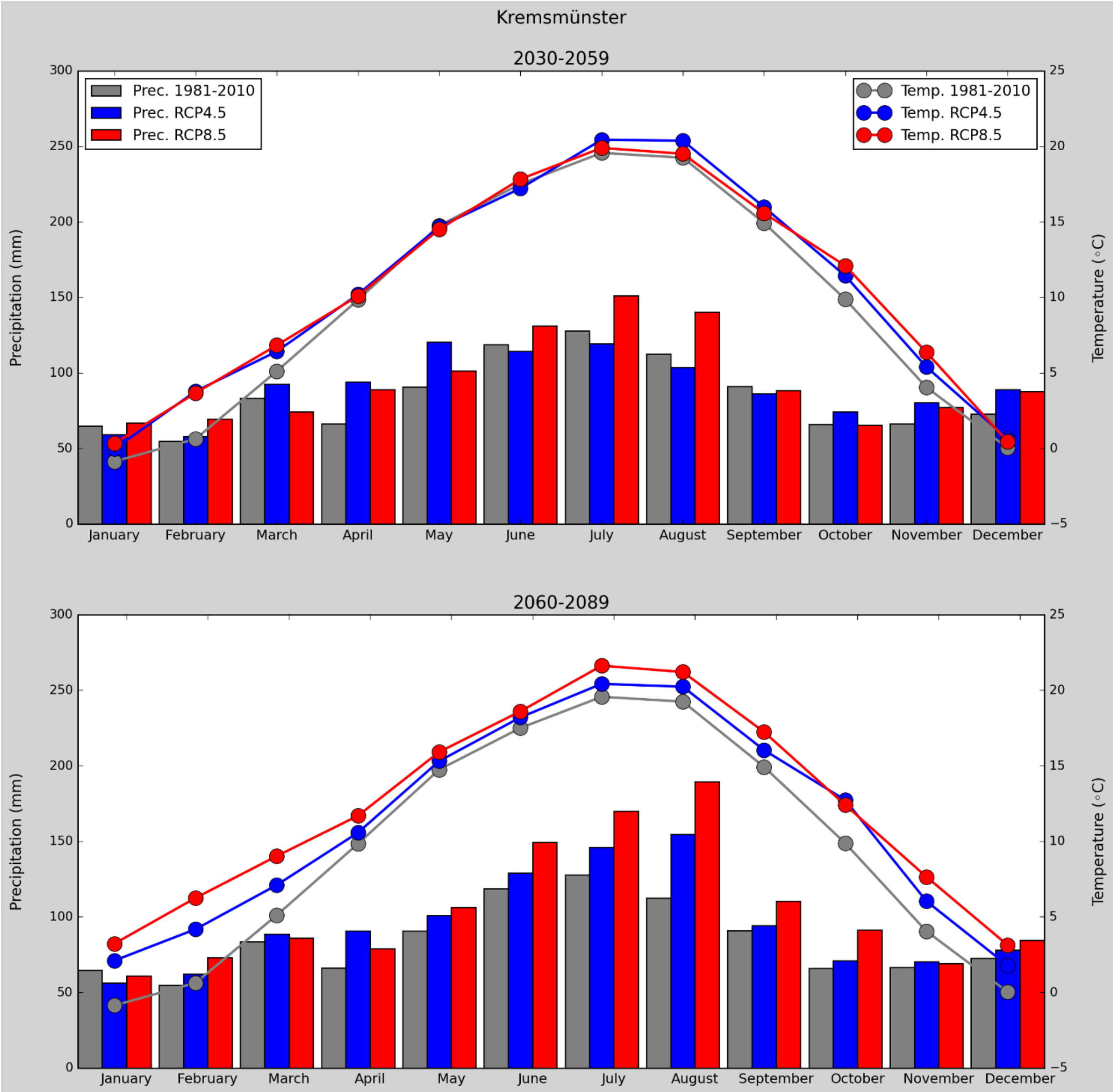

Figure 7. Climate graphs, Kremsmünster

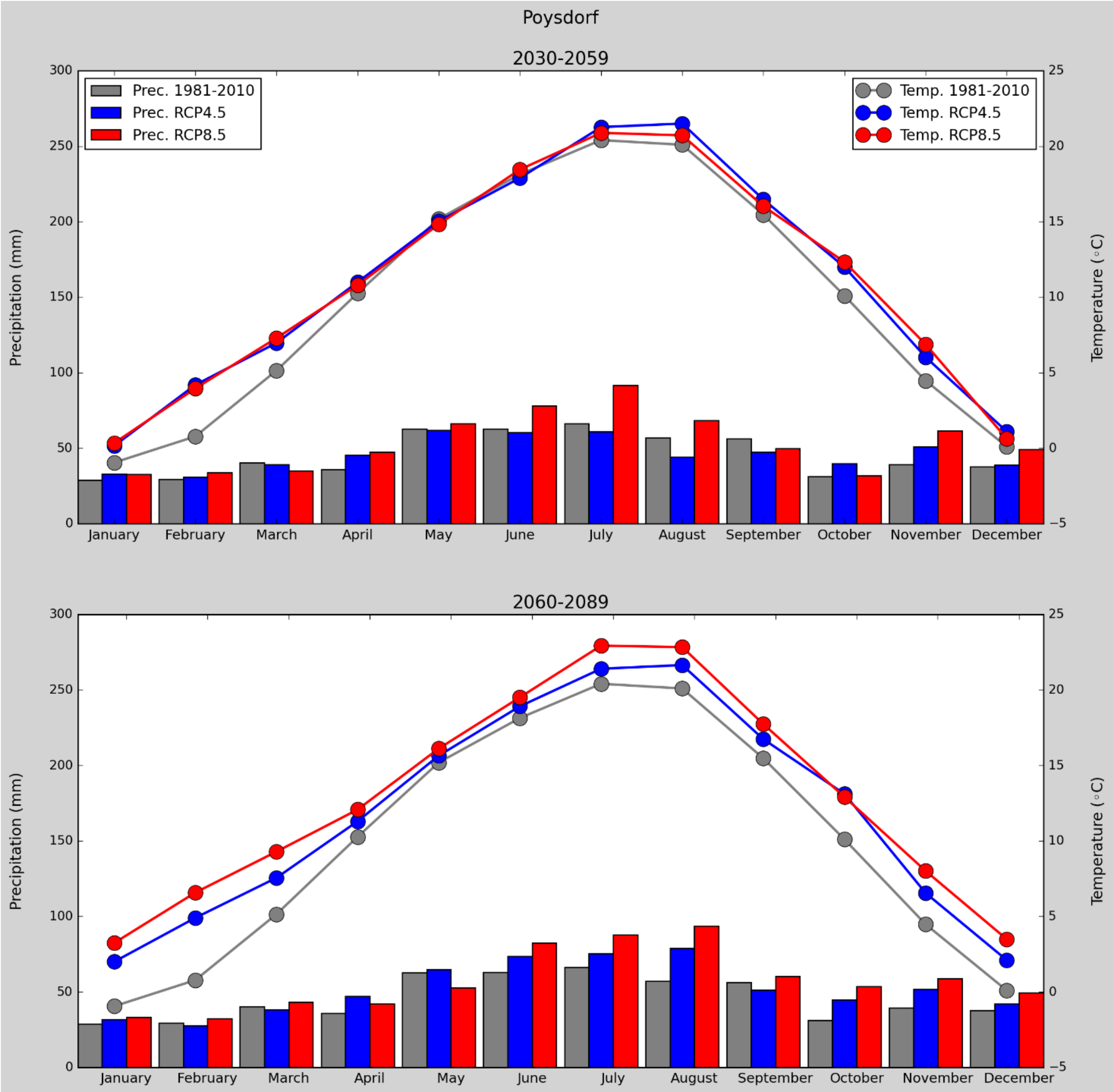

Figure 8. Climate graphs, Poysdorf

3.1.1 Projected changes

In the first climatic period, the average temperature was more or less identical under RCP4.5 and RCP8.5 at all the sites, with the July to September temperature being higher for all the sites under RCP4.5. The smallest change between baseline (obs.) and projected temperatures was found in May and June, and the biggest changes were found in the colder months. The annual temperature was more or less equal at all three sites under RCP4.5 and RCP8.5 in the first climatic period.

In the second climatic period, the differences were bigger between the emission scenarios – under RCP4.5 the temperature increase was negligible whereas the RCP8.5 scenario resulted in warmer conditions for all months apart from October compared to RCP4.5. The average temperature was projected to increase more than 3.2 °C in Bad Gleichenberg, 2.8 °C in Kremsmünster and 2.9 °C in Poysdorf under RCP8.5 in the second climatic period. The temperature increases would be much less pronounced between the two climatic periods under RCP4.5.

As expected, the precipitation trends were not as clear as for temperature. Generally, precipitation was expected to increase at all sites under climate change and the positive trend was expected to be higher in the second climatic period and under RCP8.5. Especially summer precipitation was expected to increase under RCP8.5 at all sites, whereas under RCP4.5 there was little change or even decrease. The direction of the projected seasonal change in precipitation was more or less identical in the three sites.

In the first climatic period, the August precipitation in Bad Gleichenberg would be lower under RCP4.5 whereas the late summer precipitation would increase under RCP8.5. In the spring on the other hand the changes under 8.5 would be less and precipitation level lower for March and May compared to baseline (obs.). Precipitation was distributed more equally in the second climatic period, but May precipitation was still projected to be less under both scenarios. The summer precipitation would increase clearly under both scenarios, especially RCP8.5 in the second climatic period. The fall months would also experience precipitation increases in the second climatic period.

The projected precipitation in Kremsmünster would resemble Bad Gleichenberg with RCP4.5 generally leading to more precipitation in the spring, whereas would RCP8.5 will lead to more precipitation in the summer. In the second climatic period the rain would be higher under 8.5 especially for the summer and early fall months.

In the second climatic period Poysdorf would generally stay dry, but summer precipitation could increase for both scenarios with smaller changes in spring and even decreases in May under 8.5 which was also seen in Bad Gleichenberg.

Under RCP8.5, second climatic period the average total annual precipitation sum was expected to increase from 825 to 1084 mm in Bad Gleichenberg, from 1016 to 1270 mm in Kremsmünster, and 553 to 630 mm in Poysdorf

So, generally summer precipitation and temperatures were expected to increase under RCP8.5 with an increasing trend towards the end of the century, whereas the changes were less pronounced for the spring months. Under RCP4.5 the changes were more varied, with summer precipitation decreases in first climatic period in Kremsmünster and Poysdorf and less temperature increases in the second period generally.

3.2 Bias and trend analysis (observed vs. climate scenario weather data for the baseline period)

3.2.1 Bias analysis

Climate scenario and observed weather data for the baseline period (1981-2010) were compared to assess the suitability of using the scenario data to compute agrometeorological indices and crop yields. The bias was assessed through correlation and root mean square error calculations and the results included in appendix A (Table A1-A9).

The bias analysis for all days (the full dataset) (Table A1-A3), resulted in highly significant correlation (p-value < 0.01) tests in general, meaning the alternative hypothesis of a correlation could not be rejected. This was the case for the data for all the study sites, apart from the precipitation variable, that showed much lower and thus non-significant correlations. Only the correlation between the precipitation variables from RCP8.5 scenario data and observed data for Bad Gleichenberg showed significance (Table A1). These results were not surprising. Climate change scenario data is often more biased when it comes to precipitation and therefore a low correlation was expected. The root mean square errors were also highest for precipitation and lowest for min. temperatures, indicating that the scenarios make the most accurate predictions on this variable.

Bias assessments were performed on January and July data, to assess how good the scenario data resembled the observed data for these months. Tests on the January data (Table A4-A6) resulted in less correlations than for the whole data, meaning the bias was higher. A significant correlation was only found on a few of the variables, such as max. temperature in Bad Gleichenberg and Poysdorf and solar radiation in Kremsmünster. The RMSE values was low for solar radiation was due to the low radiation values found in January. The precipitation values were also lower due to the lower precipitation amounts in winter, especially in Poysdorf. The temperatures on the other hand were more biased in January.

The July correlations (Table A7-A9) performed slightly better, and the correlations were significant for the max. and min. temperature at all sites. Not surprisingly the RMSE-scores behaved differently compared to in January with high bias for the radiation and precipitation values due to their higher levels in summer. The scenario data showed less temperature bias in July.

3.2.2 Trend analysis

Mann Kendall trend tests were performed to assess whether differences existed between climate scenario and observed weather data regarding trends in the baseline period. See appendix A (Table A10-A18).

The first test included the monthly averages (Table A10-A12) and generally showed no trends for all variables on all three data sets. The precipitation variable in the observed data for Poysdorf showed a positive trend that was not depicted in the climate scenario data, but the trend was not particularly strong.

Trend analyses were also performed for January (Table A13-A15) and July (Table A16-A18) only and here the performance was worse, especially in January. Under RCP8.5 in Kremsmünster, a positive trend was found for max. temperature that was not found in the observed data. Observed min. temperature in Bad Gleichenberg showed a positive trend, while the variable even showed a negative trend under RCP8.5, and under RCP4.5 no trend at all. Observed precipitation showed a positive trend in Kremsmünster that was not found in the simulated data. Finally, the observed radiation value in Bad Gleichenberg showed a negative trend that was not found in the rest of the data.

In July max. temperature and min. temperature showed a positive trend for all observed data across the three sites and the same trends were found in all the scenario data for the baseline period. Some mismatches were found for the other variables for July as well. It should be noted that even though there were diversions in significant trends, all the trends were very small.

3.2.3 The verdict

To summarize, the scenario data for the baseline period generally resembled the observed data set when looking at the full data set. Looking only at monthly data increased the bias. Still July data seemed to be better represented by the simulated data compared to January. This should be good news for crop model purposes as July is generally more important in terms of crop growth.

In the end, the scenario data was deemed acceptable, considering that precipitation is generally problematic in emission scenarios. It was more important to assess yields and agrometeorological conditions on a longer time scale compared to single years (Chimani et al., 2018), so even if some years are not perfect, this was acceptable.

The data were used for crop modelling purpose and therefore crop model results were also assessed and validated by comparing yields from scenario data and observed data for the baseline period. The results are described further down.

3.3 Agrometeorological indices

Table 7 shows the expected trends in key agrometeorological indices. These could be characterized as scenario-dependent indices as they were solely based on changes in weather variables and thus independent of soil WHC and choice of crop.

3.3.1.1 Mean precipitation

“Spring precipitation” was projected to increase in Kremsmünster, especially in the first climatic period under RCP4.5. The biggest increase was found in Kremsmünster but a decrease compared to the first climatic period was projected in the second climatic period under RCP4.5. For Bad Gleichenberg and Poysdorf the direction of change was dependent on scenario and period.

The baseline (obs.) “summer precipitation” was higher for all sites compared to “spring precipitation” and projected to decrease at all sites under RCP4.5 in the first climatic period. In the second climatic period all sites would experience a significant increase, especially under RCP8.5 where the increase was higher than 30% at all sites.

3.3.1.2 Potential water balance

The "potential water balance" was calculated as the sum of precipitation minus the potential evapotranspiration. Since this index does not include soil and vegetation info and does not consider the actual evapotranspiration it only tells part of the picture. The index was naturally highly influenced by the expected precipitation. Therefore the "potential water balance in spring" was increasing very strongly in Kremsmünster under all situations and remained positive as it already was in the baseline period (obs.). The development was negative in Bad Gleichenberg under all situations whereas it would generally be positive in Poysdorf. The spring balance stayed negative in these two sites under all situations.

Due to the higher temperatures in the summer months, Poysdorf had a more negative "potential water balance" in the summer period of the baseline (obs.) than in the spring. Kremsmünster still had a positive balance due to the higher amount of summer precipitation. "Potential water balance" was projected to decrease in the first climatic period for Poysdorf, decrease significantly for Kremsmünster, and increase slightly for Bad Gleichenberg. Under all the other situations, the increase was projected to be high in summer for all sites, especially in the second climatic period due to the increase in precipitation. This would lead to a positive balance in both Kremsmünster and Bad Gleichenberg, especially under RCP8.5 in the second climatic period. The increase was also projected to be significant in Poysdorf, but the balance expected to remain negative.

3.3.1.3 Max rainfall events

The baseline (obs.) max. rainfall events were higher at the humid sites, Bad Gleichenberg and Kremsmünster. The highest "1-day rain events" were found in Bad Gleichenberg, but the highest "3-day rain events" were found in Kremsmünster in the baseline period (obs.).

The magnitude of the highest annual "1-day rain events" was expected to increase in the second climatic period. A slight increase was expected under RCP4.5, but higher increases were projected for RCP8.5 in the second climatic period, especially for Kremsmünster and Poysdorf. A relatively high decrease was expected in the first climatic period for RCP4.5 in Bad Gleichenberg and Poysdorf, which highlighted the different behaviour, dependent on time period and emission scenario.

The magnitude of "3-day rain events" was generally expected to increase more than 1-day events. Increases were expected to be more significant under RCP8.5, especially for Bad Gleichenberg and Kremsmünster in the second climatic period. Poysdorf was expected to experience decreases under RCP4.5.

3.3.2 Temperature indices

3.3.2.1 Mean temperatures

"Spring temperatures" and "summer temperatures" were included to assess the projected temperature increases in key parts of the growing season. Temperature increases were projected at all sites under all situations, both in spring and summer. The increases were projected to be higher in the second climatic period for both indices for all situations compared to the first climatic period (indicated by the arrows), thus the typical growing season for all sites was expected to be warmer. Especially the spring temperatures under RCP8.5 in the second period were increasing significantly at all sites.

3.3.2.2 Characteristics days

Characteristic days were included to assess how the temperature changes would manifest themselves through the growing period.

Summer days are defined by a max. temperature above 25 °C. "Summer days in May" were assessed. The baseline (obs.) values were rather low for all the periods, being lowest in Kremsmünster and higher at the two other sites. Under RCP4.5, especially for Bad Gleichenberg a significant growth in summer days was projected, with a slower growth in the second climatic period. Kremsmünster and Poysdorf were not projected to experience the same increase and would instead experience a decrease in the first climatic period under RCP8.5. In the second climatic period the trends were expected to be much more uniform with higher increases compared to first climatic period, showing a significant growth at all three sites.

There were less baseline (obs.) "tropical days in June" (max. temperature above 30 °C) compared to "summer days in May". Again, Poysdorf and Bad Gleichenberg experienced more tropical days than Kremsmünster. Poysdorf was projected to experience a significant increase for both scenarios, with higher increases in the second climatic period. The same was seen for Bad Gleichenberg, with highest growths under RCP8.5. Under RCP4.5 Kremsmünster was even expected to experience a decrease in the first climatic period, with the biggest decrease in the second climatic period for RCP4.5.

3.3.2.3 General growing period

The "general growing period" is defined as the frost-free period between the last to the first frost, typically ranging from late winter/spring to the fall.

The three sites had rather identical growing season durations in the baseline period (obs.) with Kremsmünster having around 10 days longer than Bad Gleichenberg and around 15 days longer than Poysdorf, highlighting the frost periods, that are typical of the Pannonian climate in Poysdorf. The average growing period was April 13th to October 24th for Bad Gleichenberg, April 10th to October 30th for Kremsmünster, and April 16th to October 21st for Poysdorf.

As with the temperature trends, the growing period was expected to increase most in the second climatic period and under RCP8.5 for all sites. Equal increases were found under RCP8.5 in the first climatic period and under RCP4.5 in the second climatic period.

Especially Kremsmünster was projected to experience longer frost-free periods under RCP4.5. In the second climatic period the increase in growing season would be 34% for Kremsmünster compared to 26.5% for Poysdorf and 20.7% for Bad Gleichenberg. The increase was also projected to be lowest for Bad Gleichenberg in the first climatic period under RCP4.5.

Under RCP8.5 in the first climatic period, the frost-free period was expected to increase more significantly in Kremsmünster than in Bad Gleichenberg but in the second climatic period Poysdorf would experience the biggest increase of almost 55%. In the second climatic period under RCP8.5, growing season would increase with 61 days in Bad Gleichenberg, 94 in Kremsmünster, and 102.5 in Poysdorf. The longest growing season would still be in Kremsmünster with almost 300 days.

3.3.2.4 Huglin index

"Huglin index" was included to assess the viticulture potential and thus look at alternative crop possibilities in light of potential negative consequences of climate change. This index is calculated as the temperature sum over a threshold of 10 °C and summed for all days beginning from April to end of September. Different grapevine cultivars have different temperature requirements and their suitability in a given location can be estimated based on the Huglin value (Trnka et al., 2011c).

The results from the "Huglin index" naturally followed the general temperature trends and increased at all sites with the highest increase found in the second climatic period under RCP8.5 where increases above 30% were found at all sites. Warming would increase the viticulture potential at all sites, but the feasibility of a particular wine crop would depend on its thermal requirements as well as the time period and scenario. The "Huglin index" were highest at the warmer sites, Bad Gleichenberg and Poysdorf. These results should be questioned due to local effects and the fact that the index only includes one parameter and small scale climatic variations are not included (Trnka et al., 2010a).

			2030-2059	2060-2089
Indices	Site	Baseline	RCP4.5/8.5	RCP4.5/8.5
Mean temp. March to May (°C)	Bad	10.5	+/+	+↑/+↑
	Krems	9.9	+/+	+↑/+↑
	Poys	10.2	+/+	+↑/+↑
Mean temp. June to August (°C)	Bad	19.6	+/+	+↑/+↑
	Krems	18.9	+/+	+↑/+↑
	Poys	19.6	+/+	+↑/+↑
Mean prec. March to May (mm)	Bad	193.3	-/+	-↓/+↑
	Krems	250.8	+/+	+↓/+↓
	Poys	144.1	+/+	+↑/-↓
Mean prec. June to August (mm)	Bad	313.5	-/+	+↑/+↑
	Krems	359.2	-/+	+↑/+↑
	Poys	186.1	-/+	+↑/+↑
Potential water balance, March to May (mm)	Bad	-42.6	-/-	-↓/-↑
	Krems	30.8	+/+	+↓/+↓
	Poys	-104.3	+/+	+↑/-↓
Potential water balance, June to August (mm)	Bad	-57.2	+/+	+↑/+↑
	Krems	15.7	-/+	+↑/+↑
	Poys	-210.6	-/+	+↑/+↑
Summer days in May	Bad	6	+/+	+↑/+↑
	Krems	4.2	0/-	+↑/+↑
	Poys	5.6	+/-	+↑/+↑
Tropical days in June	Bad	2.3	+/+	+↑/+↑
	Krems	1.5	-/-	-↓/+↑
	Poys	2.2	+/+	+↑/+↑
General growing period	Bad	193.5	+/+	+↑/+↑
	Krems	202.8	+/+	+↑/+↑
	Poys	188.1	+/+	+↑/+↑
Huglin index	Bad	1809	+/+	+↑/+↑
	Krems	1613.4	+/+	+↑/+↑
	Poys	1802	+/+	+↑/+↑
Max rainfall events, 1 day (mm)	Bad	48.1	-/+	+↑/+↑
	Krems	45.7	+/+	+↑/+↑
	Poys	35.8	-/+	-↑/+↑
Max rainfall events, 3 days (mm)	Bad	66.1	+/+	+↑/+↑
	Krems	73.8	+/+	+↑/+↑
	Poys	56.6	-/-	+↑/+↑

Table 7. Projected changes in agrometeorological indices (crop and soil independent). "+" means increase and "–" means decrease of the relevant index value. Black colour means 0-15% change, green 15-30% change and red more than 30% change. The arrows in the second period shows the trends compared to the first period.

3.3.3 Soil-dependent indices

Soil- and crop-dependent indices included “dry days”, “effective growing days”, and field conditions in the form of “sowing days” and “harvest days”, since all of these are dependent on actual evapotranspiration. The results are included in the figures on the following pages and in Appendix B (Table B1-B33).

3.3.3.1 Drought indices

The definition of dry days can be seen in Table 1. “Dry days” were calculated for April-June, June-August, September-November, March-May, as defined in AGRICLIM. **Due to the vast number of results, when combining different soils, scenarios, and periods, only the 20 driest combinations for the extreme and very extreme dry days and their expected changes are presented here (Figure 9 and Figure 10). “**Dry days” were also used in the extreme years analysis (further down) but only “intensive dry days” from April to June for wheat and “extreme dry days” from March to August for maize were included since there were sufficient “dry days” in these situations and they were deemed most important for the growing season of each crop.

Figure 10 and Figure 10 show the 20 combinations between study site, time period, crop and soil type that represent the driest combinations found in the observed data for the baseline period. The full results for “dry days” (intensive, extreme, and very extreme) are included in Table B13-B15. Figure 9 represent the driest combinations for the extreme (ETa / ETr < 0.3) situations and Figure 10 for the very extreme (ETa / ETr < 0.2) situations.

To assess the expected changes in future scenarios for these combinations (the difference between the future amount of “dry days” and the observed number of dry days in the baseline period), each data point has two bars – the left showing the most ‘positive’ development, meaning the highest decrease or least increase (if no scenarios lead to a decrease in “dry days”), the bar on the right represents the most ‘negative’ development, which is the scenario that represents the highest increase in “dry days”. Thus, by looking at the scenarios, soils, and sites present it was possible to discern what factors influenced the development.

Low, mid and high WHC soils were represented in the driest combinations for both extreme and very extreme, and generally the soils with higher WHC did not experience fewer “dry days”. Poysdorf was the most represented site, which is not surprising, considering the arid Pannonian climate. Maize is more sensitive to drought, and especially in the very extreme situations, where the 11 driest situations included maize. The period that was most often represented was March to May, especially in the very extreme situations. Wheat on the other hand will generally experience fewest “dry days” in March to May and instead more “dry days” in the fall (Table B13-B15), which does not coincide with the growing season to the same degree. This was not surprising considering that precipitation was projected to generally increase in summer and decrease in spring.

Not surprisingly the RCP8.5, second climatic period was the situation that would lead to the highest increase in “dry days” but also RCP4.5, first climatic period would lead to more “dry days” for all the sites. The driest areas under extreme would generally experience fewer dry situations with even fewer “dry days” for the most ‘negative’ developments. For the very extreme situation on the other hand the situation was expected to be worse, with the driest places getting drier and generally the ‘negative’ effect from the worst scenario was higher than the ‘positive’ effect from the best scenario. Summer drought increase was expected to be less than spring and fall drought.

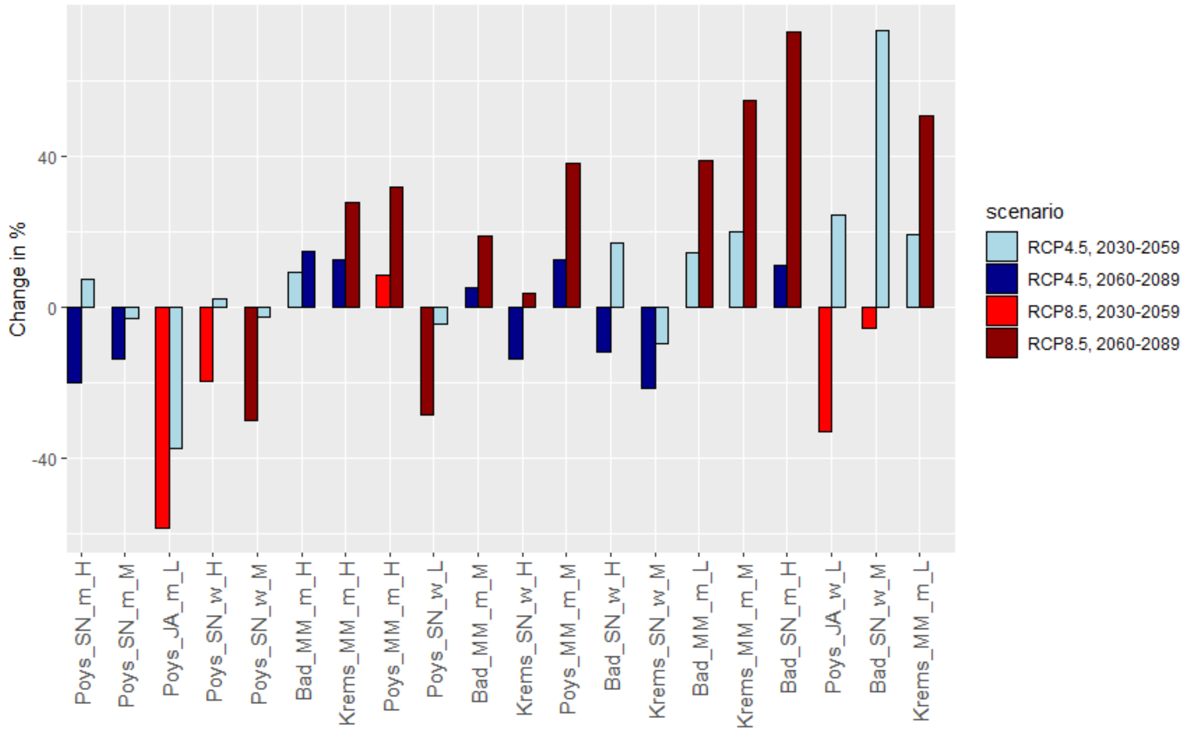

Figure 9. Extreme dry days. The 20 combinations with the most extreme dry days ***(ETa / ETr <0.3)*** *in baseline period (observed weather data) and the highest deviations found in the future scenario data compared to observed baseline. Abbrevations: Poys = Poysdorf, Krems = Kremsmünster, Bad = Bad Gleichenberg, MM = March to May, JA = June to August, SN = September to November, m = maize, w = winter wheat, L = low WHC, mid = mid WHC, high = high WHC*

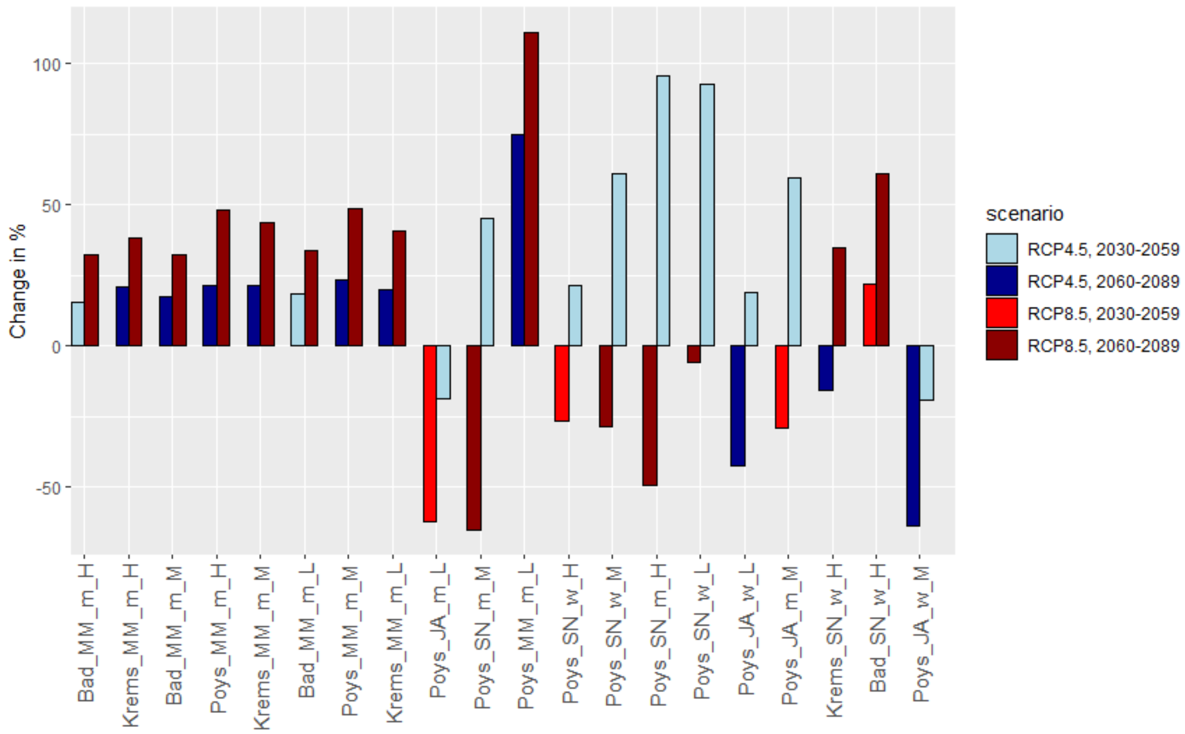

Figure 10. Very extreme dry days. The 20 combinations with the most very extreme dry days (ETa / ETr <0.3) in the baseline period (observed weather data) and the highest deviations found in the future scenario data compared to observed baseline. Abbrevations: Poys = Poysdorf, Krems = Kremsmünster, Bad = Bad Gleichenberg, MM = March to May, JA = June to August, SN = September to November, m = maize, w = winter wheat, L = low WHC, mid = mid WHC, high = high WHC

3.3.3.2 Field working days

The full field days' results are included in Table B1-B12 in the Appendix.

3.3.3.2.1 Sowing conditions

Figure 11 shows the number of calculated "sowing days" for the different periods and expected developments under the different climatic periods and scenarios. "Sowing days" are dependent on WHC – see definition in Table 1. The number of "sowing days" was negligible for mid and high WHC soils. The reason for this must be a too high-water content in the surface layer since the number of both "sowing and harvest days" was low on mid and high WHC soils. As "harvest days" are defined by soil water content in the top layer between 0 and 70% the water content had to be too high. The water content will drop faster in sandy soils, thus increasing the number of "sowing and harvesting days". **Therefore, only the low WHC soils were included here (Figure 11).**

Kremsmünster as the most humid site had fewer baseline (obs.) "sowing days" in both spring and fall than the two other sites which confirmed that the wetter situations found here could reduce the number of field days. In Bad Gleichenberg, more spring than fall "sowing days" were found, whereas both Kremsmünster and Poysdorf had more "sowing days" in the fall, especially Poysdorf.

There would be more "sowing days" in the fall for all sites, and especially Poysdorf and Bad Gleichenberg would experience growth here under all situations.

The number of spring “sowing days” would decrease in Poysdorf in the first climatic period under RCP8.5, in Kremsmünster in the first period under RCP4.5, and in Bad Gleichenberg in the first climatic period under RCP4.5 and in the second climatic period under RCP8.5. The second climatic period under RCP4.5 would generally lead to more “sowing days”, whereas the RCP8.5 would lead to more sowing days in the first climatic period.

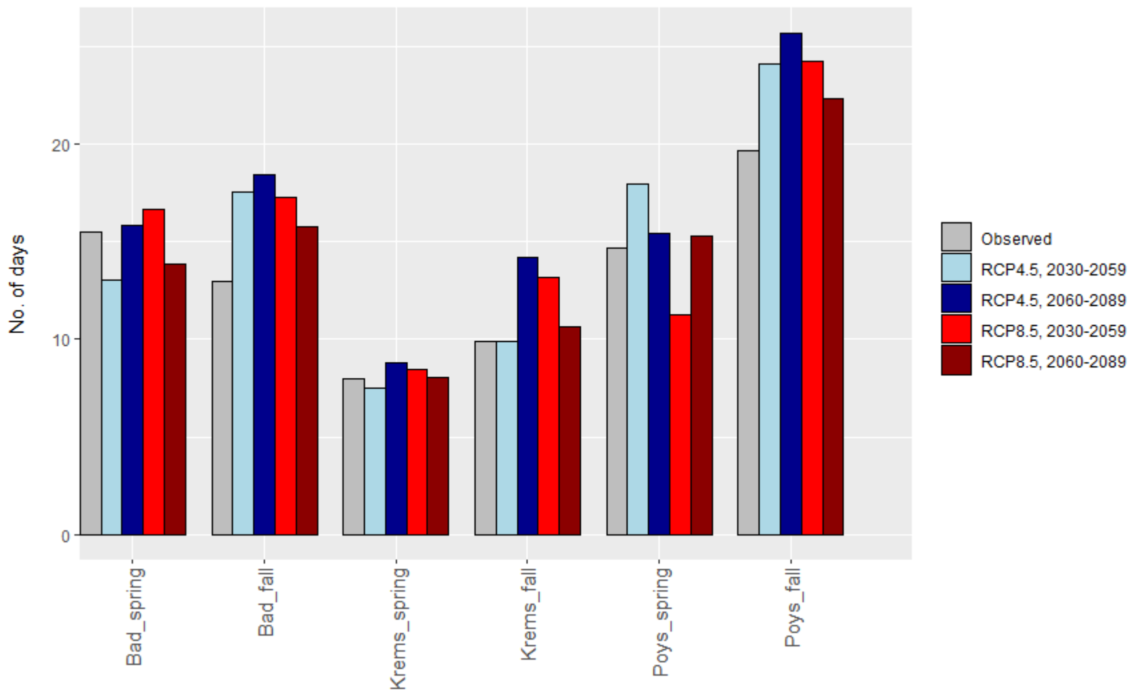

Figure 11. Sowing days in early spring (defined as the period between March 1st and April 25th) and fall. Above results are for soils with low WHC. Bad = Bad Gleichenberg, Krems = Kremsmünster, Poys = Poysdorf

3.3.3.2.2 Harvest conditions

“Harvest day” definition is included in Table 1. Figure 12 shows the number of “harvest days” for low and mid WHC soils. As seen in the figure, in Poysdorf under the climate change scenarios, increasing “summer precipitation”, would lead to fewer “harvest days”, especially on soils with medium WHC, confirming that the soils with mid and high WHC often are too wet for field days. Similarly, the number of “harvest days” would generally also decrease at the two other sites, apart from in first climatic period under RCP4.5, that would lead to more “harvest days” in August for Poysdorf and Bad Gleichenberg and Kremsmünster in July. Generally, the second climatic period under RCP8.5 would lead to the highest decrease in “harvest days”.

The number of “harvest days” in the different sites resembled “sowing days” as their definitions are almost identical – Poysdorf had the most “harvest days” for all the assessed months, whereas Kremsmünster had the fewest.

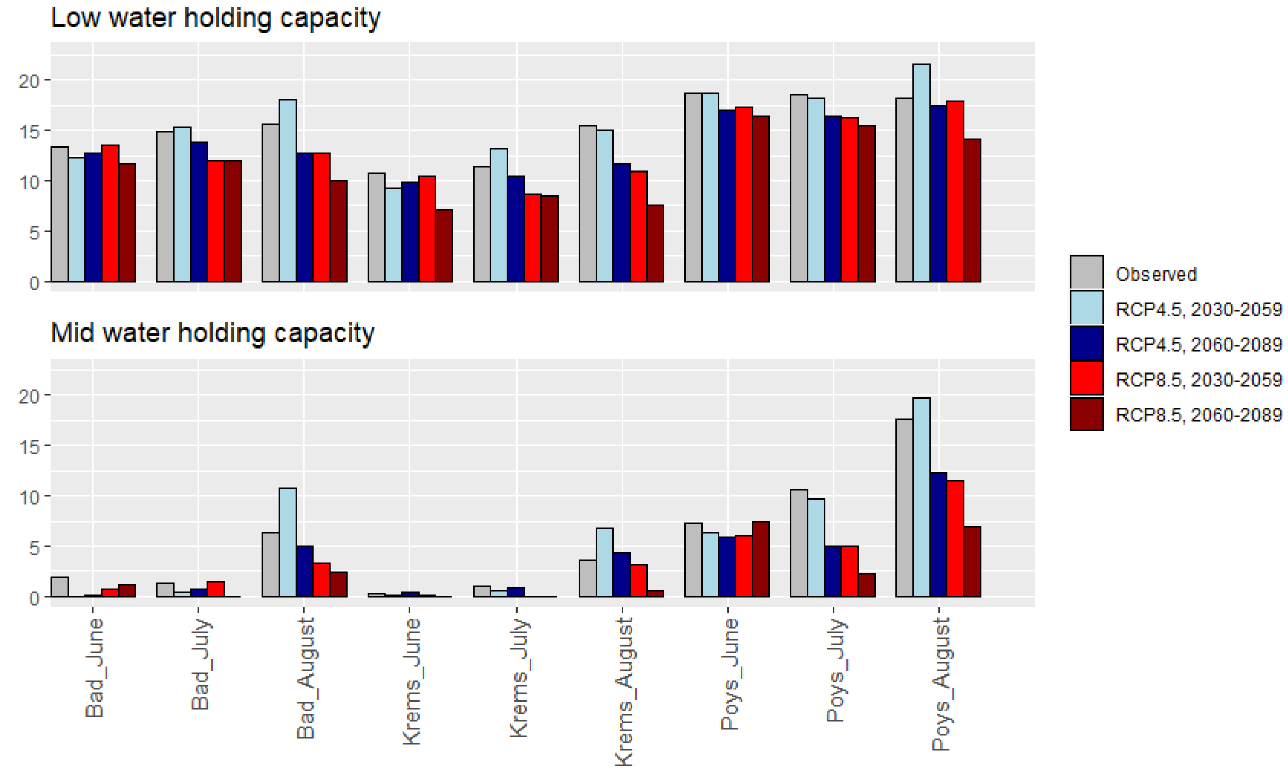

Figure 12. Harvest days in June (wheat), July (wheat) and August (maize) at the study sites. Bad = Bad Gleichenberg, Krems = Kremsmünster, Poys = Poysdorf.

3.3.3.3 Effective growing days (EGD's)

Definition of EGD's can also be found in Table 1. The full results are included in Table B16-B33. Most of the EGD's for wheat were found in April, May and June in the baseline period (obs.). The number of EGD's in March increased remarkably under climate change at all sites. Most of the EGD's for maize were found in the summer months.

Due to the combination of soils, crops, and scenarios, **only the combinations between month and soil with the highest number of observed EGD's in the baseline period (obs.) and the scenarios that would lead to the highest change were included in Figure 13**. **Only the most important months for each crop were included.**

As in the other results, RCP8.5 in the second climatic period would in most cases lead to the biggest change, both in positive and negative directions depending on the situation.

3.3.3.3.1 Wheat

March and April would both experience more EGD's at all sites, especially in Bad Gleichenberg and Kremsmünster, under RCP8.5 in the second climatic period. The later part of the growing season, May and June, could on the other hand experience less EGD's, especially in Bad Gleichenberg and Poysdorf. The decrease in precipitation expected in May could partly explain this development in Bad Gleichenberg, as Kremsmünster was expected to experience more precipitation in May.

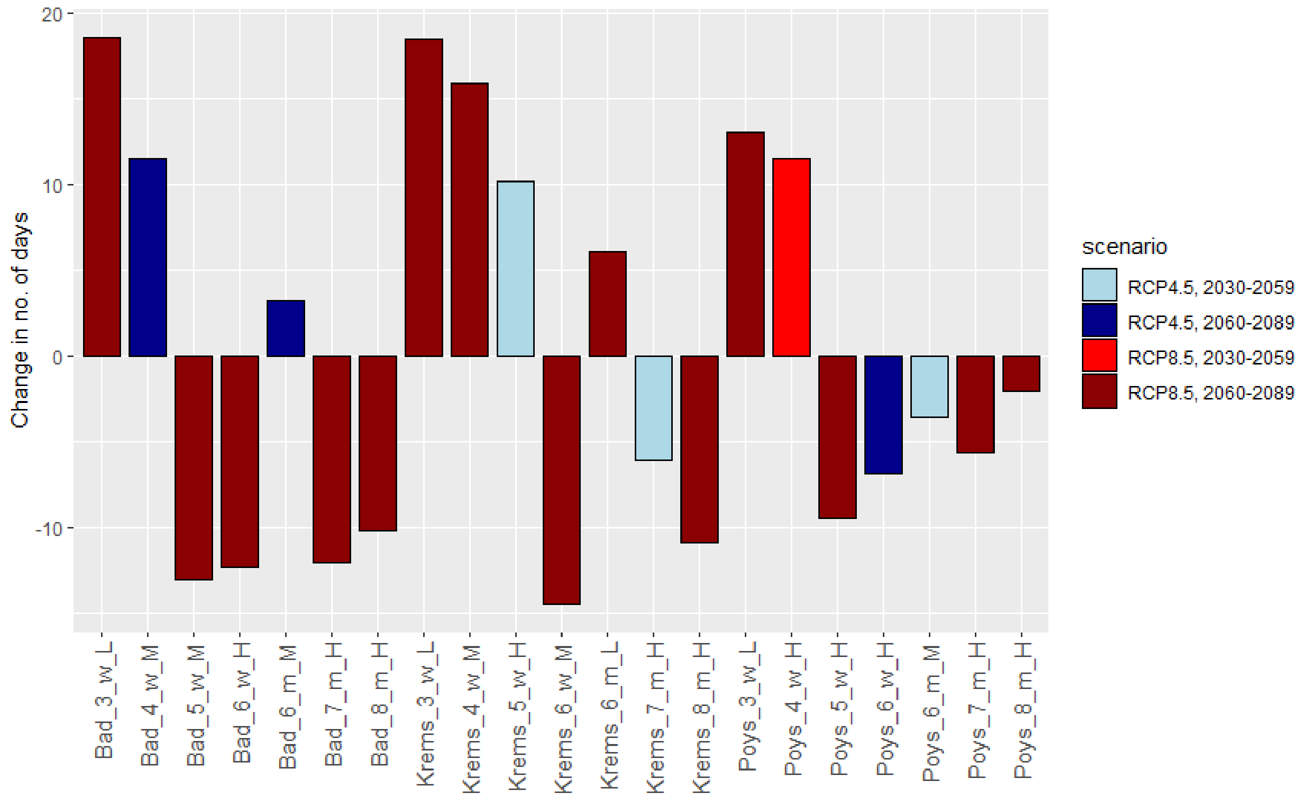

Figure 13. Change in number of effective growing days for the soil with the highest number of observed effective growing days in the baseline period for both winter wheat and maize. The scenario leading to the highest change compared to the baseline period is included. Abbrevations: Bad = Bad Gleichenberg, Krems = Kremsmünster, Poys = Poysdorf, 3-8 = the months of the year, w = winter wheat, m = maize, L = low WHC, M = mid WHC, H = high WHC

3.3.3.3.2 Wheat

Like with wheat, maize would experience fewer EGD's at the end of the growing season – both July and August EGD's were expected to decrease under climate change, whereas in June the number could increase in Bad Gleichenberg and Kremsmünster, though not as much as they would decrease in July and August.

3.4 Extreme weather events

The extreme calculations presented here were made for low WHC soils, since most of the soil indices, such as harvest and sowing days were much higher for these soils. Furthermore, low WHC soils are expected to be more sensitive to adverse events in the future (Trnka, Hlavinka & Semenov, 2015).

Figure 14 shows boxplots over the number of the assessed indices that reached an extreme level. This extreme threshold for the extreme level was set as the 95th or 5th percentile value in the observed baseline period. The direction of extreme events was based on the situation, meaning that temperature and precipitation events were assessed as extreme in both directions, since both too high and too low levels could have negative impacts. Number of field days and "effective growing days" were only considered extreme if they were significantly lower than the 5th percentile for baseline period (obs.). All the other indices where only considered extreme if significantly higher (higher than the 95th percentile for the baseline period).

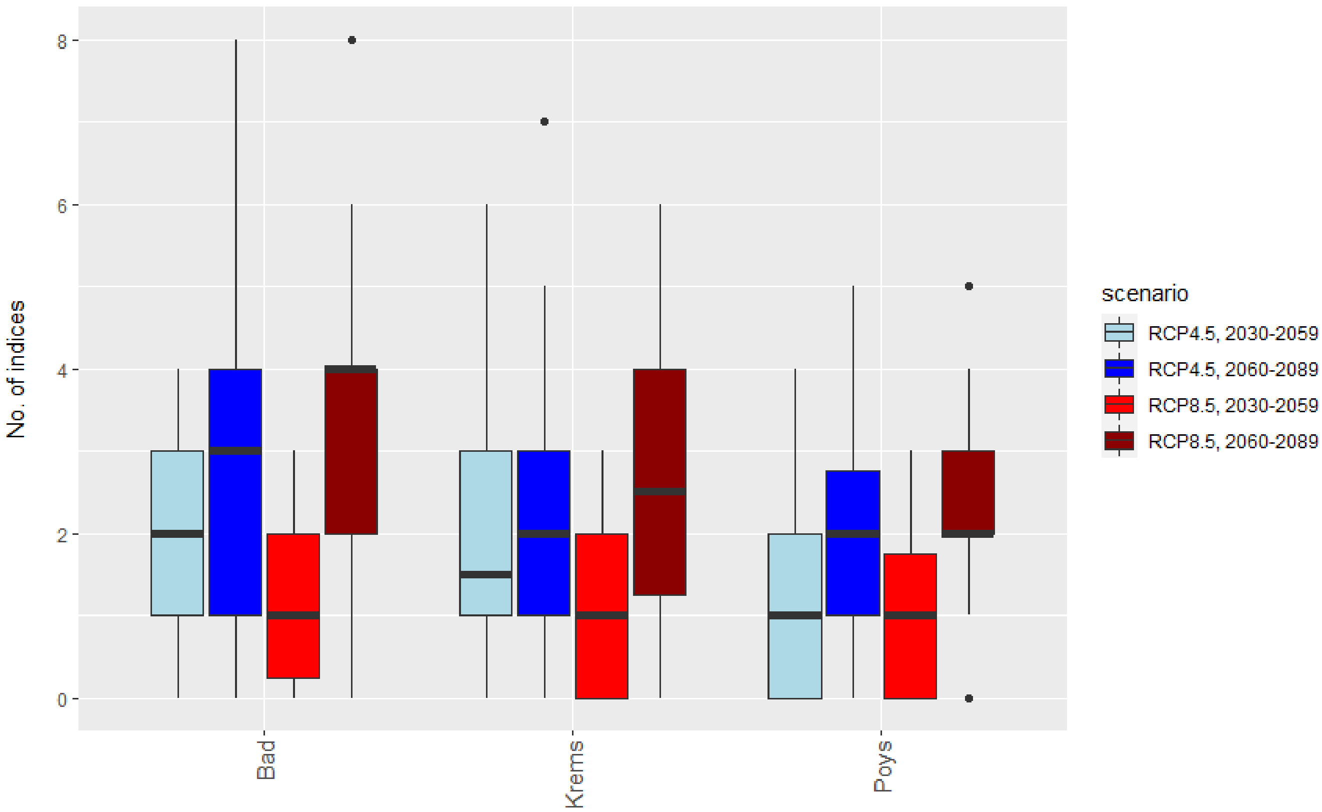

Figure 14. Extreme years under climate change. Boxplots represent the distribution of number of indices that reach an extreme level in the assessed years (higher than the baseline 95th level or lower than the 5th percentile level). The indices used for the analysis were: Mean temperature (March to May), mean temperature (June to August), mean precipitation (March to May), mean precipitation (June to August), 1-day rain events, 3-day rain events, intensive dry days (April to June) for winter wheat, extreme dry days (March to August) for maize, summer days in May, tropical days in June, sowing days (fall) for winter wheat, sowing days (spring early) for maize, harvest days (June to July) for winter wheat, harvest days (July to August) for maize, effective growing days for both winter wheat and maize.

The number of extreme events was found to be higher in Bad Gleichenberg, at least the median value was higher than at the other sites. The main explaining factor was the choice of period, where the second climatic period would lead to higher values. Interestingly under RCP8.5, the first climatic period generally looked to be the period, where least extreme events would occur. Bad Gleichenberg was projected to experience most extreme indices for all the scenarios, followed by Kremsmünster and finally Poysdorf, which was a bit surprising considering the dry and warm climate of this study site.

Figure 16, Figure 17, and Figure 17 show the ten indices with the highest proportion (according to the 95/5th percentile) of extreme years at the different sites. **These ten indices were found by finding the average proportion of extreme years for all indices according to both the 99th percentile (1st percentile) and the 95th percentile (5th percentile).** The soil indices were based on low WHC soils. The biggest changes were generally found in second climatic period under RCP8.5, which followed the same developments that were found in the other results in this thesis – that this scenario and time period would result in the biggest changes.

Temperature and precipitation indices showed a high proportion of extreme years at all three sites, with the two temperature indices being the most frequent ones in Bad Gleichenberg and Poysdorf. Extreme years for temperature were expected to increase for both spring and the summer months, whereas for precipitation “summer precipitation” was projected to lead to much more extreme years.

The figures show that all three sites and especially the more humid, Bad Gleichenberg and Kremsmünster, can experience different types of adverse conditions during summer such as extreme precipitation, heat and drought events, especially under RCP8.5 and towards the end of the century, indicating higher variability in weather conditions.

3.4.1 Bad Gleichenberg

As follows from Figure 14, the highest proportions were generally found in Bad Gleichenberg compared to the other two sites. And generally, all the indices in Figure 15 showed a significant proportion of extreme years, especially in the second climatic period under RCP8.5. For the temperature indices, the period was the most deciding factor for the proportion of extreme years, whereas for the precipitation indices, RCP8.5 would generally lead to higher proportions than RCP4.5. “Harvest days” for maize, as well as extreme precipitation (“3-day max events”) were also found to result in a high probability, especially under RCP8.5, and this generally indicated that a plethora of different extreme indices could affect Bad Gleichenberg in the future.

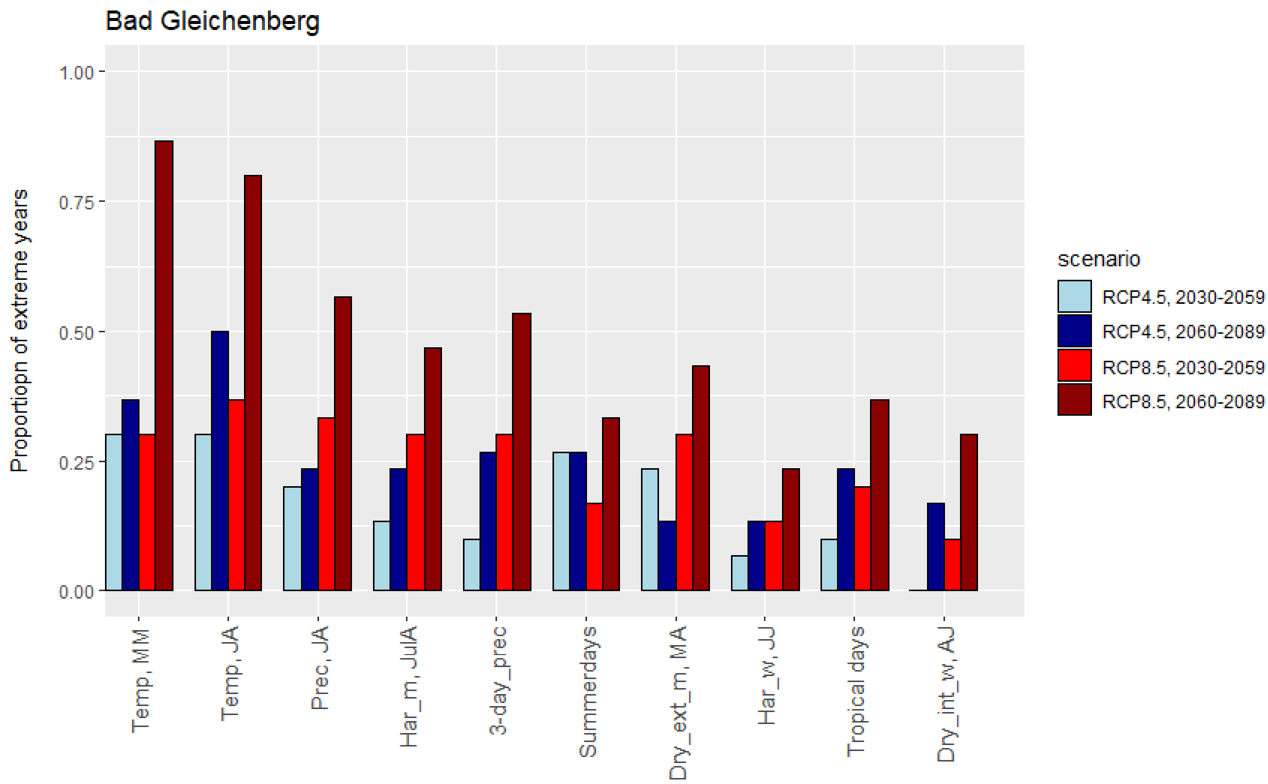

Figure 15. Most frequent indices in extreme years, Bad Gleichenberg. Abbreviations (including the ones from Figure 16 and 17): Temp, MM = Temperature (March to May), Temp, JA = Temperature (June to August), Prec, MM = Precipitation (March to May), Prec, JA = Precipitation (June to August), Har_m, JulA = Harvest days for maize (July to August), 3-day_prec = 3-day max rain event, Dry_ext_m, MA = Extreme dry days for maize (March to August), Har_w, JJ = Harvest days for wheat (June to July), Dry_int_w, AJ = Initial dry days for wheat (April to June), Sow_m, spring = Sowing days for maize, early spring, Prec, MM, low = Precipitation (March to May, low indicates that the event is below the 5th percentile), 1-day_prec = 1-day max event

3.4.2 Kremsmünster

Generally, the same picture was seen in Kremsmünster, but "harvest days" for maize was found to have the highest proportion (Figure 16). Again, the temperature and precipitation indices were found to be important and also "dry days" for maize, which was also present for Bad Gleichenberg.

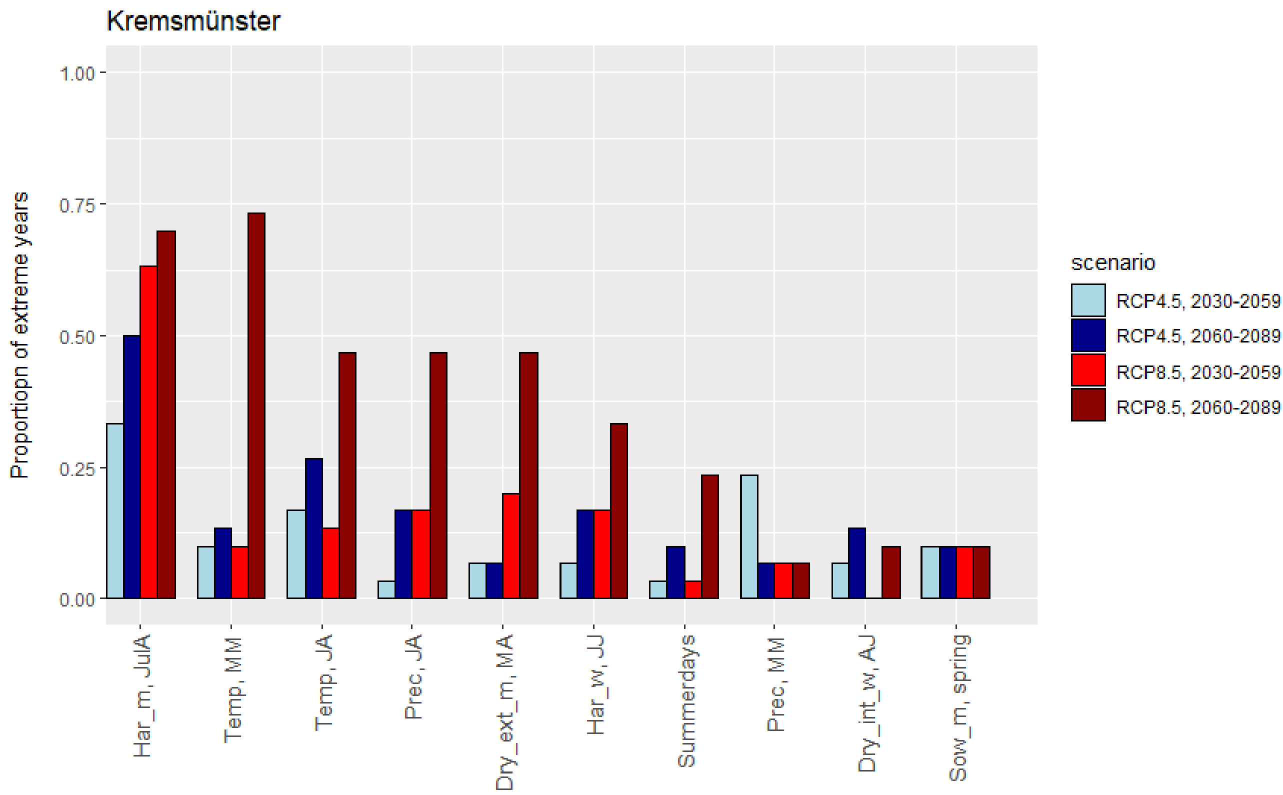

Figure 16. Most frequent indices in extreme years, Kremsmünster. Abbreviations (including the ones from figure 15 and 17): Temp, MM = Temperature (March to May), Temp, JA = Temperature (June to August), Prec, MM = Precipitation (March to May), Prec, JA = Precipitation (June to August), Har_m, JulA = Harvest days for maize (July to August), 3-day_prec = 3-day max rain event, Dry_ext_m, MA = Extreme dry days for maize (March to August), Har_w, JJ = Harvest days for wheat (June to July), Dry_int_w, AJ = Initial dry days for wheat (April to June), Sow_m, spring = Sowing days for maize, early spring, Prec, MM, low = Precipitation (March to May, low indicates that the event is below the 5th percentile), 1-day_prec = 1-day max event

3.4.3 Poysdorf

Apart from the two average temperature indices, the proportions were rather low in Poysdorf (Figure 17). No drought indices were present, which was the case for the two other sites. On the other hand, a low precipitation index for the spring months (Prec_MM, low) indicated that more years, especially under RCP8.5 in the second climatic period, could experience significantly low precipitation levels which could have a negative influence on both winter and summer crops at the site.

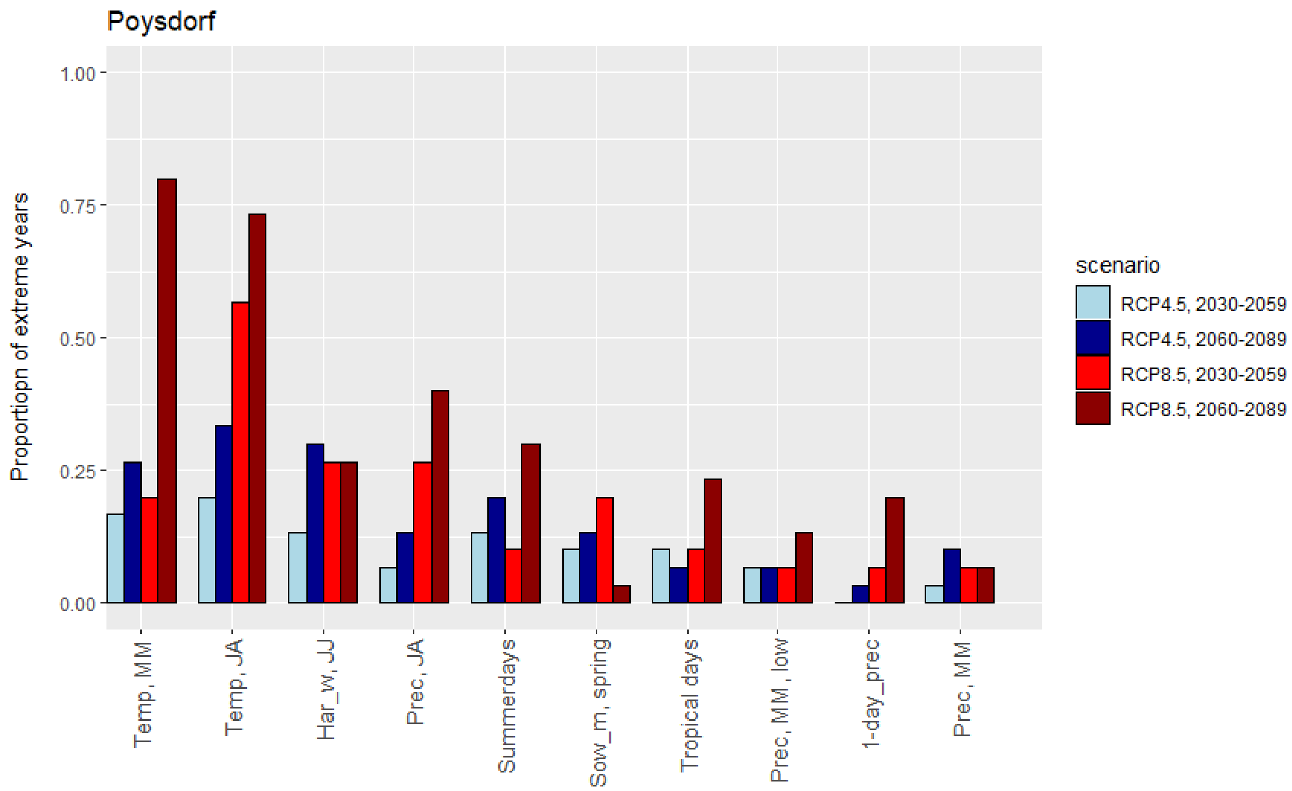

Figure 17. Most frequent indices in extreme years, Poysdorf. Abbreviations (including the ones from figure 15 and 16): Temp, MM = Temperature (March to May), Temp, JA = Temperature (June to August), Prec, MM = Precipitation (March to May), Prec, JA = Precipitation (June to August), Har_m, JulA = Harvest days for maize (July to August), 3-day_prec = 3-day max rain event, Dry_ext_m, MA = Extreme dry days for maize (March to August), Har_w, JJ = Harvest days for wheat (June to July), Dry_int_w, AJ = Initial dry days for wheat (April to June), Sow_m, spring = Sowing days for maize, early spring, Prec, MM, low = Precipitation (March to May, low indicates that the event is below the 5th percentile), 1-day_prec = 1-day max event

3.5 Winter wheat and maize grain yields

AQUACROP was used to calculate crop yields for the different scenarios and different management options in the form of irrigation and mulches. The mean rainfed and irrigated yields, net irrigation requirements and results from statistical tests related to yields are included in Appendix C (Table C1-C18).

3.5.1 Bias analysis for crop yields in the baseline period

Comparing yields based on observed and climate scenario data (both RCP4.5 and RCP8.5) for the baseline period (1981-2010) was the first step in determining the suitability of using the scenario data and the crop model to simulate future yields. Two sample t-tests, correlation tests and root mean square error calculations were performed for each area and both crops (Table C4-C9) and used to compare the crop yields. The calculations were performed for all soils. None of the computed p-values for the t-tests were below 0.05, suggesting that the null hypothesis should not be rejected, hence there were strong indications that the difference in group means was not statistically different from zero. The majority of the correlation tests were not significant and therefore the year-to-year yields were not comparable to a high degree between observed weather data and scenario data. The root mean square errors were highest in Poysdorf (Table C6 & C9), due to the higher influence of precipitation variability on yields. In Kremsmünster the yield bias was lower (Table C5 & C8) due to the higher amount of precipitation and fewer crop failure years.

The results from the t-tests suggest that AQUACROP simulated comparable crop yields for the climate scenario data (both scenarios) compared to the observed weather data for the baseline period when looking at longer time periods as done in this study. It could therefore be argued that the used climate scenario data and crop model is suitable in making future crop yield simulations for wheat (Figure 18) and maize (Figure 19) at the study sites.

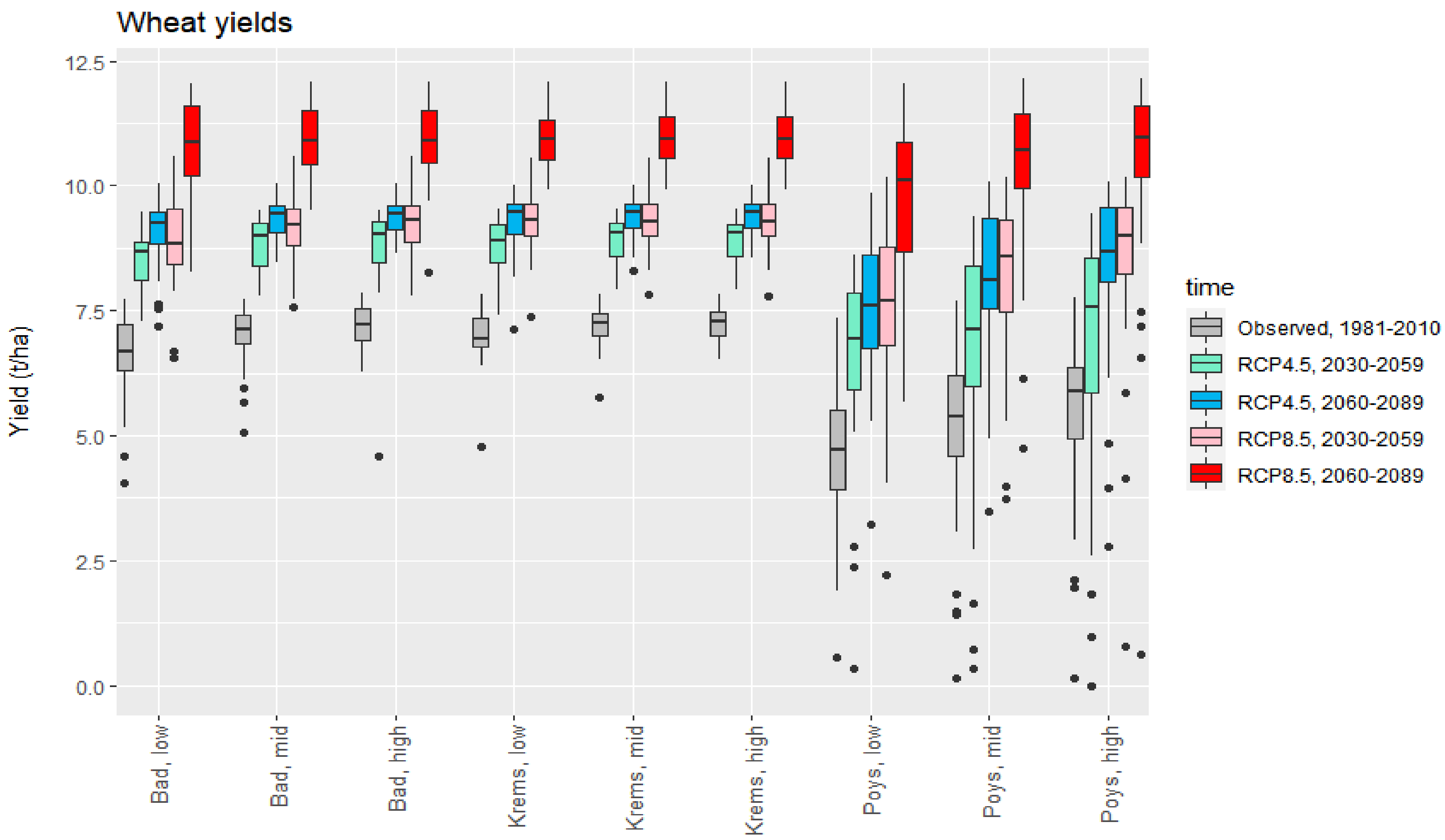

Figure 18. Rainfed wheat grain yields calculated in AQUACROP for the applied climate scenarios and observed weather data in the baseline period for the three different soil types (low, mid, high WHC) at the three different sites.

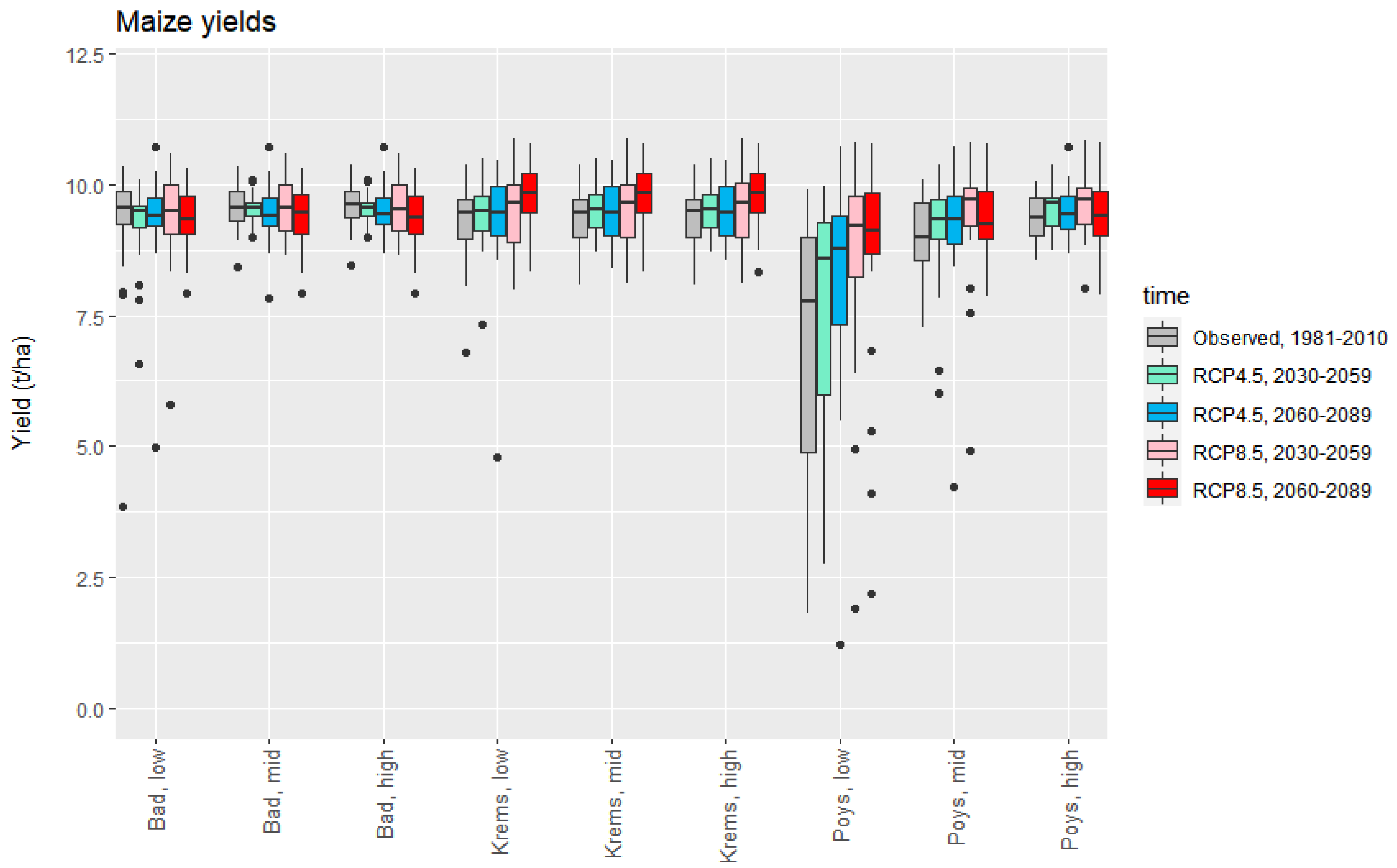

Figure 19. Rainfed grain maize yields calculated in AQUACROP for the applied climate scenarios and observed weather data in the baseline period for the three different soil types (low, mid, high WHC) at the three different sites.

3.5.2 Rainfed grain yields

Figure 19 and Figure 19 show boxplots over the computed yields for both wheat and maize under the different scenarios and climatic periods. Boxplots are helpful to visualize the interannual variability, which is another aspect that is important to consider in future years. The mean rainfed yields are included in Table C1 in the Appendix.

Wheat yields (Figure 18) showed a much greater change in future years under all situations – RCP8.5, second climatic period would clearly lead to the highest yields at all study sites. Maize yields were much more constant through the periods with no or only small further increases under the future climate scenarios. The results even indicated that wheat yields could be higher than maize yields in the future under our simulation settings (assumption of a high CO_2-fertilization effect for wheat (see Table F1) and no cultivar characteristic changes for both wheat and maize, and no change in crop management between scenarios). In the baseline period calculated with observed weather data, maize yields were clearly higher than wheat yields.

3.5.2.1 Wheat

For all the situations, the baseline wheat yields based on observed weather data were the lowest, with the three 'middle' situations (RCP4.5 first climatic period, RCP4.5 second climatic period and RCP8.5 first climatic period) resulting in rather identical yields and finally the RCP8.5 second climatic period clearly resulting in the highest yields. All the future yields in all three study sites were very significantly higher than baseline yields based on observed weather data (p-value <0.01) (Table C10-C12). Kremsmünster experienced the highest yields, followed by Bad Gleichenberg whereas Poysdorf as the driest site experienced clearly lower yields in the baseline period (obs.) with highest interannual yield variations.

Soils with higher WHC experienced higher yields in general, especially in Poysdorf. The difference was less pronounced in Bad Gleichenberg and Kremsmünster due to their better mean potential water balance. The arid, Pannonian climate of Poysdorf could lead to many years with crop stresses in rainfed agriculture, whereas the other sites would not experience low yields to the same degree.

Higher wheat yields and lower interannual variabilities were found in Bad Gleichenberg and Kremsmünster compared to Poysdorf. Both these sites showed a significant increase in yield variability especially for high WHC soils, under RCP8.5 in the two climatic periods, and under RCP4.5 in the first climatic period in Bad Gleichenberg. That being said, yield variabilities were much lower in Bad Gleichenberg and Kremsmünster compared to Poysdorf, that had much higher yield variability for all three soil types and all climate scenarios. Furthermore, Poysdorf experienced increasing yield variabilities in the future under RCP4.5 in the first climatic period, especially on the mid and high WHC soils.

3.5.2.2 Maize

The projected climate changes applied lead to higher simulated rainfed maize yields in Poysdorf where yields were increasing significantly ($p < 0.05$) for all scenarios on the low WHC soil, apart from under RCP4.5 in the first climatic period (Table C15). On mid and high WHC soils, whether an increase would be present depended on the scenario and timing but generally the changes would be much lower due to the higher baseline (obs.) maize yields on these soils.

The same situation was happening for all soils in Kremsmünster, where RCP8.5 in the second climatic period, led to very significant yield increases ($p < 0.01$). Apart from that increases were seen, but not significantly (Table C14). Climate change even resulted in negative yield changes in Bad Gleichenberg, especially on soils with mid and high WHC, but no significant changes were found, and the yields stayed in the same range (Table C13). RCP8.5 for second climatic period (2060-2089) resulted in the highest yield decreases for Bad Gleichenberg.

Generally, simulated maize yields were much more uniform, and the yield variability lower compared to wheat, especially for Bad Gleichenberg and Poysdorf. Yield variabilities would be higher for soils with lower WHC for all sites, which was not surprising.

RCP4.5 in the first climatic period (2030-2059) would lead to significantly lower yield variability in Bad Gleichenberg on all soils ($p < 0.01$) and RCP8.5 in the second climatic period ($p < 0.01$) would do the same on soils with low WHC. Apart from that the general tendency would be an increase in yield variability under climate change, caused by increasing “extreme” weather events with adverse yield effects, as shown in the previous chapter. In Kremsmünster, the most humid site, no significant changes in yield variability were found. The yield variability for low WHC soils in the baseline years (obs.) was smaller than for the other two study sites and generally the difference between the low WHC and other soils was smaller in Kremsmünster due to the higher precipitation levels.

Yield variability was much higher in Poysdorf for the low WHC soils compared to the other sites, but much more comparable for mid and high WHC soils. So, the benefit in terms of lowering yield variability when going from lower to higher WHC soils was much more substantial in Poysdorf. Increasing summer precipitation under the climate scenarios would decrease yield variability especially for low WHC soils, whereas it would increase slightly for mid WHC soils (but still remain lower than for low WHC soils), especially under RCP8.5 in the first climatic period and under RCP4.5 in the second period where significant increases were found. RCP8.5 in the second climatic period would lead to a significant increase in yield variabilities for high WHC soils in Poysdorf.

3.5.3 Yields under management (irrigation and mulches)

Estimations of net irrigation requirements were used as a proxy for irrigated grain yields. Figure 21 and Figure 21 show the irrigated winter wheat and grain maize yields for the three study sites and soils and under the different climate scenarios and periods. The average irrigated yields are included in Table C2 in the Appendix. Generally, the same pattern as for the rainfed yields were evident, especially for the already more humid sites Bad Gleichenberg and Kremsmünster. Irrigation would lead to higher yields and lower yield variabilities for wheat on all soils and maize on low WHC soils in Poysdorf, the site with the lowest potential water balance. Mulches were assessed for all sites, both in combination with irrigation and alone (Tables D1-D6). Table C16-C21 show the statistical differences between rainfed and irrigated yields for the three study sites.

3.5.3.1 Wheat

The humid climate resulted in almost identical yield trends and yield variabilities in Kremsmünster (Figure 20) due to lower irrigation requirements (Table C3). Only under RCP4.5 in the second period on the low WHC soils was a significant decrease in yield variability found for irrigated yields (Table C17). Apart from this irrigation did not lead to higher yields and lower variabilities in Kremsmünster, at least not significantly.

Not surprisingly, the situation is completely different for Poysdorf where a significant increase in yields and decrease in variability was found for all situations on all soils ($p < 0.05$) and even very significant in most situations ($p < 0.01$) (Table C18).

Bad Gleichenberg is placed between the two other study sites, with significant differences between rainfed and irrigated yields expected for the low WHC soils especially (Table C16). Significant decreases in yield variabilities were found for all situation on low soils, but still, as in Kremsmünster, since the yield variabilities were already quite low for rainfed yields, the absolute decrease in yield variabilities would be rather low.

Mulch would improve wheat yields in all sites (Table D1-D3), especially Poysdorf due to the lower precipitation amounts. But irrigation on its own led to higher yields than mulch and irrigation combined in all situations.

3.5.3.2 Maize

The results for irrigated simulated maize yields showed some of the same behaviour as for wheat (Figure 21). For Poysdorf, all of the situations on the low WHC soils would lead to very significantly lower variabilities and the same for mid WHC soils for all scenarios apart from RCP8.5 in the second climatic period (Table C21). Figure 19 shows high yield variabilities on low WHC soils for Poysdorf, which are not found in the irrigated situations (Figure 20). At the same time, the yields would also increase significantly for all situations on the low WHC soils, which was not seen on soils with higher WHC.

Even though very significant decreases in yield variabilities were found for all situations apart from under RCP8.5 in the second climatic period in Bad Gleichenberg on low WHC soils, irrigation did not lead to better yields (Table C19). Yields were very identical for rainfed and irrigated yields for Bad Gleichenberg.

In Kremsmünster only on low WHC soils under RCP4.5 in the second climatic period, a significant decrease in yield variability was found. Apart from that no significant difference between irrigated and rainfed yields was found (Table C20). For both Bad Gleichenberg and Kremsmünster irrigated and rainfed yields on mid and high WHC soils were very identical, suggesting that irrigation would not be necessary on soils with higher WHC under the applied climate change scenarios, which show increasing summer precipitation, in Bad Gleichenberg and Kremsmünster.

As for wheat, mulch could improve maize yields but not in Kremsmünster where lower yields were even found under mulches compared to rainfed (Table D5). The combination of mulches and irrigation could lead to the highest yields in Bad Gleichenberg (Table D4) and Poysdorf (Table D6) but the difference between irrigation alone and irrigation combined with mulches was negligible.

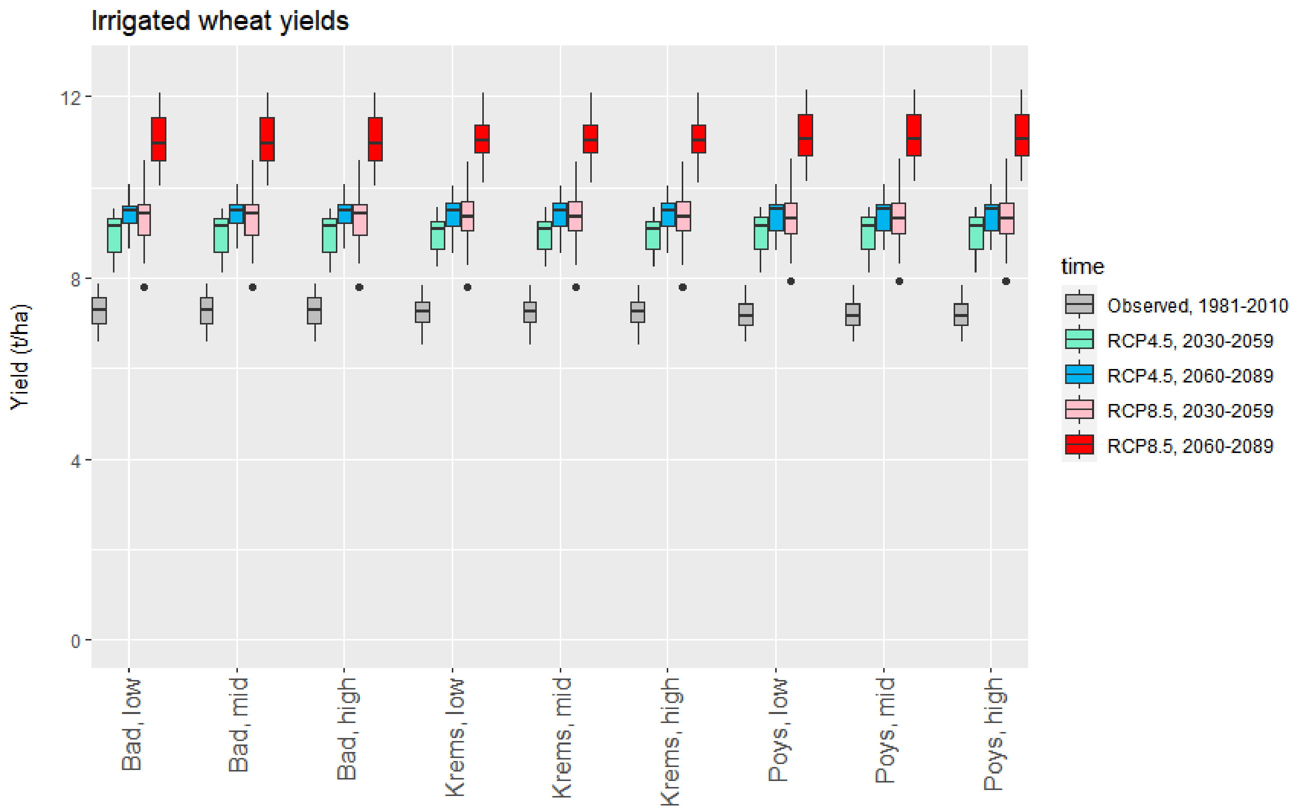

Figure 20. Irrigated wheat yields calculated in AQUACROP

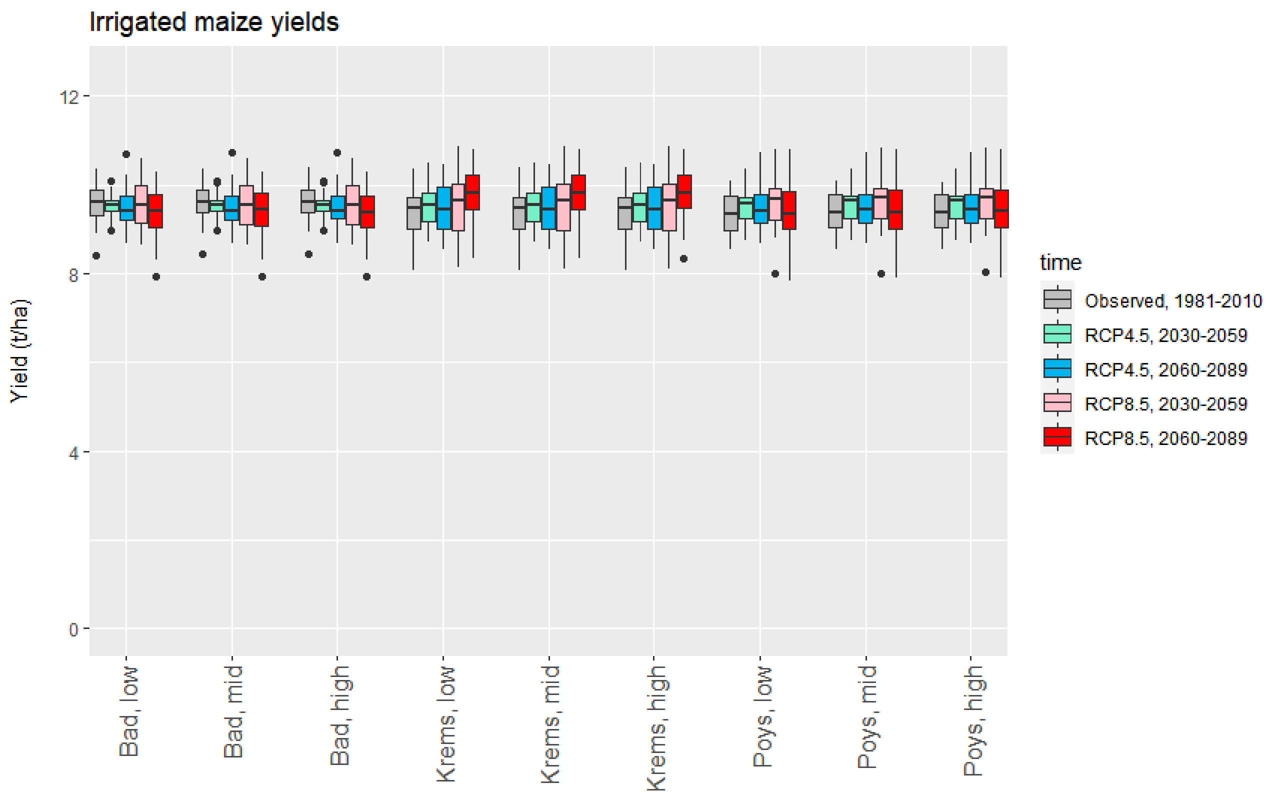

Figure 21. Irrigated maize yields calculated in AQUACROP

3.6 Correlations between rainfed yields and agrometeorological indices

Table 8-13 show all the significant correlations between rainfed yields and agrometeorological indices. **The filtered extreme events (defined as the indices reaching an extreme high level or frequency for a particular year– see chapter 3.4) were included as an explaining variable for the low WHC soils.** The variables with an underline were the ones that were very significantly (p-value < 0.01) correlated to yields whereas the others were less significant (p-value < 0.05). The variables marked green were positively correlated to grain yields, whereas the red ones were negatively.

3.6.1 Wheat

3.6.1.1 Temperature indices vs. yield

In Bad Gleichenberg significant, negative correlations were found between yields and number of "summer days in May" and "tropical days in June" (Table 8). This is based on the upper temperature threshold for wheat crop development of 26°C as defined for the simulation (Table 2), which is the standard upper temperature in AQUACROP for wheat simulations. Multiple temperature indices (indicating high temperature conditions) were found to have a negative relationship with wheat yields under RCP4.5 in the second climatic period on low and mid WHC soils (Table 8 -9). However, under the RCP8.5 scenario, few correlations with temperature indices were found and even a positive link between average spring temperatures and grain yields were found under RCP8.5 in the first climatic period on high WHC soils.

Kremsmünster showed the same tendencies as Bad Gleichenberg – temperature indices such as "summer days in May" and "tropical days in June" were mainly negatively correlated with yields (Table 9). Under RCP8.5 in the first climatic period, negative correlations were found between "summer days" and yields for all soils. "Spring temperatures" were found to be positively correlated under RCP8.5 in the first climatic period for all soils and also for high WHC soils in the baseline period.

Temperature indices were found to be much less correlated to yields in Poysdorf, compared to the two other study sites due to other dominating limiting growth factors (Table 10) (see below). Only "summer temperatures" on mid WHC soils in baseline (obs.) and "summer days in May" under RCP4.5 in the first climatic period on high WHC soil were found to be correlated with wheat yields and in both instances, the least important correlation of all significant correlations.

3.6.1.2 Precipitation indices vs. yield

Positive correlations were found between precipitation indices and yields in Bad Gleichenberg but only on low and mid WHC soils (Table 8), indicating that the lower WHC turned water into the limiting factor for growth. For mid WHC soils under the future climate scenarios, no correlations were found between precipitation and yields apart from under RCP4.5 in the second climatic period. The correlations were all positive and included "spring precipitation" and "potential water balance in the spring", both due to the importance of "spring precipitation" for winter crops and also the expected stagnation or decrease in "spring precipitation" compared to "summer precipitation". Both "summer and spring precipitation" indices were found to positively correlate with baseline (obs.) yields for both low and mid WHC soils.

Precipitation indices were found to be much less important for wheat yields in Kremsmünster compared to the other sites, and these correlations were mainly found in the baseline period (Table 9). All correlations were positive. "Summer precipitation" and "potential water balance in the summer" were found to be correlated to yield in baseline period (obs.), whereas some correlations were found between "spring precipitation" and "potential water balance in the spring" under RCP4.5 in the second climatic period on low WHC soils. "Max 3-day rainfall" events were expected to increase in the future and under RCP4.5 in the second climatic period, negative correlation between this variable and yield was found.

Not surprisingly many significant correlations were found between precipitation indices and yield in Poysdorf, especially on low WHC soils where correlations were found under all situations (Table 10). For mid WHC soils, correlations were found under RCP4.5 in the first climatic period and under RCP8.5 in the second climatic period. Just like at the other study sites, apart from "max. rainfall events" in Kremsmünster, all the correlations were found to be positive in Poysdorf. In the baseline years, and under RCP4.5 in the first climatic period, both summer and spring indices were found to be important, but in the later period and under RCP8.5 in both climatic periods, very significant correlations were found for "spring precipitation" and "potential water balance in spring", due to the expected stagnation or decrease in precipitation. A positive correlation was also found between "max rainfall events" in baseline period (obs.) on low WHC soils.

3.6.1.3 Effective growing days vs. yield

EGD's were, as expected, positively correlated with wheat yields, and found to be significant, especially under RCP4.5 at all study sites (Table 8-10). In addition to this, correlations were found under RCP8.5 in the first climatic period for Poysdorf (Table 10).

3.6.1.4 Drought indices vs. yield

"Dry days" were mostly negatively correlated to yields, and also not surprisingly correlations were mainly found on the low WHC soils.

In Bad Gleichenberg "dry days in summer" was found to be more important in the baseline period on low and mid WHC soils (Table 8). Under RCP4.5 on low WHC soils and under RCP8.5 in the first climatic period, spring drought was found to be very important, once again indicating the expected changes in precipitation. Interestingly, under RCP8.5 in the second climatic period on high WHC soils, there was a positive correlation between yield and spring and summer drought, indicating that less precipitation (which is related to higher sun radiation and photosynthesis potential) could be beneficial for wheat yields, when water is still not a limiting factor.

Some of the same patterns were found in Kremsmünster for "dry days in spring and summer" where negative correlations were mainly found (Table 9). "Summer drought" was important in the baseline period with observed weather data, whereas "spring drought" was more important under both future climate scenarios, especially under RCP4.5 in the second climatic period on mid and high WHC soils where it was found to be the most important variable of all. There was a positive correlation between "summer drought" and yields under RCP8.5 in the first climatic period on high WHC soils, which could indicate that "summer precipitation" would be so high here, that days with less rainfall with resulting more sunlight and photosynthesis potential could be beneficial for yields. No correlations were found under RCP8.5 in the second climatic period, indicating that the higher precipitation levels were able to decrease or even remove the negative effects from drought.

The correlations between drought indices and wheat yields were all negative in Poysdorf (Table 10). Like in the other two sites, "summer drought" was found to be most important for the baseline period (obs.), whereas "spring drought" was found to be more important under the applied future climate scenarios, especially under RCP4.5 in the first climatic period. One interesting thing, when comparing Poysdorf to the other two sites is, that spring drought was found to be highly, negatively correlated to yields under RCP8.5 in the second climatic period on mid and high WHC soils indicating that the lack of precipitation together with temperature increases in spring would result in more "dry days" and related decrease of "potential water balance" which would have a negative effect on yields.

3.6.1.5 Growing season length vs. yield

As said in the methodology chapter, growing season length used in the correlation analyses was the number of growing days needed from sowing to maturity in AQUACROP, as these were crop-specific and expected to be more directly related to yields (compared to the "general growing period" calculated in AGRICLIM). Whereas most of the other variables had a relatively clear positive or negative relationship with wheat yields, "growing season length" was more diffuse.

For Bad Gleichenberg, correlations were only found for mid and high WHC soils (Table 8) – under RCP8.5, negative correlations between "growing season length" and yields were found, whereas under RCP4.5 in the first climatic period, a positive correlation was found, which could indicate more negative effects from longer "growing season" under higher temperatures as in RCP8.5.

In Kremsmünster, the same trends were seen with negative correlations found between "growing season length" and yields under RCP8.5 on all soils (Table 9).

In Poysdorf the relationship was completely different and there were exclusively positive correlations found between "growing season length" and yields (Table 10). Especially on high WHC soils, number of growing days was important, being the most important variable under all situations. For the mid and low WHC soils under RCP8.5, no correlations were found. Under RCP4.5 in the second climatic period on mid and high WHC soils, "growing season length" was found to be the only significant correlation.

3.6.1.6 Atmospheric CO2-level vs. yield

Perhaps the most interesting variable in relation to wheat is CO_2. A positive relationship between increasing CO_2 and wheat yields was not surprising, considering that wheat as a C3-crop could benefit much more than maize from the higher CO_2 content in the atmosphere.

CO_2 turned out to be one of the mostly correlated variables (exclusively positive), especially on the higher WHC soils (due to less water limitation) and under the future climate scenarios. In Bad Gleichenberg all simulations (Table 8), apart from under RCP4.5 in the second climatic period had a positive correlation between yields and CO_2. Especially under RCP8.5, these correlations were found to be the highest and highly significant.

Whereas Kremsmünster (Table 9) was more or less identical to Bad Gleichenberg, the situation was a bit different in Poysdorf (Table 10). CO_2 was still here seen as highly correlated under RCP8.5 but not under RCP4.5 at all.

CO_2 was highly positively correlated to yields, especially in the cases where negative correlations for instance from drought and temperature were less pronounced. At least under RCP4.5 in the first climatic period, many other both positive and negative correlations were found, perhaps diminishing the relative importance of CO2. Discerning the relative effect of CO_2 on wheat yields is not easy but the consensus must be that increasing CO_2 will result in higher potential wheat yields. Since atmospheric CO_2-levels are expected to stabilize under RCP4.5, the higher yields found also under this scenario, could explain why fewer correlations were found between wheat yields and CO_2 under RCP4.5 compared to RCP8.5.

3.6.2 Maize

The overall difference between correlations of agrometeorological indices vs. maize and wheat yields was the direction of the correlations. A higher proportion of the maize correlations were negative compared to wheat at all the sites (Table 11-13), indicating that impacts of the chosen agrometeorological indices were more negative for maize under the settings applied in this study.

For Bad Gleichenberg (Table 11), a higher number of correlations were found for the simulations in the second climatic period, especially under RCP8.5 whereas fewer correlations were found for the baseline period compared to wheat. This indicated that the effect of agrometeorological indices on maize yields could increase in the future.

This was not the case for Kremsmünster (Table 12), where fewer correlations were found, especially for mid and high WHC soils. Still, under both climate scenarios in the second climatic period on low WHC soils, more correlations were found compared to wheat.

Many correlations were found in Poysdorf (Table 13) on low and mid WHC soils, especially under RCP4.5. On high WHC soils, fewer correlations were found, mainly under RCP8.5 in the second climatic period.

3.6.2.1 Temperature indices vs. yield

In general, maize as a C4-crop has higher optimum temperature and threshold values than wheat (Sheaffer, C. C., & Moncada, 2012). Upper temperature threshold for crop development was set to 30 °C as was the standard setting for maize in AQUACROP (Table 2).

In Bad Gleichenberg, different temperature indices were correlated to yields – “summer temperatures”, “tropical days in June” and “summer days in May”. Whereas the first two had a negative correlation with yields, the latter had a positive correlation with yields. For low WHC soils, correlations were found with “summer temperatures” in all situations (Table 11), whereas for high WHC soils only under RCP8.5 was this correlation found.

The same temperature indices showed a significant positive correlation at the coldest site, Kremsmünster (Table 12), and “summer temperatures” was the index with the highest correlation value in the second climatic period in all situations, apart from under RCP4.5 on low WHC soil (but it was still highly correlated here). “Summer days in May” was found to be positively correlated with yields under RCP8.5 in the first climatic period but not correlated in the second climatic period where the summer temperature indices (including “tropical days in June”) had a negative effect.

All correlated temperature indices signifying an increase in temperature had a negative effect in Poysdorf (Table 13), probably due to its more frequent co-incidence with drought events (cross correlation to yield). High “summer temperatures” was also important in both climatic periods apart from under RCP4.5 on high WHC soils. High “spring temperatures” also had a negative effect under RCP4.5 for the first climatic period on mid WHC soils but as at the other sites, high “summer temperatures” was the most important temperature index.

3.6.2.2 Precipitation indices vs. yield

Extreme and average precipitation indices were both negatively and positively correlated to yields, depending on the site and its climatic and soil conditions.

Such correlating precipitation indices were found in Bad Gleichenberg on low WHC soils (Table 11) in the baseline period and under RCP4.5 in the first climatic period where “summer precipitation” and “potential water balance in summer” had a positive effect. Under RCP8.5 in the second climatic period (2060-2089) the correlations between precipitation indices and yield were all negative. “Summer precipitation” and “potential water balance in summer” had a higher and more negative correlation compared to the same spring indices. This could be explained by the increase in expected summer precipitation and causally by a cross-correlation to lower solar radiation levels. “3-day max. rainfall events were also correlating on all soils but to a lesser degree than the other precipitation indices.

Significant correlations between precipitation indices and maize yields were only found on low WHC soils in Kremsmünster (Table 12), and all of these correlations were negative. “Spring precipitation”, “potential water balance” and “3-day max rainfall” were all negatively correlated with maize yields under RCP4.5 in the second climatic period whereas also “summer precipitation” was negatively correlated in the baseline period (obs.).

In Poysdorf precipitation indices were found to correlate with yields on all soils (Table 13) but especially for low and mid WHC soils. All the precipitation indices were, apart from in one instance, positively correlated to yield which was not surprising given the arid climate in Poysdorf, making soil water availability the main limiting factor. “Summer precipitation” and “potential water balance in summer” had a positive correlation in all the situations on the low WHC soils. The same indices were also found to be positive on mid WHC soils in the baseline period and the first climatic period. “Potential water balance in spring” had a negative effect on high WHC soils in the baseline period (obs.).

3.6.2.3 Effective growing days vs yield

EGD's were, not surprisingly, also positively correlated to maize yields. For Bad Gleichenberg, correlations were found under all scenarios on low WHC soils (Table 11) apart from under RCP8.5 in the second climatic period. For mid WHC soils, correlation was found under RCP4.5 in the second climatic period. For Poysdorf (Table 13) the same correlations on low WHC soil as for Bad Gleichenberg were found.

The results for Kremsmünster differed from the other study sites as EGD correlations were found mainly under RCP8.5 in the second climatic period on all soils (Table 12).

3.6.2.4 Drought indices vs. yield

"Dry days in summer" was found to have a negative correlation with maize yields in Bad Gleichenberg especially under RCP4.5 and RCP8.5 in the first climatic period depending on soil (Table 11). Interestingly, no significant correlations with drought indices were found under RCP8.5 in the second climatic period but since precipitation indices were here negatively correlated, this indicated that this period was more characterized by an abundance of water and perhaps that water stagnation could be a bigger problem than drought. Another explanation could be that lower solar radiation due to more cloudiness could reduce photosynthesis.

Drought was less important in Kremsmünster, due to higher precipitation (Table 12). Drought indices were only found to be negatively correlating on low WHC soils in the baseline period, under RCP4.5 in the second climatic period, and under RCP8.5 in the first climatic period. As in Bad Gleichenberg, only "dry days in summer" had an influence.

Finally, in arid Poysdorf drought indices were significantly and negatively correlated to maize yields on all soils (Table 13). As at the other study sites, only "dry days in summer" was found to be correlating and in all cases it was negative. Compared to the other sites, drought was also found to be important under RCP8.5 in the second climatic period and was even found to be the most important on low WHC soils.

3.6.2.5 Growing season length vs. yield

"Growing season length" was found to have a positive correlation with yields in most future situations in Bad Gleichenberg (Table 11). In Kremsmünster (Table 12) "growing season length" had the same positive effect in the second climatic period under both scenarios and was highly correlating under RCP8.5 in the second climatic period on all soils. "Growing season length" was negatively correlated with yield in the baseline period (obs.).

In Poysdorf, growing season length had an exclusively positive correlation with yields (Table 13). It was found to be one of the most important indices, especially on low and mid WHC soils, where very significant correlations were found in all situations (apart from one) in the climatic periods. On high WHC soils, correlations were only found under RCP8.5. The overall positive correlation is in contrast to wheat. A possible explanation for this could be the that the longer wheat season will expand into the summer months with more potential adverse events whereas the longer maize season will expand into the fall months with less of these.

3.6.2.6 Atmospheric CO2-level vs. yield

Maize being a C4-crop, CO_2 was not expected to be generally significantly correlated with yields. In Bad Gleichenberg and Poysdorf no correlations were found. In Kremsmünster positive correlations were found in the baseline period (obs.) on mid and high WHC soils (Table 12). As the CO_2 levels were lower in the baseline period, an increase in CO_2 may have had a higher influence on maize yields than in the future climatic periods where the higher CO_2 content would not benefit maize yields to a high degree (Supit et al., 2012), indicating a decreasing relative CO2 effect with higher CO2 levels approaching a saturation level.

Bad, wheat, low WHC soil	RCP4.5		RCP8.5	
Baseline (obs.)	2030-2059	2060-2089	2030-2059	2060-2089
Effective days	Effective days	Tropical days	CO_2	CO_2
Dry_int_JJA	Summer days	Pot_MAM	Prec_MAM	Pot_MAM
Harvesting_days_JJA	Dry_int_MAM	Effective days	Effective days	Prec_MAM
Pot_JJA	CO_2	Prec_MAM	Pot_MAM	
Prec_MAM		Dry_int_MAM	Summer days	
Prec_JJA		Summer days		
Pot_MAM		Dry_int_JJA		
Dry_int_MAM		Ext_95		
Tropical days		Ext_99		
Temp_JJA				

Mid WHC soil	RCP4.5		RCP8.5	
Baseline (obs.)	2030-2059	2060-2089	2030-2059	2060-2089
Harvesting_days_JJA	CO_2	Effective days	CO_2	CO_2
Effective days	Summer days	Tropical	Growing season	Growing season
Pot_JJA		Summer days		
Prec_JJA		Harvesting_days_JJA		
Dry_int_JJA		Prec_MAM		
Prec_MAM		Pot_MAM		
Tropical days				
Pot_MAM				

High WHC soil	RCP4.5		RCP8.5	
Baseline (obs.)	2030-2059	2060-2089	2030-2059	2060-2089
CO_2	Growing season		CO_2	CO_2
	Summer days		Dry_int_MAM	Growing season
	CO_2		Temp_MAM	Dry_int_MAM
			Growing season	Dry_int_JJA
			Effective days	

Table 8. Significant correlations between agrometeorological indices and wheat yields for Bad Gleichenberg. Abbreviations: MAM = March to May, JJA = June to August, Temp = temperature, Prec = precipitation, Dry_int = intensive dry days, Pot = potential water balance, Ext_95 = extreme years (95th percentile), Dry_ext = extreme dry days. The indices with underscore are significantly correlated to yields (p-value < 0.01). Red colour = negative correlation yield, green colour = positive correlation.

Krems, wheat, low WHC soil	RCP4.5		RCP8.5	
Baseline (obs.)	2030-2059	2060-2089	2030-2059	2060-2089
Effective days	CO_2	Effective days	CO_2	CO_2
Dry_int_JJA	Effective days	Tropical days	Growing season	Growing season
Pot_JJA	Summer days	Ext_95	Temp_MAM	
Tropical days	Ext_95	Rain_3days	Summer days	
Temp_JJA	Dry_int_MAM	Dry_int_MAM		
		Ext_99		
		Summer days		
		Pot_MAM		
		Prec_MAM		

Mid WHC soils	RCP4.5		RCP8.5	
Baseline (obs.)	2030-2059	2060-2089	2030-2059	2060-2089
CO_2	CO_2	Dry_int_MAM	CO_2	CO_2
Pot_JJA	Summer days	Effective days	Growing season	Growing season
Dry_int_JJA		Summer days	Temp_MAM	
Effective days		Rain_3days	Dry_int_MAM	
Prec_JJA		Tropical days	Summer days	

High WHC soils	RCP4.5		RCP8.5	
Baseline (obs.)	2030-2059	2060-2089	2030-2059	2060-2089
CO_2	CO_2	Dry_int_MAM	CO_2	CO_2
Temp_MAM	Dry_int_MAM	Effective days	Dry_int_MAM	Growing season
Dry_int_MAM	Summer days	Summer days	Temp_MAM	
Prec_JJA			Summer days	
Pot_JJA			Growing season	
Dry_int_JJA			Dry_int_JJA	

Table 9. Significant correlations between agrometeorological indices and wheat yields for Kremsmünster. Abbreviations: MAM = March to May, JJA = June to August, Temp = temperature, Prec = precipitation, Dry_int = intensive dry days, Pot = potential water balance, Ext_95 = extreme years (95th percentile), Dry_ext = extreme dry days. The indices with underscore are significantly correlated to yields (p-value < 0.01). Red colour = negative correlation yield, green colour = positive correlation.

Poys, wheat, low WHC soils	RCP4.5		RCP8.5	
Baseline (obs.)	2030-2059	2060-2089	2030-2059	2060-2089
Dry_int_JJA	Dry_int_MAM	Growing season	Pot_MAM	CO_2
Effective days	Growing season	Pot_MAM	Prec_MAM	Pot_MAM
Prec_JJA	Effective_days	Prec_MAM	CO_2	Prec_MAM
Prec_MAM	Pot_MAM	Effective days	Effective days	Sowing days
Pot_JJA	Dry_int_JJA		Harvesting_days_JJA	Pot_JJA
Pot_MAM	Pot_JJA			
Rain_3days	Prec_MAM			
Harvesting_days_JJA	Prec_JJA			
Dry_int_MAM				

Mid WHC soils	RCP4.5		RCP8.5	
Baseline (obs.)	2030-2059	2060-2089	2030-2059	2060-2089
Growing season	Dry_int_MAM	Growing season	CO_2	CO_2
Prec_JJA	Growing season		Effective days	Dry_int_MAM
Harvesting_days_JJA	Harvesting_days_JJA			Prec_MAM
Dry_int_JJA	Effective days			Pot_MAM
CO_2	Dry_int_JJA			
Temp_JJA	Pot_JJA			
	Pot_MAM			
	Prec_JJA			

High WHC soils	RCP4.5		RCP8.5	
Baseline (obs.)	2030-2059	2060-2089	2030-2059	2060-2089
Growing season	Growing season	Growing season	Growing season	Growing season
Prec_JJA	Pot_JJA		CO_2	CO_2
CO_2	Prec_JJA		Summer days	Dry_int_MAM
	Dry_int_JJA			
	Dry_int_MAM			
	Pot_MAM			
	Summer days			

Table 10. Significant correlations between agrometeorological indices and wheat yields for Poysdorf. Abbreviations: MAM = March to May, JJA = June to August, Temp = temperature, Prec = precipitation, Dry_int = intensive dry days, Pot = potential water balance, Ext_95 = extreme years (95th percentile), Dry_ext = extreme dry days. The indices with underscore are significantly correlated to yields (p-value < 0.01). Red colour = negative correlation yield, green colour = positive correlation.

Bad, maize, low WHC soils	RCP4.5		RCP8.5	
Baseline (obs.)	2030-2059	2060-2089	2030-2059	2060-2089
Dry_ext_JJA	Harvesting_days_JJA	Ext_99	Dry_ext_JJA	Growing season
Pot_JJA	Pot_JJA	Dry_ext_JJA	Temp_JJA	Prec_JJA
Harvesting_days_JJA	Prec_JJA	Ext_95	Growing season	Temp_JJA
Prec_JJA	Dry_ext_JJA	Growing season	Rain_3days	Summer days
Temp_JJA	Effective days	Summer days	Effective days	Pot_JJA
Effective days	Temp_JJA	Temp_JJA		Tropical days
		Tropical days		Pot_MAM
		Effective days		Prec_MAM
				Rain_3days

Mid WHC soils	RCP4.5		RCP8.5	
Baseline (obs.)	2030-2059	2060-2089	2030-2059	2060-2089
Pot_JJA	Growing season	Growing season	Temp_JJA	Prec_JJA
Temp_JJA		Temp_JJA	Growing season	Growing season
		Effective_days	Dry_ext_JJA	Pot_JJA
		Dry_ext_JJA		Temp_JJA
		Tropical days		Summer days
		Harvesting_days_JJA		Tropical days
		Summer days		Pot_MAM
				Prec_MAM
				Rain_3days

High WHC soils	RCP4.5		RCP8.5	
Baseline (obs.)	2030-2059	2060-2089	2030-2059	2060-2089
	Growing season		Temp_JJA	Prec_JJA
			Growing season	Growing season
			Dry_ext_JJA	Pot_JJA
				Temp_JJA
				Summer days
				Tropical days
				Pot_MAM
				Prec_MAM
				Rain_3days

Table 11. Significant correlations between agrometeorological indices and maize yields for Bad Gleichenberg. Abbreviations: MAM = March to May, JJA = June to August, Temp = temperature, Prec = precipitation, Dry_int = intensive dry days, Pot = potential water balance, Ext_95 = extreme years (95th percentile), Dry_ext = extreme dry days. The indices with underscore are significantly correlated to yields (p-value < 0.01). Red colour = negative correlation yield, green colour = positive correlation.

Krems, maize low WHC soils	RCP4.5		RCP8.5	
Baseline (obs.)	2030-2059	2060-2089	2030-2059	2060-2089
Dry_ext_JJA		Tropical days	Dry_ext_JJA	Temp_JJA
Prec_MAM		Ext_99	Summer days	Growing season
Pot_MAM		Rain_3days	Ext_95	Tropical days
Prec_JJA		Growing season		Effective days
		Summer days		
		Ext_95		
		Temp_JJA		
		Dry_ext_JJA		
		Prec_MAM		
		Effective days		
		Pot_MAM		

Mid WHC soils	RCP4.5		RCP8.5	
Baseline (obs.)	2030-2059	2060-2089	2030-2059	2060-2089
Growing season		Temp_JJA	Summer days	Temp_JJA
CO_2		Tropical days		Growing season
		Growing season		Effective days
				Tropical days

High WHC soils	RCP4.5		RCP8.5	
Baseline (obs.)	2030-2059	2060-2089	2030-2059	2060-2089
Growing season		Temp_JJA	Summer days	Temp_JJA
CO_2		Growing season		Growing season
				Dry_ext_JJA
				Tropical days
				Effective days

Table 12. Significant correlations between agrometeorological indices and maize yields for Kremsmünster. Abbreviations: MAM = March to May, JJA = June to August, Temp = temperature, Prec = precipitation, Dry_int = intensive dry days, Pot = potential water balance, Ext_95 = extreme years (95th percentile), Dry_ext = extreme dry days. The indices with underscore are significantly correlated to yields (p-value < 0.01). Red colour = negative correlation yield, green colour = positive correlation.

Poys, maize Low WHC soils	RCP4.5		RCP8.5	
Baseline (obs.)	2030-2059	2060-2089	2030-2059	2060-2089
Pot_JJA	Pot_JJA	Growing season	Pot_JJA	Dry_ext_JJA
Prec_JJA	Prec_JJA	Dry_ext_JJA	Dry_ext_JJA	Growing season
Harvesting_days_JJA	Dry_ext_JJA	Temp_JJA	Prec_JJA	Pot_JJA
Effective_days	Growing season	Pot_JJA	Growing season	Temp_JJA
	Effective days	Tropical	Harvesting_days_JJA	Prec_JJA
	Harvesting_days_JJA	Prec_JJA	Temp_JJA	
	Ext_99	Effective days	Effective days	
	Temp_JJA	Harvesting_days_JJA		
	Sowing days	Ext_99		

Mid WHC soils	RCP4.5		RCP8.5	
Baseline (obs.)	2030-2059	2060-2089	2030-2059	2060-2089
Effective days	Pot_JJA	Growing season	Pot_JJA	Temp_JJA
Pot_JJA	Dry_ext_JJA	Temp_JJA	Temp_JJA	Growing season
Dry_ext_JJA	Growing season	Dry_ext_JJA	Growing season	Dry_ext_JJA
Prec_JJA	Prec_JJA	Tropical	Dry_ext_JJA	
	Temp_JJA		Prec_JJA	
	Temp_MAM			
	Harvesting_days_JJA			

High WHC soils	RCP4.5		RCP8.5	
Baseline (obs.)	2030-2059	2060-2089	2030-2059	2060-2089
Pot_MAM		Effective days	Temp_JJA	Temp_JJA
			Growing season	Growing season
				Dry_ext_JJA

Table 13. Significant correlations between agrometeorological indices and maize yields for Poysdorf. Abbreviations: MAM = March to May, JJA = June to August, Temp = temperature, Prec = precipitation, Dry_int = intensive dry days, Pot = potential water balance, Ext_95 = extreme years (95th percentile), Dry_ext = extreme dry days. The indices with underscore are significantly correlated to yields (p-value < 0.01). Red colour = negative correlation yield, green colour = positive correlation.

3.7 Correlations between irrigated yields and agrometeorological indices

Correlations between yields and agrometeorological indices were also performed for some of the irrigated yields (through net irrigation requirement). These were only made under RCP8.5, both climatic periods, and low WHC soil since most change was expected here. See Table E1 & E2 in Appendix for an overview of the significant correlations between irrigated yields and agrometeorological indices.

3.7.1 Indices vs. wheat grain yield

Under irrigation, CO_2 kept being very positively and significantly correlated to wheat yields, while growing season length were negatively. “Spring temperatures” were found to be positively correlated with yields in the first climatic period at all sites (Table E1), which was only found for Kremsmünster for rainfed yields (Table 9). The difference between rainfed and irrigated correlations was smaller in Kremsmünster, which makes sense due to the humid climate, and the lower net irrigation requirement.

As in Bad Gleichenberg, “spring precipitation” was important for rainfed yields in Poysdorf but was not found to be important under irrigation and instead replaced by “spring temperatures” becoming the dominating growth limiting factor. Due to the higher water availability under irrigation, higher temperatures in spring were more acceptable at these two sites than under rainfed.

Irrigation led to fewer correlations with agrometeorological indices in Bad Gleichenberg and Poysdorf, but not so in Kremsmünster, indicating the higher positive effective in the two warmer study sites.

3.7.2 Indices vs. maize grain yield

Irrigation generally led to less negative correlations, especially in Kremsmünster and Poysdorf (Table E1).

In Bad Gleichenberg many negative correlations were found in the second climatic period, as was the case for rainfed. “Summer precipitation” was found to be negatively correlated with yields, which was already found for rainfed, indicating that more water would not improve the situation.

The changes were not big for Kremsmünster. Drought was no longer found to be important in the first climatic period (as it was for rainfed).

In Poysdorf, irrigation led to fewer correlations, and all the precipitation indices were no longer important. “Dry days in summer” were still important in the second climatic period although not as important as under rainfed.

“Summer temperatures” kept being important and negatively correlated with yields in all three study sites, indicating that even under irrigation, heat episodes and rising temperatures would generally not be beneficial for crop yields. However, the crop model does not account for any “cooling” effect due to irrigation on the canopy, which may bias these results. Growing season length was still found to be positively correlated to yields in most situations.

3. 8 Correlations rainfed yields vs. extreme weather events

Correlations were also found between number of “extreme” values of indices per year and rainfed yields on low WHC soils (see Figure 14 where a list of the used indices were also included). Correlations were found both between the number of indices surpassing the $99^{th}/1^{st}$-percentile and number of indices surpassing the $95^{th}/5^{th}$-percentile.

All correlations found between number of extreme indices and yields were negative (see Table 8-13). Significant correlations were found for both wheat and maize in certain situations. For Bad Gleichenberg correlations were found under RCP4.5 in the second climatic period for wheat (Table 8) and for maize (Table 11). For maize, the correlations were found to be very significant.

The situation was rather identical in Kremsmünster where very significant correlations were also found under RCP4.5 in the second climatic period for wheat (Table 9) and for maize (Table 12). A few other correlations were found – under RCP8.5 in the first climatic period for maize and under RCP4.5 in the first climatic period for wheat.

The results for Poysdorf differed a little bit compared to the other sites. For wheat, no correlations were found. For maize, very significant correlations were found under RCP4.5 in both climatic periods.

For Kremsmünster, mainly the extreme variables based on the 95^{th} percentile were correlating whereas in Poysdorf the 99^{th} variable extreme events were found to be more important, indicating the more extreme events could have a higher impact here.

4. Discussion

4.1 Limitations of the study

4.1.1 Uncertainties in crop model and climate change studies

Crop models are based on algorithms and plant processes, and the interaction between crops and environment. Due to the innate complexity of these interactions and systems, these models can't capture everything, and are only simplified versions of reality (Mahallati, 2020). In climate change and crop modelling studies, the sources of uncertainties are manifold and could be the result of the climate projections from the GCM's, the emission scenarios and the crop models themselves (Thaler et al., 2021).

The results of crop modelling studies are only as good/valid as the data allows, and therefore it is important to assess data quality when using simulated data in climate change studies. Downscaling procedures can be problematic in topographically complex areas, for instance Austria, and small-scale meteorological processes such as precipitation might not be accounted for in the downscaled data (Chimani et al., 2018). Bad Gleichenberg has a more complex topography than the other two study sites and according to Thaler et al. (2021) potential for more errors in the downscaled data. Comparing crop model results for the years 1981-2010 (the baseline period) based on observed vs. climate scenario weather input data generally showed few errors or biases. That being said, precipitation patterns did generally not perform well, and it is expected that this could also be the case for the future climate scenario data. Even though the climate data is bias-corrected monthly, daily deviations can still lead to different situations under critical growth phases, thus resulting in different yields, even though monthly values are comparable (Thaler et al., 2021). So, the low correlation values between the baseline period observed (real) and simulated climate scenario precipitation levels obtained in this study indicate that especially daily deviations are normal and will be in the future as well. The reason is the chaotic nature of precipitation and other weather variables pattern at that small time scale, potentially leading to different cropping situations and uncertainties in final crop yields. Therefore, only climatological periods (30-years) of simulations will represent a climatological normal, where single observed years cannot be directly compared but rather an average of 30 years. This is a fundamental condition under which climate change studies must be performed, and seasonal precipitation has still been found to be highly uncertain and more spatially variable in previous studies (Gcg & Kaur, 2017; Trnka et al., 2010a). The crop model outputs, however, did not differ to a high degree between observed weather and climate scenario input data on a longer scale represented by the baseline period. Therefore, the crop model and its results were deemed acceptable to be used in this study.

One of the strengths of AQUACROP is the low amount of input variables and crop specific parameters that must be included. However, no field data and local calibrations were performed in this study. The generic wheat file was used, and only few changes on the temperature response (through GDD requirement) were performed for the maize crop file. Since AQUACROP relies on a set of conservative parameters, even without local calibration it is possible to make computations for various scenarios. Studies and tests have shown that these conservative parameters for maize were applicable in different climates and situations (Vanuytrecht et al., 2014). That being said, local calibration could have been performed by tuning crop parameters that depend on cultivar and local environment and management, such as maximum canopy cover and validating the GDD in the field (Vanuytrecht et al., 2014). Other types of local calibrations that could also have been used is the relative cover of weeds that could have been assessed visually in the field as well as calibration of the crop response to fertility stress (Raes & van Gaelen, 2017). Furthermore, vernalization requirement (for winter cereals) is not included in AQUACROP (Vanuytrecht et al., 2014) and therefore the model is only applicable for wheat under winter conditions where either vernalization is fulfilled in all years even under climate scenarios (which is the case for Central Europe) or the crop has no vernalization requirement at all (in very warm climates) (Eitzinger et al., 2013).Low correlations were found between simulated crop yields based on observed (real) and simulated (climate scenario) daily input data for the baseline period, indicating that year-to-year yields did not resemble each other significantly. This was not surprising considering the simulated (climate scenario) data for the baseline period is not able to represent daily real precipitation patterns due to the probability approach of generating daily precipitation. Due to the timing and importance of precipitation, divergences in yields were bound to happen. This also confirmed that it makes sense to look at normal periods and compare yields and their relationship to agrometeorological indices on longer time horizons. It does not make sense to make comparisons for exact times or a certain year since the statistical value could be much lower and due to errors or bias in the data (Chimani et al., 2018). Results from t-tests indicated no mean differences in annual mean yields based on observed and climate scenario data. This shows that the climate scenario data can be expected to represent the mean yield response in future 30-year periods acceptably, also under limiting conditions.

4.1.2 Other limitations of the study

The choice of sowing dates was another aspect that could be improved. Having the sowing day on the same date each year is not realistic since meteorological properties would differ from year to year. Another possibility would have been to generate automatic sowing dates based on either precipitation or temperature indices which is possible in AQUACROP. This method was used in (Thaler et al., 2021) where sowing dates were established when specific soil temperature and moisture conditions were met. This resulted in some years not being modelled since these conditions were never met, for instance in case of a very dry or warm fall, thus not making it possible to model wheat yields for that year.

In AQUACROP, either temperature or precipitation indices have to be chosen and thus no mixed index can be used to decide on suitable sowing days, which could be considered a limitation. Furthermore, already having the problem with expanding growth over two years, using automatic sowing conditions were found to result in many problems and big annual differences in sowing time. Having an automatic sowing time such as in other updated crop models could make sense for future years. Changing sowing times could be used as an adaptation strategy in the future to change the growing period and limit negative climate effects. One consequence of climate change could be later sowing days for winter wheat, which was not considered in this study.

The initial plan was to include heat indices, calculated in AGRICLIM, in the analysis. Examples of such indices include “number of episodes with extreme heat”, characterized as continuous periods with min. temperature above 20 °C and max. temperature above 35 °C for a number of days, or “Number of heat stress days" with max. temperatures above 35 °C and the ratio between actual and potential evapotranspiration less than 0.5. But the number of heat events were found to be negligible at all sites for both the baseline and also future climatic periods. No specific heat indices were therefore included in the analysis. Projected increase in "Summer precipitation" could have a positive effect and diminish the impact of extreme heat in summer – as the number of heat stress day was based on both temperature and evapotranspiration ratio. However, other indicators of higher (increasing) temperatures showed in several cases negative yield responses.

Another important aspect not considered in the study (and models applied) are potential effects of climate change on pest pressures and related effects on crop yield level. Furthermore, fertilization and other crop management options were assumed as optimum and/or constant in the assessment. Certain yield risks such as flooding, or hails were not considered as well. For these reasons, the yields found are potentially too high.

4.1.3 Global circulation models

As recommended in Thaler et al. (2021) using an ensemble of climate scenarios and impact models, performing calibration and validation of crop growth models, considering extreme events and different adaptation and management strategies are examples of how to take the uncertainties of climate change studies into account and potentially minimizing them. Some of these strategies were followed in this thesis, whereas others were considered to be out of the scope. Using an ensemble of climate scenarios, soils, study sites etc. made it possible to make a more holistic climate change impact assessment.

Especially precipitation is highly uncertain in climate change scenarios and at the same time extremely important for crop model results so one should be careful to draw general conclusions if the data is limited. Only data from one GCM was used in this study that predicted an increase in precipitation which did not agree with earlier studies in the area. So this study showed why it is important to use data from an ensemble of GCM's which for instance was done in (Thaler et al., 2021).

4.2 Wheat and maize yields

The results of this study show that climate change can result in different crop responses at the three study sites depending on timing, emission scenario, management and choice of crop which must be considered in local adaptation strategies. Yield increases were found for wheat under all situations whereas maize yields were found to be much more stagnating or even declining under the applied future climate change scenarios.

The same trends, with increasing winter crop yields and stagnating summer crop yields were found in the same study sites in an earlier study (Thaler et al., 2021) using the DSSAT crop model. The reduced CO_2-fertilization for C4-crops and a shorter growing season were used to explain the stagnating or even decreasing maize yields in the study (Thaler et al., 2021). There are big debates on the relative effect of the CO_2-fertilization effect. In our study the 100% increase, in winter wheat yields in Poysdorf on all soils under RCP8.5, is a very high effect compared to earlier studies. This difference could be explained by different CO_2-effect settings in the models applied. For Bad Gleichenberg and Kremsmünster the yield increases found in this study were lower, but still over 50% under RCP8.5 in the second climatic period.

Pot experiments, and so-called FACE-studies have found that a doubling of CO_2 concentration in the atmosphere could lead to a 40-60 % increase in yields for C3-crops through an increase in photosynthesis rate and biomass accumulation as well as reducing stomatal conductance which increases water use efficiency (Lobell & Gourdji, 2012a; Supit et al., 2012; Thaler et al., 2012). Increasing CO_2 could therefore potentially have a marked positive influence in arid areas, prone to water stress (Sakschewski et al., 2014). This could explain why much higher yield increases are found in Poysdorf in this study. Lalic et al. (2013) found that winter wheat yields could increase up to around 80 % in the Pannonian lowland under CO_2 levels at 1050 ppm. These CO_2 levels are a bit higher than 836 ppm that is projected in 2089 under RCP8.5. In light of these higher yields in the future, Lalic et al. (2013) concluded that an increase in CO_2 could have a more pronounced positive effect on wheat yields compared to the depressing effect of rising temperatures and changing precipitation regimes. They reported, however, big variations of crop yield responses to rising CO2-levels, depending on cultivars and several environmental conditions. Our study, therefore, just represents a maximum positive response to rising CO2-levels (for wheat).

In spite of this, the increases in wheat yield seem slightly exaggerated in this study and a possible explanation is the fact that other stresses such as fertility and weed stress were not considered in AQUACROP. Nutrients and soil fertility were assumed to be optimal which is not necessarily a realistic assumption. Nonetheless the main reason behind the increase in wheat yields must be CO_2 fertilization which was confirmed in the correlations. As yields and CO_2 increase through the years, the high correlations found between these are not surprising. Under RCP4.5 in both climatic periods in Poysdorf and in the second climatic period in Bad Gleichenberg and Kremsmünster, no correlations were found between CO_2 and yields. This is not surprising as the increase in CO_2 is levelling off around mid-century under RCP4.5 and the increases generally are lower than for RCP8.5. So, the lack of correlation in these cases can be explained by the fact that other growth limiting factors (represented by indices), both negative and positive correlated, were found, especially many precipitation indices. The results indicate that the CO_2 effect is strongest in situations with less limiting factors and less correlations with other agrometeorological indices.

The general consensus is that summer crops such as maize will generally face more climate-related risks in the future as the number and intensity of adverse events with a negative impact on cropping yields will generally coincide more with the growth period of summer crops (Lalić et al., 2014). More negative correlations between agrometeorological indices and maize yields were found than for wheat, showing the same trend as earlier studies. Thaler et al. (2021) even found yield decreases for both rainfed and irrigated maize in the 2071-2100 period. As in other studies, few significant yield trends were found for maize under climate change in this study –Poysdorf on low WHC soils under RCP8.5 in both climatic periods with increases around 28% and under RCP4.5 in the second climatic period (Table C15) and also in Kremsmünster under RCP8.5 in the second climatic period (Table C14). The higher precipitation in summer would benefit maize on the sandy soil due to its low WHC (Thaler et al., 2021).

No correlations between CO_2 and maize yields were found (apart from in Kremsmünster in the baseline period (obs.) (Table 12), indicating that the yield increases found in Poysdorf could not be explained by the increasing CO_2. Maize is a C4-crop and the photosynthetic response only increases steeply at CO_2 concentrations that are well below the current ambient levels, and the positive effects will therefore be negligible (Supit et al., 2012). In light of this, stagnating or decreasing maize yields will be a natural consequence, as rising summer temperatures is also expected to have a negative effect on maize, especially at high temperature increases where temperature is outside of the optimal photosynthetic interval (30-35°C), leading to decreases in CO_2 assimilation (Supit et al., 2010), and especially in combination with drought stress. The number of heat stress days would have been a useful combined indicator, including both the temperature and drought stress but the number of these was, as said, negligible due to the high summer precipitation.

The correlation analysis confirmed that both temperature (increase) and precipitation (increase) indices were in general highly negatively correlated with maize yields. These together can lead to lower net photosynthesis due to less sunshine, less gross photosynthesis, and more respiration losses because of temperature increases. In the light of this combined with the lack of CO_2 fertilization, stagnating and decreasing maize yields is a logical consequence.

Even though increasing CO_2 can lead to higher wheat yields, issues with nutrient quality should be considered. Studies have found that wheat as a C3-crop could experience lower zinc, iron and protein levels under elevated CO_2 levels due to reduced nitrogen concentrations, whereas the change in maize and other C4-crops is negligible (Mbow et al., 2019; Myers et al., 2014). This is not surprising as the CO_2 effect is lower in the latter. Nutrient quality and lack of protein is important to consider in the broader realm of food security in the future.

4.3 Irrigated vs. rainfed yields

The irrigation requirements were calculated in AQUACROP. Irrigated yields could potentially have been higher if irrigation schemes had been created and tested.

The general trend was lower net irrigation requirements under climate change (Table C3), especially under RCP8.5 in the second climatic period where the lowest irrigation requirements were found consistently due to the projected increase in precipitation. This contrasts some of the earlier studies in Central Europe based on previous climate scenarios with less summer precipitation, where it was found that intensive droughts in the summer months could limit rainfed crop yields (Trnka et al., 2011b). The results from this study, using the updated RCP-based climate scenarios, seem to be more positive regarding rainfed potential as more precipitation is shown in the summer, especially under RCP8.5, which was also seen in the correlations were spring precipitation and drought generally had a higher influence than the summer equivalent. However, it cannot be said so far, which precipitation scenarios for summer will play out for Central European regions finally, so high uncertainty is remaining in this aspect.

The majority of Europe's wheat production is rainfed (Trnka, Hlavinka & Semenov, 2015), and in general a big part of the agricultural production in the Czech Republic and Austria is rainfed. But that being said, the results of this study indicate that irrigation can have a positive effect on wheat yields, and very significantly in dry areas. Higher irrigation requirements were found for wheat compared to maize due to the lower water productivity. Irrigated areas are expected to face less climate-related risks for instance from warming, as irrigation can diminish water stress and result in higher transpiration rates that can cool the crop canopy (Lobell & Gourdji, 2012a). Thus wheat could be less exposed to adverse weather events if irrigated (Trnka et al., 2010a; Trnka, Hlavinka & Semenov, 2015).

Although rainfed agriculture will probably face more climate-risks most years, a study found that crop yields will be acceptable in most years in Central Europe (Trnka et al., 2010a). The results of this study seems to confirm this but still many crop failures were found especially at the less humid site and clearly irrigation would be very beneficial here and decrease the interannual variability. The effect would be strongest for wheat yields. Trnka et al. (2011c) found that the rainfed potential would increase in humid, Atlantic regions but be restricted in dry areas in Central and Southern Europe unless irrigation was applied which seems to be confirmed in this study.

A question that must be asked is whether irrigation is worth it in a certain situation. If local water recourses diminish, especially in dry areas such as Mediterranean and Pannonian Lowlands, both the potential for irrigated and rainfed agriculture will shrink and adaptation possibilities will be limited under climate change (Trnka et al., 2010a). Places that traditionally have not depended on irrigation, may lack the necessary infrastructure and access to water (Lobell & Gourdji, 2012a). A thorough assessment should be made before making investments in new irrigation infrastructure.

As said, less irrigation is generally needed under climate change and the applied RCP8.5 scenario in this study. The reason for this is the projected increase and timing of precipitation. Other studies have found that increased summer drought in the future can occur when spring and summer crops reach crop stages that are sensitive to drought such as anthesis and grain filling (Asadi, Bannayan & Monti, 2018; Jancic, 2017). Even though summer droughts were generally found to be less of a problem in this study compared to spring drought, higher temperatures could still lead to a shorter grain filling period and lower yields (Jancic, 2017). Many studies, depending on different climate scenarios applied and different local climatic conditions, found an expected increase in summer drought and this could be problematic for especially maize in the future (Jancic, 2017; Trnka et al., 2011b).

Even if irrigation requirements could decrease in the future as found in this study, this is highly dependent on changes in precipitation as well as the timing of growing season and sensitive crop stages. This confirms that an ensemble of GCM’s makes sense to use in a study like this, as the timing and magnitude of precipitation can differ between these which could influence the crop results.

It is difficult to assess future irrigation requirements due to variable precipitation that is difficult to assess and very local. The results from this study indicate that especially wheat could benefit from future irrigation, especially on low WHC soils, due to the lack of spring precipitation, whereas the increase in summer precipitation could result in lower differences between rainfed and irrigated maize yields. Making proper assessment and planning of irrigation water extraction as well as formulating strategies for enhancing water use efficiency could help to decrease the amount of water needed. This could also decrease negative consequences such as local over-extraction of water resources that could endanger regional wetlands due to lowered ground water levels (Riediger et al., 2014).

4.4 Adaptation requirements at the three study sites

The main aim of this study was to make a local and regional assessment of how climate change could impact cropping risks and yields at three study sites with the help of crop model results and agrometeorological indices.

The driest region in this study, represented by the site Poysdorf, located in the Pannonian basin, is generally the site where most adaptation is needed to minimize yield variabilities and increase yields. The highest irrigation requirements were found here – more than double as high for maize compared to the other study sites. For maize on mid and high WHC soils, the effect of irrigation was not very high, and could be omitted but for wheat the effect was high on all soils and increased yields and decreased yield variabilities significantly. If other GCM's were used in the modelling, more summer drought and heat risks could be present for Poysdorf due to the arid climate which would increase the cropping risks and impact. Thus, more adaptation in the timing of crop growth would be needed. An optimization of crop rotations (e.g. between winter and summer crops) would probably be the best solution at this site, both to diversify, which is an important adaptation strategy, but also because both spring and summer temperatures are expected to result in more extreme temperatures, both of which could have negative influences on respectively winter and summer crops.

The situation is naturally different for the humid site Kremsmünster where the result from irrigation and mulch on crop yields and yield variabilities are so insignificant, that the argument for irrigating maize and wheat is not very strong. "Dry days in the spring" was generally negatively correlated to wheat yields, so even here the projected dry spring could lead to lower yields, but the question is to what degree. If so, a stronger preference to summer crops could be given, if the seasonal weather patterns found in this study would resemble reality. One thing that must be considered for Kremsmünster is the lower number of field days compared to the other sites and adaptation efforts should consider this and improve field accessibility and the timing of sowing should be more flexible.

On paper, Bad Gleichenberg would be expected to have the best growth possibilities being warm and humid but for this reason more extreme years were found here compared to the other two sites (Figure 14). Correlations between number of indices reaching an extreme level and yields were not found to be higher in Bad Gleichenberg compared to the other sites. Once again, the question is whether the to calculate extreme years as the number of assessed indices that cross the threshold ($95^{th}/5^{th}$ percentile and $99^{th}/1^{st}$ percentile of the observed weather data for the baseline period) is a good proxy for assessing extreme events in the future. Irrigation could also be beneficial in Bad Gleichenberg but mostly on low WHC soils. In the second climatic period there were many correlations with agrometeorological indices, and this could indicate that there are some unknowns regarding how the cropping yields could behave under these circumstances. The negative relationship between precipitation, as well as the "3-day max rain events" indicate that the problem will not be too little but rather too much precipitation in Bad Gleichenberg in the latter part of this century under RCP8.5. One solution could be to change summer growth season to earlier in the year but then the question would be whether the lower spring precipitation could be a problem if no irrigation is used. A well thought out irrigation scheme would be necessary to avoid leaching and other problems. And the timing of this should also be considered as "dry days in summer" were negatively correlated with yields in the first climatic period under RCP8.5 and therefore a flexible adaptation approach should be employed based on the climate warming signal and timing of change.

Irrigation was found to lead to higher yields for both crops in all the study sites. Using only irrigation was even found to be better than a combination of mulching and irrigation in most situations. That being said, mulch on its own resulted in higher yields. Mulch and crop residues can increase soil water content by reducing soil evaporation, protect against temperature changes and reduce soil erosion among other things (Eitzinger et al., 2013; Sheaffer, C. C., & Moncada, 2012). The methods of mulching could be questioned. Here synthetic plastic mulches were used with a reduction of evaporation loss of 100% - this method was used to see the highest effect of mulches. But this leads to lower irrigation requirements and thus lower irrigation amounts in this study. Using fixed irrigation schedules combined with mulches could potentially have resulted in higher yields than irrigation or mulch alone but this was not assessed.

One aspect that should also be considered in relation to irrigation is the leaching of nutrients such as nitrate. Since nutrients were considered to be optimal under all situations in this study, this relationship was not considered. Eitzinger et al. (2013) found that sandy soils with lower WHC could experience lower yields under irrigated compared to rainfed due to the nutrient leaching which also points to the importance of a proper assessment of irrigation timing, method, and magnitude.

More sophisticated irrigation schemes could have been employed in this study such as drip or sprinkler irrigation. Only the water requirements were established here. The focus of this study was not on adaptation per se and therefore this was not included.

Another adaptation strategy is to change cultivars, for instance to late- or early-ripening cultivars that can reduce the timing of crop growth and minimize the risk of adverse events. Examples of such adaptation method used in Central Europe was changing to later ripening maize cultivars and no longer growing summer crops such as maize in the driest regions (Trnka et al., 2011b). (Trnka et al., 2014) found that an adaptation to climate change in the form of cultivars with longer duration such as late-ripening cultivars could increase the chance of heat and drought stress and based on these results, using early-ripening cultivars could be a sensible approach. The problem with these could be a reduction in effective global radiation and lower yields (Trnka, Hlavinka and Semenov, 2015). According to the results of this study, changing to early-ripening cultivars seems to be a sensible adaptation strategy, especially in Bad Gleichenberg and Poysdorf, to diminish potential summer cropping risks (especially heat and drought risk). The reduction in effective global radiation does not seem to be a problem, as more effective growing days are projected in the beginning of the season and less in the end. In the end how precipitation behave and the local infrastructure in relation to irrigation will determine which solution makes most sense. Here it is just concluded that both irrigation and cultivar change.

“Huglin index” was assessed in the study, and all sites showed an increase in viticulture potential, especially the two warmer sites, Bad Gleichenberg and Poysdorf and the number of potential wine cultivars would increase. Even though this index is flawed and simplified, this indicated other adaptation possibilities and the possibility of expanding wine production at the study sites. This could be part of a diversification strategy which could be a useful strategy under climate change and minimize potential losses.

In light of the same (and probably more negative) trend for summer crops, Eitzinger et al. (2013) recommended winter crops as an alternative to reduce yield risk. The results of this study confirmed that replacing maize areas with winter wheat could be a possible adaptation strategy for instance under RCP8.5 in the latter part of the century due to the higher yields compared to maize. But there are many problematic indications for rainfed wheat. The irrigation requirements calculated were consistently higher for wheat than maize, and clearly irrigation had a positive effect in Poysdorf where rainfed wheat yields were low with high variabilities, also higher than for maize with many crop failures. Another alternative for maize is, to replace it by drought and heat tolerant summer crops, such as more drought resistant cultivars for instance millet and sorghum. For most new crop types, however, field technology, processing technology, market options etc. need to be developed and be invested in.

Overall, if the RCP8.5 would resemble reality in the second climatic period, a higher amount of wheat areas (or other winter crop options) could be a good thing, even without huge irrigation amounts, as the biggest overall yields were found here. Irrigation could be used to further increase yields and decrease interannual yield variability, especially for crops with high area-related cost return (increasing cost-effectiveness of irrigation investments).

It should be noted, that even though adaptation in this study did not improve maize yields to a high degree apart from decreases in yield variabilities there should be a potential to improve yields. Experimenting with cultivars and sowing dates as well as hedgerows, tillage and optimal irrigation could increase maize yields, especially if a combination of measures is applied.

Adaptations at the farm level are much more flexible, short-term and easier to implement than long-term societal and structural adaptations such as changes in land use (Thaler et al., 2012). Locally relevant studies are important for farmers – an example was the investment in wine production in Upper Austria following a study describing the local potential, mentioned in (Trnka et al., 2011b). The present study confirms the need to look at the regional scale, as the three study sites will respond differently to climate change depending on crop, soil type, management etc. There is a need for regionalization of the adaptation policy where aspects such as cultivar breeding, choice of technology, and research is focused on regional conditions and circumstances (Trnka et al., 2011c, 2014).

5. Conclusions

Agrometeorological indices and crop model results were used to assess the potential impacts of climate change on cropping risks and future crop yields at three weather stations sites in Austria, representing different climatic regions. Considering management, different soils and crops, different emission scenarios and different time periods made it possible to perform a thorough assessment of possible climate impact trajectories in three different Central European climates.

In Poysdorf where the main limiting growth factor is available soil water, many crop failures are expected for rainfed yields. This region would benefit from irrigation and other water saving strategies such as mulches or hedgerows. In regions with fewer limiting growth factors such as represented by the site Bad Gleichenberg, the cropping risks are expected to be more varied, and the extreme events are expected to be higher due to the warm and wet climate. Kremsmünster is expected to experience the highest crop yields, highlighting the effect of high precipitation levels on crop growth and the cropping risks will be more related to wet soils and lack of field days. The recommendation following these results is that adaptation, especially under climate change must be local and flexible because of the local nature of precipitation in a country with complex topography such as Austria.

The choice between summer or winter crops (adapted crop rotations) and irrigated or rainfed agriculture depends on the emission scenario and time period considered, especially after mid-century where RCP4.5 and RCP8.5 will lead to big differences in precipitation and temperature. The results are positive when it comes to summer crops under climate change which contradicts earlier studies from Central Europe. This is based mainly on the fact that the earlier climate scenarios applied predicted in general drier summer conditions in Central Europe than the new generation of EUROCORDEX applied in our study. This highlights the importance of using data from different global circulation models in impact studies (applying an ensemble of scenarios) to cover a wider range of future climate “probabilities”. In our study, this approach was not possible due to resource limitations. However, the applied climate scenarios represent a near medium response according to temperature and precipitation trends among the ÖKS15 scenario ensemble.

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Appendix A: Bias and trend tests for the weather data

Information regarding the tables in appendix A

The correlation tests performed were based on Pearson's correlation test that takes a number between -1 and 1 to measure the strength of the correlation. '*' indicates a significant correlation (p-value < 0.05), '**' indicates a very significant correlation (p-value < 0.01). Baseline is based on observed weather data.

Abbreviations:

TMAX = max. temperature
TMIN = min. temperature
PREC = precipitation
SRAD = solar radiation

Bias tests

All days

Bad	RCP4.5				RCP8.5			
	TMAX	TMIN	PREC	SRAD	TMAX	TMIN	PREC	SRAD
Cor	0.792**	0.780**	0.017	0.666**	0.792**	0.778**	0.022*	0.671**
RMSE	6.046	5.009	8.172	6.164	6.046	5.046	8.156	6.123

Table A1. Correlation test and root mean square error (RMSE) of weather variables. Considering all days of the year in the baseline period (1981-2010) for Bad Gleichenberg

Krems	RCP4.5				RCP8.5			
	TMAX	TMIN	PREC	SRAD	TMAX	TMIN	PREC	SRAD
Cor	0.790**	0.770**	-0.003	0.638**	0.788**	0.770**	0.012	0.644**
RMSE	6.048	4.901	8.145	6.658	6.093	4.913	8.223	6.597

Table A2. Correlation test and root mean square error (RMSE) of weather variables. Considering all days of the year in the baseline period (1981-2010) for Kremsmünster

Poys	RCP4.5				RCP8.5			
	TMAX	TMIN	PREC	SRAD	TMAX	TMIN	PREC	SRAD
Cor	0.806**	0.747**	-0.015	0.702**	0.805**	0.746**	0.000	0.707**
RMSE	6.050	5.207	5.667	5.975	6.088	5.237	5.617	5.918

Table A3. Correlation test and root mean square error (RMSE) of weather variables. Considering all days of the year in the baseline period (1981-2010) for Poysdorf

January

Bad	RCP4.5				RCP8.5			
	TMAX	TMIN	PREC	SRAD	TMAX	TMIN	PREC	SRAD
Cor	0.070*	0.015	-0.023	0.044	0.063	0.014	-0.013	0.055
RMSE	6.412	5.920	4.512	2.493	6.401	5.893	4.519	2.485

Table A4. Correlation test and root mean square error (RMSE) of weather variables. Considering only days in January in the baseline period (1981-2010) for Bad Gleichenberg

Krems	RCP4.5				RCP8.5			
	TMAX	TMIN	PREC	SRAD	TMAX	TMIN	PREC	SRAD
Cor	0.056	0.032	0.018	0.110**	0.057	0.043	0.009	0.125**
RMSE	6.565	6.631	5.808	2.118	6.573	6.612	5.825	2.085

Table A5. Correlation test and root mean square error (RMSE) of weather variables. Considering only days in January in the baseline period (1981-2010) for Kremsmünster

Poys	RCP4.5				RCP8.5			
	TMAX	TMIN	PREC	SRAD	TMAX	TMIN	PREC	SRAD
Cor	0.086**	0.041	-0.050	0.056	0.074*	0.038	-0.057	0.071*
RMSE	6.435	6.781	3.261	2.045	6.481	6.798	3.391	2.054

Table A6. Correlation test and root mean square error (RMSE) of weather variables. Considering only days in January in the baseline period (1981-2010) for Poysdorf

July

Bad	RCP4.5				RCP8.5			
	TMAX	TMIN	PREC	SRAD	TMAX	TMIN	PREC	SRAD
Cor	0.138**	0.076*	-0.009	0.042	0.024	0.019	0.003	0.045
RMSE	4.680	3.630	10.899	7.928	4.899	3.753	10.780	7.938

Table A7. Correlation test and root mean square error (RMSE) of weather variables. Considering only days in July in the baseline period (1981-2010) for Bad Gleichenberg

Krems	RCP4.5				RCP8.5			
	TMAX	TMIN	PREC	SRAD	TMAX	TMIN	PREC	SRAD
Cor	0.147**	0.106**	-0.003	0.031	0.068*	0.041	-0.009	0.020
RMSE	5.479	3.402	10.705	8.992	5.682	3.489	11.236	9.089

Table A8. Correlation test and root mean square error (RMSE) of weather variables. Considering only days in July in the baseline period (1981-2010) for Bad Gleichenberg

Poys	RCP4.5				RCP8.5			
	TMAX	TMIN	PREC	SRAD	TMAX	TMIN	PREC	SRAD
Cor	0.100**	0.124**	-0.019	0.010	0.007	0.044	-0.011	0.008
RMSE	5.690	3.857	7.952	8.258	5.906	4.033	7.662	8.270

Table A9. Correlation test and root mean square error (RMSE) of weather variables. Considering only days in July in the baseline period (1981-2010) for Bad Gleichenberg

Trend tests

All days

Bad	TMAX		TMIN		PREC		SRAD	
	tau	p-value	tau	p-value	tau	p-value	tau	p-value
Baseline	0.042	0.238	0.0369	0.297	-0.010	0.786	-0.010	0.775
RCP4.5	0.032	0.358	0.0420	0.234	0.036	0.304	-0.001	0.973
RCP8.5	0.034	0.341	0.0495	0.161	0.059	0.096	-0.008	0.822

Table A10. Mann-Kendall trend test of weather variables for the baseline period (1981-2010) in Bad Gleichenberg, considering all days of the year. P-values below 0.05 indicates significant trend.

Krems	TMAX		TMIN		PREC		SRAD	
	tau	p-value	tau	p-value	tau	p-value	tau	p-value
Baseline	0.051	0.147	0.0451	0.202	0.036	0.302	0.023	0.514
RCP4.5	0.032	0.365	0.0403	0.254	-0.012	0.731	-0.014	0.684
RCP8.5	0.041	0.242	0.0511	0.148	-0.006	0.855	-0.017	0.623

Table A11. Mann-Kendall trend test of weather variables for the baseline period (1981-2010) in Kremsmünster, considering all days of the year. P-values below 0.05 indicates significant trend.

Poys	TMAX		TMIN		PREC		SRAD	
	tau	p-value	tau	p-value	tau	p-value	tau	p-value
Baseline	0.034	0.333	0.057	0.106	0.077*	0.030*	0.054	0.126
RCP4.5	0.034	0.338	0.047	0.181	0.035	0.328	-0.007	0.834
RCP8.5	0.036	0.302	0.056	0.113	0.047	0.182	-0.005	0.886

Table A12. Mann-Kendall trend test of weather variables for the baseline period (1981-2010) in Poysdorf, considering all days of the year. P-values below 0.05 indicates significant trend.

January

Bad	TMAX		TMIN		PREC		SRAD	
	tau	p-value	tau	p-value	tau	p-value	tau	p-value
Baseline	0.033	0.135	0.071 **	0.001**	0.013	0.614	-0.113 **	0.000**
RCP4.5	-0.006	0.769	-0.033	0.130	0.002	0.937	0.021	0.332
RCP8.5	-0.040	0.065	-0.054 *	0.014*	0.023	0.347	0.028	0.205

Table A13. Mann-Kendall trend test of weather variables for the baseline period (1981-2010) in Bad Gleichenberg, considering only days in January. P-values below 0.05 indicates significant trend.

Krems	TMAX		TMIN		PREC		SRAD	
	tau	p-value	tau	p-value	tau	p-value	tau	p-value
Baseline	0.000	0.988	0.019	0.394	-0.061*	0.011*	-0.003	0.906
RCP4.5	-0.035	0.112	-0.031	0.160	0.012	0.618	-0.028	0.210
RCP8.5	-0.047*	0.033*	-0.056 **	0.010**	-0.006	0.796	0.011	0.622

Table A14. Mann-Kendall trend test of weather variables for the baseline period (1981-2010) in Kremsmünster, considering only days in January. P-values below 0.05 indicates significant trend.

Poys	TMAX		TMIN		PREC		SRAD	
	tau	p-value	tau	p-value	tau	p-value	tau	p-value
Baseline	0.001	0.963	0.033	0.130	0.014	0.573	0.058*	0.012*
RCP4.5	-0.013	0.562	-0.004	0.852	0.003	0.894	-0.001	0.964
RCP8.5	-0.040	0.068	-0.039	0.079	0.032	0.189	0.020	0.373

Table A15. Mann-Kendall trend test of weather variables for the baseline period (1981-2010) in Poysdorf, considering only days in January. P-values below 0.05 indicates significant trend.

July

Bad	TMAX		TMIN		PREC		SRAD	
	tau	p-value	tau	p-value	tau	p-value	tau	p-value
Baseline	0.032**	0.000**	0.028**	0.000**	-0.006	0.413	-0.014*	0.029*
RCP4.5	0.081**	0.000**	0.125**	0.000**	0.044	0.060	-0.014	0.516
RCP8.5	0.048*	0.029*	0.077**	0.000**	0.047*	0.049*	-0.025	0.258

Table A16. Mann-Kendall trend test of weather variables for the baseline period (1981-2010) in Bad Gleichenberg, considering only days in July. P-values below 0.05 indicates significant trend.

Krems	TMAX		TMIN		PREC		SRAD	
	tau	p-value	tau	p-value	tau	p-value	tau	p-value
Baseline	0.108**	0.000**	0.115**	0.000**	0.045	0.056	0.024	0.269
RCP4.5	0.071**	0.001**	0.100**	0.000**	0.003	0.898	-0.016	0.464
RCP8.5	0.072**	0.001**	0.118**	0.000**	0.012	0.608	-0.011	0.602

Table A17. Mann-Kendall trend test of weather variables for the baseline period (1981-2010) in Bad Kremsmünster, considering only days in July. P-values below 0.05 indicate significant trend.

Poys	TMAX		TMIN		PREC		SRAD	
	tau	p-value	tau	p-value	tau	p-value	tau	p-value
Baseline	0.071**	0.001**	0.177**	0.000**	0.063**	0.009**	0.073**	0.001**
RCP4.5	0.087**	0.000**	0.128**	0.000**	0.039	0.098	-0.021	0.337
RCP8.5	0.062**	0.005**	0.123**	0.000**	0.036	0.135	-0.017	0.439

Table A18. Mann-Kendall trend test of weather variables for the baseline period (1981-2010) in Poysdorf, considering only days in July. P-values below 0.05 indicate significant trend.

Appendix B: Soil indices

Information regarding the tables in Appendix B

Baseline (1981-2010) is based on observed weather data. The definitions of the different dry days can be found in Table 1. Sowing days in early spring: March 1st to April 25th and in late spring: April 26th to May 20th.

Field indices

Wheat

Bad, low WHC	Sowing	Harvest		
	Fall	Jun	Jul	August
Baseline	13.0	13.3	14.8	13.0
RCP4.5, 2030-2059	17.6	12.3	15.4	16.9
RCP4.5, 2060-2089	18.4	12.7	13.8	12.3
RCP8.5, 2030-2059	17.3	13.4	11.9	10.9
RCP8.5, 2060-2089	15.8	11.7	11.9	9.7

Table B1. Mean number of sowing and harvest days for wheat on low WHC soils in Bad Gleichenberg over the different periods.

Bad, mid WHC	Sowing	Harvest		
	Fall	Jun	Jul	Aug
Baseline	0.1	2.0	1.3	1.2
RCP4.5, 2030-2059	4.4	0.0	0.4	5.1
RCP4.5, 2060-2089	2.6	0.1	0.8	1.6
RCP8.5, 2030-2059	0.8	0.7	1.5	1.5
RCP8.5, 2060-2089	2.2	1.1	0.0	1.3

Table B2. Mean number of sowing and harvest days for wheat on mid WHC soils in Bad Gleichenberg over the different periods.

Krems, low WHC	Sowing	Harvest		
	Fall	Jun	Jul	Aug
Baseline	9.9	10.8	11.3	12.3
RCP4.5, 2030-2059	9.9	9.3	13.1	11.9
RCP4.5, 2060-2089	14.2	9.8	10.5	9.5
RCP8.5, 2030-2059	13.2	10.4	8.6	8.2
RCP8.5, 2060-2089	10.7	7.2	8.5	6.7

Table B3. Mean number of sowing and harvest days for wheat on low WHC soils in Kremsmünster over the different periods.

Krems, mid WHC	Sowing	Harvest		
	Fall	Jun	Jul	Aug
Baseline	0.0	0.3	1.0	0.5
RCP4.5, 2030-2059	0.5	0.1	0.6	1.0
RCP4.5, 2060-2089	0.0	0.4	0.9	0.2
RCP8.5, 2030-2059	0.0	0.2	0.0	0.8
RCP8.5, 2060-2089	0.4	0.0	0.0	0.4

Table B4. Mean number of sowing and harvest days for wheat on mid WHC soils in Kremsmünster over the different periods.

Poys, low WHC	Sowing	Harvest		
	Fall	Jun	Jul	Aug
Baseline	19.6	18.6	18.6	19.7
RCP4.5, 2030-2059	24.1	18.7	18.2	20.8
RCP4.5, 2060-2089	25.7	17.1	16.4	15.9
RCP8.5, 2030-2059	24.2	17.3	16.2	15.1
RCP8.5, 2060-2089	22.3	16.4	15.5	14.3

Table B5. Mean number of sowing and harvest days for wheat on low WHC soils in Poysdorf over the different periods.

Poysdorf, mid WHC	Sowing	Harvest		
	Fall	Jun	Jul	Aug
Baseline	3.5	7.3	10.6	9.6
RCP4.5, 2030-2059	8.8	6.4	9.7	12.2
RCP4.5, 2060-2089	4.6	6.0	5.0	6.8
RCP8.5, 2030-2059	3.6	6.1	5.0	4.1
RCP8.5, 2060-2089	2.1	7.4	2.2	2.9

Table B6. Mean number of sowing and harvest days for wheat on mid WHC soils in Poysdorf over the different periods.

Maize

Bad, low WHC	Sowing		Harvest			
	Spring (e)	Spring (l)	Jun	Jul	Aug	Sep
Baseline	15.5	7.0	12.4	17.3	15.6	11.3
RCP4.5, 2030-2059	13.1	5.8	11.3	18.0	18.1	15.0
RCP4.5, 2060-2089	15.9	6.1	12.8	16.0	12.8	12.3
RCP8.5, 2030-2059	16.7	6.2	12.0	15.1	12.8	15.3
RCP8.5, 2060-2089	13.9	6.8	13.1	14.2	10.1	13.2

Table B7. Mean number of sowing and harvest days for maize on low WHC soils in Bad Gleichenberg over the different periods. Sowing days are (e) = early spring, and (l) = late spring.

Bad, mid WHC	Sowing		Harvest			
	Spring (e)	Spring (l)	Jun	Jul	Aug	Sep
Baseline	0.0	0.0	0.3	4.3	6.4	1.3
RCP4.5, 2030-2059	0.0	0.0	0.3	5.6	10.8	7.7
RCP4.5, 2060-2089	0.0	0.0	1.4	3.6	5.1	2.0
RCP8.5, 2030-2059	0.0	0.0	0.5	4.1	3.4	2.9
RCP8.5, 2060-2089	0.0	0.0	1.0	2.3	2.4	0.8

Table B8. Mean number of sowing and harvest days for maize on mid WHC soils in Bad Gleichenberg over the different periods. Sowing days are (e) = early spring, and (l) = late spring.

Krems, low WHC	Sowing		Harvest			
	Spring (e)	Spring (l)	Jun	Jul	Aug	Sep
Baseline	8.0	6.0	8.4	13.1	15.4	11.1
RCP4.5, 2030-2059	7.5	3.3	8.5	15.5	15.1	12.4
RCP4.5, 2060-2089	8.8	3.8	9.2	13.0	11.7	9.0
RCP8.5, 2030-2059	8.4	5.0	9.5	11.9	10.9	9.7
RCP8.5, 2060-2089	8.1	4.5	9.8	11.2	7.5	7.2

Table B9. Mean number of sowing and harvest days for maize on low WHC soils in Kremsmünster over the different periods. Sowing days are (e) = early spring, and (l) = late spring.

Krems, mid WHC	Sowing		Harvest			
	Spring (e)	Spring (l)	Jun	Jul	August	Sep
Baseline	0.0	0.0	0.2	2.1	3.6	1.4
RCP4.5, 2030-2059	0.0	0.0	0.0	3.4	6.8	3.5
RCP4.5, 2060-2089	0.0	0.0	0.3	2.9	4.4	0.9
RCP8.5, 2030-2059	0.0	0.0	0.0	2.0	3.2	0.8
RCP8.5, 2060-2089	0.0	0.0	0.5	1.6	0.6	0.3

Table B10. Mean number of sowing and harvest days for maize on mid WHC soils in Kremsmünster over the different periods. Sowing days are (e) = early spring, and (l) = late spring.

Poys, low WHC	Sowing		Harvest			
	Spring (e)	Spring (l)	Jun	Jul	Aug	Sep
Baseline	14.7	14.6	18.8	18.6	18.2	16.1
RCP4.5, 2030-2059	17.9	8.3	16.2	19.5	21.6	18.8
RCP4.5, 2060-2089	15.4	9.2	15.8	17.5	17.5	17.4
RCP8.5, 2030-2059	11.3	7.6	15.8	17.4	18.0	17.3
RCP8.5, 2060-2089	15.3	8.9	16.8	17.5	14.1	12.9

Table B11. Mean number of sowing and harvest days for maize on low WHC soils in Poysdorf over the different periods. Sowing days are (e) = early spring, and (l) = late spring.

Poys, mid WHC	Sowing		Harvest			
	Spring (e)	Spring (l)	Jun	Jul	Aug	Sep
Baseline	0.0	0.0	1.5	11.5	17.7	12.8
RCP4.5, 2030-2059	0.0	0.0	2.1	14.0	19.7	15.0
RCP4.5, 2060-2089	0.0	0.0	3.0	11.3	12.3	6.2
RCP8.5, 2030-2059	0.0	0.0	1.3	9.2	11.5	7.5
RCP8.5, 2060-2089	0.0	0.0	2.8	9.8	6.9	3.1

Table B12. Mean number of sowing and harvest days for maize on mid WHC soils in Poysdorf over the different periods. Sowing days are (e) = early spring, and (l) = late spring.

Drought

Bad	Low WHC					Mid WHC					High WHC				
	Base	4.5		8.5		Base	4.5		8.5		Base	4.5		8.5	
		1	2	1	2		1	2	1	2		1	2	1	2
Dry (intensive)															
JA, w	34.3	47.3	45.6	37.4	48.5	33.8	41.8	28.2	40.7	53.2	33.6	47.2	50.0	47.3	61.3
SN, w	68.0	73.6	67.9	68.8	73.1	71.2	70.0	64.3	74.4	76.7	74.4	78.9	76.4	75.4	83.8
MM, w	13.3	7.1	7.3	6.3	14.2	15.5	5.1	4.3	4.5	12.8	24.9	6.4	6.1	9.1	11.9
JA, m	28.1	34.2	33.5	30.0	41.1	22.5	30.3	30.8	27.7	38.8	18.5	26.0	28.8	24.9	37.4
SN, m	84.8	86.9	86.4	86.6	87.4	88.4	89.6	89.1	88.7	90.0	89.3	90.8	90.4	90.0	90.9
MM, m	88.8	85.8	84.2	86.9	80.3	90.4	87.5	85.2	88.0	80.7	90.8	88.4	86.8	88.8	83.0
Dry (extreme)															
JA, w	8.1	18.1	11.6	9.5	9.6	4.4	3.5	0.4	6.4	6.1	2.5	5.8	2.6	3.7	3.8
SN, w	32.3	38.2	30.8	32.9	31.8	37.2	64.5	60.0	35.2	36.5	43.4	50.7	38.4	40.6	46.1
MM, w	0.3	0.1	1.2	0.2	4.0	0.0	2.2	1.8	0.0	1.6	1.3	0.0	0.0	0.0	0.4
JA, m	8.9	18.3	16.0	12.3	18.8	7.1	15.7	15.7	10.3	19.2	6.2	13.3	15.1	11.7	23.8
SN, m	14.3	27.6	21.4	27.4	36.0	23.0	38.8	33.0	37.6	42.9	38.4	55.8	42.6	48.4	66.4
MM, m	40.3	46.1	47.0	53.0	56.0	50.8	55.1	53.4	54.3	60.2	56.0	61.2	64.3	61.5	63.5
Dry (very extreme)															
JA, w	1.5	2.7	2.0	1.0	0.9	0.6	0.0	0.0	0.3	0.1	0.0	0.0	0.0	0.0	0.0
SN, w	2.3	13.5	5.6	4.9	6.9	3.6	20.3	13.9	6.2	8.4	6.9	11.0	8.4	8.4	11.1
MM, w	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JA, m	2.5	9.8	6.1	2.9	4.3	2.0	7.4	3.9	1.7	2.8	0.6	3.1	0.6	1.0	1.1
SN, m	0.4	12.9	3.3	4.3	3.3	1.0	12.7	3.5	3.1	3.1	0.9	7.3	0.0	0.2	3.0
MM, m	26.3	31.1	31.7	34.9	35.2	27.9	32.9	32.8	35.5	37.0	29.7	34.3	34.3	37.8	39.2

Table B13. Mean number of dry intensive, dry extreme and dry very extreme days in Bad Gleichenberg for low, mid and high WHC soils. JA = June to August, SN = September to November, MM = March to May. '1' = 2030-2059, '2' = 2060-2089, Base = baseline, w = wheat, m = maize

Krems	Low WHC					Mid WHC					High WHC				
	Base	4.5		8.5		Base	4.5		8.5		Base	4.5		8.5	
		1	2	1	2		1	2	1	2		1	2	1	2
Dry (intensive)															
JA, w	22.9	33.5	29.9	23.5	31.7	18.4	30.9	32.4	27.2	40.9	23.2	32.1	42.4	36.3	56.6
SN, w	65.2	69.7	65.5	66.7	69.8	67.4	72.7	70.2	69.0	74.5	74.0	76.6	75.2	76.1	78.5
MM, w	12.3	2.0	3.2	2.5	3.7	16.7	4.6	1.8	4.8	3.0	32.8	14.4	5.4	12.9	3.8
JA, m	22.5	30.2	26.9	20.7	28.1	19.1	26.1	23.8	19.0	27.4	16.5	24.0	22.1	18.6	26.2
SN, m	79.5	85.3	83.6	83.4	88.0	82.0	87.2	85.9	85.5	90.2	81.5	88.2	86.7	84.9	90.7
MM, m	89.1	88.7	87.3	89.3	83.7	90.6	90.0	89.0	90.7	85.5	91.3	90.9	90.1	91.7	87.6
Dry (extreme)															
JA, w	4.1	5.4	6.3	3.8	3.7	2.0	3.1	2.6	2.2	2.3	0.8	1.4	2.1	0.1	2.0
SN, w	35.0	33.1	29.3	30.4	33.2	42.2	38.1	33.1	33.7	37.4	47.8	45.9	41.2	44.3	46.1
MM, w	0.0	0.0	0.3	0.0	0.1	0.0	0.0	0.0	0.0	0.0	1.9	0.0	0.0	0.4	0.0
JA, m	7.1	12.7	10.3	6.3	8.1	5.6	9.9	8.8	5.6	9.4	5.4	10.1	9.1	6.5	12.1
SN, m	10.1	15.9	16.9	10.5	22.4	15.4	26.9	25.6	23.3	39.5	33.2	45.5	45.7	37.6	55.2
MM, m	35.5	42.3	42.9	42.7	53.5	40.2	48.2	52.2	49.6	62.2	55.0	63.1	62.1	64.5	70.3
Dry (very extreme)															
JA, w	0.4	0.2	1.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SN, w	1.5	1.9	3.6	1.7	3.5	1.3	3.9	5.5	2.8	4.3	8.3	8.0	7.1	7.1	11.2
MM, w	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JA, m	1.5	3.4	2.6	2.2	1.1	1.0	1.9	1.1	1.8	0.3	0.7	1.2	0.6	0.9	0.0
SN, m	0.1	4.6	2.2	1.1	0.4	0.0	3.9	1.7	0.8	0.3	0.0	1.9	0.4	0.6	0.0
MM, m	25.0	30.3	29.9	31.6	35.2	26.5	32.9	32.2	33.0	37.9	28.2	35.0	34.1	34.8	39.1

Table B14. Mean number of dry intensive, dry extreme and dry very extreme days in Kremsmünster for low, mid and high WHC soils. JA = June to August, SN = September to November, MM = March to May. '1' = 2030-2059, '2' = 2060-2089, Base = baseline, w = wheat, m = maize

Poys	Low WHC					Mid WHC					High WHC				
	Base	4.5		8.5		Base	4.5		8.5		Base	4.5		8.5	
		1	2	1	2		1	2	1	2		1	2	1	2
Dry (intensive)															
JA, w	66.4	71.7	66.9	60.7	68.6	67.2	69.9	67.7	61.0	72.6	57.3	63.3	68.0	50.7	74.4
SN, w	80.0	82.1	76.7	76.8	78.0	82.0	83.2	81.4	79.3	81.5	82.2	84.6	80.8	78.7	79.9
MM, w	24.5	17.6	16.2	14.2	29.3	22.8	12.9	8.6	9.8	23.0	26.4	14.6	7.3	10.8	18.0
JA, m	83.0	58.9	52.2	48.9	57.4	43.5	51.9	44.7	40.2	48.4	30.7	37.8	31.6	30.6	40.4
SN, m	89.8	90.2	89.1	89.8	89.5	90.9	91.0	90.1	90.4	90.6	90.9	91.0	90.4	90.5	91.0
MM, m	56.9	88.6	88.1	89.3	85.7	90.7	89.5	88.6	89.2	85.3	91.0	90.0	88.5	90.5	86.7
Dry (extreme)															
JA, w	37.9	47.1	33.8	25.5	29.9	32.0	38.7	28.5	20.0	27.6	16.9	23.8	16.2	12.9	20.0
SN, w	53.8	51.5	42.9	44.0	38.4	58.7	57.1	44.8	45.8	41.2	59.3	60.6	51.4	47.7	48.0
MM, w	1.7	3.2	3.9	2.4	11.0	0.3	1.0	0.9	0.8	5.8	0.3	0.2	0.3	0.0	1.6
JA, m	60.7	37.9	32.6	25.3	32.6	22.5	29.3	25.8	19.3	29.5	13.8	20.0	19.7	15.8	25.7
SN, m	32.0	46.6	43.5	45.3	41.2	62.7	60.9	54.2	57.0	56.3	72.1	77.4	57.8	65.1	63.9
MM, m	28.3	49.0	47.6	46.3	58.0	46.0	56.9	51.7	54.8	63.5	55.0	66.3	61.7	59.6	72.5
Dry (very extreme)															
JA, w	11.1	13.2	6.4	7.0	7.5	6.3	5.0	2.2	3.9	3.7	0.4	0.3	0.9	0.6	0.2
SN, w	12.1	23.3	12.8	13.4	11.4	14.6	23.5	12.3	12.6	10.4	14.9	18.1	12.9	10.8	13.4
MM, w	0.1	0.0	0.2	0.2	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JA, m	24.7	20.1	17.2	9.3	12.9	8.9	14.2	13.0	6.3	9.3	3.2	9.0	5.5	2.9	5.8
SN, m	3.2	28.9	12.0	15.3	8.2	21.2	30.7	13.7	14.4	7.4	12.7	24.9	10.2	10.4	6.5
MM, m	17.6	32.6	30.8	32.5	37.3	25.7	33.9	31.7	33.0	38.2	27.0	34.8	32.7	34.6	39.9

Table B15. Mean number of dry intensive, dry extreme and dry very extreme days in Poysdorf for low, mid and high WHC soils. JA = June to August, SN = September to November, MM = March to May. '1' = 2030-2059, '2' = 2060-2089, Base = baseline, w = wheat, m = maize

Effective growing days

Wheat

Bad, low WHC	Mar	Apr	May	June	Jul
Baseline	1.3	11.2	15.5	12.0	3.4
RCP4.5, 2030-2059	8.1	17.9	13.0	5.9	2.6
RCP4.5, 2060-2089	13.5	20.9	13.2	3.6	2.7
RCP8.5, 2030-2059	11.7	17.2	14.4	6.3	3.4
RCP8.5, 2060-2089	19.9	15.5	6.0	2.5	3.4

Table B16. Mean number of effective growing days for wheat on low WHC soils in Bad Gleichenberg over the different periods

Bad, mid WHC	Mar	Apr	May	June	Jul
Baseline	1.1	9.6	18.0	12.4	2.3
RCP4.5, 2030-2059	6.7	19.7	16.1	5.6	1.5
RCP4.5, 2060-2089	11.5	21.2	14.2	2.4	1.1
RCP8.5, 2030-2059	9.2	17.9	16.1	5.1	1.7
RCP8.5, 2060-2089	17.5	14.9	4.9	0.9	0.9

Table B17. Mean number of effective growing days for wheat on mid WHC soils in Bad Gleichenberg over the different periods

Bad, high WHC	Mar	Apr	May	June	Jul
Baseline	0.2	7.2	16.7	12.4	2.2
RCP4.5, 2030-2059	3.6	14.8	20.5	5.0	0.6
RCP4.5, 2060-2089	4.4	16.5	12.6	1.2	0.2
RCP8.5, 2030-2059	6.0	15.4	15.3	3.0	0.4
RCP8.5, 2060-2089	12.0	11.2	3.9	0.1	0.1

Table B18. Mean number of effective growing days for wheat on high WHC soils in Bad Gleichenberg over the different periods

Krems, low WHC	Mar	Apr	May	June	Jul
Baseline	1.8	10.7	18.3	15.6	7.5
RCP4.5, 2030-2059	5.8	22.5	25.1	17.6	3.8
RCP4.5, 2060-2089	11.3	23.5	21.4	10.6	4.3
RCP8.5, 2030-2059	10.2	21.0	22.7	13.5	4.8
RCP8.5, 2060-2089	20.3	24.3	14.2	4.0	3.1

Table B19. Mean number of effective growing days for wheat on low WHC soils in Kremsmünster over the different periods

Krems, mid WHC	Mar	Apr	May	June	Jul
Baseline	1.1	9.1	19.4	16.7	5.7
RCP4.5, 2030-2059	4.9	20.5	25.7	15.6	2.5
RCP4.5, 2060-2089	9.4	23.7	22.5	9.6	1.9
RCP8.5, 2030-2059	8.6	20.8	24.7	12.6	2.2
RCP8.5, 2060-2089	17.4	25.1	13.2	2.2	1.2

Table B20. Mean number of effective growing days for wheat on mid WHC soils in Kremsmünster over the different periods

Krems, high WHC	Mar	Apr	May	June	Jul
Baseline	0.3	3.3	14.9	14.9	6.1
RCP4.5, 2030-2059	0.7	12.2	25.1	12.6	1.3
RCP4.5, 2060-2089	5.1	17.3	19.2	7.7	0.6
RCP8.5, 2030-2059	3.5	12.5	20.5	11.4	1.6
RCP8.5, 2060-2089	10.0	17.4	12.9	1.4	0.1

Table B21. Mean number of effective growing days for wheat on high WHC soils in Kremsmünster over the different periods

Poys, low WHC	Mar	Apr	May	June	Jul
Baseline	1.2	5.4	10.8	5.3	0.5
RCP4.5, 2030-2059	4.2	9.8	9.5	1.8	0.5
RCP4.5, 2060-2089	6.6	10.2	7.4	1.4	1.0
RCP8.5, 2030-2059	6.5	9.9	7.4	3.3	1.3
RCP8.5, 2060-2089	14.3	7.0	2.6	1.0	1.1

Table B22. Mean number of effective growing days for wheat on low WHC soils in Poysdorf over the different periods

Poys, mid WHC	Mar	Apr	May	June	Jul
Baseline	1.1	6.3	11.9	5.9	0.4
RCP4.5, 2030-2059	3.5	9.8	10.2	2.9	0.2
RCP4.5, 2060-2089	7.2	13.3	7.5	1.1	0.5
RCP8.5, 2030-2059	6.0	13.8	11.0	2.8	0.9
RCP8.5, 2060-2089	13.0	8.9	2.6	0.6	0.4

Table B23. Mean number of effective growing days for wheat on mid WHC soils in Poysdorf over the different periods

Poys, high WHC	Mar	Apr	May	June	Jul
Baseline	0.1	3.9	12.5	7.7	0.2
RCP4.5, 2030-2059	1.5	11.6	11.8	2.8	0.0
RCP4.5, 2060-2089	3.6	10.8	8.9	0.8	0.1
RCP8.5, 2030-2059	5.6	15.5	12.6	3.0	0.3
RCP8.5, 2060-2089	11.5	9.2	3.1	0.0	0.0

Table B24. Mean number of effective growing days for wheat on high WHC soils in Poysdorf over the different periods

Maize

Bad, low WHC	May	Jun	Jul	Aug	Sep
Baseline	0.2	16.7	15.3	7.1	0.4
RCP4.5, 2030-2059	1.2	17.5	14.3	4.3	0.1
RCP4.5, 2060-2089	1.9	17.2	15.6	2.6	0.3
RCP8.5, 2030-2059	1.1	16.9	15.9	5.9	0.3
RCP8.5, 2060-2089	3.4	15.8	12.4	1.3	0.1

Table B25. Mean number of effective growing days for maize on low WHC soils in Bad Gleichenberg over the different periods

Bad, mid WHC	May	Jun	Jul	Aug	Sep
Baseline	0.2	16.4	18.5	7.4	0.0
RCP4.5, 2030-2059	1.0	17.3	16.3	4.5	0.0
RCP4.5, 2060-2089	1.6	19.6	17.2	2.4	0.1
RCP8.5, 2030-2059	1.0	18.5	17.6	5.2	0.0
RCP8.5, 2060-2089	3.4	18.2	12.8	0.5	0.0

Table B26. Mean number of effective growing days for maize on mid WHC soils in Bad Gleichenberg over the different periods

Bad, high WHC	May	Jun	Jul	Aug	Sep
Baseline	0.2	16.6	25.1	10.5	0.0
RCP4.5, 2030-2059	1.2	17.4	19.9	3.9	0.0
RCP4.5, 2060-2089	1.5	19.7	20.6	2.6	0.0
RCP8.5, 2030-2059	0.4	16.3	19.5	5.7	0.1
RCP8.5, 2060-2089	2.1	17.4	13.0	0.3	0.0

Table B27. Mean number of effective growing days for maize on high WHC soils in Bad Gleichenberg over the different periods

Krems, low WHC	May	Jun	Jul	Aug	Sep
Baseline	0.1	13.9	21.0	11.2	2.3
RCP4.5, 2030-2059	0.2	13.8	15.5	8.7	0.9
RCP4.5, 2060-2089	1.0	16.2	19.4	7.3	1.4
RCP8.5, 2030-2059	0.1	14.9	20.8	12.3	1.9
RCP8.5, 2060-2089	2.3	19.9	18.7	4.5	0.2

Table B28. Mean number of effective growing days for maize on low WHC soils in Kremsmünster over the different periods

Krems, mid WHC	May	Jun	Jul	Aug	Sep
Baseline	0.0	13.6	23.1	11.7	1.9
RCP4.5, 2030-2059	0.3	13.8	18.4	10.0	0.8
RCP4.5, 2060-2089	0.6	16.3	21.4	7.7	0.8
RCP8.5, 2030-2059	0.0	14.5	23.2	13.1	1.9
RCP8.5, 2060-2089	1.9	21.1	19.7	3.8	0.0

Table B29. Mean number of effective growing days for maize on mid WHC soils in Kremsmünster over the different periods

Krems, high WHC	May	Jun	Jul	Aug	Sep
Baseline	0.0	10.9	24.6	15.0	1.9
RCP4.5, 2030-2059	0.1	9.0	18.5	10.5	0.7
RCP4.5, 2060-2089	0.4	15.0	23.8	9.2	1.2
RCP8.5, 2030-2059	0.0	10.1	23.5	14.1	2.1
RCP8.5, 2060-2089	0.5	16.8	20.1	4.1	0.0

Table B30. Mean number of effective growing days for maize on high WHC soils in Kremsmünster over the different periods

Poys, low WHC	May	Jun	Jul	Aug	Sep
Baseline	0.0	8.1	4.2	1.0	0.0
RCP4.5, 2030-2059	0.4	7.3	4.9	0.1	0.0
RCP4.5, 2060-2089	0.5	10.4	6.1	1.3	0.3
RCP8.5, 2030-2059	0.3	9.6	8.1	1.7	0.1
RCP8.5, 2060-2089	0.5	9.9	4.7	0.5	0.0

Table B31. Mean number of effective growing days for maize on low WHC soils in Poysdorf over the different periods

Poys, mid WHC	May	Jun	Jul	Aug	Sep
Baseline	0.0	11.1	7.0	1.0	0.0
RCP4.5, 2030-2059	0.2	7.6	5.4	0.2	0.0
RCP4.5, 2060-2089	0.7	11.5	6.6	1.2	0.1
RCP8.5, 2030-2059	0.4	11.6	9.5	2.5	0.0
RCP8.5, 2060-2089	0.8	12.3	5.1	0.5	0.0

Table B32. Mean number of effective growing days for maize on mid WHC soils in Poysdorf over the different periods

Poys, high WHC	May	Jun	Jul	Aug	Sep
Baseline	0.0	11.7	12.3	2.2	0.0
RCP4.5, 2030-2059	0.6	10.6	10.0	1.5	0.0
RCP4.5, 2060-2089	1.0	15.1	11.5	2.4	0.4
RCP8.5, 2030-2059	0.2	11.7	13.9	2.7	0.0
RCP8.5, 2060-2089	0.5	10.6	6.7	0.2	0.0

Table B33. Mean number of effective growing days for maize on high WHC soils in Poysdorf over the different periods

Appendix C: Yield and statistics

Information regarding the tables in Appendix C

Baseline is always based on observed weather data. '*' indicate a significant correlation/test result (p-value < 0.05), '**' indicate a very significant correlation/test result (p-value < 0.01).

Important to note that we only have 30 data points here (yields per year), therefore much higher correlations needed to get significance compared to the bias tests on the weather data where daily data was used (Table A1-A9).

Rainfed yields

Wheat	Low WHC			Mid WHC			High WHC		
	Bad	Krems	Poys	Bad	Krems	Poys	Bad	Krems	Poys
Baseline	6.59	6.95	4.58	6.98	7.20	5.02	7.20	7.25	5.15
RCP4.5, 1	8.53	8.83	6.58	8.86	8.91	6.68	8.75	8.92	6.84
RCP4.5, 2	9.06	9.25	7.60	9.32	9.37	8.08	9.37	9.40	8.37
RCP8.5, 1	8.88	9.25	7.60	9.19	9.27	8.16	9.26	9.27	8.41
RCP8.5, 2	10.73	10.97	9.64	10.93	10.98	10.28	10.89	10.98	10.28
Maize	Low WHC			Mid WHC			High WHC		
	Bad	Krems	Poys	Bad	Krems	Poys	Bad	Krems	Poys
Baseline	9.31	9.26	6.88	9.58	9.37	9.04	9.61	9.38	9.37
RCP4.5, 1	9.26	9.42	7.68	9.53	9.51	9.16	9.54	9.51	9.52
RCP4.5, 2	9.36	9.35	8.25	9.46	9.48	9.21	9.51	9.50	9.46
RCP8.5, 1	9.46	9.54	8.79	9.61	9.57	9.42	9.62	9.57	9.64
RCP8.5, 2	9.37	9.84	8.79	9.39	9.84	9.42	9.39	9.84	9.47

Table C1. Mean rainfed wheat and maize grain yields (tonnes/hectare) for low, mid, and high WHC soils in the three study sites over the different periods. '1' = 2030-2059, '2' = 2060-2089

Irrigated yields

Wheat	Low WHC			Mid WHC			High WHC		
	Bad	Krems	Poys	Bad	Krems	Poys	Bad	Krems	Poys
Baseline	7.25	7.25	7.21	7.25	7.25	7.21	7.25	7.25	7.21
RCP4.5, 1	8.96	8.96	8.97	8.96	8.96	8.97	8.96	8.96	8.97
RCP4.5, 2	9.39	9.41	9.38	9.39	9.41	9.38	9.39	9.41	9.38
RCP8.5, 1	9.28	9.30	9.28	9.28	9.30	9.28	9.28	9.30	9.28
RCP8.5, 2	11.02	11.02	11.09	11.02	11.02	11.09	11.02	11.02	11.09
Maize	Low WHC			Mid WHC			High WHC		
	Bad	Krems	Poys	Bad	Krems	Poys	Bad	Krems	Poys
Baseline	9.60	9.37	9.34	9.61	9.38	9.37	9.61	9.38	9.38
RCP4.5, 1	9.54	9.51	9.50	9.54	9.51	9.52	9.54	9.51	9.52
RCP4.5, 2	9.51	9.50	9.45	9.51	9.50	9.46	9.51	9.50	9.46
RCP8.5, 1	9.61	9.57	9.62	9.62	9.57	9.63	9.62	9.57	9.64
RCP8.5, 2	9.39	9.84	9.45	9.39	9.84	9.46	9.39	9.84	9.47

Table C2. Mean irrigated wheat and maize grain yields (tonnes/hectare) for low, mid, and high WHC soils in the three study sites over the different periods. '1' = 2030-2059, '2' = 2060-2089. Based on Net irrigation requirements.

Net irrigation requirements

Wheat	Low WHC			Mid WHC			High WHC		
	Bad	Krems	Poys	Bad	Krems	Poys	Bad	Krems	Poys
Baseline	112.9	81.3	204.4	89.9	58.0	186.8	40.8	16.9	153.2
RCP4.5, 1	78.3	45.9	159.7	58.1	26.3	141.9	18.9	5.1	108.3
RCP4.5, 2	66.4	41.6	127.4	45.9	27.2	107.0	14.8	9.2	64.7
RCP8.5, 1	73.0	35.1	130.7	53.7	18.4	110.5	18.3	4.1	69.4
RCP8.5, 2	49.1	17.3	107.5	32.4	8.5	89.7	9.1	1.8	48.7

Maize	Low WHC			Mid WHC			High WHC		
	Bad	Krems	Poys	Bad	Krems	Poys	Bad	Krems	Poys
Baseline	87.4	35.2	150.5	37.1	18.1	117.0	10.6	3.9	45.3
RCP4.5, 1	63.0	40.8	144.5	40.4	23.7	112.5	12.1	4.9	45.0
RCP4.5, 2	47.1	34.6	121.1	25.8	16.9	94.4	10.1	5.7	30.5
RCP8.5, 1	39.2	17.7	91.8	22.4	9.4	63.3	9.2	3.2	21.6
RCP8.5, 2	26.7	12.7	81.6	13.4	5.6	56.5	6.7	2.7	18.6

Table C3. Net irrigation requirements (mm) for wheat and maize on low, mid, and high WHC soils over the different periods. '1' = 2030-2059, '2' = 2060-2089.

Bias test for baseline yields (based on scenario vs. observed weather data) calculated in AQUACROP

Wheat

Bad, wheat	Low WHC		Mid WHC		High WHC	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Cor	0.06	0.14	0.07	0.19	0.37*	0.33
t-test	0.68	0.61	0.39	0.22	0.40	0.34
RMSE	1.20	1.07	0.80	0.73	0.44	0.48

Table C4. Correlation test, t-test and root mean square (RMSE) for baseline wheat yields (1981-2010) in Bad Gleichenberg (obs. vs. scenario weather data) on low, mid, and high WHC soils

Krems, wheat	Low WHC		Mid WHC		High WHC	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Cor	0.14	0.01	0.37*	0.26	0.63**	0.49**
t-test	0.16	0.25	0.42	0.51	0.54	0.64
RMSE	0.74	0.77	0.47	0.51	0.32	0.37

Table C5. Correlation test, t-test and root mean square (RMSE) for baseline wheat yields (1981-2010) in Kremsmünster (obs. vs. scenario weather data) on low, mid, and high WHC soils

Poys, wheat	Low WHC		Mid WHC		High WHC	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Cor	0.00	-0.07	0.18	0.20	0.20	0.25
t-test	0.71	0.96	0.85	0.77	0.66	0.63
RMSE	2.60	2.72	2.80	2.79	2.69	2.62

Table C6. Correlation test, t-test and root mean square (RMSE) for baseline wheat yields (1981-2010) in Poysdorf (obs. vs. scenario weather data) on low, mid, and high WHC soils

Maize

Bad, maize	Low WHC		Mid WHC		High WHC	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Cor	-0.09	-0.02	-0.02	-0.02	0.14	0.06
t-test	0.45	0.93	0.51	0.67	0.55	0.45
RMSE	1.91	1.33	0.65	0.61	0.58	0.58

Table C7. Correlation test, t-test and root mean square (RMSE) for baseline maize yields (1981-2010) in Bad Gleichenberg (obs. vs. scenario weather data) on low, mid, and high WHC soils

Krems, maize	Low WHC		Mid WHC		High WHC	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Cor	0.42	0.52	-0.22	-0.06	-0.30	-0.14
t-test	0.79	0.58	0.72	0.48	0.78	0.53
RMSE	0.90	0.84	0.95	0.88	0.96	0.89

Table C8. Correlation test, t-test and root mean square (RMSE) for baseline maize yields (1981-2010) in Kremsmünster (obs. vs. scenario weather data) on low, mid, and high WHC soils

Poys, maize	Low WHC		Mid WHC		High WHC	
	RCP4.5	RCP8.5	RCP4.5	RCP8.5	RCP4.5	RCP8.5
Cor	0.28	0.60**	-0.19	-0.11	-0.16	-0.23
t-test	1.00	0.89	0.24	0.24	0.61	0.52
RMSE	2.95	2.22	1.39	1.34	0.75	0.73

Table C9. Correlation test, t-test and root mean square (RMSE) for baseline maize yields (1981-2010) in Poysdorf (obs. vs. scenario weather data) on low, mid, and high WHC soils

Rainfed baseline vs. future yields – testing both mean and variance

Wheat

Bad, wheat	Low WHC		Mid WHC		High WHC	
	t-test	f-test	t-test	f-test	t-test	f-test
RCP4.5, 2030-2059	0.000** (+)	0.056	0.000** (+)	0.165	0.000** (+)	0.000** (+)
RCP4.5, 2060-2089	0.000** (+)	0.223	0.000** (+)	0.018-	0.000** (+)	0.500
RCP8.5, 2030-2059	0.000** (+)	0.838	0.000** (+)	0.924	0.000** (+)	0.041* (+)
RCP8.5, 2060-2089	0.000** (+)	0.951	0.000** (+)	0.853	0.000** (+)	0.000** (+)

Table C10. Comparison of the means (t-test) and variance (f-test) of future climatic wheat yields compared to baseline yields (obs. weather data) in Bad Gleichenberg on low, mid, and high WHC soils. P-values below 0.05 indicate significance. '+' and '-' indicate the direction of a significant change.

Krems, wheat	Low WHC		Mid WHC		High WHC	
	t-test	f-test	t-test	f-test	t-test	f-test
RCP4.5, 2030-2059	0.000** (+)	0.604	0.000** (+)	0.715	0.000** (+)	0.082
RCP4.5, 2060-2089	0.000** (+)	0.682	0.000** (+)	0.778	0.000** (+)	0.621
RCP8.5, 2030-2059	0.000** (+)	0.399	0.000** (+)	0.048* (+)	0.000** (+)	0.001** (+)
RCP8.5, 2060-2089	0.000** (+)	0.788	0.000** (+)	0.077	0.000** (+)	0.001** (+)

Table C11. Comparison of the means (t-test) and variance (f-test) of future climatic wheat yields compared to baseline yields (obs. weather data) in Kremsmünster on low, mid, and high WHC soils. P-values below 0.05 indicate significance. '+' and '-' indicate the direction of a significant change.

Poys, wheat	Low WHC		Mid WHC		High WHC	
	t-test	f-test	t-test	f-test	t-test	f-test
RCP4.5, 2030-2059	0.000** (+)	0.111	0.005** (+)	0.098	0.004** (+)	0.055
RCP4.5, 2060-2089	0.000** (+)	0.778	0.000** (+)	0.405	0.000** (+)	0.924
RCP8.5, 2030-2059	0.000** (+)	0.302	0.000** (+)	0.585	0.000** (+)	0.586
RCP8.5, 2060-2089	0.000** (+)	0.362	0.000** (+)	0.735	0.000** (+)	0.148

Table C12. Comparison of the means (t-test) and variance (f-test) of future climatic wheat yields compared to baseline yields (obs. weather data) in Poysdorf on low, mid, and high WHC soils. P-values below 0.05 indicate significance. '+' and '-' indicate the direction of a significant change.

Maize

Bad, maize	Low WHC		Mid WHC		High WHC	
	t-test	f-test	t-test	f-test	t-test	f-test
RCP4.5, 2030-2059	0.852	0.006** (-)	0.646	0.004** (-)	0.481	0.005** (-)
RCP4.5, 2060-2089	0.849	0.169	0.367	0.552	0.380	0.694
RCP8.5, 2030-2059	0.580	0.134	0.793	0.355	0.951	0.303
RCP8.5, 2060-2089	0.802	0.000** (-)	0.167	0.320	0.103	0.240

Table C13. Comparison of the means (t-test) and variance (f-test) of future climatic maize yields compared to baseline yields (obs. weather data) in Bad Gleichenberg on low, mid, and high WHC soils. P-values below 0.05 indicate significance. '+' and '-' indicate the direction of a significant change.

Krems, maize	Low WHC		Mid WHC		High WHC	
	t-test	f-test	t-test	f-test	t-test	f-test
RCP4.5, 2030-2059	0.421	0.098	0.338	0.079	0.368	0.090
RCP4.5, 2060-2089	0.729	0.169	0.497	0.985	0.468	0.915
RCP8.5, 2030-2059	0.190	0.579	0.277	0.474	0.303	0.417
RCP8.5, 2060-2089	0.006** (+)	0.174	0.006** (+)	0.854	0.007** (+)	0.781

Table C14. Comparison of the means (t-test) and variance (f-test) of future climatic maize yields compared to baseline yields (obs. weather data) in Kremsmünster on low, mid, and high WHC soils. P-values below 0.05 indicate significance. '+' and '-' indicate the direction of a significant change.

Poys, maize	Low WHC		Mid WHC		High WHC	
	t-test	f-test	t-test	f-test	t-test	f-test
RCP4.5, 2030-2059	0.203	0.333	0.608	0.159	0.193	0.390
RCP4.5, 2060-2089	0.026* (+)	0.075	0.507	0.030* (+)	0.493	0.860
RCP8.5, 2030-2059	0.002** (+)	0.062	0.121	0.031* (+)	0.064	0.157
RCP8.5, 2060-2089	0.002** (+)	0.108	0.047* (+)	0.851	0.522	0.039* (+)

Table C15. Comparison of the means (t-test) and variance (f-test) of future climatic maize yields compared to baseline yields (obs. weather data) in Poysdorf on low, mid, and high WHC soils. P-values below 0.05 indicate significance. '+' and '-' indicate the direction of a significant change.

Rainfed vs. irrigated yields statistics

Wheat

Bad, wheat	Low WHC		Mid WHC		High WHC	
	t-test	f-test	t-test	f-test	t-test	f-test
RCP4.5, 2030-2059	0.002** (+)	0.061	0.374	0.426	0.246	0.000** (-)
RCP4.5, 2060-2089	0.025* (+)	0.000** (-)	0.475	0.355	0.864	0.924
RCP8.5, 2030-2059	0.048* (+)	0.022* (-)	0.569	0.566	0.855	0.997
RCP8.5, 2060-2089	0.139	0.029* (-)	0.548	0.482	0.456	0.108

Table C16. Comparison of the means (t-test) and variance (f-test) of future rainfed wheat yields compared to future irrigated wheat yields (same period and scenario) in Bad Gleichenberg on low, mid, and high WHC soils. P-values below 0.05 indicate significance. '+' and '-' indicate the direction of a significant change.

Krems, wheat	Low WHC		Mid WHC		High WHC	
	t-test	f-test	t-test	f-test	t-test	f-test
RCP4.5, 2030-2059	0.280	0.215	0.672	0.539	0.701	0.617
RCP4.5, 2060-2089	0.201	0.004** (-)	0.646	0.470	0.858	0.988
RCP8.5, 2030-2059	0.741	0.787	0.851	0.933	0.848	0.944
RCP8.5, 2060-2089	0.694	0.757	0.764	0.749	0.764	0.749

Table C17. Comparison of the means (t-test) and variance (f-test) of future rainfed wheat yields compared to future irrigated wheat yields (same period and scenario) in Kremsmünster on low, mid, and high WHC soils. P-values below 0.05 indicate significance. '+' and '-' indicate the direction of a significant change.

Poys, wheat	Low WHC		Mid WHC		High WHC	
	t-test	f-test	t-test	f-test	t-test	f-test
RCP4.5, 2030-2059	0.000** (+)	0.000** (-)	0.000** (+)	0.000** (-)	0.000** (+)	0.000** (-)
RCP4.5, 2060-2089	0.000** (+)	0.000** (-)	0.000** (+)	0.000** (-)	0.005** (+)	0.000** (-)
RCP8.5, 2030-2059	0.000** (+)	0.000** (-)	0.001** (+)	0.000** (-)	0.024* (+)	0.000** (-)
RCP8.5, 2060-2089	0.000** (+)	0.000** (-)	0.018* (+)	0.000** (-)	0.070	0.000** (-)

Table C18. Comparison of the means (t-test) and variance (f-test) of future rainfed wheat yields compared to future irrigated wheat yields (same period and scenario) in Poysdorf on low, mid, and high WHC soils. P-values below 0.05 indicate significance. '+' and '-' indicate the direction of a significant change.

Maize

Bad, maize	Low WHC		Mid WHC		High WHC	
	t-test	f-test	t-test	f-test	t-test	f-test
RCP4.5, 2030-2059	0.053	0.000** (-)	0.872	0.924	0.993	0.996
RCP4.5, 2060-2089	0.441	0.000** (-)	0.682	0.251	1.000	1.000
RCP8.5, 2030-2059	0.445	0.007** (-)	0.964	0.941	1.000	1.000
RCP8.5, 2060-2089	0.905	0.988	0.994	0.996	0.999	0.999

Table C19. Comparison of the means (t-test) and variance (f-test) of future rainfed maize yields compared to future irrigated maize yields (same period and scenario) in Bad Gleichenberg on low, mid, and high WHC soils. P-values below 0.05 indicate significance. '+' and '-' indicate the direction of a significant change.

Krems, maize	Low WHC		Mid WHC		High WHC	
	t-test	f-test	t-test	f-test	t-test	f-test
RCP4.5, 2030-2059	0.469	0.080	0.979	0.984	0.999	0.998
RCP4.5, 2060-2089	0.524	0.002** (-)	0.917	0.822	0.999	0.999
RCP8.5, 2030-2059	0.900	0.843	0.990	0.992	0.991	0.991
RCP8.5, 2060-2089	0.992	0.983	1.000	0.998	1.000	1.000

Table C20. Comparison of the means (t-test) and variance (f-test) of future rainfed maize yields compared to future irrigated maize yields (same period and scenario) in Kremsmünster on low, mid, and high WHC soils. P-values below 0.05 indicate significance. '+' and '-' indicate the direction of a significant change.

Poys, maize	Low WHC		Mid WHC		High WHC	
	t-test	f-test	t-test	f-test	t-test	f-test
RCP4.5, 2030-2059	0.000** (+)	0.000** (-)	0.058	0.000** (-)	0.967	0.975
RCP4.5, 2060-2089	0.002** (+)	0.000** (-)	0.280	0.000** (-)	0.978	0.983
RCP8.5, 2030-2059	0.023* (+)	0.000** (-)	0.365	0.002** (-)	0.997	1.000
RCP8.5, 2060-2089	0.082	0.000** (-)	0.812	0.875	0.997	0.998

Table C21. Comparison of the means (t-test) and variance (f-test) of future rainfed maize yields compared to future irrigated maize yields (same period and scenario) in Poysdorf on low, mid, and high WHC soils. P-values below 0.05 indicate significance. '+' and '-' indicate the direction of a significant change.

Appendix D: Management and mulch runs

Wheat

Bad	Low WHC		Mid WHC		High WHC	
	2030-59	2060-89	2030-59	2060-89	2030-59	2060-89
Rainfed	8.88	10.73	9.19	10.93	9.26	10.89
NET	9.28	11.02	9.28	11.02	9.28	11.02
Mulch	9.01	10.79	9.23	10.94	9.26	10.91
Mulch+NET	9.26	10.97				

Table D1. Wheat yields in Bad Gleichenberg for the different management options considered in this study and compared to rainfed yields. NET = irrigated yields based on net irrigation requirements. Everything calculated for the RCP8.5 scenario.

Krems	Low WHC		Mid WHC		High WHC	
	2030-59	2060-89	2030-59	2060-89	2030-59	2060-89
Rainfed	9.25	10.97	9.27	10.98	9.27	10.98
NET	9.30	11.02	9.30	11.02	9.30	11.02
Mulch	9.26	10.97	9.27	10.98	9.27	10.98
Mulch+NET	9.27	10.98				

Table D2. Wheat yields in Kremsmünster for the different management options considered in this study and compared to rainfed yields. NET = irrigated yields based on net irrigation requirements. Everything calculated for the RCP8.5 scenario.

Poys	Low WHC		Mid WHC		High WHC	
	2030-59	2060-89	2030-59	2060-89	2030-59	2060-89
Rainfed	7.60	9.64	8.16	10.28	8.41	10.28
NET	9.28	11.09	9.28	11.09	9.28	11.09
Mulch	8.23	10.08	8.70	10.72	9.05	10.83
Mulch+NET	9.25	11.04				

Table D3. Wheat yields in Poysdorf for the different management options considered in this study and compared to rainfed yields. NET = irrigated yields based on net irrigation requirements. Everything calculated for the RCP8.5 scenario.

Maize

Bad	Low WHC		Mid WHC		High WHC	
	2030-59	2060-89	2030-59	2060-89	2030-59	2060-89
Rainfed	9.46	9.37	9.61	9.39	9.62	9.39
NET	9.61	9.39	9.62	9.39	9.62	9.39
Mulch	9.51	9.39	9.62	9.39	9.62	9.39
Mulch+NET	9.62	9.40				

Table D4. Maize yields in Bad Gleichenberg for the different management options considered in this study and compared to rainfed yields. NET = irrigated yields based on net irrigation requirements. Everything calculated for the RCP8.5 scenario.

Krems	Low WHC		Mid WHC		High WHC	
	2030-59	2060-89	2030-59	2060-89	2030-59	2060-89
Rainfed	9.54	9.84	9.57	9.84	9.57	9.84
NET	9.57	9.84	9.57	9.84	9.57	9.84
Mulch	9.40	9.84	9.42	9.84	9.42	9.84
Mulch+NET	9.43	9.84				

Table D5. Maize yields in Bad Kremsmünster for the different management options considered in this study and compared to rainfed yields. NET = irrigated yields based on net irrigation requirements. Everything calculated for the RCP8.5 scenario.

Poys	Low WHC		Mid WHC		High WHC	
	2030-59	2060-89	2030-59	2060-89	2030-59	2060-89
Rainfed	8.79	8.79	9.42	9.42	9.64	9.47
NET	9.62	9.45	9.63	9.46	9.64	9.47
Mulch	9.03	9.24	9.51	9.47	9.64	9.47
Mulch+NET	9.64	9.48				

Table D6. Maize yields in Poysdorf for the different management options considered in this study and compared to rainfed yields. NET = irrigated yields based on net irrigation requirements. Everything calculated for the RCP8.5 scenario.

Appendix E

Information regarding the table in Appendix E

All the indices included in the tables were significantly related to yield. The indices with an underscore were very significantly correlated (p-value < 0.01).

Correlations for irrigated yields

Wheat					
Bad Gleichenberg		Kremsmünster		Poysdorf	
2030-2059	2060-2089	2030-2059	2060-2089	2030-2059	2060-2089
CO_2	CO_2	CO_2	CO2	CO_2	CO_2
Temp_MAM	Growing season	Temp_MAM	Growing season	Temp_MAM	Growing season
Growing season		Summer days		Growing season	
		Growing season			
		Dry_int_MAM			

Maize					
Bad Gleichenberg		Kremsmünster		Poysdorf	
2030-2059	2060-2089	2030-2059	2060-2089	2030-2059	2060-2089
Temp_JJA	Prec_JJA	Summer days	Temp_JJA	Temp_JJA	Growing season
Growing season	Growing season		Growing season	Growing season	Temp_JJA
Dry_ext_JJA	Pot_JJA		Tropical		Dry_ext_JJA
	Temp_JJA		Effective days		
	Summer days				
	Tropical				
	Pot_MAM				
	Prec_MAM				
	Rain_3days				
	Effective days				

Table E1. Significant correlations between agrometeorological indices and irrigated wheat and maize yields for the three study sites on low WHC soils under RCP8.5. Abbreviations: MAM = March to May, JJA = June to August, Temp = temperature, Prec = precipitation, Dry_int = intensive dry days, Pot = potential water balance, Dry_ext = extreme dry days, Effective days = effective growing days, Growing season = growing season days

Appendix F: CO_2-response for the two crops

Winter wheat

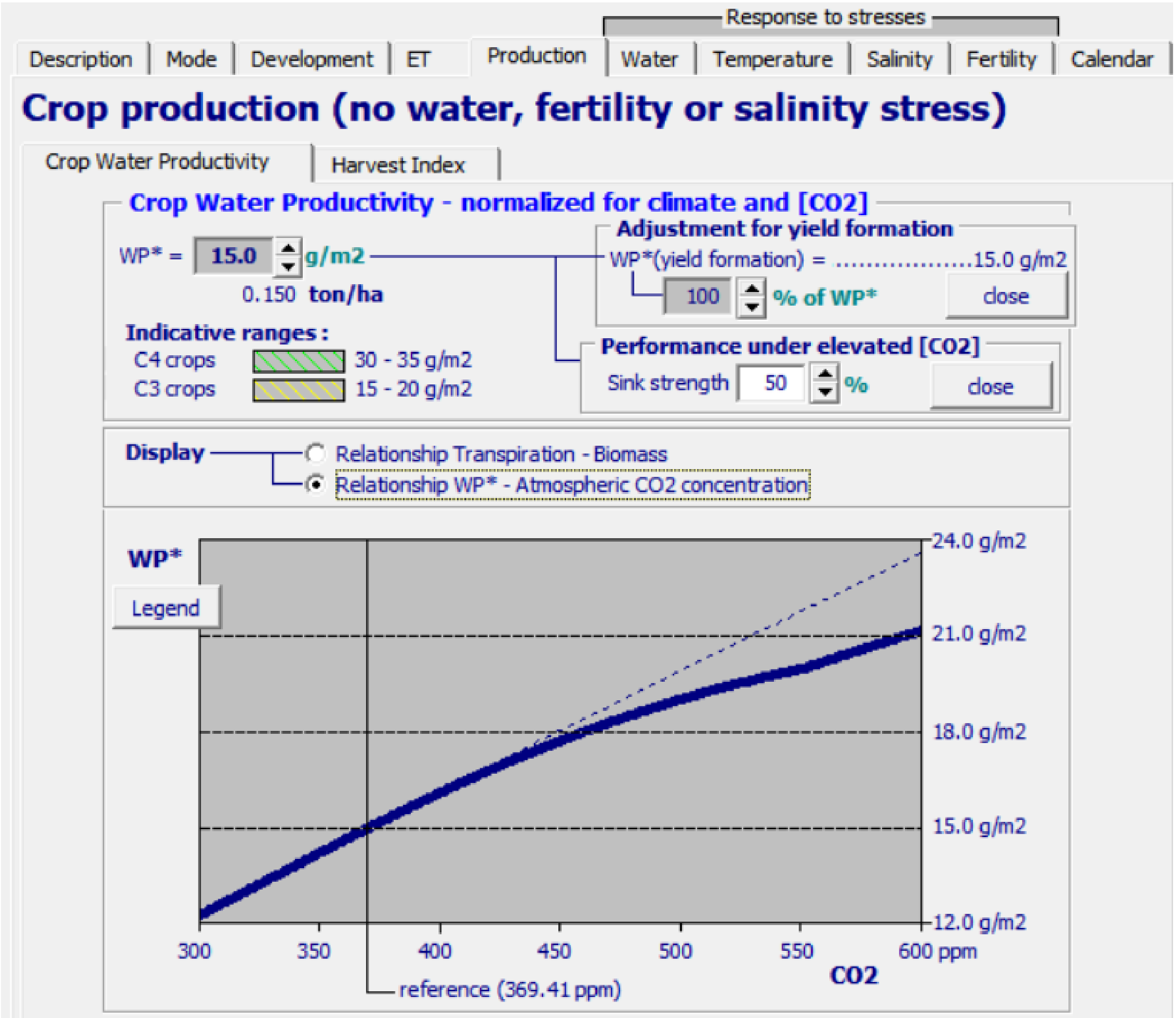

Figure F1. The effect of increasing ambient CO_2 on biomass water productivity for wheat

Maize

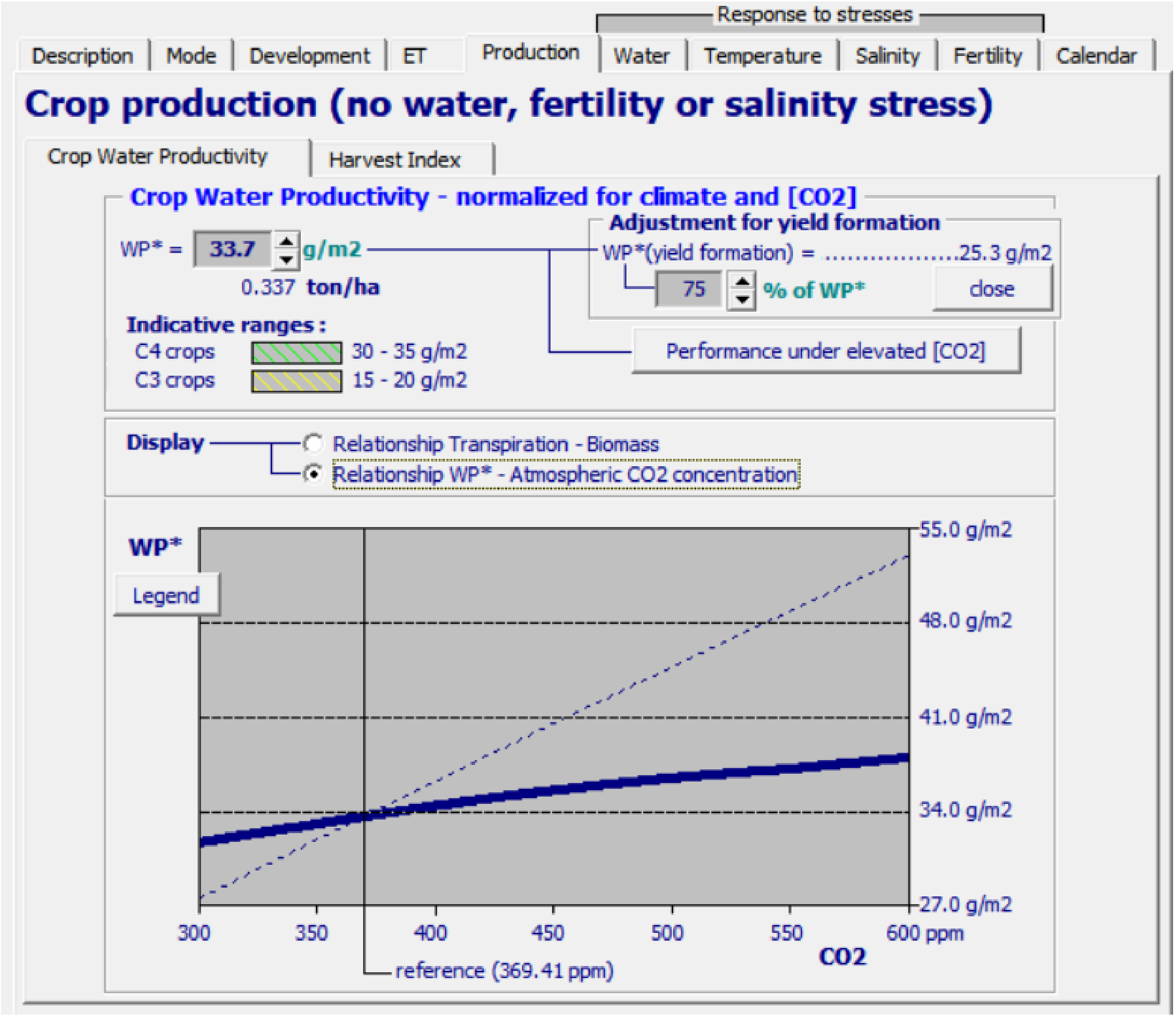

Figure F2. The effect of increasing ambient CO2 on biomass water productivity for maize