Climate Adaptation Strategies Assessment on the Northern-German Agriculture System: A Crop Model Study

Dissertation for the attainment of the dignity of Doctor of Natural Sciences of the Faculty of Mathematics, Informatics, and Natural Sciences,

Department of Earth Sciences of the University of Hamburg

submitted by

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Hamburg 2021

Accepted as Dissertation at the Department of Earth Sciences

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This dissertation is dedicated to those who made it to the end despite the odds.

Remember that if people treat you hardly, you can do better and teach those who come after you that there is always a better way to do things.

Declaration on oath

I hereby declare upon oath that I have written the present dissertation independently and have not used further resources and aids than those stated.

Andrea Catalina Fajardo

Schwülper, October 29th, 2021

Summary

Agriculture is a sector that is highly sensitive to climate. Heatwave events in Germany, like in 2018, show us the relevance of having crop production systems focusing on climate mitigation and adaptation to produce more stable yields in the future. Crop models like the Environmental Policy Integrated Climate (EPIC) allow testing management strategies and their potential effects on yields, nitrogen emissions, and total organic carbon in the long term under three CO2 emissions scenarios that include the Representative Concentration Pathways (RCP) of 2.6, 4.5, and 8.5.

This research uses a version of the EPIC model that includes an automatic irrigation option based on a specific field capacity fraction that allows a more realistic irrigation scheme in the model. These values range from no irrigation (0%) to 100% (full irrigation). This option allows a more realistic irrigation scheme in the model. The co-benefit with modified crop calendars and the inclusion of soybeans were also assessed.

Lastly, it was analyzed the correlation strength between crop yields and temperature and precipitation indicators. This exploratory assessment helps explain the reason for the increase of crop yield penalties in the future.

Although this study was conducted in a small area in northern Germany, the results are still relevant for regions with similar climatic conditions. They may apply similar adaptation strategies in the future to cope with climate change.

Zusammenfassung

Die Landwirtschaft ist ein Sektor, der sehr empfindlich auf das Klima reagiert. Hitzewellen in Deutschland wie im Jahr 2018 zeigen, dass eine landwirtschaftliche Produktion mit Fokus auf Klimaanpassung und -minderung notwendig ist, um in Zukunft stabilere Erträge zu erzielen. Anbaumodelle wie EPIC ermöglichen es, verschiedene Bewirtschaftungsstrategien und ihre potenziellen Auswirkungen auf die Erträge, Stickstoffemissionen und den gesamten organischen Kohlenstoff unter den drei RCP-Szenarien (2.6, 4.5 und 8.5) in langfristigen Zeiträumen zu testen.

Die in dieser Forschung entwickelte und angewandte Methodik mit einer Version von EPIC, die eine automatische Bewässerung auf der Grundlage eines bestimmten Prozentsatzes der Feldkapazität verwendet, ermöglicht ein realistischeres Bewässerungsschema in dem Modell. Darüber hinaus war es möglich, fünf verschiedene Anbaukalender zu testen, um zu ermitteln, welche Kombinationsstrategien die Ertragsverluste in Zukunft verringern könnten.

Schließlich war es von Bedeutung, die Korrelationsstärke zwischen Ernteerträgen und Temperatur- und Niederschlagsindikatoren zu analysieren. Auf diese Weise konnte festgestellt werden, welche Faktoren die Ernteerträge stärker beeinträchtigen können als die Berechnung des Bodenfeuchtedefizits.

Obwohl diese Studie in einem kleinen Gebiet in Norddeutschland durchgeführt wurde, sind die Ergebnisse auch für größere Regionen mit ähnlichen klimatischen Bedingungen relevant, in denen in Zukunft ähnliche Anpassungsstrategien zur Bewältigung des Klimawandels angewendet werden könnten.

Acknowledgments

I want to thank HICSS Cooperation between GERICS and Hamburg University through the IMLAND Project, who have supported me during my Ph.D. journey.

I want to thank both of my supervisors for their help and guide. They have taught me how to supervise people and work in a team. So like Dr. Rasche and Dr. Doro for their assistance with the EPIC model. Additionally, all colleagues at GERICS, especially the climate modelers, to be willing to answer all my questions related to climate data.

Thanks to Helmholtz Zentrum Hereon and GERICS for writing my Ph.D. dissertation and learning a lot from excellent colleagues.

To Dr. Eulalia Gomez for being there in those low moments where I wanted to give up. To my FNU fellows for all the social hours to take a break from the Ph.D. life. To my extended family in Germany for all your kindness and support. Without them, I would not be able to pull it through.

Declaration of authorship

Andrea Catalina Fajardo Puente, born in Barranquilla, Colombia, on 25 September of 1990.

Chapter	Title	Contribution of the first author: Andrea Catalina Fajardo	Contribution of co-authors
Three	Evaluating the viability of soybeans cultivation as an adaptation measure to climate change in Lower Saxony using EPIC	***Conceptualization*** Mostly done by me ***Literature Review*** Entirely done by me ***Results Analysis*** Entirely done by me ***Manuscript Writing*** Mostly done by me	***Conceptualization*** Luca Doro Uwe Schneider Livia Rasche ***Model Changes*** Luca Doro ***Manuscript Editing*** Sabine Egerer Livia Rasche Uwe Schneider
Four	Cropping calendars may partially mitigate yield losses under warmer temperatures with restricted irrigation amount: Case Study in Northern Germany	***Conceptualization*** Mostly done by me ***Literature Review*** Entirely done by me ***Results Analysis*** Entirely done by me ***Manuscript Writing*** Mostly done by me	***Conceptualization*** Luca Doro ***Model Changes*** Luca Doro ***Manuscript Editing*** Sabine Egerer Luca Doro Livia Rasche Uwe Schneider

Five	Warmer Germany: temperature indices are moderately correlated to yields that may indicate soil water deficit in the future under climate change	***Conceptualization*** Mostly done by me ***Literature Review*** Entirely done by me ***Results Analysis*** Entirely done by me ***Manuscript Writing*** Mostly done by me	***Conceptualization*** Luca Doro ***Model Changes*** Luca Doro ***Manuscript Editing*** Luca Doro Livia Rasche Uwe Schneider

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ABBREVIATIONS

BAU	Business as Usual
CC	Climate Change
CORDEX	Coordinated Regional Climate Downscaling Experiment
CLC	CORINE Land Cover
DEM	Digital Elevation Model
EFAC	European Federation of Agricultural Consultants
EIP-AGRI	The agricultural European Innovation Partnership
EPIC	Environmental Policy Integrated Climate
EU	European Union
FC	Field Capacity
GCM	Global Circulation Model
GERICS	Climate Service Center Germany
HICSS	Helmholtz Institute for Climate Service Science
HRU	Homogeneous Response Units
IPCC	Intergovernmental Panel on Climate Change
Lat	Latitude
Lon	Longitude
NELS	Northeastern Lower Saxony
Obj	Objective
PO	Porosity
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
RQ	Research Question
SD	System Dynamics

SLS	**Southern Lower Saxony**
SM	**Soil Moisture**
SMD	**Soil Moisture Deficit**
SOC	**Soil Organic Carbon**
SOYB	**Soybeans**
SPEI	**Standardized Potential Evapotranspiration Index**
SSP	**Shared Socioeconomic Pathways**
TOC	**Total Organic Carbon**
TS	**Temperature Stress**
WS	**Water Stress**
WSF	**Water Stress Factor**
WWHT	**Winter Wheat**

Chapter 1

INTRODUCTION

Independently of the continuous development of more efficient technologies to improve the agricultural sector, crop yields are vulnerable to climate conditions. Continous changing climatic conditions exacerbate this situation in the agriculture sector[1]. According to the IPCC report, for each 0.5°C of global warming, the frequency and intensity of climate extremes such as heatwaves and droughts will increase noticeably[2]. In addition, this sector bears additional challenges like human population increase[3,4], land and freshwater shortage, and societal pressure to be more sustainable and environmentally friendly[5,6].

Implementation of several adaptation strategies may tackle these challenges: conservation agriculture, increasing irrigation efficiency, and agroforestry[2]. However, more research is required to investigate the potential synergies of several adaptation management options and their impacts on several components in the agricultural system to include its inherent complexities. Recent studies have focused on assessing the impacts on soil [7,8], crop yields[9], and one single strategy and its multiple co-benefits in the crop system[10–12].

A further challenge is the reduction of agricultural efficiency since there is an expansion in crops converted to animal protein for human consumption.[13,14]. The increasing global meat consumption trend represents a growing pressure on crop yields used as feed[15]. In addition, some regions require importing this livestock feed, burdening local and international markets supply[16].

The European Union (EU) faces this challenge since meat production is expected to increase 1% per year on average, reaching by 2030 a volume of 365 million tons[17]. According to the EFAC (European Federation of Agricultural Consultants), the percentage of soybeans used in the EU to feed pigs was 29%, for layers 22%, and broilers 37%, while this amount was lower in compound feed for dairy cattle (10%) and beef cattle (14%). This highlights that ruminants are not as dependent on these protein plants as monogastric animals like pigs[18]. In 2018 the report about protein deficiency for the European Parliament stated that about

70% of the raw materials are imported mainly from Brazil, Argentina, and the USA. Approximately. 60% of these imports are soybean by-products derived from vegetable oil production used as animal feed. In this sense, as meat production increases, soybean (Glycine max (L.)) production must follow this trend[19].

If local protein plant production cannot match meat consumption levels, Europe will depend more on soybeans imports than before. To put this situation into perspective, the worldwide cultivation of soybeans has increased more than ten times in the last 50 years: from 27 to 350 million tons. Following this current trend, it is expected to increase up to 434 million tons[18]. This increment could intensify cultivation areas in the USA, Argentina, and Brazil[18].

One of the most relevant reasons for this high dependency on imported protein plants is that these crops are not economically competitive with local crops. The agricultural European Innovation Partnership (EIP-AGRI) assessed the potential yield production of different protein crop yields and benchmarked it to wheat and maize since protein crops could replace them. In the case of soybean production assuming stable market conditions, its yields must be increased at least 63% to keep up with wheat yield levels to make them more competitive in the European context[18].

The EU produced 956 thousand tons of soybeans in 2018, representing only 0.8% of USA or Brazil production and about 2% of Argentina production for the same year[20–22.] Germany also reported for 2018 a level of 24 thousand tons of soybeans, representing an increase of 20% compared to 2017[21,22].

From 2015 to 2018, there have been some initiatives in Germany to produce more legumes locally, especially soybeans, like the projects German Soybean Promotion Council (Deutscher Soja Förderring) and the Soybean Network Project (Projekt Soja-Netzwerk). The primary purpose is to foster sustainable soybean production, including German environmental regulations and social standards. This local cultivation could reduce protein soybean imports alleviating rainforest deforestation to expand soybean cultivation[23].

Climate projections based on the Special Report on Emissions Scenarios (SRES) from The Fifth Assessment Report (AR5)[24] of the IPCC for Northern Germany, where these initiatives took place, reveal an increase in temperature of 2.5°C by the end of the century compared to 1971-2000. In summer, it is expected to increment about 3°C[25,26]. The direct produced effect is the extension of the vegetation period around two months. Besides, heat waves, like in 2018, will be experienced more often, about 50%[26]. Additionally, the frost days in the Northern Hemisphere are expected to decrease by the end of the century. According to (Liu et al., 2012), the number of days with a minimum temperature lower than 0°C increases, affecting frost stress on the plants[27]. To avoid these potential risks, part of the German Adaptation Plan in agriculture includes promoting methods to improve soil fertility, soil structure, and water retention mechanisms in drought-risk farms[28].

In the context of the future potential challenges in agriculture, this dissertation project assesses the co-benefit of applied management strategies like modifying crop calendars, irrigation scheduling, and soybeans within the crop rotation on yields, humus formation, water retention, and soil fertility under several future climatic conditions [29].

The case study is in the northern German Federal State of Lower-Saxony. This research project is part of the Integrative modeling lab on agricultural adaptation in North Germany Project (IMLAND) in the frame of Helmholtz Institute for Climate Science) (HICSS) - conjunction between Hamburg University and Helmholtz-Zentrum Hereon[30].

Research questions, objectives, and dissertation structure

Local adaptation efforts require knowledge of climate change's effects on agricultural processes such as crop yields, water balance elements, nitrogen emissions, and soil carbon content. This situation applies to the case study area since detailed district-level information is needed to prevent climate change risks in the agricultural sector[26].

Consequently, the potential co-benefits of several management strategies in an agricultural system were assessed. In addition, the correlation strength between climate indices with crop yields was investigated to help understand the relationship between climate variability and yield losses.

EPIC simulations include crop rotations containing wheat, corn, sugar beet, potato, and soybean. However, literature shows that, at the global level, temperature and precipitation trends have impacted wheat and corn the most. For this reason, the analysis shown in Chapters 3, 4, and 5 is for these two crops only[31].

This thesis aims **to extend the understanding of how climate change may affect agricultural processes related mainly to yield levels in Northern Germany for different adaptation measures applications.** The following research questions (RQ) are defined to fulfill the main aim of this dissertation:

RQ 1 How will climate change affect current crop management systems in Lower Saxony?

RQ 2 Will soybean cultivation in Lower Saxony become agronomically more viable under climate change in the 21st century?

RQ 3. How does the integration of soybeans in typical crop rotations impact the performance of companion crops, and how will these impacts vary with climate change?

RQ 4. What co-effects will soybean cultivation have on soil processes and soil properties, and how will these co-effects vary with climate change?

RQ 5. How will irrigation influence soil organic carbon and nitrogen emissions, and how will these influences vary with climate change?

RQ 6. How will rescheduling planting and harvesting dates affect crop yields and soil organic carbon under particular climate developments?

RQ 7. How strongly are meteorological climate indicators correlated with crop yields? Which meteorological indicators are best suited to predict agricultural performance?

To answer these research questions, research objectives were defined based on a modeling framework developed in EPIC.

Obj1. Compare the overall agronomic performance of crop rotations, modified by integrating soybeans, in Lower Saxony for alternative climate projections.

Obj2. Estimate how irrigation requirements in Lower Saxony vary with climate change.

Obj3. Assess climatic and management requirements to make soybean cultivation competitive with conventionally grown crops in Lower Saxony.

Obj4. Assess the correlation of meteorological indicators with agricultural performance in Lower Saxony for alternative climate scenarios.

The thesis results are in three papers submitted to the Journal of Agricultural Systems. Table 1 summarizes the contribution of each to both the research questions and objectives.

Table 1 shows the research questions (RQ.) and in which chapters they are answered. Additionally, we offer the research objectives (Obj.) associated with the RQ and in which articles they are fulfilled.

		Chapter 3	Chapter 4	Chapter 5
RESEARCH QUESTIONS	RQ 1.	X		
	RQ 2.	X		
	RQ 3.	X		
	RQ 4	X		
	RQ 5.		X	
	RQ 6.		X	
	RQ 7.			X
	RQ 8.			X
RESEARCH OBJECTIVES	Obj. 1.	X		
	Obj. 2.		X	
	Obj. 3.	X		
	Obj. 4.			X

Structure of this Dissertation

The general structure of the dissertation, including the research and technical challenges, is illustrated in figure 1.

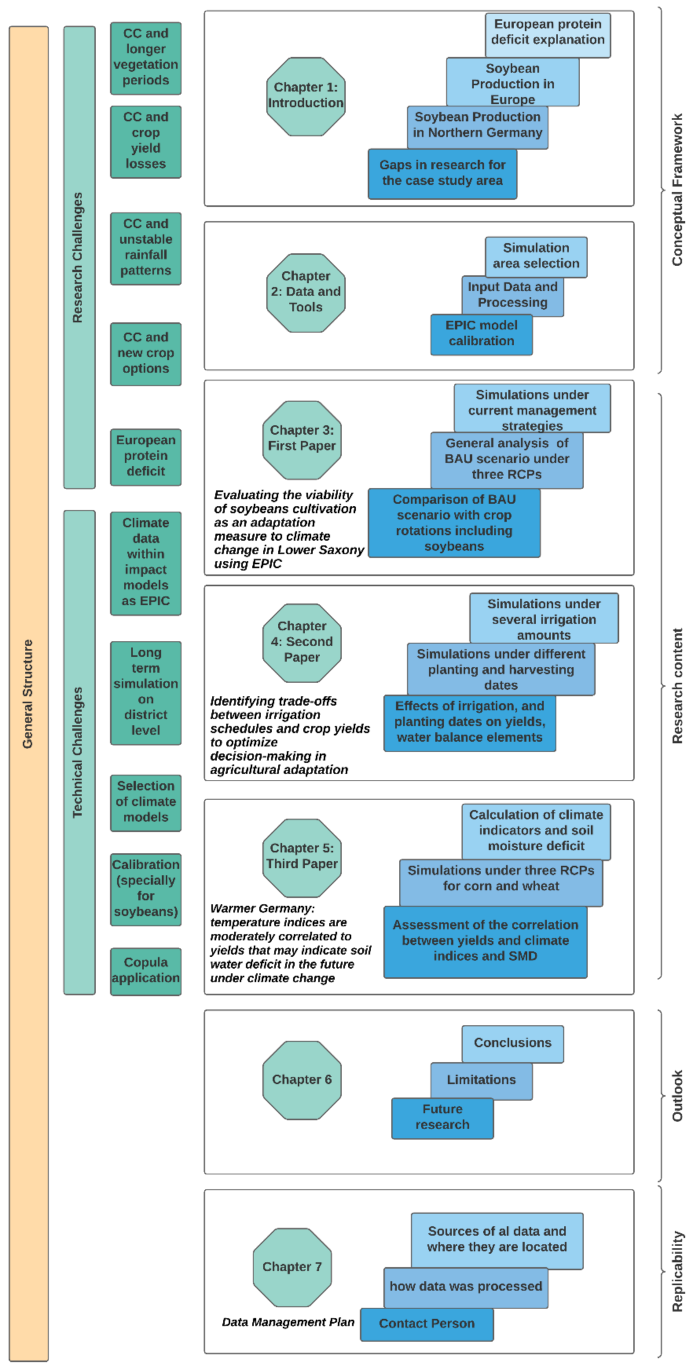

Figure 1 depicts the general structure of this dissertation. Chapter 1 is the introduction that justifies soybean research in Northern Germany as a management strategy throughout this dissertation. Chapter 2 depicts in detail the methodology and dataset used for Chapters 3, 4, and 5. Chapter 3 assesses the viability of soybeans within the crop rotation with current management strategies under climate change scenarios. Chapter 4 analyzes the effect of five irrigation amounts and crop calendar strategies on crop yields. Chapter 5 assesses the correlation between crop yield and climate indices and crop yields and soil moisture deficit. Chapter 6 describes the limitation encountered during this research and how they can be continued. This dissertation faces two types of challenges: technical and research-related. Formerly related to the effect of management strategies (e.g., planting soybeans, more irrigation, planting, and harvesting dates) on crop yields and water balance *elements under climate change scenarios. Latter are challenges related to the EPIC model and data preparation, especially climate data.*

A summary of each chapter is provided down below:

Chapter 2 gives a detailed introduction to the methodology, tools, and data used for this research. Additionally, it includes input data preparation for the primary research tool for this dissertation, which is the processed-based crop model EPIC.

Chapter 3 evaluates the viability of soybeans cultivation as an adaptation measure to attain more stable yields for existent crops under three climate scenarios (RCP 2.6, 4.5, and 8.5) in the case study region. I performed this analysis with current management options and irrigation amounts. Present and potential soybean yields were also studied.

Chapter 4 identifies potential relationships between several irrigation amounts, planting and harvesting schedules, corresponding crop yields, and enhancement of soil processes. I did this investigation only for one crop rotation that gave better results from Chapter 3.

Chapter 5 assesses the correlation strength between crop yields and climate indicators and yields and soil moisture deficits. The management strategies used for this study are the ones selected as better ones in the previous chapter.

Chapter 6 summarizes the main conclusions and limitations of this research and proposes ideas for future research.

Chapter 7 includes the data management plan (DMP) of this research. This DMP includes data preparation during the research and what must do with it after this research project. It also describes the type of data I have used and how collected, organized, and stored, including the used formats. This DMP allows replicating the simulations conducted in Chapters 3, 4, and 5.

Chapter 2

DATA AND TOOLS FOR THIS RESEARCH

This chapter describes the primary research tool used in this research with the crop model EPIC, including the input data required to conduct the simulations to characterize an agricultural system in Northern Germany.

Simulation area

This map represents the fourteen districts that take part in EPIC simulations. I divided the simulation area into two main groups according to their location and dominant soil: northeastern, heath dominated by the poor, sandy soils represented mainly by podzol soils; and southern part, which are productive loamy soils with high natural fertility. This allows comparing the impact of soil texture in the crop rotation with and without soybeans.

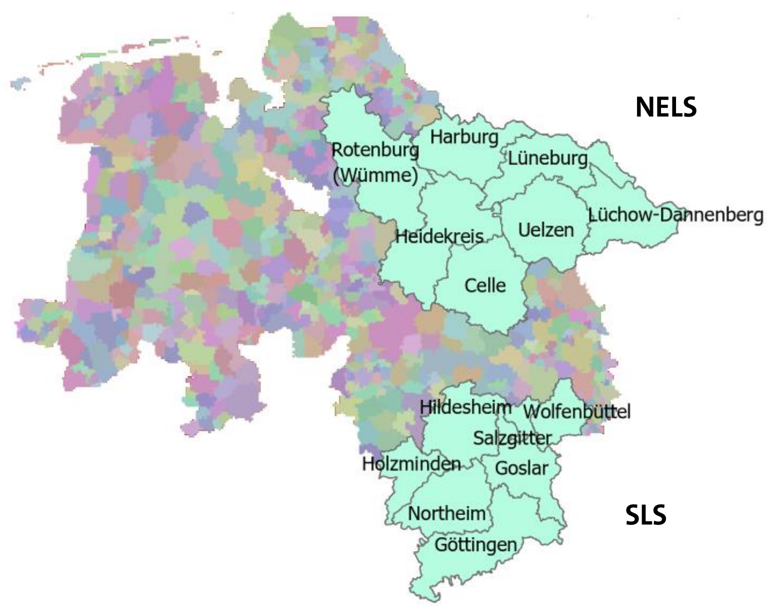

Figure 2 shows the districts in Lower Saxony that were selected to conduct this research are highlighted in light green color.

North-Eastern Lower Saxony (NELS): Celle, Harburg, Lüchow-Dannenberg, Lüneburg, Uelzen, Heidekreis, Rotenburg-Wümme

Southern Lower Saxony (SLS): Goslar, Göttingen, Hildesheim, Holzminden, Northeim, Salzgitter, Wolfenbüttel

EPIC Crop Model

The Erosion Productivity Impact Calculator (EPIC) model was initially developed in the early 1980s to simulate the effects of soil erosion on its crop productivity[32–34]. The EPIC model was developed by the USDA (United States Department of Agriculture) to assess how agricultural activities affect the status of US soil and water resources[33–35]. The model has been continuously expanded to simulate many other processes relevant for land use in agriculture[33,36–38]. This resulted in the change of the model's name to Environmental Policy Integrated Climate[39].

The major components in EPIC are crop growth, yield and competition, weather simulation, hydrological, nutrient and carbon cycling, soil temperature and moisture, soil erosion, tillage, and plant environmental control.

Up twelve different crops can be modeled at the same time, allowing intercrop and cover-crop mixtures. Several simulated processes can include tillage effects on crop residues and bulk density, wind and water erosion, and hydrology (Figure 3.e and 3.f). The model also simulates soil temperature and heat flow; C, N, and P cycling; fertilizer and irrigation effects on crops; pesticide fate; and economics[40].

EPIC works on a daily resolution, capable of simulating up to a hundred years in the future. In this sense, long-term soil assessments like humus build-up processes are calculated, but also analyzing yearly or seasonal processes as yield levels (Figure 3.g), water usage (Figure 3.f), fertilizer, and pesticides requirements are possible (Figure 3.e). EPIC is a field-scale model, which means that it can simulate homogenous drainage areas in terms of weather, soil, landscape, crop rotation, and management operation parameters[41].

The following diagram depicts the general input information—in blue and the obtained output information—in orange. There are several input information tiers in the EPIC model depending on the specific research goal at hand. However, to allow the model run, climatic information is required, as well as descriptive data about the region in terms of the geography and topography, and of course, all management information related to the crop calendars (including the type of crops), nutrient, irrigation information (rainfed systems are also possible).

EPIC requires daily weather to simulate each crop from planting to harvesting (Figure 2.2.3.a). For this reason, the weather information is provided in a daily resolution. Regarding the representation of a climatic trend, a daily period of at least thirty years must be given to the model. In this specific research, I have used a total of 66 years to represent the future, which was split into two periods: near future (2035-2065) and far future (2070-2100). This strategy makes it possible to observe the changes in the future climatic conditions associated with the utilized climate scenario.

As mentioned above, EPIC can simulate long-term processes. To allow the model to obtain an equilibrium state for such processes, I have run the model, including a spin-up period of 95 years. Consequently, the simulations for the future are set up for 132 years, but only the last 66 years are used for analysis.

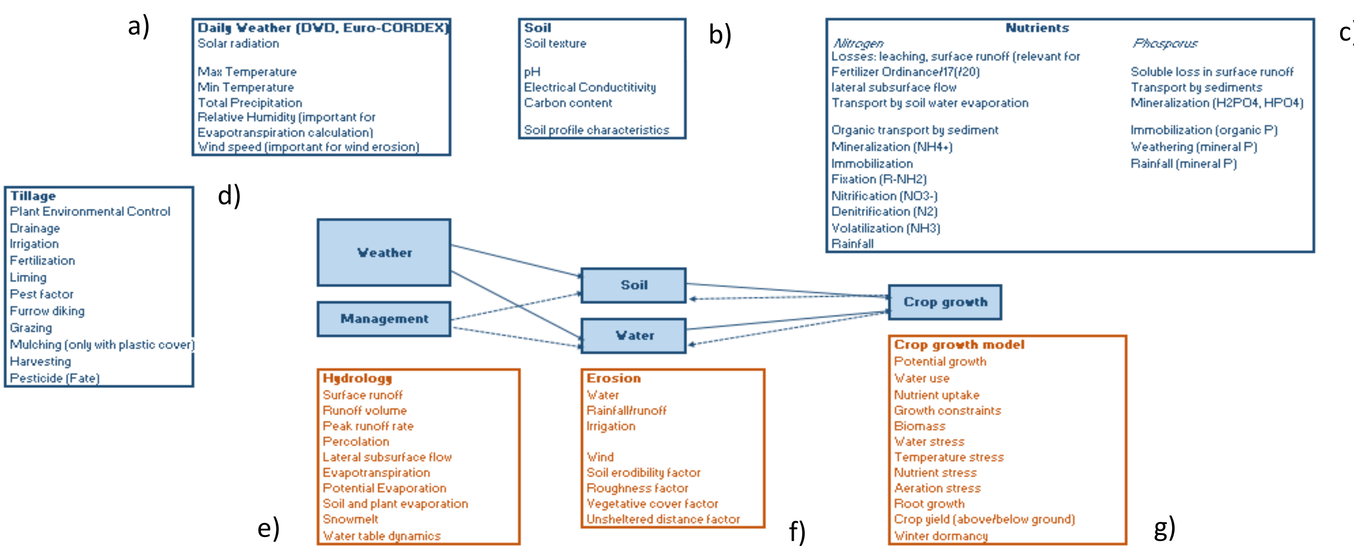

Figure 3 depicts a general description of EPIC together with required input information and outputs (modified from Flach, 2018). The input information is represented in the blue framed boxes in the upper part. The results obtained from the model are the orange framed boxes in the lower part. The leading five processes in EPIC are weather (a), management (d and e), soil (b), water (e and f), and crop growth and development (g).

Reported yields have intrinsically spatial and management differences that are hidden in an average value. As a modeler, it is impossible to represent this with EPIC as these variabilities are entirely unknown. In this sense, each district is characterized with simulation units to consider different soil properties, geographical and climatic conditions. When starting this research (the year 2018), the reported yields in the simulation area (Figure 2.1.2) are available for the period 1979-2018[42].

Through the calibration procedure, relevant parameters adjustment allows attaining higher yields for Northern Germany but reducing plant stresses. However, it was not desirable to modify all crop parameters as many of them are based on experience or field tests, which are not available, and it is out of the scope of this research. In this sense, it is not desirable to over-calibrate the model to get the expected results for the wrong reasons that may mislead the results' interpretation.

Consequently, I adjusted the following parameters using literature and testing directly in the model:

- Biomass-Energy Ratio (WA) refers to the potential growth rate per unit intercepted photosynthetically active radiation. This means that WA corresponds to a free stress environment.[43–45]
- Harvest Index (HI): It relates the proportion of the effectiveness of plants in delivering seed. It is the proportion of grain respect total over-the-ground biomass[46]. EPIC adjusts this parameter as water stress (WS) occurs from near flowering to maturity[43].
- The optimal temperature for plant growth (TOP): Temperature is the most critical short-term parameter that affects crop yields[47]. Moreover, temperature affects each crop in different ways. In this sense, every plant has a specific temperature interval portrayed by minimum, maximum, and optimum values[48]. The latter represents the temperature that allows attaining a higher level of yield. Desirable are growing

species that have a TOP close to the mean environment temperature of the place. For this reason, these values come from experimentation(Environmental Policy Integrated Climate Model - Users' Manual Version 0810 2014). Most of them are available in academic literature.

- Base Temperature (TBS): The base temperature represents the value underneath which plant development is zero[50]. TBS as TOP is crop/species-specific.
- Heat Units (HU): Plants lack self-preserving their constant internal temperatures. Respectively, their growth, as mentioned before, is highly dependent on air temperature variations surrounding them. HU is a heuristic concept that relates plant development with temperature trajectory among the different plant growth stages. HU concept assumes: 1) growth only happens when the average daily temperature is higher than TBS. 2) there is a linear relationship between crop growth and daily heat accumulation within a specific range, which is crop-specific. 3) Heat units among development phases –crop-specific- remain constant on spatial and time scales[51].

For this project, I use the following formula to calculate HU:

$$HU = \left(\frac{T_{max}+T_{min}}{2}\right) - TBS \quad \textbf{EQUATION 1}$$

OUT extension. This HU value is calculated over the actual growing period, which starts by planting until its harvesting. I use the result of this calculation as the initial input for EPIC. Then, in an iterative process, I use the actual HU value in EPIC that the model calculates directly shown in the output file. The following figure depicts this general procedure:

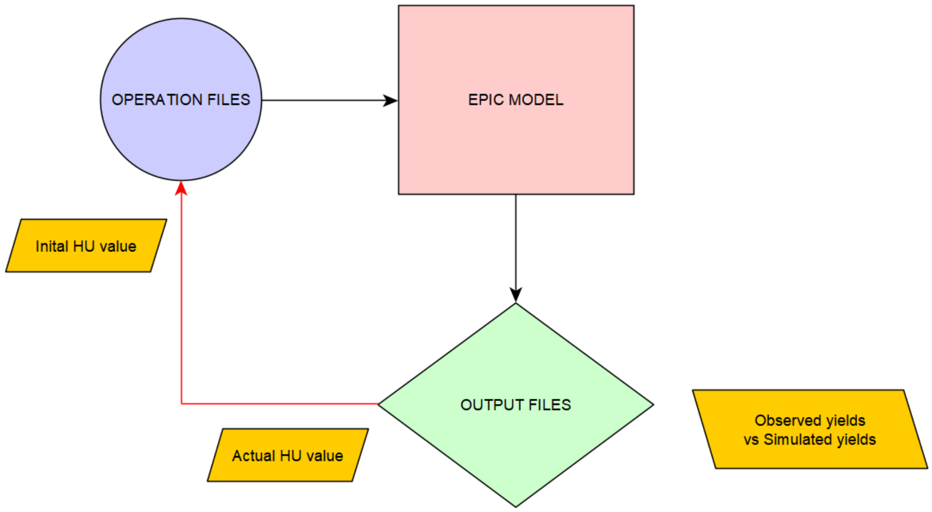

Figure 4 shows the General description of the calibration process in the EPIC model, in which the observed yields are compared with the simulated yields. If the difference is higher than ± 1 t/ha, then the HU value that the model uses is used for new simulation runs until the difference is reduced (Line red in the figure)

After this process, I used the actual HU values for each crop in the management file in the planting operation with .OPS extension.

Crop planting date: Though this is not a crop parameter per se, it affects the HU accumulation, or in other words, the achieved yields. I took the dates from KTBL edition 2018/2019[52] (The Board of Trustees for Technology and Construction in Agriculture in English) that indicate the periods in which the most common crops were planted and harvested in Germany for most years. This information does not account for exceptionally earlier or later dates of scattered planting and harvesting, nor abnormal seasons caused by climatic or even by economic conditions[53]. In this sense, to increase the yields, I shifted the planting dates to earlier days.

I plotted observed and simulated yields to compare each crop rotation visually. Each district was calibrated for four crop rotations shifting one year each crop to ensure starting with each simulated plant. This means that each crop appears every four years.

Climate input information in EPIC

the EPIC model requires daily resolution climatic information. The required variables include precipitation, maximum and minimum air temperature, and shortwave solar radiation. EPIC has five methods to estimate potential evapotranspiration, including Penman-Monteith (usually for windy conditions), Penman, Priestly-Taylor, Hargreaves, and Baier-Robertson[54,55]. If the Penman methods are selected to calculate potential evaporation, wind speed and relative humidity are also required. Daily wind speed is also needed for studies that focus on wind-induced erosion or dust emission and distribution[54,55]. Although solar radiation can be generated based on other information provided to the model when it is not available, it is used to estimate the parameters that affect crop growth. It is required in the Priestley-Taylor evapotranspiration method[54,55]. For this research, maximum and minimum temperature, precipitation, solar radiation, and relative humidity are given to EPIC to run the simulations. Additionally, the evapotranspiration calculation was calculated with the Hargreaves method[56,57].

Even though Regional Climate Models (RCM) present advantages over Global Circulation Model (GCM), it is necessary to mention that RCM depends to a certain degree on its driving GCM. In this sense, its outcomes certainty of the climate projections depends on both the RCM and its driving GCM. Hence, one RCM-GCM combination only produces one potential event out of many other outcomes, which are logically an incomplete representation of reality. To represent a spectrum of products to use ensemble simulations combining different RCMs with various driving GCMs. Nevertheless, for this study, I only obtained one bias-corrected RCM-GCM combination. This is enough to conduct a general analysis of the future climate impacts on potential soybean production in the selected region.

Regarding future simulations, climate projections are required to obtain the climatic variables that EPIC requires as input information. Since the study case is in Europe, Coordinated Regional Climate Downscaling Experiment (CORDEX) projections in the European domain[58,59] are the most appropriate datasets since they have a finer spatial resolution of 12.5 km (EUR-11). This spatial resolution enables the analysis of spatial climate variability and its future changes, as well as extreme daily impacts[59].

This climate projections dataset for all 88 combinations has daily precipitation, air temperature, and solar radiation[59,60]. They can be input directly into the model. Nevertheless, some Regional Climate Models (RCM) - COSMO-Climate Local Model (CCL) combinations do not provide relative humidity. This condition reduces the total ensemble that can be used for EPIC purposes up to 80 combinations.

Different Representative Concentration Pathways (RCPs) are among these combinations that specify the CO2 concentration levels at the end of the 21st century. These RCPs also include temporal evolution of atmospheric greenhouse gas, and aerosol concentrations are prescribed in global climate models. This process for the specified pathways forecasts a set of potential climate evolutions. RCPs offer many viable scenarios to specific characteristics of radiative forcing and emphasize that the long-term concentration concentrations are of concern and that the trajectory has taken over time to achieve that result[61].

The selection method for this research is based on the number of scenarios in the literature that lead to the corresponding radiative forcing. In the case of RCP 2.6, more than 20 scenarios in the literature lead to similar levels of forcing. RCP4.5 corresponds to the' class IV' scenarios in AR4 (comprising most simulations evaluated in AR4, i.e., 118) [62]. Finally, RCP8.5 leads to a rate of forcing close to the 90th percentile for baseline scenarios[62]. However, the latest literature review was still able to define around 40 scenarios with a comparable level of forcing. Compared to RCP 6.0, the number of situations leading to this stage is comparatively tiny, about 10[62].

Table 2 shows the meaning of the three selected CO2 Emission Scenarios, including the CO2-eq concentration in ppm and the significance of the pathway based on Moss RH et al., 2010

Name	Radiative forcing	Concentration (ppm)	Pathway
RCP 8.5	>8.5 W/m2 in 2100	>1370 CO2eq in 2100	Rising
RCP 4.5	~4.5 W/m2 at stabilization after 2100	~650 CO2eq (at stabilization after 2100)	Stabilization without overshoot
RCP 2.6	Peak at ~3 W/m2 before 2100 and then declines	Peak at ~490 CO2eq before 2100 and then declines	Peak and decline

The calibration method is conducted by simulating yields in the reference period of 1979 to 2018. For that period, the required climatic information is obtained from reanalysis data since the observation weather information is not complete for all the required variables that EPIC requires for the reference period. ERA5 Reanalysis Data is available for the European continent, which allowed to download the information for Lower Saxony and then cropped it out for each district.

It is relevant to mention that RCMs must correctly reproduce the past climate conditions for the desired horizontal scale. To ensure this is the case and to assess the EPIC model biases, EPIC simulations with ERA5 reanalysis data for 1979-2005 with a horizontal resolution of about 0.25° x 0.25° or about 30 km are compared to simulations run with hindcast for the same period (Supplementary material of Chapter 3). The use of reanalysis data instead of arbitrary GCM data for this period allows an assessment of the RCM's skill for reproducing the current climate without influences of any possible GCM bias[63,64].

The specific climate projection information for this research is obtained from the Regridded and Corrected Data Sets for the IMPACT2C SlowTrack Models[58]. The RCM-GCM combination is CSC-REMO2009- MPI-ESM-LR for three RCPs[61,62] (2.6, 4.5, and 8.5). The RCP scenarios are from 2006 to 2100, having a hindcast from 1951 to 2005. In figure 5, the average precipitation and temperature for the two selected future periods (Section EPIC Crop

Model) for the three selected RCP scenarios. Precipitation changes are expected to be negative across the near and distant future periods and RCP scenarios. Even though RCP 8.5 in 2070-2099 may have more rainfalls than RCP 2.6 and 4.5 for both future periods (Figure 6).

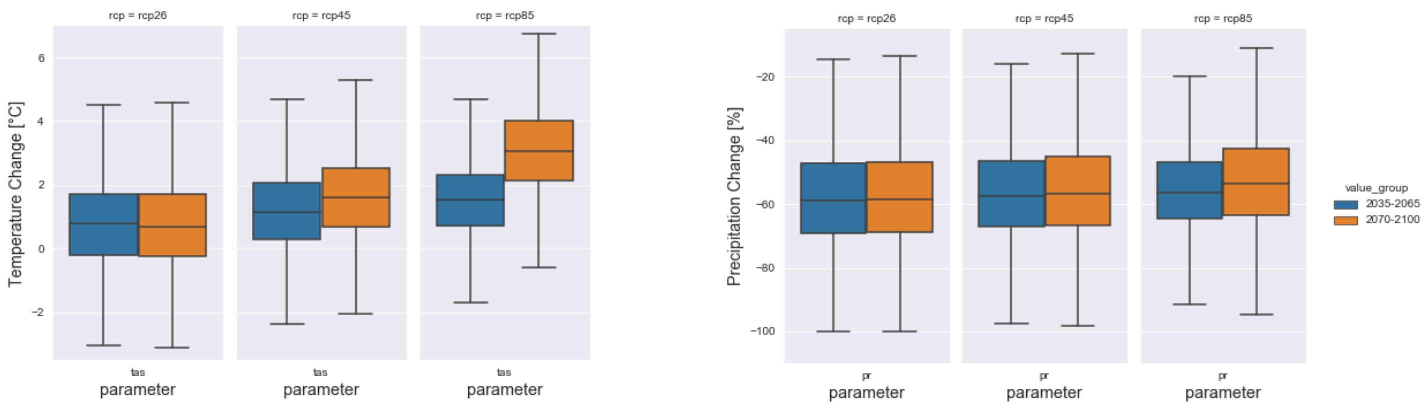

Figure 5 displays the change of average surface temperature (tas) (left side) and precipitation (pr) (right side) compared to the reference period (1979-2017). Results are divided in two future periods: near (2035-2065) and far (2070-2100), blue and orange bar respectively. In the case of precipitation, relative change is calculated and absolute change for average surface temperature. Average temperatures are expected to increase by about 2°C for RCP 8.5 in the far future. Total average precipitation is expected to reduce by around 60% for most scenarios, except for RCP 8.5 whose loses might be reduced by

In this thesis, one bias-corrected model (MPI-CSC-REMO2009) was used to conduct the simulations with EPIC as the variability of this model is like the variability of the EURO-CORDEX combinations for the three selected RCPs (Figure 2.3.2). We compared the average temperature and precipitation changes to observational data from 1971-2018 for future periods (2035-2099). In the case of temperature, the average change for MPI-CSC-REMO2009 is about one grade lower than the average for the models' ensemble. This difference applies to three RCP scenarios. Precipitation average changes are almost the same for RCP 2.6. In contrast, the average precipitation changes for RCP 4.5 and 8.5 are about 5% higher for MPI-CSC-REMO2009 than for the ensemble models.

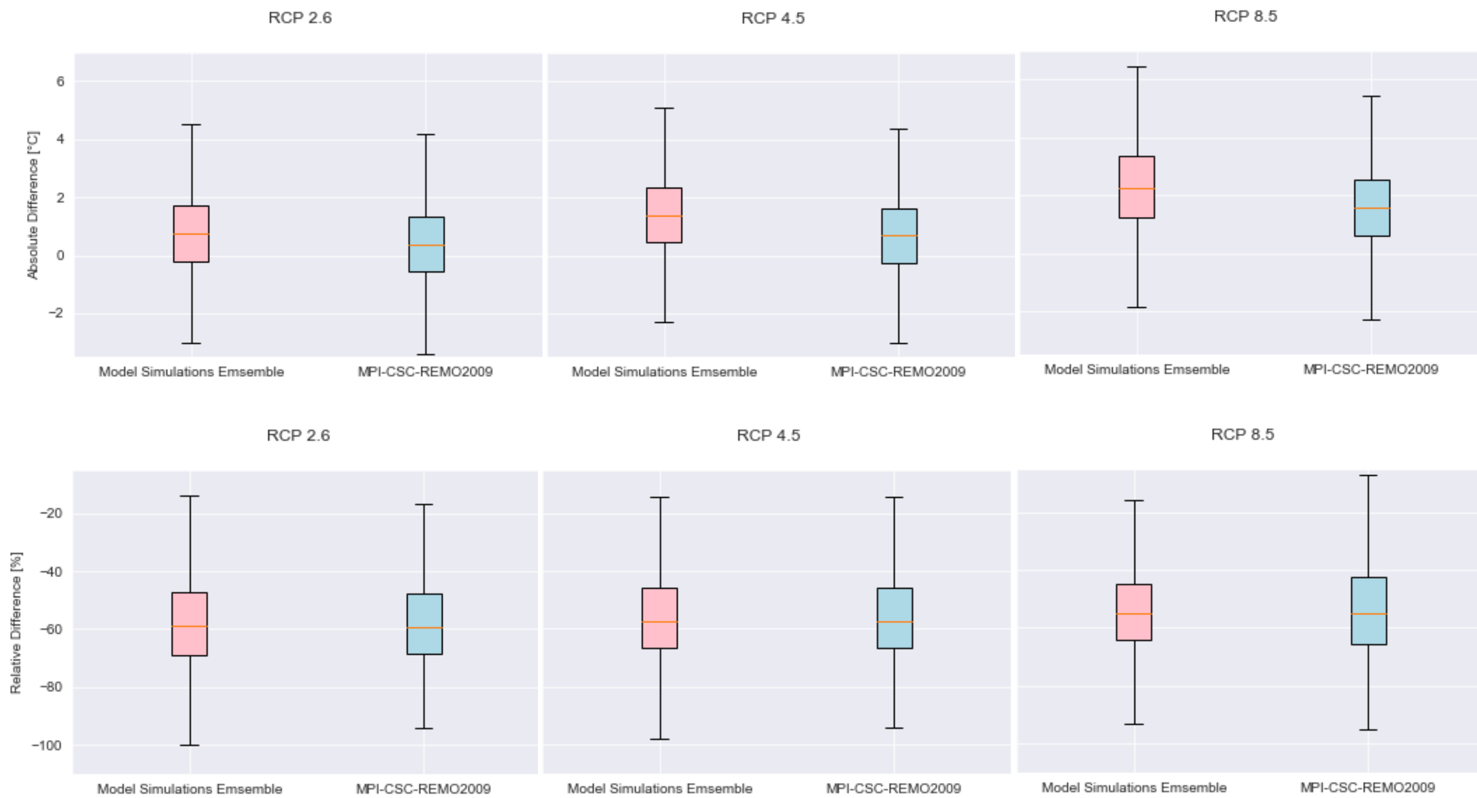

Figure 6 presents the distribution of the model ensemble (pink bars) and MPI-CSC-REMO2009 (blue bars) for average surface temperature (tas) and precipitation (pr) for each RCP scenario. As we can see from the plot, MPI-CSC-REMO2009 in average has lower temperature by around 0.5°C than the whole climate ensemble. In the case of precipitation losses, MPI-CSC-REMO2009, in average, for RCP 4.5 and 8.5 are slightly higher than for the climate models ensemble.

To display this with more clarity, I plotted a time series of 30 years running average for the whole combinations for precipitation, maximum and minimum temperature, including the average among those combinations and MPI-CSC-REMO2009 for two realizations each (r1i1p1 and r2i1p1) to compare visually:

- Spread differences among the model ensemble and the selected model for this research for the three RCP climate scenarios.
- Spatial differences between NELS and SLS districts in terms of climate trajectories.

Each RCP scenario is plotted in one color: RCP 2.6 in black, RCP 4.5 in blue, and RCP 8.5 in red. The thickest lines represent the average among the models' ensemble. MPI-CSC-REMO2009 lines are the second thickest ones on the plots. Each of the fine lines is one model combination.

NELS DISTRICTS

CELLE

In the case of maximum temperature and precipitation, the model MPI-CSC-REMO2009 for the three RCPS is close enough (lower than the average) to the average for the three RCP scenarios. This pattern applies only for RCP 2.6 and 8.5 for minimum temperature. In the case of RCP 4.5, for one realization of the model, the minimum temperature is above average and for the other realization is below average.

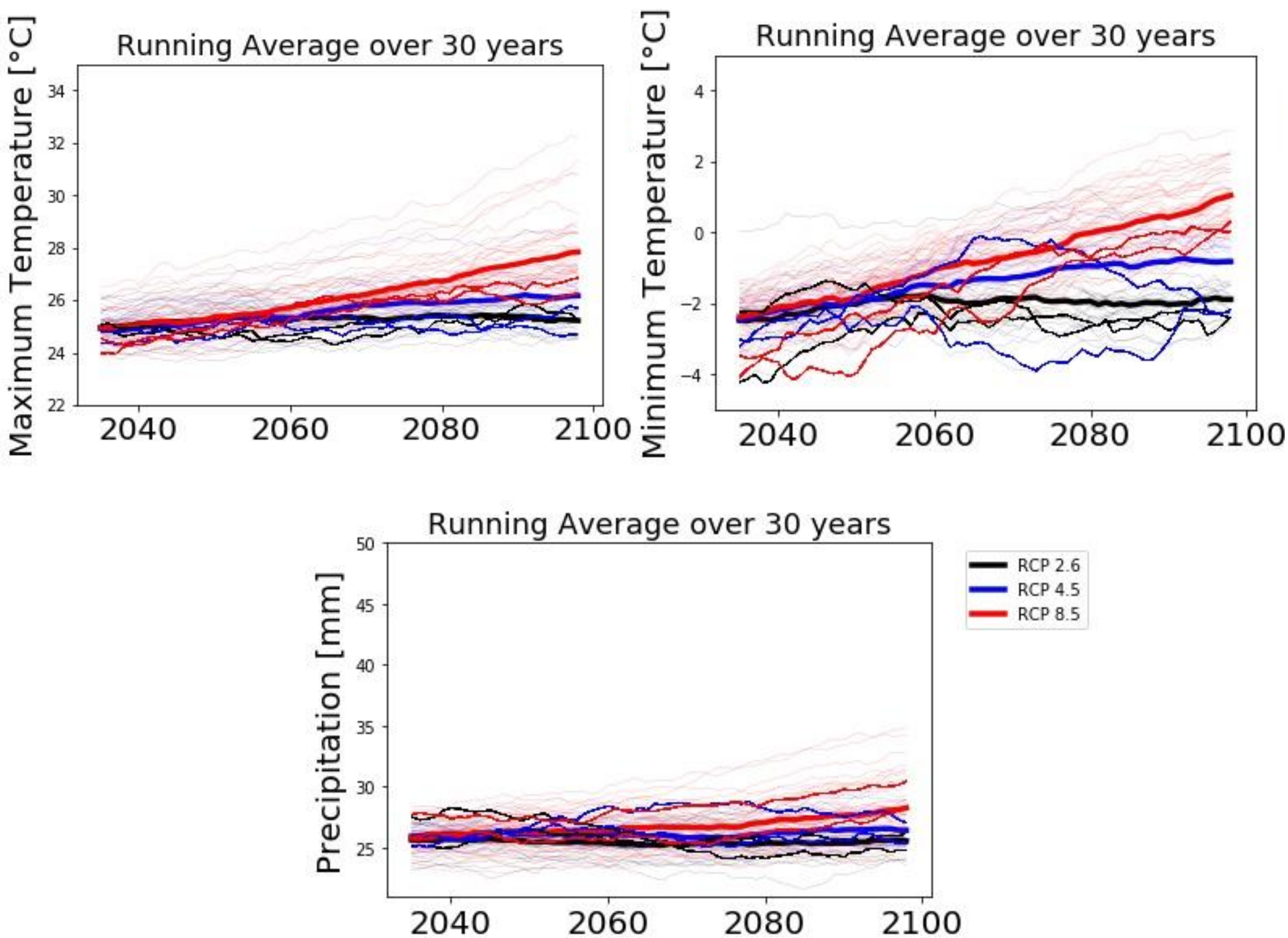

Figure 7 shows the running 30 years average of the three most relevant climate parameters in EPIC: maximum and minimum temperature, and precipitation. Each thin line is one of projection. The second thickest lines are the average across the ensemble. The thickest lines is the used model in this dissertation.

HARBURG

In the case of maximum temperature, the model MPI-CSC-REMO2009 for the three RCPS is close enough (lower than the average) to the average for the three RCP scenarios. It is similar for precipitation, but MPI-CSC-REMO2009 is above the model's average.

This pattern applies only for RCP 2.6 and 8.5 for minimum temperature. In the case of RCP 4.5, for one realization of the model, the minimum temperature is above average and for the other realization is below average.

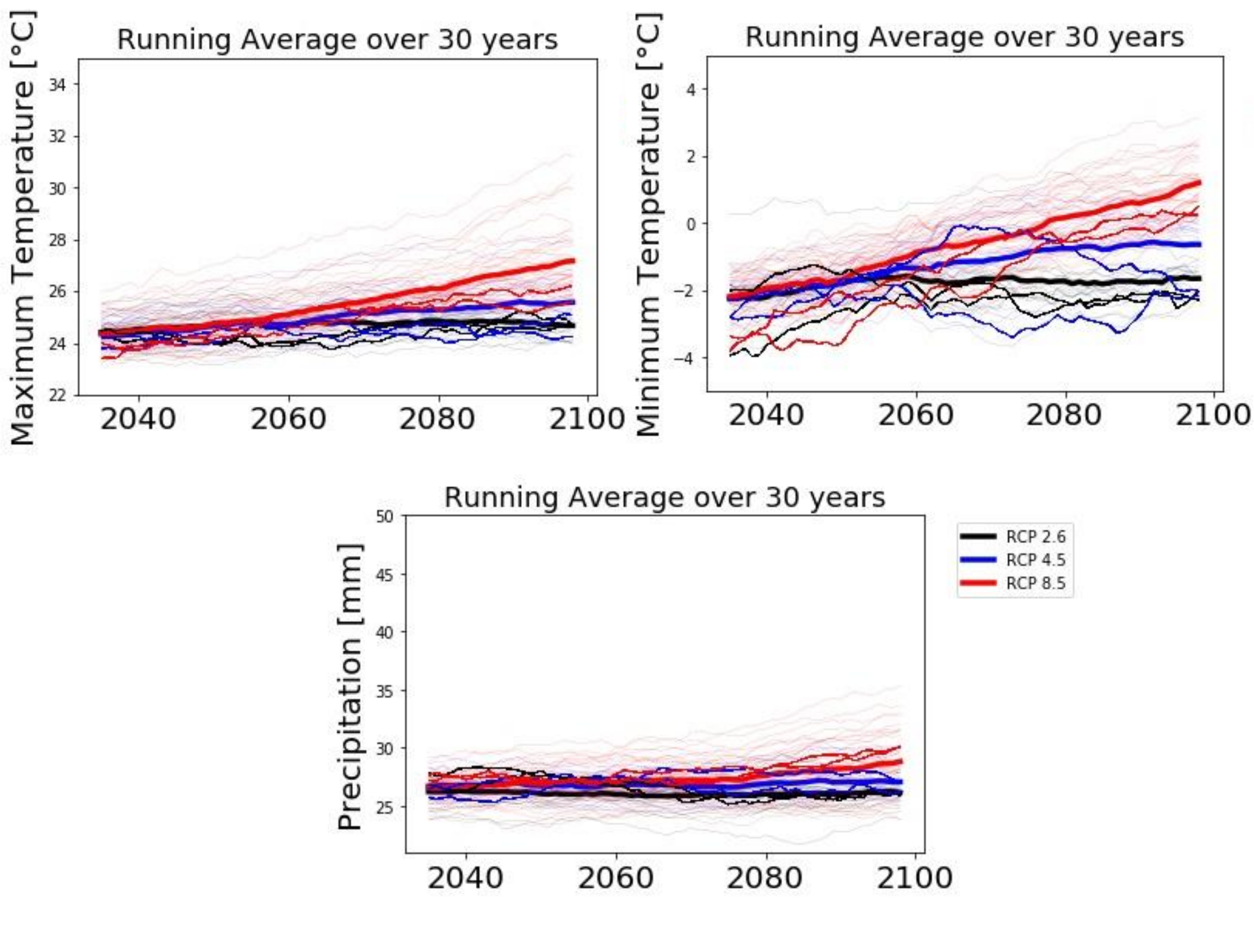

Figure 8 shows the running 30 years average of the three most relevant climate parameters in EPIC: maximum and minimum temperature, and precipitation. Each thin line is one of projection. The second thickest lines are the average across the ensemble. The thickest lines is the used model in this dissertation.

LÜNEBURG

In the case of maximum temperature, the model MPI-CSC-REMO2009 for the three RCPS is close enough (lower than the average) to the average for the three RCP scenarios. It is similar for precipitation is similar, but MPI-CSC-REMO2009 is above the model's average. This pattern applies only for RCP 2.6 and 8.5 for minimum temperature. In the case of RCP 4.5, for one realization, the minimum temperature is above average and the other realization below average.

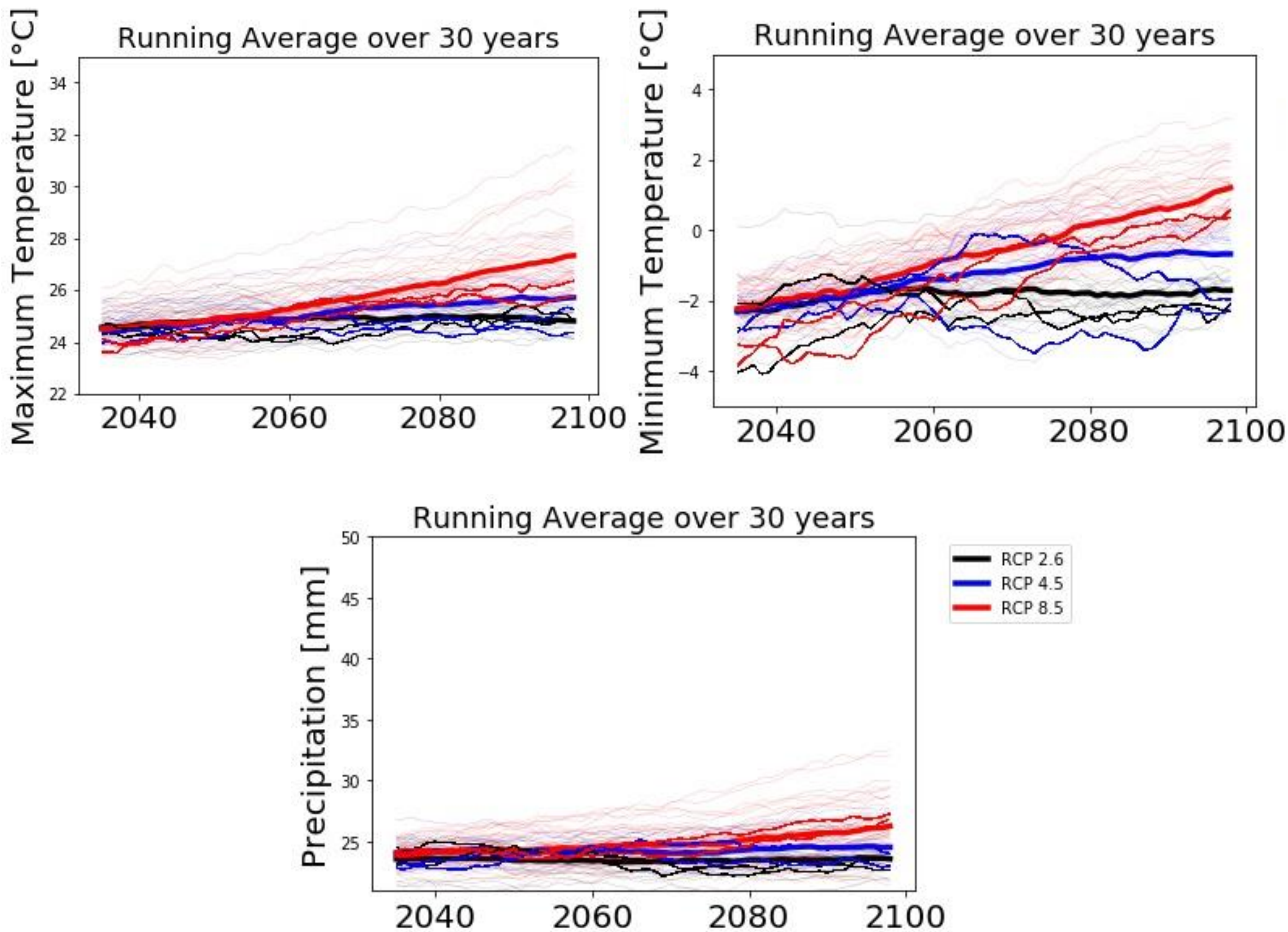

Figure 9 shows the running 30 years average of the three most relevant climate parameters in EPIC: maximum and minimum temperature, and precipitation. Each thin line is one of projection. The second thickest lines are the average across the ensemble. The thickest lines is the used model in this dissertation.

LÜCHOW-DANNENBERG

In the case of maximum temperature, the model MPI-CSC-REMO2009 for the three RCPS is close enough (lower than the average) to the average for the three RCP scenarios. It is similar for precipitation is similar, but MPI-CSC-REMO2009 is above the model's average.

Additionally, for the three RCP scenarios, this district's precipitation is lower than the previous districts. This pattern applies only for RCP 2.6 and 8.5 for minimum temperature. In the case of RCP 4.5, for one realization, the minimum temperature is above average and the other realization below average.

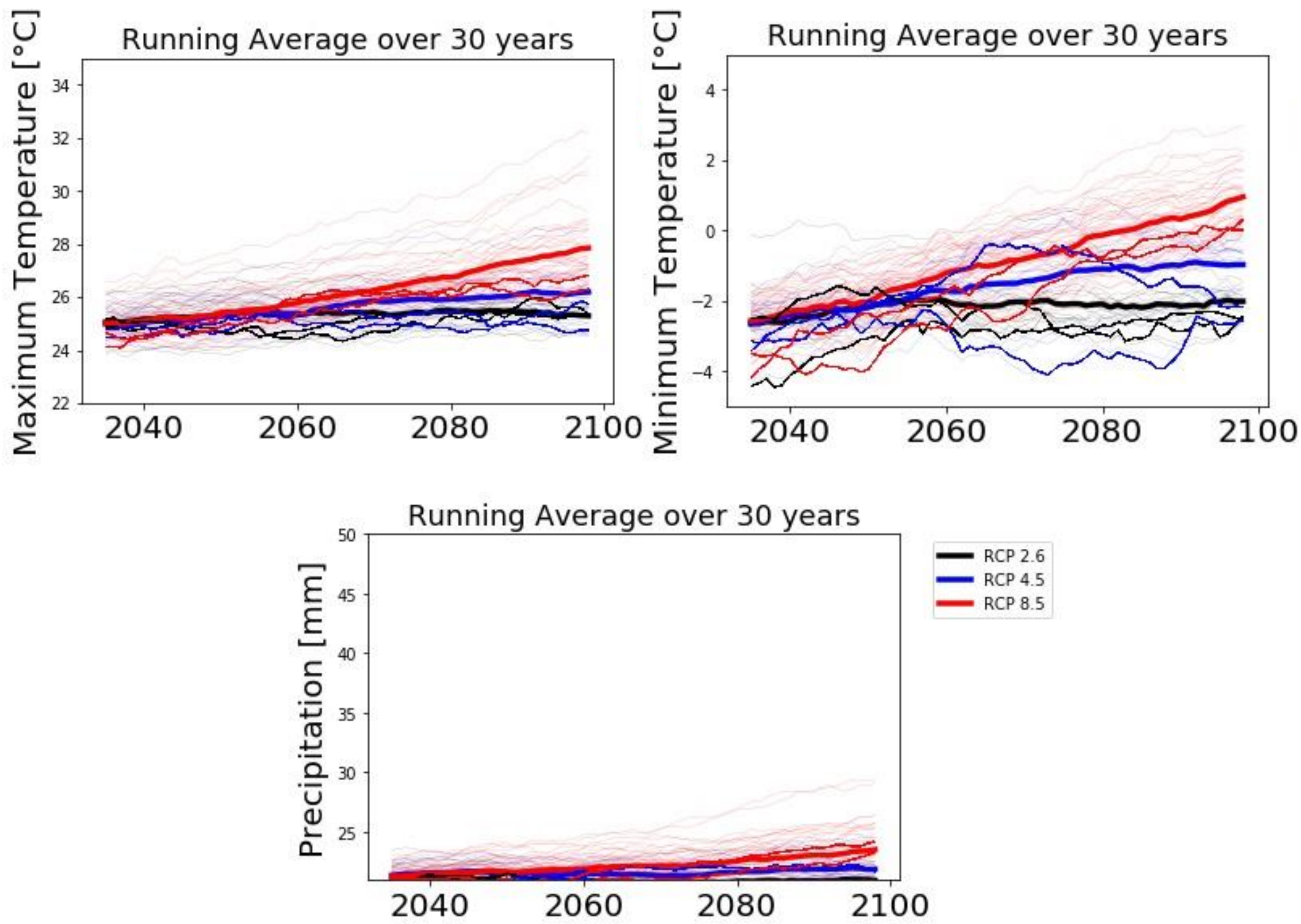

Figure 10 shows the running 30 years average of the three most relevant climate parameters in EPIC: maximum and minimum temperature, and precipitation. Each thin line is one of projection. The second thickest lines are the average across the ensemble. The thickest lines is the used model in this dissertation.

ROTENBURG-WÜMME

In the case of maximum temperature, the model MPI-CSC-REMO2009 for the three RCPS is close enough (lower than the average) to the average for the three RCP scenarios. It is similar for precipitation is similar, but MPI-CSC-REMO2009 is above the model's average.

This pattern applies only for RCP 2.6 and 8.5 for minimum temperature. In the case of RCP 4.5, for one realization, the min temperature is above average and the other below.

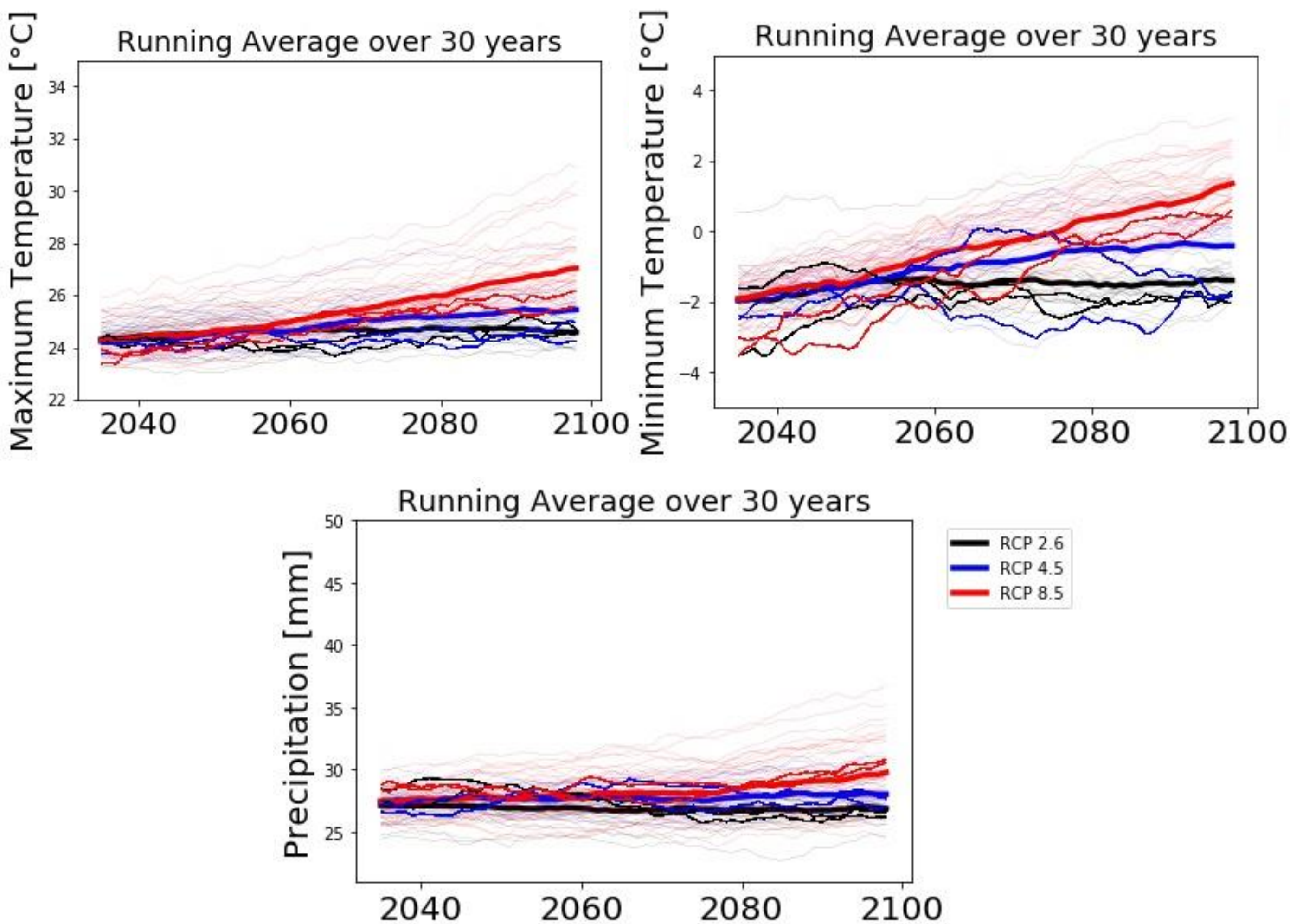

Figure 11 In the case of maximum temperature, the model MPI-CSC-REMO2009 for the three RCPS is close enough (lower than the average) to the average for the three RCP scenarios. For precipitation is similar, but MPI-CSC-REMO2009 is above the models average. . Each thin line is one of projection. The second thickest lines are the average across the ensemble. The thickest lines is the used model in this dissertation.

UELZEN

In the case of maximum temperature, the model MPI-CSC-REMO2009 for the three RCPS is close enough (lower than the average) to the average for the three RCP scenarios. It is similar for precipitation is similar, but MPI-CSC-REMO2009 is above the model's average. This behavior applies only for RCP 2.6 and 8.5 for minimum temperature. In the case of RCP 4.5, for one realization, the minimum temperature is above average and the other realization below average.

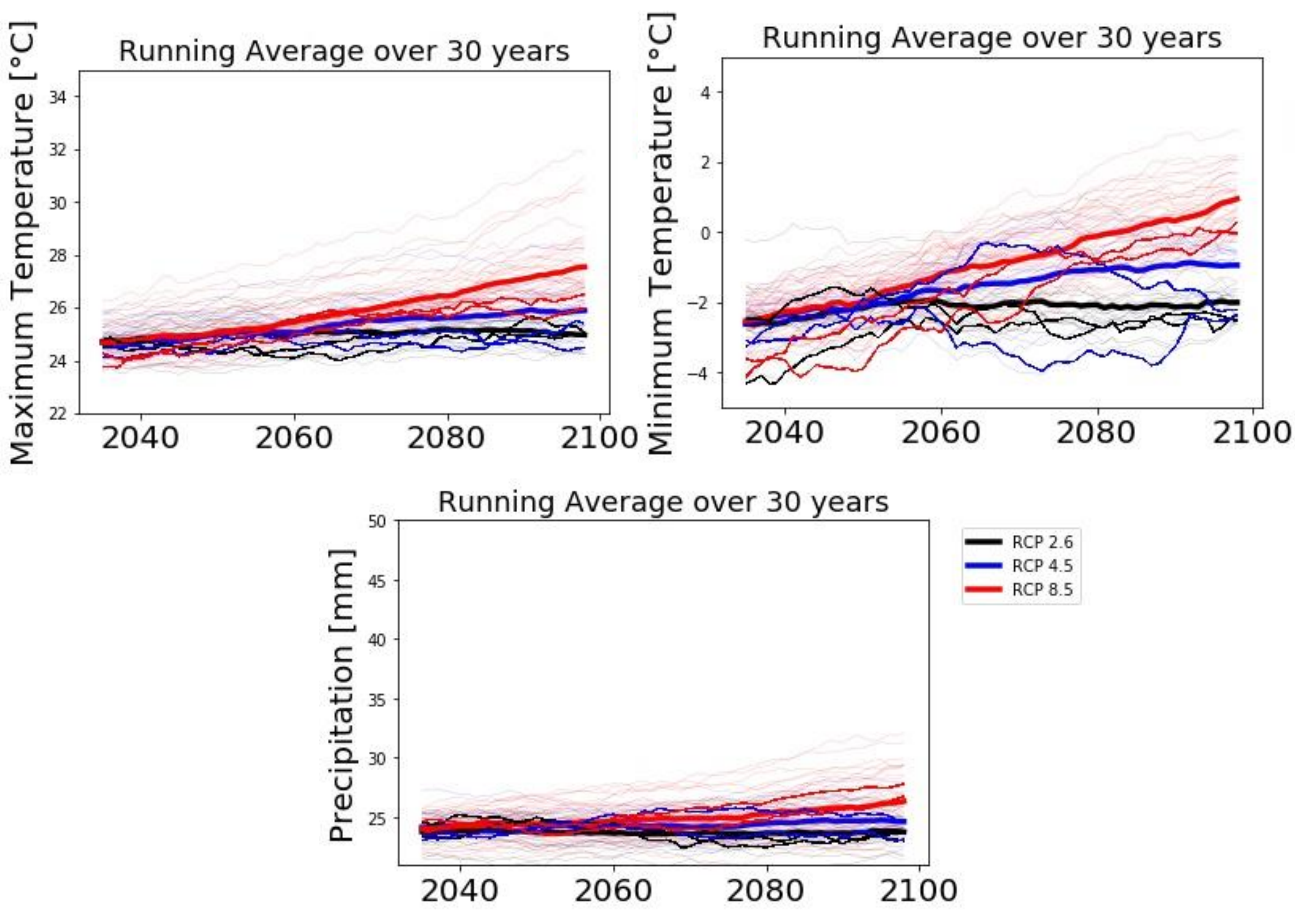

Figure 12 shows the running 30 years average of the three most relevant climate parameters in EPIC: maximum and minimum temperature, and precipitation. Each thin line is one of projection. The second thickest lines are the average across the ensemble. The thickest lines is the used model in this dissertation.

SLS DISTRICTS

GÖTTINGEN

In the case of maximum temperature, the model MPI-CSC-REMO2009 for the three RCPS is close enough (lower than the average) to the average for the three RCP scenarios. It is similar for precipitation is similar, but MPI-CSC-REMO2009 is above the model's average.

This behavior applies only for RCP 2.6 and 8.5 for minimum temperature. In the case of RCP 4.5, for one realization, the min temperature is above average and the other below.

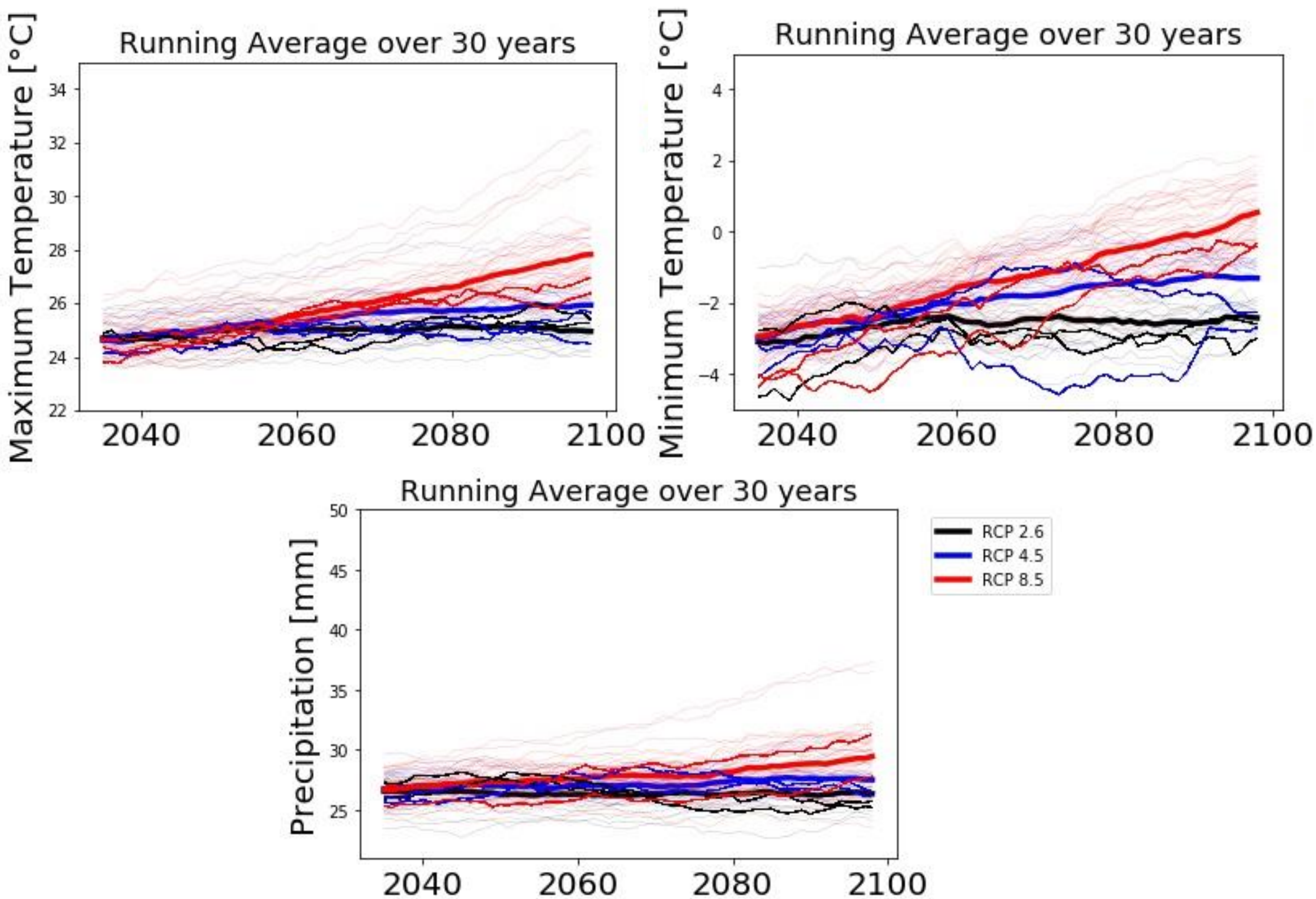

Figure 13 shows the running 30 years average of the three most relevant climate parameters in EPIC: maximum and minimum temperature, and precipitation. Each thin line is one of projection. The second thickest lines are the average across the ensemble. The thickest lines is the used model in this dissertation.

GOSLAR

In the case of maximum temperature, the model MPI-CSC-REMO2009 for the three RCPS is close enough (lower than the average) to the average for the three RCP scenarios. It is similar for precipitation is similar, but MPI-CSC-REMO2009 is above the model's average. This pattern applies only for RCP 2.6 and 8.5 for minimum temperature. In the case of RCP 4.5, for one realization, the minimum temperature is above average and the other realization below average. Precipitation is, on average, about 10 mm higher than the previous districts for all three RCP scenarios.

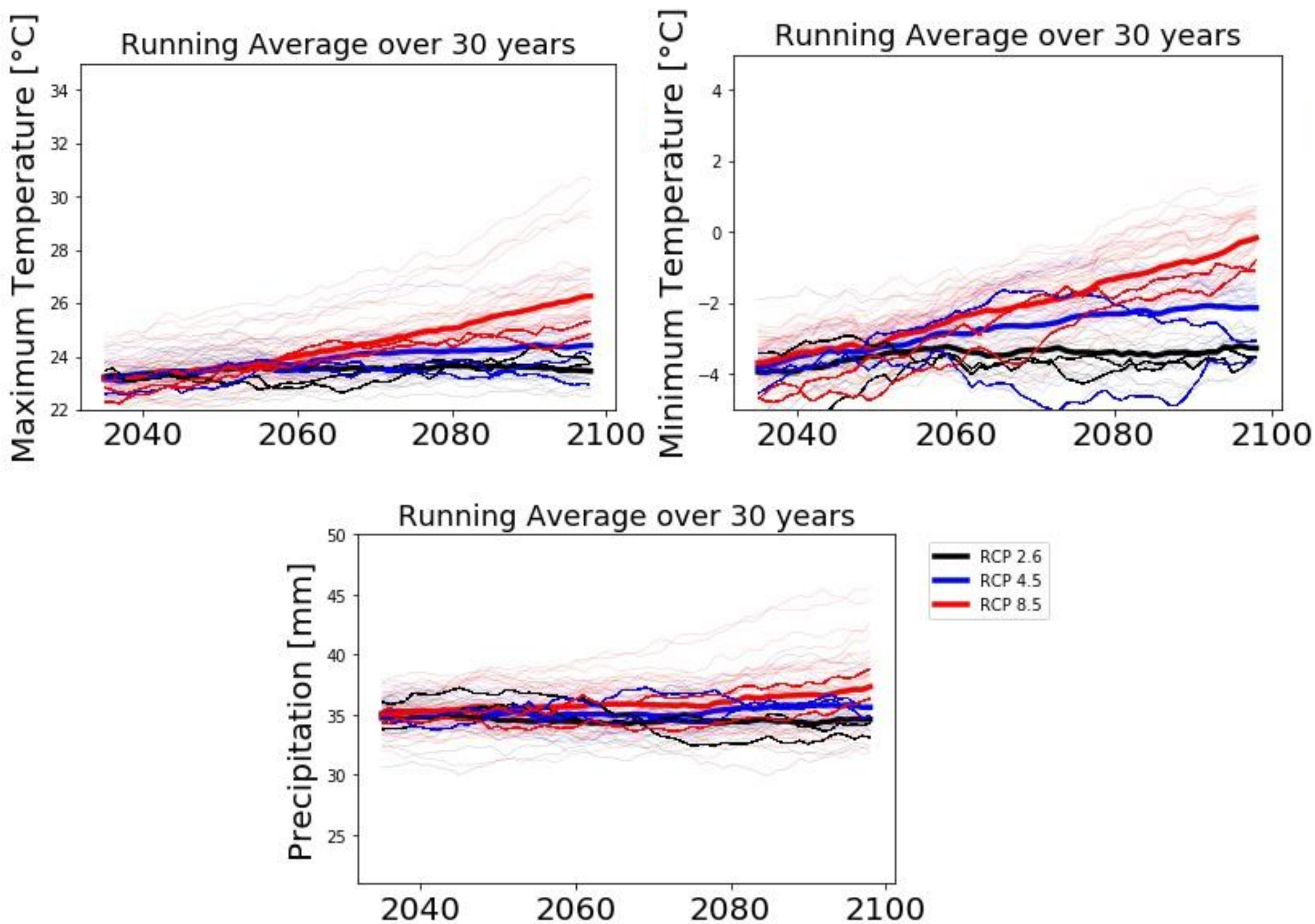

Figure 14 shows the running 30 years average of the three most relevant climate parameters in EPIC: maximum and minimum temperature, and precipitation. Each thin line is one of projection. The second thickest lines are the average across the ensemble. The thickest lines is the used model in this dissertation.

HOLZMINDEN

In the case of maximum temperature, the model MPI-CSC-REMO2009 for the three RCPS is close enough (lower than the average) to the average for the three RCP scenarios. It is similar for precipitation is similar, but MPI-CSC-REMO2009 is above the model's average.

This pattern applies only for RCP 2.6 and 8.5 for minimum temperature. In the case of RCP 4.5, for one realization, the minimum temperature is above average and the other realization below average. Precipitation is, on average, about 10 mm higher than the previous districts for all three RCP scenarios.

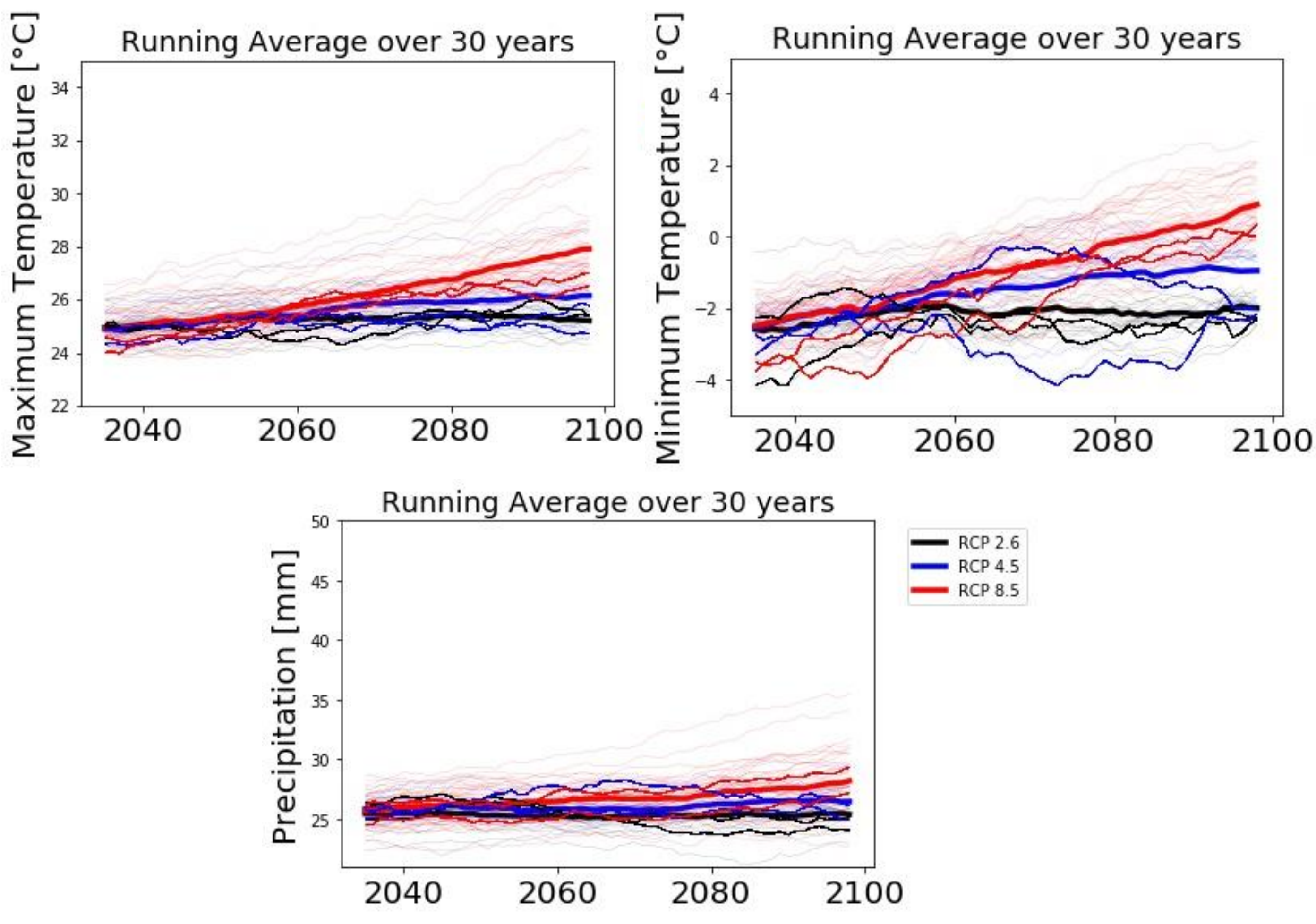

Figure 15 shows the running 30 years average of the three most relevant climate parameters in EPIC: maximum and minimum temperature, and precipitation. Each thin line is one of projection. The second thickest lines are the average across the ensemble. The thickest lines is the used model in this dissertation

HILDESHEIM

In the case of maximum temperature, the model MPI-CSC-REMO2009 for the three RCPS is close enough (lower than the average) to the average for the three RCP scenarios. It is similar for precipitation is similar, but MPI-CSC-REMO2009 is above the model's average.

This pattern applies only for RCP 2.6 and 8.5 for minimum temperature. In the case of RCP 4.5, for one realization, the minimum temperature is above average and the other realization below average.

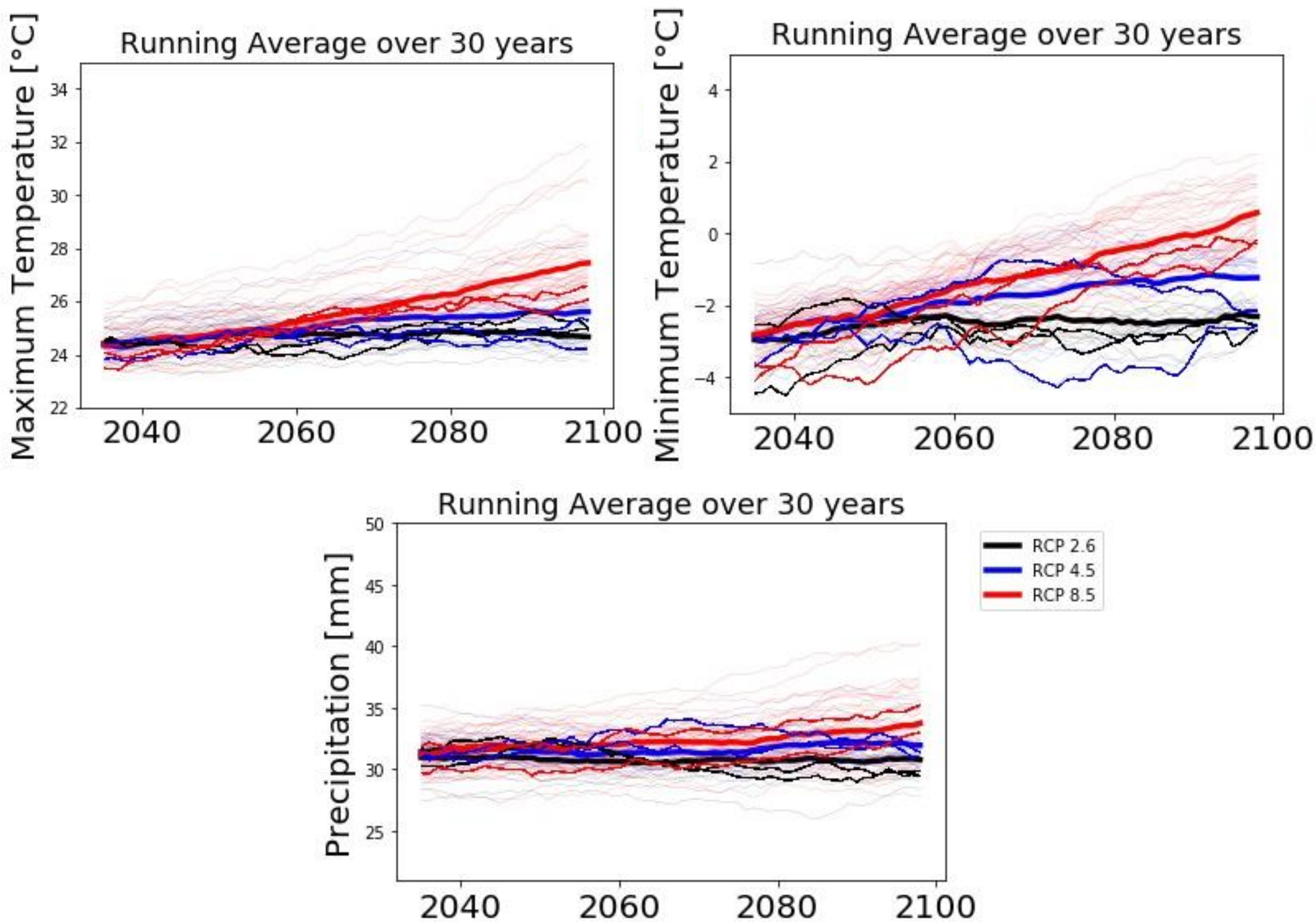

Figure 16 shows the running 30 years average of the three most relevant climate parameters in EPIC: maximum and minimum temperature, and precipitation. Each thin line is one of projection. The second thickest lines are the average across the ensemble. The thickest lines is the used model in this dissertation.

NORTHEIM

In the case of maximum temperature, the model MPI-CSC-REMO2009 for the three RCPS is close enough (lower than the average) to the average for the three RCP scenarios. It is similar for precipitation is similar, but MPI-CSC-REMO2009 is above the model's average.

This pattern applies only for RCP 2.6 and 8.5 for minimum temperature. In the case of RCP 4.5, for one realization, the minimum temperature is above average and the other realization below average.

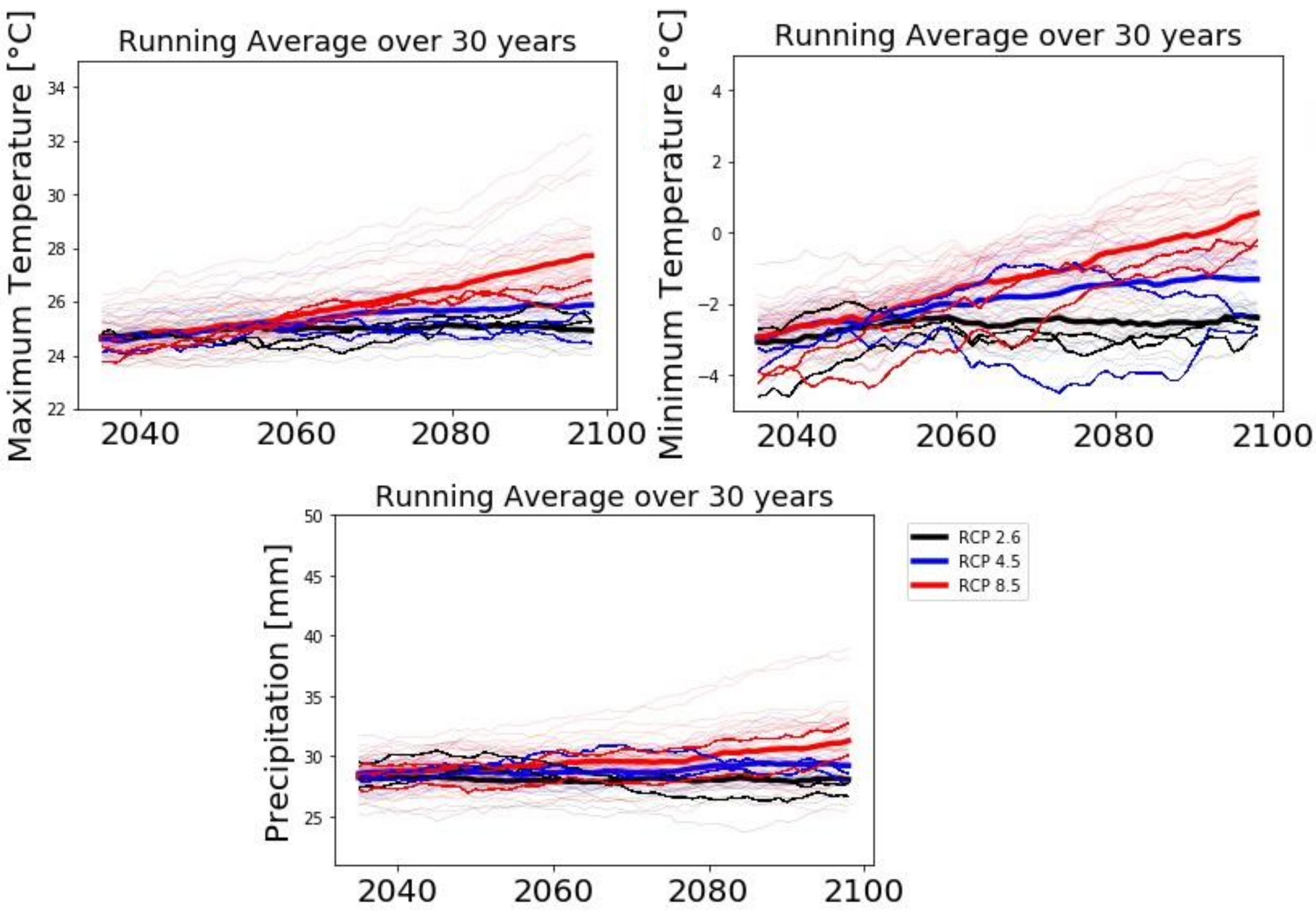

Figure 17 shows the running 30 years average of the three most relevant climate parameters in EPIC: maximum and minimum temperature, and precipitation. Each thin line is one of projection. The second thickest lines are the average across the ensemble. The thickest lines is the used model in this dissertation.

SALZGITTER

In the case of maximum temperature, the model MPI-CSC-REMO2009 for the three RCPS is close enough (lower than the average) to the average for the three RCP scenarios. It is similar for precipitation is similar, but MPI-CSC-REMO2009 is above the model's average.

This pattern applies only for RCP 2.6 and 8.5 for minimum temperature. In the case of RCP 4.5, for one realization, the minimum temperature is above average and the other realization below average.

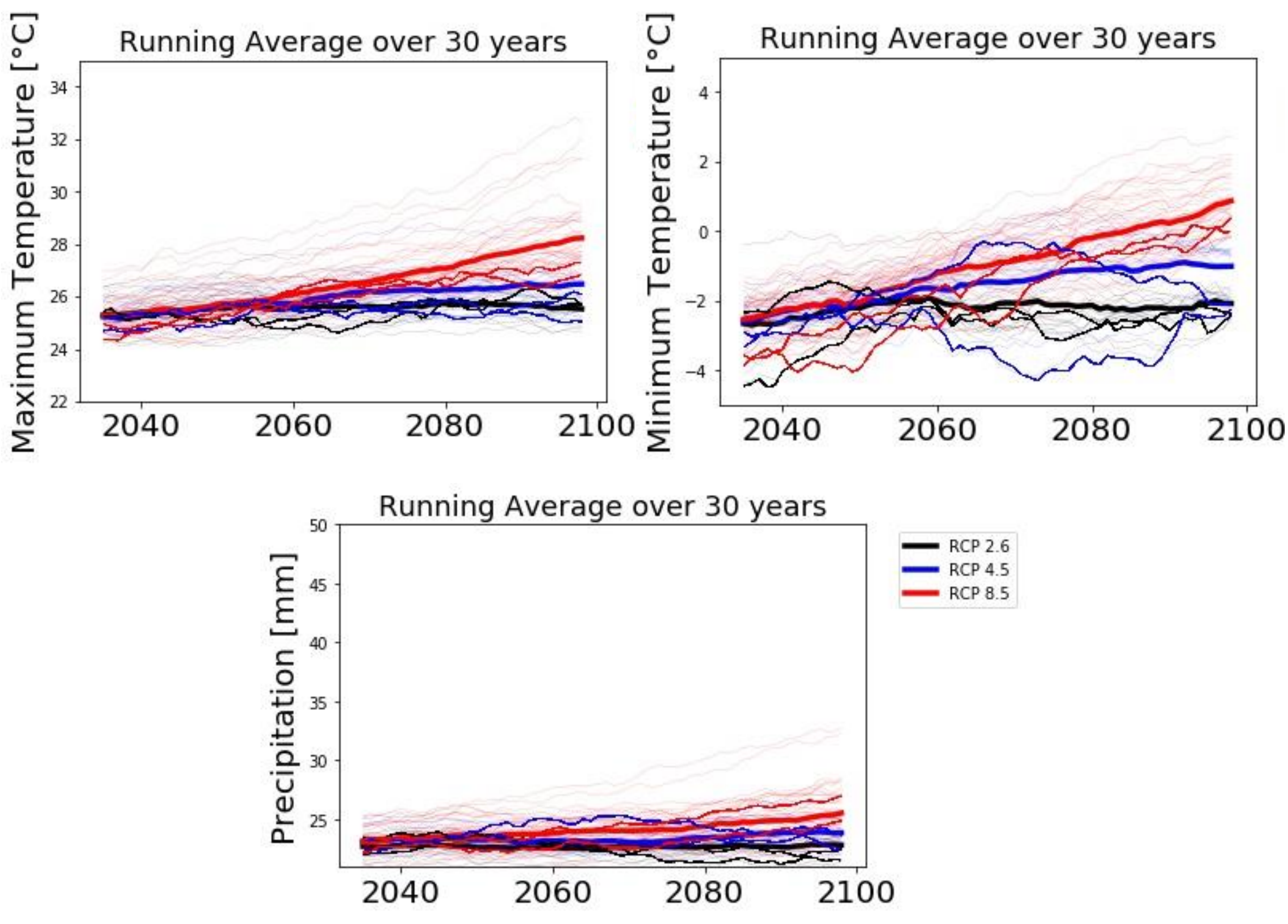

Figure 18 shows the running 30 years average of the three most relevant climate parameters in EPIC: maximum and minimum temperature, and precipitation. Each thin line is one of projection. The second thickest lines are the average across the ensemble. The thickest lines is the used model in this dissertation.

WOLFENBÜTTEL

In the case of maximum temperature, the model MPI-CSC-REMO2009 for the three RCPS is close enough (lower than the average) to the average for the three RCP scenarios. It is similar for precipitation is similar, but MPI-CSC-REMO2009 is above the model's average.

This pattern applies only for RCP 2.6 and 8.5 for minimum temperature. In the case of RCP 4.5, for one realization, the minimum temperature is above average and the other realization below average.

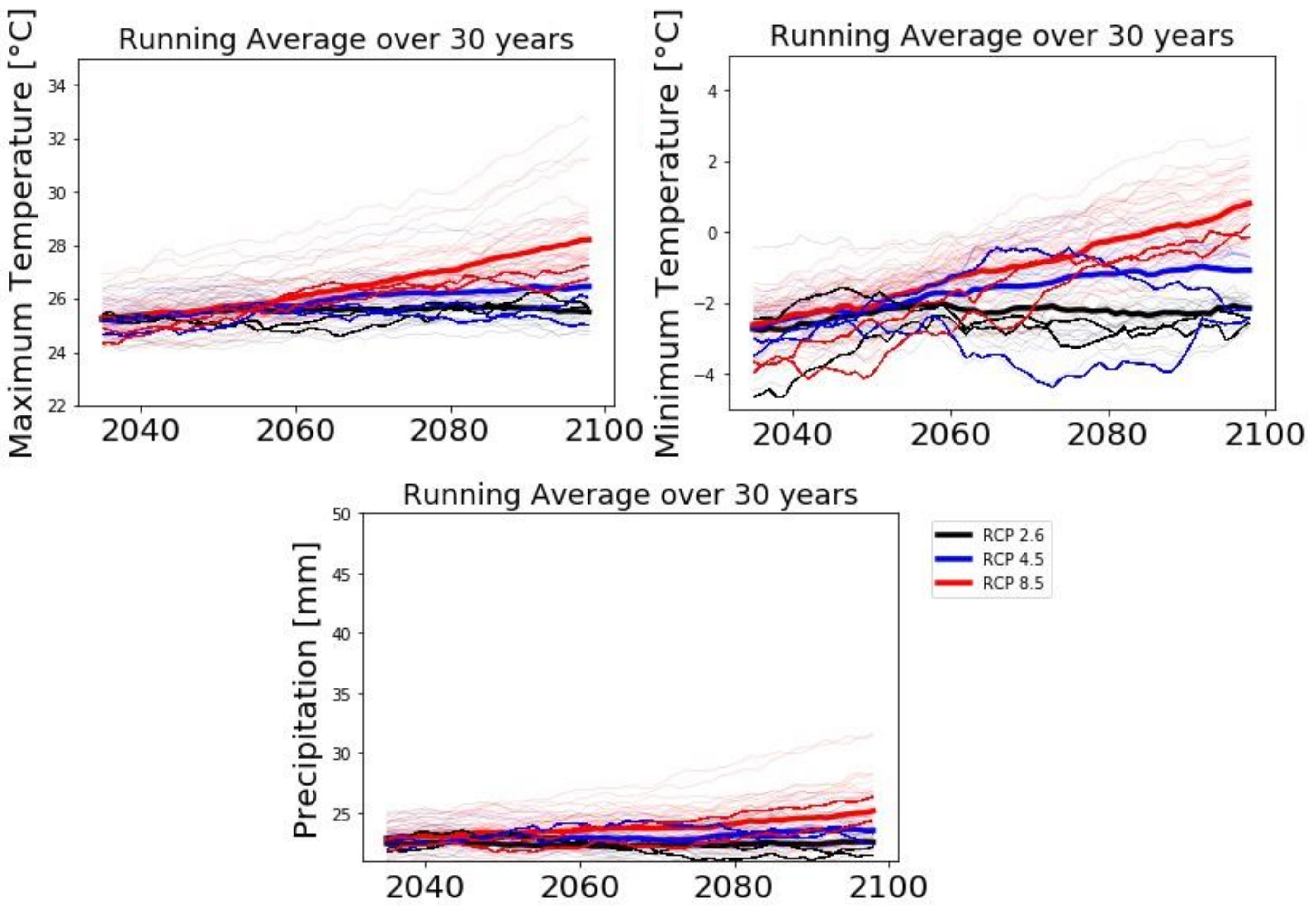

Figure 19 shows the running 30 years average of the three most relevant climate parameters in EPIC: maximum and minimum temperature, and precipitation. Each thin line is one of projection. The second thickest lines are the average across the ensemble. The thickest lines is the used model in this dissertation.

Homogeneous Response Units (HRU) Procedure

EPIC model does not have an actual spatial dimension. In theory, a simulation in EPIC could represent a farm, field, or whole region. Although, especially for a more considerable extension, the inclusion of geographical differences in terms of soil texture and climate is not considered[54,55]. These divergences are decisive for the attained yields and the applied management approaches on a specific location. Under those circumstances, HRU comes in handy as they aggregate information on soil elevation, slope, texture, climate data grid, and land cover into different classes.

HRU[65] is a basic spatial frame for implementing climate change and land management alternative scenarios into global and regional modeling. Therefore, it is one of the essential inputs for the delineation of landscape units.

The concept of homogenous response units (HRU) was adopted after slight modification from earlier works[65–68] as a general concept for delineating basic spatial units. As a support for the classification, I used the GEO-BENE[69] global database for biophysical modeling. This global database intends to support modeling with EPIC, and the data on soil, topography, climate, land cover, and land use worldwide.

In the case of Lower-Saxony, the reclassification of elevation, soil texture, and the slope is based on the method reported on Rastislav Skalský et al., 2008[69] as depicted in Table 4.

Table 3 shows the subclasses utilized in the HRU procedure that includes the subclasses for the digital elevation model (DEM), the slope inclination, and the soil texture

Layer	Unit	Class interval
DEM	meters	1(0-150), 2(150-300),3(300-450),4(450-600),5(600-1100),6(1100-2500),7(>2500)
slope inclination	degree	1(0-3),2(3-6),3(6-10),4(10-15),5(15-30),6(30-50),7(>50)
soil	-	1(sandy),2(loamy),3(clay),4(stony),5(peat),88(no-soil)

According to figure 20, some areas fall into classes one and two in the region, which is flat.

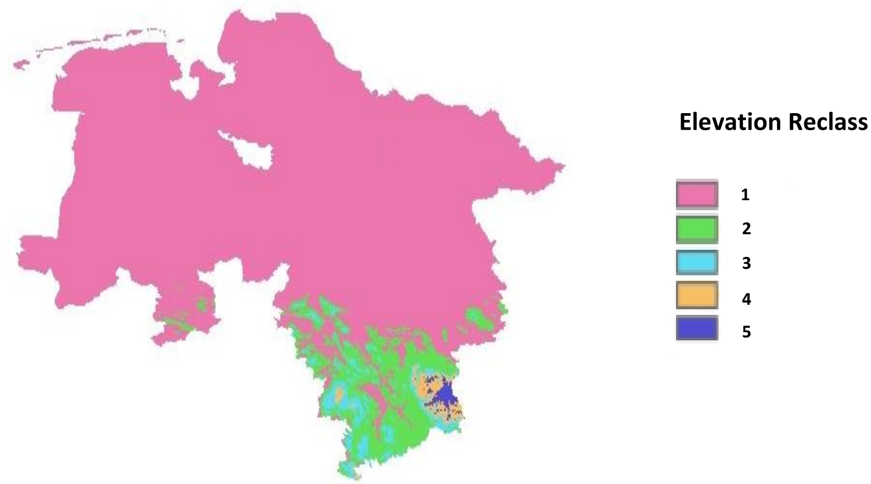

Figure 20 represents the location of each of the pre-defined elevation classes from the DEM in the case study region defined in table 4.

For the soil textures in the region was necessary to find the equivalence between the German soil classification with the FAO universal soil classification system to reclassify as it is stated in this figure based on Tamalika Chakraborty, 2010[70]

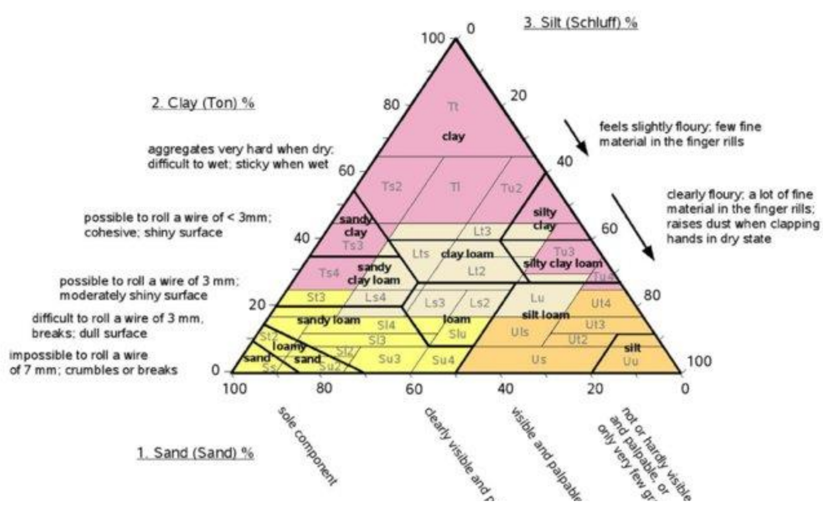

Figure 21 represents the translation from the German soil classification system to the FAO soil classification system. The German classification are represented with the gray letters under the textures clay, silty clay, sandy clay, sandy loam, silt loam, silt, loamy sand, clay loam, and sand.

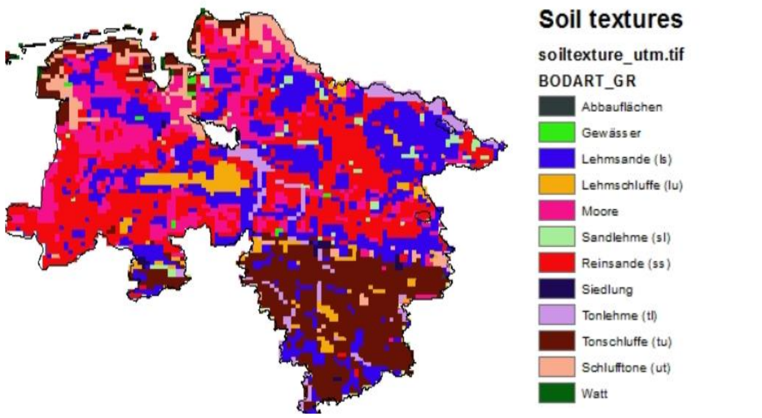

Figure 22 is the classification of soil textures according to the German soil classification as available from BÜK200. These soil textures were before they were classified according to table 4.

This map depicts the soil texture based on the German soil classification. One can observe from the map that there are substantial changes among northeastern and southern regions. The former has as most dominant soils clay sand (in German Lehmsande – ls) and pure sands (Reinsande – ss); the latter has mainly silty (in German Tonschluffe –tu) and clay silty soils (in German Lehmschluffe – lu).

The correspondence between the German classification and GEO-BENE global database (please see again Table 4) is as it follows and further depicted in table 5:

Table 4 illustrates the assigned classes for the soil texture and areas described in the National German soil database (Please refer to table 2.5.1 to review the subclasses for the soil layer)

German Original Name	English Name	Assigned Class
Abbauflächen	Mining Area	Class 88
Gewässer	Water	Class 88
Lehmsande (ls)	Loamy Sand	Class 2
Lehmschluffe (lu)	Silt loam	Class 2
Moore	Moors	Class 88
Sandlehme (sl)	Sandy Loam	Class 1
Reinsande (ss)	Sand	Class 1
Siedlung	Settlement	Class 88
Tonlehme (tl)	Clay	Class 3
Tonschluffe (tu)	Clay Silt	Class 3

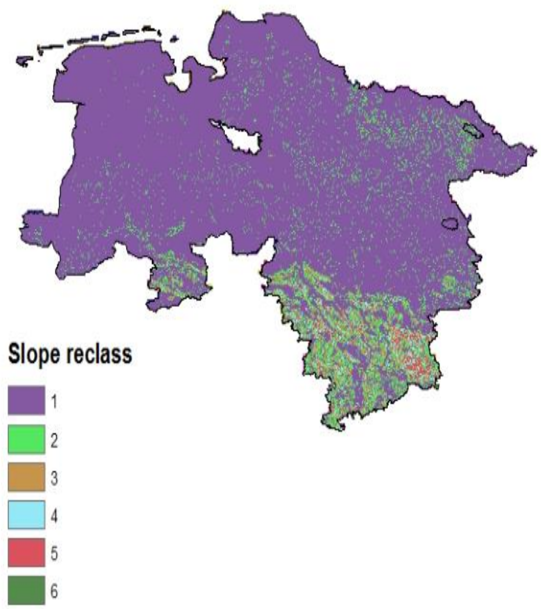

Figure 23 shows the area after the slope reclassification. Most of the area is reclassified as Class 1, which is sandy soil. In the southern part of Lower Saxony is mostly class 2 that is loamy sand.

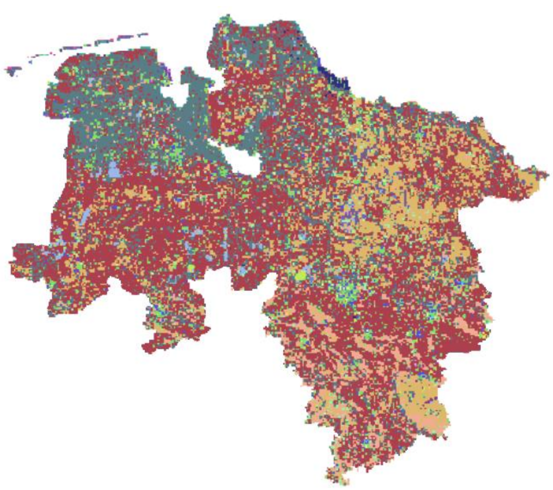

Figure 24 shows the CLC distribution of the study case region that includes all potential land use without extracting the agricultural land use.

The same procedure applies for slope reclassification, as shown in this figure. Interestingly, more than 80% of the surface falls into category number one. In other words, the region is, to a significant extent, flat (Figure 23).

This procedure is relevant for the selected climate data as there is a difference in height between the terrain in the forecast model and the actual terrain in the climate models[71]. Even though the region is flat, I decided not to correct the climate data in terms of height.

To use only agricultural land, I select these areas with the help of CORINE Land Cover (CLC) [72]. This database provides information on the biophysical characteristics of the Earth's surface, as shown in this map (Figure 24).

The CLC inventory began in 1985 (the reference year 1990). It consists of a list of land cover in 44 classes. CLC uses a Minimum Mapping Unit (MMU) of 25 hectares (ha) for areal phenomena and a minimum width of 100 m for linear phenomena.

Figure 25 shows the land cover for the agriculture area only after extracting the total CLC from figure 24.

After extracting the agricultural extensions using the CLC layer, it looks like in figure 25. This procedure allows reducing the number of HRU significantly.

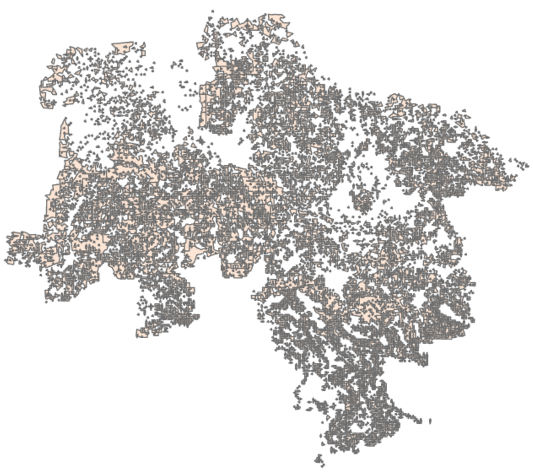

Figure 26 depicts the overlapping of the soil, land cover, elevation and slope layers after combining Figures 20, 22,23 25, and information included in table 4.

After overlapping all these previous layers plus the climate grid (Figures 20, 22, 23, 25, and information included in table 4), HRUs are obtained – 227 polygons in total (Figure 26).

I obtain the total simulation units (SimuIDs) from these polygons as points, the single simulations in EPIC.

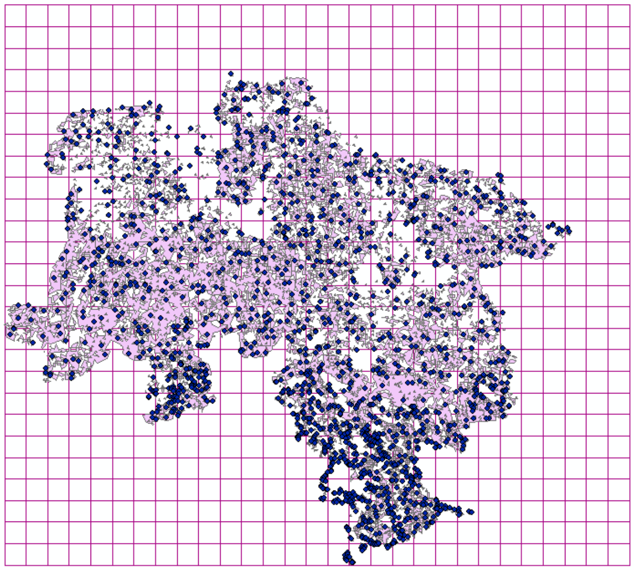

Figure 27 is the overlapping of the NetCDF grid above the rest required layers (previous figure)

Climate Data Grid: The climate data are NetCDF files. In ArcMap 10.6, I inserted them as a raster layer using the option Make NetCDF Raster Layer**.** When the file is not read correctly, one can create a grid with the correspondent cell size as represented on the left (Figure 27).

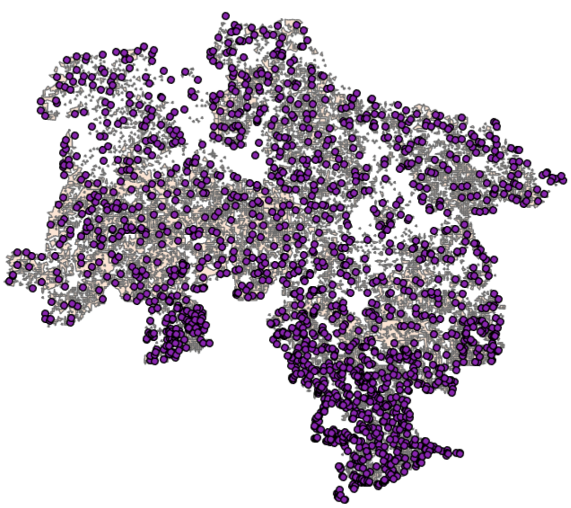

Figure 28 is the representation of each simulation unit as purple points over the study case area.

The total SimuIDs for this region are 1724. This means that to simulate the whole region of Lower Saxony, including geographical differences, one must simulate this number of points in EPIC (Figure 28).

Input data for EPIC

To define the EPIC simulation units and prepare the input data for the selected, I need to determine the soil data, geopolitical boundaries, and weather data extension. These layers intersect with the defined HRUs. This process allows obtaining the required simulation units.

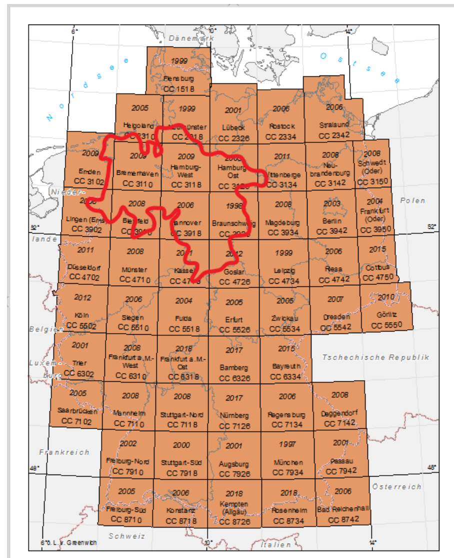

Figure 29 represents the soil grids that cover whole Lower Saxony, highlighted in red, from BÜK 200 that need to be downloaded to obtain the required soil information for the EPIC

The soil data required for EPIC is from the German Federal Institute for Geosciences and Natural Resources (*Bundesanstalt für Geowissenschaften und Rohstoffe BGR*). The current level of detail for nationwide evaluations is provided by the soil survey map on a scale of 1:200,000 (BÜK200)[73]. It includes 55 individual map sheets, as is shown in figure 29.

It is not easy to find all required soil parameters be in one source. In this case, this German soil database provides depth to the bottom of layer (Z), bulk density (BD), sand content (SAN), silt content (SIL), pH, and organic carbon concentration (WOC) – both only for some layers. The literature helps to obtain the rest of the parameters as the upcoming tables depict.

SOIL ALBEDO

Table 5 shows the used values for soil albedo based on the soil type found in the literature. For this dissertation, the average value from this range is the one used for the EPIC simulations.

Table 5 depicts the soil albedo values based on their soil type (Please refer to figure 21 to look at the German soil classification) used for the EPIC simulations for this research, including the value range found in the literature and the actual value used in the simulations.

Soil Type	Soil Surface	Albedo Range	Albedo Value	Source
U	Soils, dark, wet to light, dry	0.05-0.5	0.275	Oke (1987)
Ss	Dry sandy soil	0.25-0.45	0.35	Rosenberg et al. (1983)
Ss	Wet sand	0.09	0.09	Van Wijk and Scholte Ubing (1963)
Ss	dry sand	0.18	0.18	Van Wijk and Scholte Ubing (1963)
Tu	Wet dark clay	0.02-0.08	0.05	Van Wijk and Scholte Ubing (1963)
Tu	Dry dark clay	0.16	0.16	Van Wijk and Scholte Ubing (1963)
	Bare fields	0.12-0.25	0.185	Van Wijk and Scholte Ubing (1963)
	Green grass	0.16-0.27	0.215	Van Wijk and Scholte Ubing (1963)

PH

The German soil database includes code for the pH but not the actual values. Table 6 shows the translation of the pH codes found on BÜK 200.

Table 6 shows the German pH codes used in the soil database to describe the acidic or alkaline soil levels with corresponding pH values.

Level	Value	Description	Source
a3	8.60	alkaline	Ad-hoc-AG Boden 2005
a2	8.25	weakly alkaline	Ad-hoc-AG Boden 2005
a1	7.55	very weakly alkaline	Ad-hoc-AG Boden 2005
s0	7.00	neutral	Ad-hoc-AG Boden 2005
s1	6.45	very weakly acidic	Ad-hoc-AG Boden 2005
s2	5.25	weakly acidic	Ad-hoc-AG Boden 2005
s3	5.05	moderately acidic	Ad-hoc-AG Boden 2005
s4	4.35	very acidic	Ad-hoc-AG Boden 2005
s5	4.00	very acidic	Ad-hoc-AG Boden 2005

HUMUS LEVEL

As in the previous section, humus levels are given with codes in the soil database. For the actual values, please refer to Table 7

Table 7 translates the values of humus levels from the codes found on the German soil database, including the organic carbon content in percentage.

Humus class	Humus percentage	Organic carbon percentage	Source
h0	0	0.00	Ad-hoc-AG Boden 2005
h1	1	0.58	Ad-hoc-AG Boden 2005
h2	1.5	0.87	Ad-hoc-AG Boden 2005
h3	3	1.75	Ad-hoc-AG Boden 2005
h4	6	3.49	Ad-hoc-AG Boden 2005
h5	11.5	6.69	Ad-hoc-AG Boden 2005
h6	15	8.72	Ad-hoc-AG Boden 2005

PH BASED ON HUMUS LEVEL

In the soil database, not all layers have pH values available. However, there is a way to correlate the soil type and humus content with the approximate pH value, as shown in Table 8.

Table 8 describes the values of pH according to their corresponding humus levels (rows h0 to h6) and soil type (columns from S to t soil type) based found on BÜK 200.

Soil type	h0	h1	h2	h3	h4	h5	h6	Source
S	5.50	5.50	5.50	5.50	5.50	5.00	4.25	LUFA Oldenburg, 1979
ls	6.00	6.00	6.00	6.00	5.50	5.00	4.25	LUFA Oldenburg, 1979
tU	6.00	6.00	6.00	6.00	5.50	5.00	4.25	LUFA Oldenburg, 1979
sl	6.80	6.80	6.80	6.80	6.50	6.00	5.00	LUFA Oldenburg, 1979
tl	6.80	6.80	6.80	6.80	6.80	6.00	5.00	LUFA Oldenburg, 1979
Ut	6.80	6.80	6.80	6.80	6.80	6.00	5.00	LUFA Oldenburg, 1979
t	6.80	6.80	6.80	6.80	6.80	6.00	5.00	LUFA Oldenburg, 1979

CARBONATE CONTENT

Carbonate content is described in codes. Table 9 describes the values of carbonate content based on the principles found in the soil database.

Table 9 shows the German carbonate content codes used in the soil database used in this dissertation for the EPIC simulations with their corresponding values and description found in the literature.

Carbonate Level	Value	Description	Source
c0	0.00	carbonate free	Ad-hoc-AG Boden 2005, Bodenkundliche Kartieranleitung, 5 Aufl. Hannover
c1	0.50	very low in carbonate	Ad-hoc-AG Boden 2005, Bodenkundliche Kartieranleitung, 5 Aufl. Hannover
c2	1.25	low carbonate	Ad-hoc-AG Boden 2005, Bodenkundliche Kartieranleitung, 5 Aufl. Hannover

c3	6.00	containing carbonate	Ad-hoc-AG Boden 2005, Bodenkundliche Kartieranleitung, 5 Aufl. Hannover
c4	17.50	rich in carbonate	Ad-hoc-AG Boden 2005, Bodenkundliche Kartieranleitung, 5 Aufl. Hannover
c5	37.50	very rich in carbonate	Ad-hoc-AG Boden 2005, Bodenkundliche Kartieranleitung, 5 Aufl. Hannover
c6	62.50	extremely high in carbonate	Ad-hoc-AG Boden 2005, Bodenkundliche Kartieranleitung, 5 Aufl. Hannover
c7	75.00	carbonate	Ad-hoc-AG Boden 2005, Bodenkundliche Kartieranleitung, 5 Aufl. Hannover

BULK DENSITY

As in the case of carbonate content, the bulk density must be translated from the assigned code to the actual value to be used as input information (See Table 10).

Table 10 describes the bulk density values based on the German soil database and their meaning and corresponding values found in the literature.

Level	Level value	Value g/cm3 (T/m3)	Description	Source
Ld1	1	1.30	very low	Ad-hoc-AG Boden 2005
Ld2	2	1.43	low	Ad-hoc-AG Boden 2005
Ld3	3	1.65	medium	Ad-hoc-AG Boden 2005
Ld4	4	1.85	high	Ad-hoc-AG Boden 2005
Ld5	5	1.95	very high	Ad-hoc-AG Boden 2005

SATURATED CONDUCTIVITY

Saturated conductivity is not directly in the soil database. However, according to literature is possible to correlate the soil texture and its corresponding bulk density to a specific saturated conductivity value in mm/h (Refer to Table 11).

Table 11 describes the values of saturated conductivity in mm/h based found on the soil database used for the EPIC simulations based on the soil type and bulk density (rows Ld1 to Ld5) found in the literature.

Soil Type	Ld1	Ld2	Ld3	Ld4	Ld5	Source
Ss, mS	161.05	132.88	87.41	52.62	37.21	Rawls et al. 1998
fS	104.28	79.29	44.55	24.72	18.70	Rawls et al. 1998
gS	420.02	297.00	142.20	76.52	69.05	Rawls et al. 1998
Uu	15.38	11.61	6.15	2.74	1.55	Rawls et al. 1998
Ut2	18.80	14.15	7.37	3.03	1.47	Rawls et al. 1998
Uz3	17.59	12.71	5.64	1.23	-0.31	Rawls et al. 1998
Ut4	18.23	13.15	6.12	2.13	0.94	Rawls et al. 1998
Us	14.99	10.80	5.04	1.84	0.92	Rawls et al. 1998
Uls	18.18	14.15	7.87	3.34	1.44	Rawls et al. 1998
Lu	19.05	14.88	8.58	4.28	2.60	Rawls et al. 1998
Tt, Tu2, Tl,Tu3	25.49	16.91	5.93	0.99	0.21	Rawls et al. 1998
Tu4	26.10	17.81	7.00	1.82	0.79	Rawls et al. 1998
Lt3	20.54	15.66	8.43	3.67	1.87	Rawls et al. 1998
Lt2	28.59	22.90	13.58	6.28	2.98	Rawls et al. 1998
Lts	19.01	14.84	8.53	4.24	2.56	Rawls et al. 1998
Ts2, Ts3	26.82	19.90	10.15	4.41	2.58	Rawls et al. 1998
Ts4	31.52	24.25	13.48	6.40	3.74	Rawls et al. 1998
Sl2	89.13	70.13	41.86	23.12	16.00	Rawls et al. 1998
Sl3	45.88	35.99	21.59	12.44	9.15	Rawls et al. 1998
Sl4	40.33	31.61	18.77	10.45	7.38	Rawls et al. 1998
Slu	35.17	27.56	15.80	7.42	3.96	Rawls et al. 1998
St2	72.85	58.02	35.09	18.75	12.01	Rawls et al. 1998
St3	56.04	43.31	24.61	12.55	8.14	Rawls et al. 1998
Su2	74.09	56.55	31.72	16.91	12.07	Rawls et al. 1998
Su3	43.50	33.70	19.26	9.89	6.43	Rawls et al. 1998
Su4	38.75	30.54	18.02	9.34	5.86	Rawls et al. 1998
Ls2	26.57	21.18	12.65	6.35	3.65	Rawls et al. 1998

Ls3	29.42	23.46	14.33	7.96	5.38	Rawls et al. 1998
Ls4	34.27	28.65	18.86	10.49	6.42	Rawls et al. 1998

FIELD CAPACITY

Field Capacity values are not be found in the soil database. According to the literature, the soil texture can be correlated to the field capacity, as in Table 12.

Table 12 describes the field capacity content values based on the soil database used in the EPIC simulations

Soil type	Field Capacity [m/m]	Source
SS	0.07	Ad-hoc-AG Boden 2005
Su3	0.21	Ad-hoc-AG Boden 2005
Su4	0.23	Ad-hoc-AG Boden 2005
Su2	0.18	Ad-hoc-AG Boden 2005
St2	0.16	Ad-hoc-AG Boden 2005
Sl2	0.18	Ad-hoc-AG Boden 2005
Sl3	0.18	Ad-hoc-AG Boden 2005
UU	0.26	Ad-hoc-AG Boden 2005
Us	0.25	Ad-hoc-AG Boden 2005
Uls	0.22	Ad-hoc-AG Boden 2005
Ut2	0.26	Ad-hoc-AG Boden 2005
Ut3	0.25	Ad-hoc-AG Boden 2005
Ut4	0.21	Ad-hoc-AG Boden 2005
Lu	0.17	Ad-hoc-AG Boden 2005

SOIL RELEVANCE FOR THIS RESEARCH

This research uses the processed-based crop model EPIC, whose main inputs are the main soil description. This includes its texture, pH, organic content, electrical conductivity, nitrogen initial organic, among others for each layer.

For this first paper –**Chapter 3** – we did a first spatial analysis of the fourteen selected districts in the study region – NELS and SLS – as each of this group – as explained in the

Simulation Area Section– NELS is mainly sandy-textured soil, and SLS is silt-clay textured soil.

Even though, when we tried to see the effect of changing the texture on crop yields under the three RCP climate scenarios, there were no significant changes as expected – see chapter Chapter 3: Paper 1 – The main reason for this is that, as mentioned before, EPIC describes the soil texture, but also many physical and chemical parameters. These were not changed for this assessment.

Since soil is an essential, complex, and living ecosystem relevant for human economic activities primarily related to agriculture, forestry, and horticulture, in other words, soil protection is necessary to ensure our existence on this planet for current and future generations.

Additionally, soil constitutes the central carbon pool representing about 65% of the stored in the atmosphere and plant and animal life[74] as posted in figure 30.

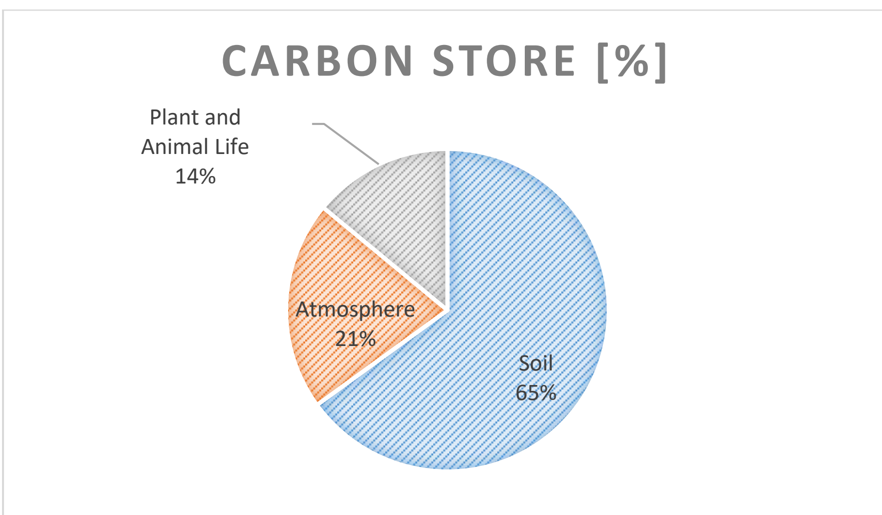

Figure 30 Carbon storage pools at a global scale. More than half corresponds to the soil as the main carbon storage pool.

Intensive agriculture negatively affects the soil's natural capacity to store carbon in the long run by being a source of carbon and nitrogen emissions. Together, both EU croplands and grasslands are net sources of emissions, releasing about 75,3 million tons of carbon dioxide equivalent (MtCO2e) in 2017(Institute for European Environmental Policy 2020). In this sense, agriculture plays a crucial role in capturing and storing carbon in soils and biomass by restoring soil functions with sustainable management strategies.

Conversation tillage, water efficiency irrigation, planting, harvesting scheduling, green mulching are just some management options that one can apply to make use of soil and water resources more efficiently. Thus, farmers can treat soils as a renewable resource, which leads to avoiding erosion, degradation, salinization, contamination – in the case of conventional agriculture – and its destruction.

Chapter 4 (Second paper) assesses the correlation of planting and harvesting scheduling and irrigation amounts and date with crop yields**. Chapter 5 (Third paper)** also estimates which climate predictor is more suitable for defining crop yield losses. Among such predictors include Soil Moisture Deficit (SMD) and climate indices as proxies for moisture measurement.

For clarity purposes, in this study, I am referring to agricultural drought when drought is used. In simple words, this drought phenomenon refers to the interaction between current climatic conditions and farming factors related to management (e.g., increasing irrigation, changes in land use) that negatively affect agricultural production in terms of yield (e.g., biomass, caloric content). For this reason, agricultural drought goes beyond climatic drought as human actions play a role in escalating drought increasing yield losses[76].

Chapter 3

CHAPTER 3

Evaluating the viability of soybeans cultivation as an adaptation measure to climate change in Lower Saxony using EPIC

ABSTRACT

CONTEXT

The agricultural sector is susceptible to climate variability. Due to climate change, it will suffer several impacts on yield quantities and stability in the future. Climate projections show an increased frequency and strength of droughts and flooding that negatively impact farmers' income due to yield losses.

OBJECTIVE

We used the crop model EPIC to perform simulations in Northern Germany to assess soybeans' potential as an adaptation measure to enhance existing crops such as winter wheat and silage corn. This research seeks a district-level assessment to understand the geographical differences and potential advantages in soil properties and climate.

METHODS

The future was divided into 2035-2065 and 2070-2100 for each simulated RCP scenario: 2.6, 4.5, and 8.5. We simulated a crop rotation of potato-sugar beet-corn-wheat, including soybeans in different positions to assess where yields may obtain a higher positive impact compared with the simulations without soybeans.

RESULTS AND CONCLUSIONS

The simulations show a strong influence of the climate on yield changes in the future, especially having high yield losses for RCP 8.5 for both winter wheat and silage corn. Existing irrigation conditions might be sufficient to attain stable yields for current crop rotation or soybeans within the crop scheme. Although soybeans' presence may lead to a slight increase in yields, this was only shown when soybeans were within the crop rotation and not when soybeans replaced winter wheat or silage corn. Winter wheat showed better performance in terms of yield stability than silage corn in the presence of soybeans. However, the potential of soybean is limited due to the lack of water availability for irrigation and increasing temperatures in the future, namely scenario RCP 8.5.

SIGNIFICANCE

This research supports the decision-making process of implementing new adaptation measures in agriculture since the current management applied options may not be sufficient to keep the region's present-day wheat and corn yields.

Keywords: legumes, soil activity, agriculture, RCP scenarios, crop model, northern Germany

HIGHLIGHTS

- Northern Germany may be warm enough to plant soybeans for the period (2035-2100)
- Higher nutrients availability for winter wheat and silage corn due to the inclusion of soybeans
- Potential benefits are minimal for RCP 8.5 in 2070-2100 as plants are heavily temperature stressed

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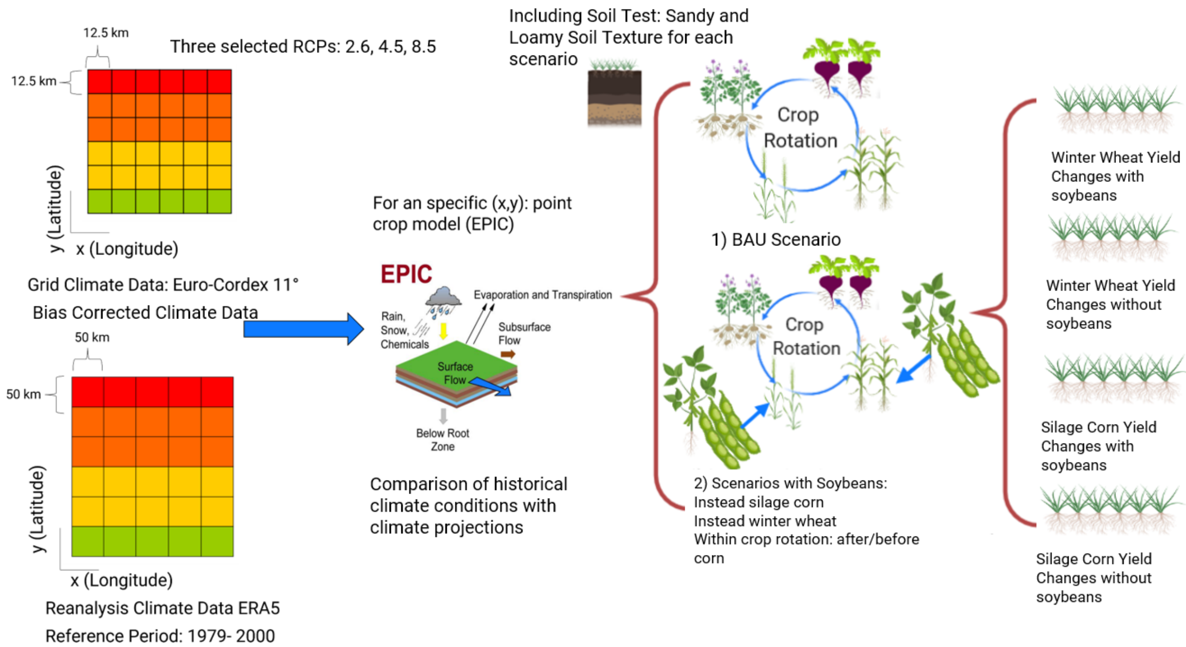
GRAPHICAL ABSTRACT



INTRODUCTION

Climate projections based on the Special Report on Emissions Scenarios (SRES) from The Fifth Assessment Report (AR5)[24] of the United Nations Intergovernmental Panel on Climate Change (IPCC) for Northern Germany, specifically for the federal state of Lower Saxony, reveal an increment in annual mean temperature of 2.5 degrees by the end of the 21st century compared to the period 1971-2000. This increase is expected to be more pronounced during summer, about three °C[26]. Consequently, the vegetation period will increase by up to two months. Heatwaves, as experienced in 2018, will occur more frequently. The KLIFF research alliance, "Climate Impact Research in Lower Saxony," estimated that the average duration of heat periods in summer could increase by about 50%[25]. According to Kreyling et al. (2011), the number of thaw-freeze cycles is projected to decrease in Northeastern Germany by around 61% compared to 1971-2000, affecting soil microbiological activities plant processes[77].

Agricultural production is susceptible to climate variability and will suffer various impacts because of climate change. This situation will most likely economically affect the farmers in the region. In 2018, severe drought episodes reduced crop yields in Northern Germany by 22%[78]. The affected crops include the most commonly planted crops, silage corn and winter wheat. These adverse effects could be reduced if adaptation measures were applied that promised more stable yields. One option for adaptation could be to cultivate crops better suited for changing climate conditions, improving soil characteristics for agricultural production.

A crop that could meet these requirements is soybean since it can fix nitrogen from the atmosphere and boost soil organic matter (Mazzilli et al.,2014[79]; Zhu et al., 2012[80]; Villamil et al., 2006[81]). Besides fertilization, nitrogen fixation is the most critical pathway for plants to obtain this element, a vital limiting component of most plant growth processes[82]. Similarly, soil organic matter serves as a nutrient source for plants, provides a habitat for microorganisms, and binds soil particles into aggregates improving its water-holding capacity[83]. Previous studies have shown the adaptation potential of soybeans to future climatic conditions. Ahumada et al., 2018 describe a positive impact of high levels of CO2 on the fertilization effects of soybeans in Argentina using a modeling framework[84]. Nasielski et al., 2015 reported that soybeans in an agroforestry system promoted yield stability in Ontario, Canada[85]. In the case of Europe, Balko et al., 2014 stated that specific soybean varieties showed tolerance towards chilling in a field test in Northern Germany, allowing their cultivation as a protein crop[86].

There have been other initiatives like Soybean Promotion German Council (*Deutscher Soja-Förderring*)[23,87] and Protein feed from Lower Saxony (*Eiweißfutter aus Niedersachsen*)[88]. The first initiative focuses solely on soybeans, the second on domestic legumes such as peas. Both projects aim to promote the expansion of legumes in Lower Saxony by testing different varieties and management options on the field to reduce the import of soybeans. The Chamber of Agriculture in the federal state of Lower Saxony has tested soybean cultivation on experimental fields in the region, obtaining average yields of about 2.7 t/ha with irrigation[89]. However, soybeans' production (t/ha) needs to increase by around 63% to compete with wheat or corn in added financial value for farmers[18].

While field trials can provide detailed short-term data on plant and soil processes and properties[90], they do not offer information on the long-term effects of having soybeans and peas in a crop rotation in Northern Germany[13]. How will yields, fertilization, and water usage be affected, and how will climate change and an increased CO2 concentration in the atmosphere impact these factors? To answer these questions, we used the Environmental Policy Integrated Climate (EPIC) model to assess how crop yields are affected by different climate scenarios and crop rotations with and without legumes until the end of the century. EPIC is a process-based crop model that predicts how soil erosion, crop yields, irrigation water use, and soil processes are affected by climate characteristics (including CO2 concentration) and management options such as crop rotation strategies[92]. We also tested the suitability of soybeans as an adaptation measure in specific districts in the federal state of Lower Saxony.

This study presents the first analysis of the long-term potential of soybean cultivation in Northern Germany, using three climate scenarios (RCP 2.6, 4.5, and 8.5). With this research, we aim to be able to answer the following questions. Firstly, may soybeans be planted in the future with similar yields as today? Secondly, may crop yields be attained in the future with similar current levels with existing irrigation amounts? Finally, can soybeans improve planted crops in the regions?

DATA AND METHODS

This study focuses on fourteen districts in the federal state of Lower Saxony in northwestern Germany, illustrated in Figure 31. The predominant economic sector in the area is agriculture. 80% of the local jobs are directly or indirectly dependent on agriculture, which is more than any other federal state[93]. The cultivated area comprises 2.6 million hectares, of which about 33% are solely used for cereal production. Lower Saxony is one of

Germany's primary producers of winter wheat and silage corn, with a national share of 12% and 29%, respectively[94].

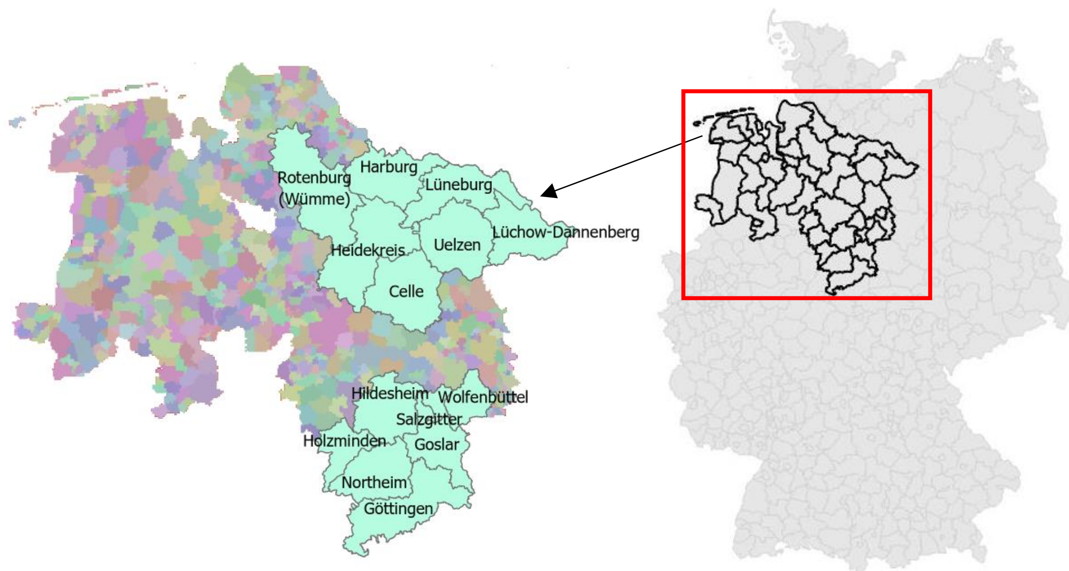


Figure 31 Left: Federal State of Lower Saxony; highlighted in light green are the fourteen districts considered in this study. Right side: Localization of Lower Saxony in Germany

SIMULATION SETUP

Two different crop rotation scenarios were used to analyze soybeans' effect on other crops' yields. Firstly, a BAU crop rotation without legumes, and secondly, a legume scenario including soybeans within the crop rotation before and after corn.

We divided the simulation area into two main groups according to their location and predominant soil: Northeastern Lower Saxony (NELS), with poor, sandy soils (mostly podzols); and Southern Lower Saxony (SLS), where productive loamy soils with high natural fertility are characteristic (Figure 31). We run the simulations for three RCPs and include annual CO2 increases as an input to EPIC.

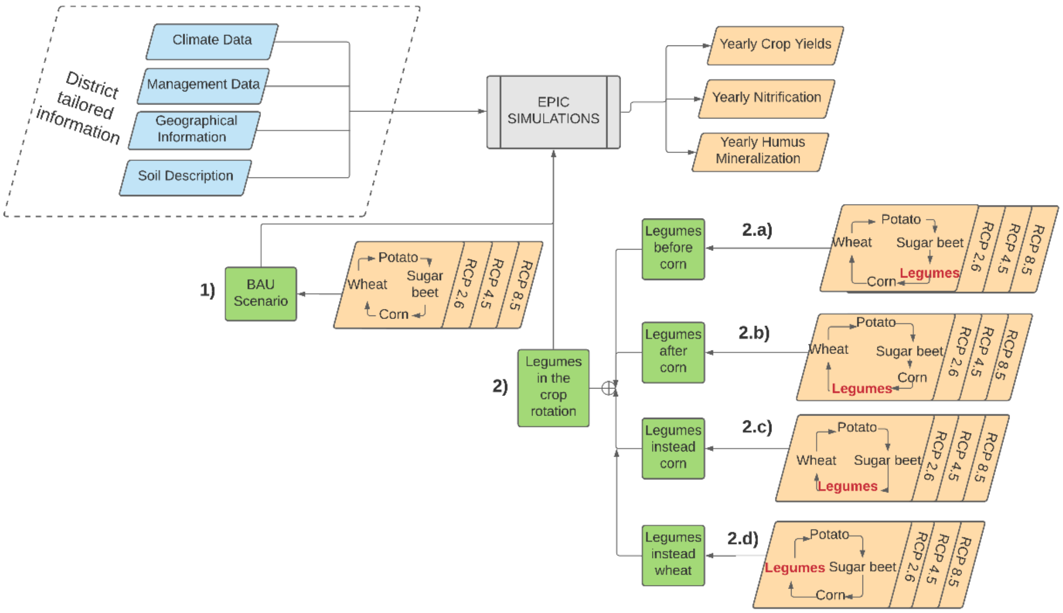


Figure 32 Description of the simulation setup with EPIC. Green boxes represent the scenarios. Orange boxes are the simulated crop rotations, and blue boxes are the input data used for all scenarios

Crop yields are influenced by both climate and the soil characteristics where the soil is planted. For this reason, in this research, we have simulated a four-year crop rotation (Figure 32), including time and geographical cycle. The inclusion of the entire crop rotation cycle allows reducing climate bias on crop yield results. As explained above, silage corn and winter wheat are the most relevant crops in the region. For this reason, though we simulated a crop rotation including potato and sugar beet, the future impact assessment on yields was conducted for winter wheat and silage corn.

EPIC CROP MODEL

The Erosion Productivity Impact Calculator (EPIC) model was initially developed by the USDA (United States Department of Agriculture) in the early 1980s to simulate the effects of soil erosion on crop productivity and assess how agricultural activities affect the status of US soil and water resources[32–34]. The model has been continuously expanded to simulate many other processes relevant for land use and agriculture[32,33,36,38]. EPIC works in a daily resolution, being capable of simulating future conditions. Long-term soil assessments like humus build-up processes can be examined yearly or seasonal scales for yield levels, water usage, fertilizer, and pesticide requirements. EPIC is a field-scale model that simulates homogenous areas in weather, soil, landscape, and management operation parameters[95].

In EPIC, it is possible to set up an irrigation trigger, such that the plants are irrigated each time there is water stress. We compared reported data from 2002 to 2018 on irrigation with EPIC irrigation outputs using different irrigation levels. We found that the values of 1.50 and 8.00 mm agree well for this purpose as the minimum and maximum single application volumes, respectively. Likewise, we established in the model configuration 94 mm as the total annual irrigation volume allowed. We decided to take a higher value than 80 mm, the legal permitted in the region since farmers can exceed their contingency if a drought occurs during a vegetation period of 30 mm[96]. For this purpose, we used 94 mm, which corresponded to the amount of water taken for irrigation in 2003.

EPIC requires five weather parameters as input (Table 13). Precipitation is decisive for agriculture, as past drought caused crop yield reductions in Germany[97,98]. Additionally, extreme events such as heatwaves have also negatively impacted crop yields[99,100]. For this reason, we focused our weather analysis on precipitation, maximum and minimum temperature, and their influence on potential crop reduction in the future.

We run EPIC v.0810 for three RCP scenarios (RCP 2.6, 4.5, and 8.5) to test the districts' yield behavior heterogeneity. To analyze the direct weather effect on the yields, we calculated the absolute difference of maximum and minimum mean Temperature in contrast to the reference period (1979-2017) for two periods in the future: 2035-2065 and 2070-2100. For precipitation, we calculated the relative difference also against the mean rainfall for the reference period. This research's specific climate projection information is obtained from the Regridded and Corrected Data Sets for the IMPACT2C SlowTrack Models[58]. The RCM-GCM combination is CSC-REMO2009- MPI-ESM-LR for three RCPs (2.6, 4.5, and 8.5)[61,62].

We calibrated the model by comparing reported yields (1979-2018)(Erntestatistik online - AktuelleErnteberichte Niedersachsen 2018) with the same period's simulated ones under the same conditions. We used reanalysis data taken from ERA5[102] for the reference period since this database serves as a complete version of weather station data.

INPUT DATA

Table 13 shows the most relevant parameters utilized to calibrate and run the model for the different scenarios.

Table 13 shows relevant parameters used for EPIC simulations, including climate, CO2 concentrations for each RCP scenario, management information for each simulated crop, topographic and soil information.

Category	Parameters	Reference
Climate: Historical (1979-2018) Lower Saxony Daily data	Maximum daily mean temperature (°C) Minimum daily mean temperature (°C) Relative Humidity (%)	Copernicus Programme Climate Reanalysis: Run with ERA5 (Re-analysed data)[102]
Climate Projections (2030-2100): RCP2.6 RCP 4.5 RCP8.5 Daily Data	(Shortwave) Solar radiation (MJ/m2) Precipitation Quantity (mm)	IMPACT2C Quantifying projected impacts under 2 °C warming Report on climate-change information. (2014)[11]) The model used: CSC-REMO2009- MPI-ESM-LR for three RCPs (2.6,4.5 and 8.5)
CO2 Concentration RCP 2.6 RCP 4.5 RCP 8.5	Yearly CO2 concentration (ppm-CO2-eq) For the daily values, the annual values were repeated for each day in the same year	"GGI Scenario Database" web application is: International Institute for Applied System Analysis (IIASA) GGI Scenario Database Ver 2.0, 2009[103]
Topographic information	Slope Elevation	Digital Elevation Model (DEM) Lower Saxony from high precision DTM dataset of Germany[104]
Soil information	Soil texture Soil type Organic Carbon content Bulk density Carbonate content pH	Soil Map of Germany at scale 1:200,000 (BÜK200)[73]
	Soil albedo	Rosenberg et al. (1983)[105]

	Soil Hydrologic Group	Global Hydrologic Soil Groups (HYSOGs250m) for Curve Number-Based Runoff Modelling[106]
	Soil water at field capacity (1500 kPa)	Bodenbewertungsinstrument Sachsen; Stand 03/2009[107]
Land Use	Agricultural Area	Copernicus CORINE Land Cover Database 2018[72]
Soybean (*Glycine max*) operation information	Seeding Density: 70 grains/m2 Planted May 12th Harvested August 28th Manure 112.05 kg/ha Kali 2.50 kg/ha Phosphorus 4.50 kg/ha	Soybean field tests in Germany: Hiltbrunner et al. (2012)[108] Kunz et al. (2015)[109] Weber et al. (2016)[110]
Sugarbeet (*Beta vulgaris L*) operation information	Seeding density: 11 plants/ha Planted March 16th Harvested: September 5th PK-Solution 450 kg/ha Kali-Mg 140 kg/ha 28-10-10 soluble solution 400 kg/ha	Sugar beet field tests in Germany: Kunz et al. (2015)[109] KTBL-Datensammlung 2018/19[52] Direct operation information from farmers of the region
Wheat (*Triticum aestivum L.*) operation information	Seeding Density: 40 grains/m2 Planted October 25th Harvested July 20th 28-10-10 soluble solution 720 kg/ha Seeding density: 40 plants/m2 Planted March 16th Harvested August 20th 28-10-10 soluble solution 480 kg/ha	KTBL-Datensammlung 2018/19[52] Direct operation information from farmers of the region
Potatoes (*Solanum tuberosum*)	Seeding Density: 40 grains/m2	KTBL-Datensammlung 2018/19[52] Direct operation information from farmers of the region

operation information	Planted April 4th Harvested September 18th PK-Solution 500 kg/ha Manure 24.5 kg/ha 28-10-10 soluble solution 400 kg/ha	
Corn (*Zea mays* L.) operation information		KTBL-Datensammlung 2018/19[52] Direct operation information from farmers of the region

AGGREGATED CLIMATE INFORMATION

To have a general visualization of the distributions of precipitation, maximum and minimum temperature among the three RCPs scenarios, we made boxplots representing each RCP scenario for both groups of districts. We calculated the absolute difference based on the reference period; the relative difference was computed for precipitation (Figure 33).

As Figure 33 illustrates, maximum temperature increases towards RCP scenarios. For the near future, the variability does not change among the RCP 4.5 and 8.5. In contrast, for RCP 2.6, the spread over the data is substantially lower. Period 2070-2100 shows a more evident increasing trend across the three RCP scenarios. In the case of precipitation, for the period 2035-2065, precipitation level losses between RCP 2.6 and RCP 8.5 are similar. Rainfall amounts for RCP 4.5 are expected to rise around 20%.

Interestingly, the opposite is foreseen to occur for the distant future period. An increase in rainfall is likely to happen for RCP 8.5. Minimum temperatures for both periods ascend; however, this trend is more evident in the distant future. This trend is also shown with the variability between the RCP scenarios.

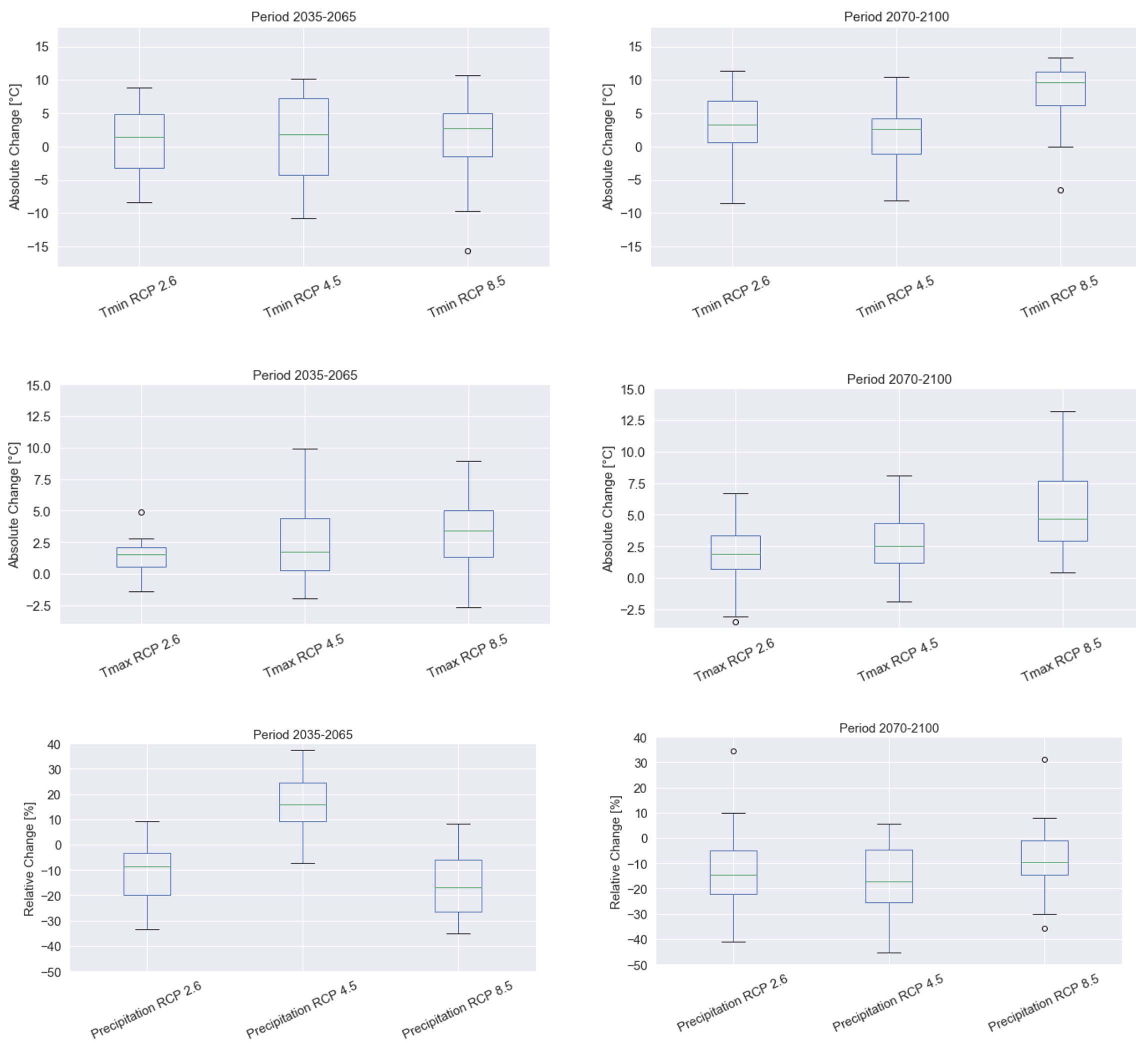


Figure 33 describes the minimum temperature, maximum temperature and precipitation changes respect to the reference period respectively for each RCP scenario (x axis). Temperature is represented using absolute change and precipitation with relative change (y axis). The future periods was split in two: near future, left side and far future, right side.

We provide ERA5 climate data to analyze the expected changes for the three climate RCP scenarios. Figures 33 displays future warmer future Temperatures than in figure 34. On the other hand, precipitation fluctuations show that it is expected to lower total precipitation levels.

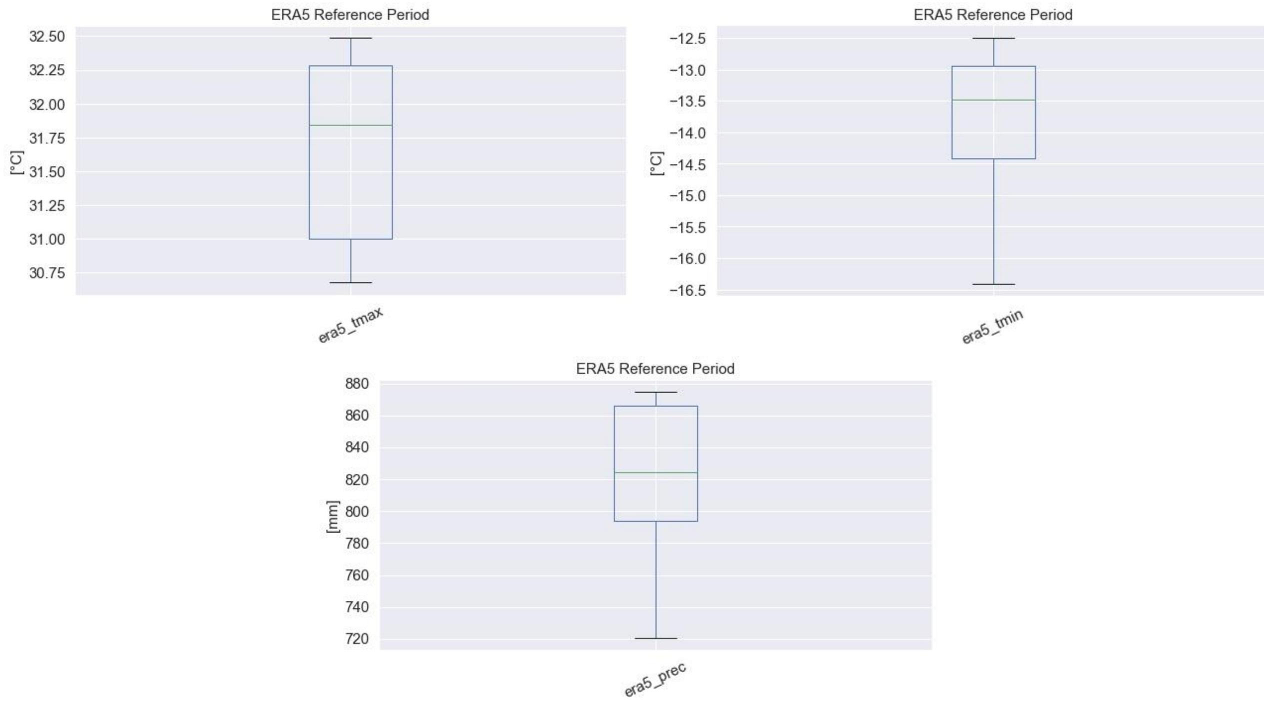


Figure 34 describes the minimum temperature, maximum temperature and precipitation for the reference period respectively

RESULTS

This section divided all NELS and SLS results using maps to distinguish potential geographical differences between districts. Firstly, we show possible soybean production in the future with boxplots for the various RCP scenarios compared with reference period production. Secondly, we illustrate the effect of soybeans within the crop rotation on soil processes. Lastly, we display maps of all fourteen districts' yield changes for winter wheat and silage corn relative to the BAU scenario's reference period and their comparison with soybeans' presence within the crop rotation.

SOYBEAN YIELDS

The calibration process for soybeans was slightly different for the rest of the crops. There is no information on soybean cultivar for the region except for some field tests done in the area from 2009 to 2012(Trial report on organic soybean cultivation in Lower Saxony 2012 translated from[111]). EPIC could represent the actual yields with an average standard deviation of about 0.35 t/ha. After this calibration process, we simulated soybeans for all districts for the reference period to compare expected future yields for the three RCP scenarios (Figure 35). All scenarios show an increase of 50% in soya yields compared to the reference period yield. Even for the distant future (2070-2100), yields are higher than those produced during 1979-2017. However, this increase is even higher for the nearer future (2035-2065). For the RCP 8.5 scenario, the difference in yield production between the near and distant future is more pronounced than the other two climate scenarios. Interestingly, for RCP 2.6, the yields are more variable than for the two different climate scenarios. This could be explained as Temperatures are expected to be warmer, which provides an advantage for the growth of soybean since the optimum Temperature is 21°C, and the base Temperature is 5°C.

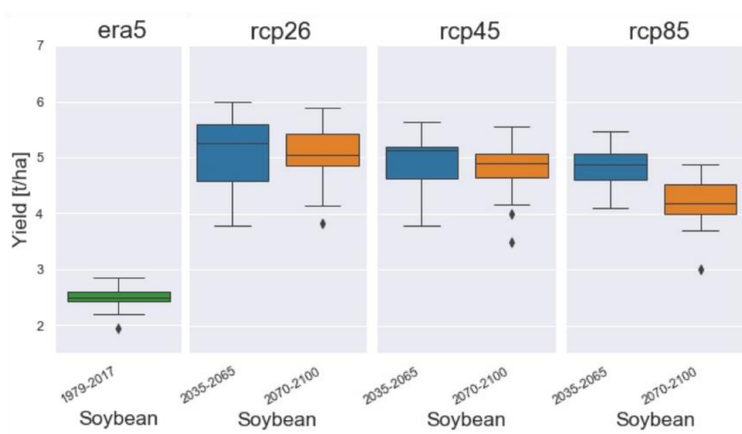


Figure 35 shows soybean yields for the reference period (left). It also shows soybean yields under three different RCP scenarios in the near and distant future (right).

SOYBEAN EFFECT ON THE ACTIVITY OF THE SOIL

The most significant increase in soil activity processes (Figure 36) - nitrification and humus mineralization- are present in scenario RCP 2.6 for 2070-2100. In RCP 4.5 and 8.5, the increase between the near and distant future is less evident. This rise indicates that more soil nutrients are available for the plant's roots on the soil when soybean is within crop rotation than the BAU scenario.

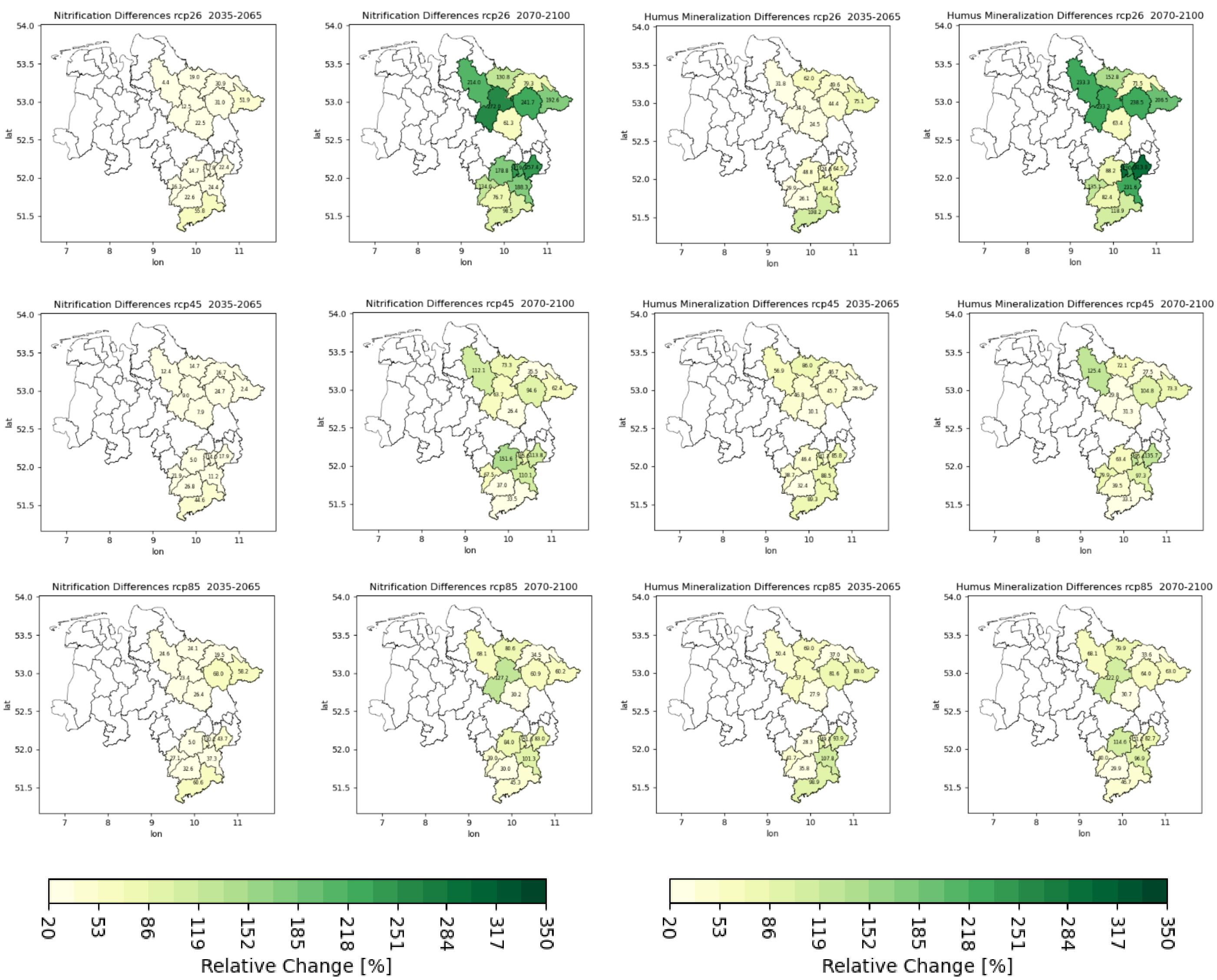


Figure 36 shows two soil processes (nitrification (left) and humus mineralization (right)) with and without soybeans under three RCPs for near and distant future periods

RELATIVE YIELD CHANGES DIFFERENCES AMONG DISTRICTS

Table 14 shows the base yields for winter wheat and silage corn for all districts to calculate the yield changes for each tested scenario. These values were used to calculate the relative change in yield between the reference period and future yields shown in the following maps.

Table 14 depicts reference yields for Winter Wheat and Silage Corn for NELS and SLS, respectively

	District	**Winter Wheat [t/ha]**	**Silage Corn [t/ha]**
NELS	Celle	5.99	37.46
	Harburg	5.68	36.76
	Lüchow (Dannenberg)	5.73	38.11
	Heidekreis	5.52	36.33
	Uelzen	5.90	37.75
	Rotenburg	5.49	37.00
	Lüneburg	5.92	37.01
SLS	Holzminden	6.48	40.29
	Northeim	6.41	42.71
	Salzgitter	6.81	37.22
	Wolfenbüttel	6.48	40.93
	Hildesheim	7.03	39.75
	Goslar	6.54	38.74
	Göttingen	6.39	41.23

The following maps display (Figure 37-40) the relative changes in yield among the fourteen simulated districts to contrast the BAU scenario with legumes within the crop rotation and the potential effect of soil texture on crop yields. As Figure 6 shows, for RCP 4.5 and 8.5, winter wheat yields in all districts are negatively affected in the distant future. Remarkably, for RCP 8.5 in the period, 2070-2100 winter wheat yield losses reach on average up to 65%. The geographical location only offers a competitive advantage for NELS districts in the case of RCP 2.6. For the other two climate scenarios, this is not evident among the districts. Interestingly, the positive yields a relative change in Celle, Harburg, and Heidekreis increase from the near future to the distant future for RCP 2.6 and 4.5.

Silage corn shows a similar behavior as winter wheat. Nevertheless, for RCP 4.5 in the period 2035-2065, SLS districts' changes are improved compared to the same period for climate scenario RCP 2.6. In the RCP 8.5 climate scenario, yield relative negative change reaches values above 62% for winter wheat.

For both crops, it is notable to see that at first glance at figure 38 and 40 in RCP2.6, there is an apparent yield increase; in RCP 4.5, it is indifferent, and in RCP 8.5, the situation gets worse.

Figure 38 depicts the relative change of winter wheat yield between the BAU scenario (Figure 37) and soybeans within crop rotation (after the silage corn scenario). For RCP 2.6, yields are increased for both future periods than the BAU scenario for NELS and SLS districts. Additionally, this improvement is more visible for SLS than NELS districts. For RCP 8.5, there are no significant differences compared to the BAU scenario. On the contrary, for RCP 4.5, the relative changes for both future periods worsen when soybeans are part of the crop rotation.

There are no differences in yields between soybeans and peas in light of the simulation conditions when the legumes are within the crop rotation for winter wheat and silage corn. Those maps are to be found in the supplementary material.

There are not so many differences for winter wheat when legumes are planted after or before corn. On the other hand, corn yields may improve by having legumes within the crop rotation, as figure 3.6 shows. Interestingly, this described enhancement is more evident for scenario RCP 2.6 for all districts. In contrast, for scenario RCP 4.5, the improvement is better for NELS than SLS for the period 2070-2100; on the other hand, for period 2035-2065 for scenario RCP 8.5, NELS yields are improved, but then they get worse for distant future.

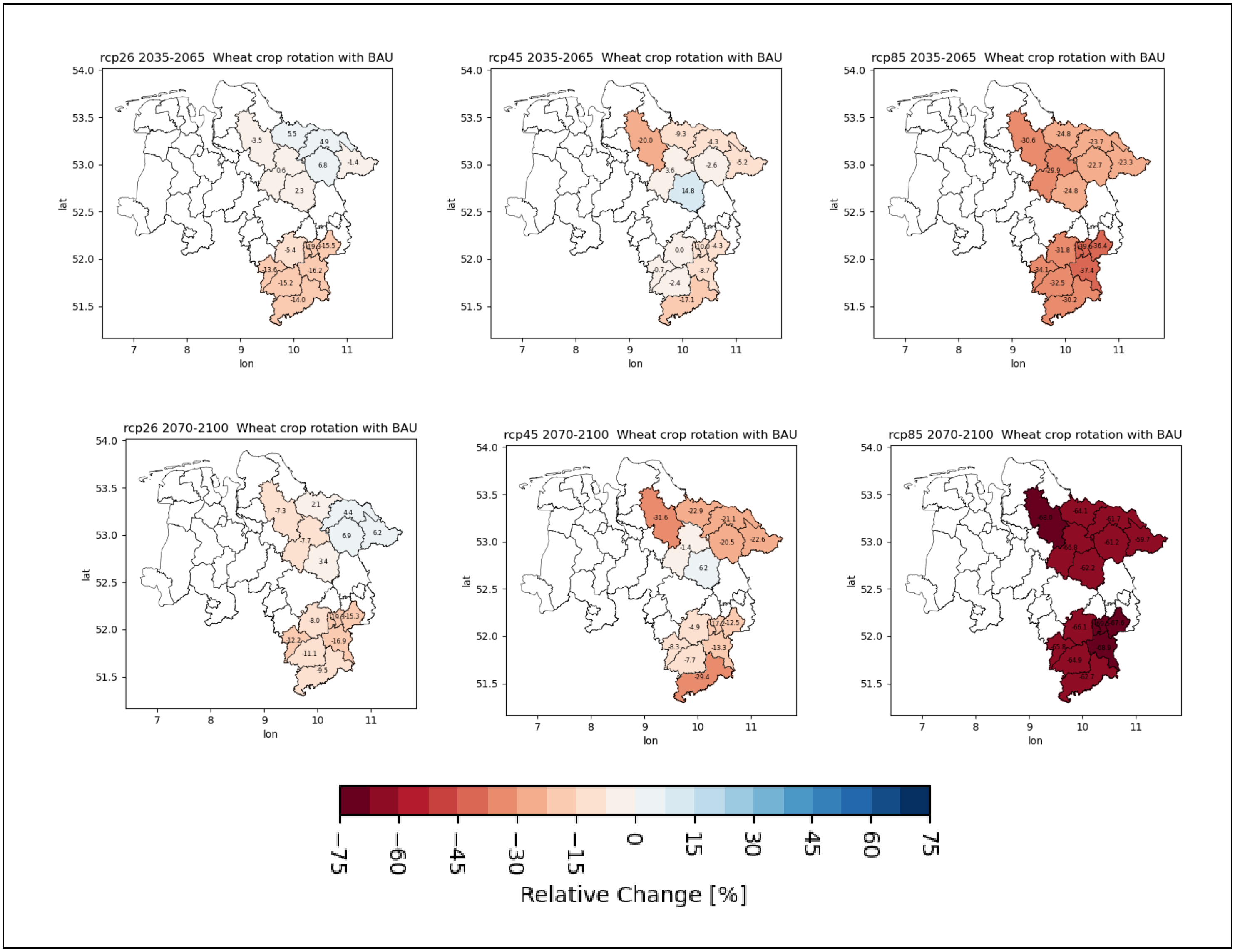


Figure 37 shows the winter wheat yield changes compared to the reference period under three RCPs scenarios. It also highlights two time periods (near future is in the row above, 2035-2065; distant future is the row below, 2017-2100).

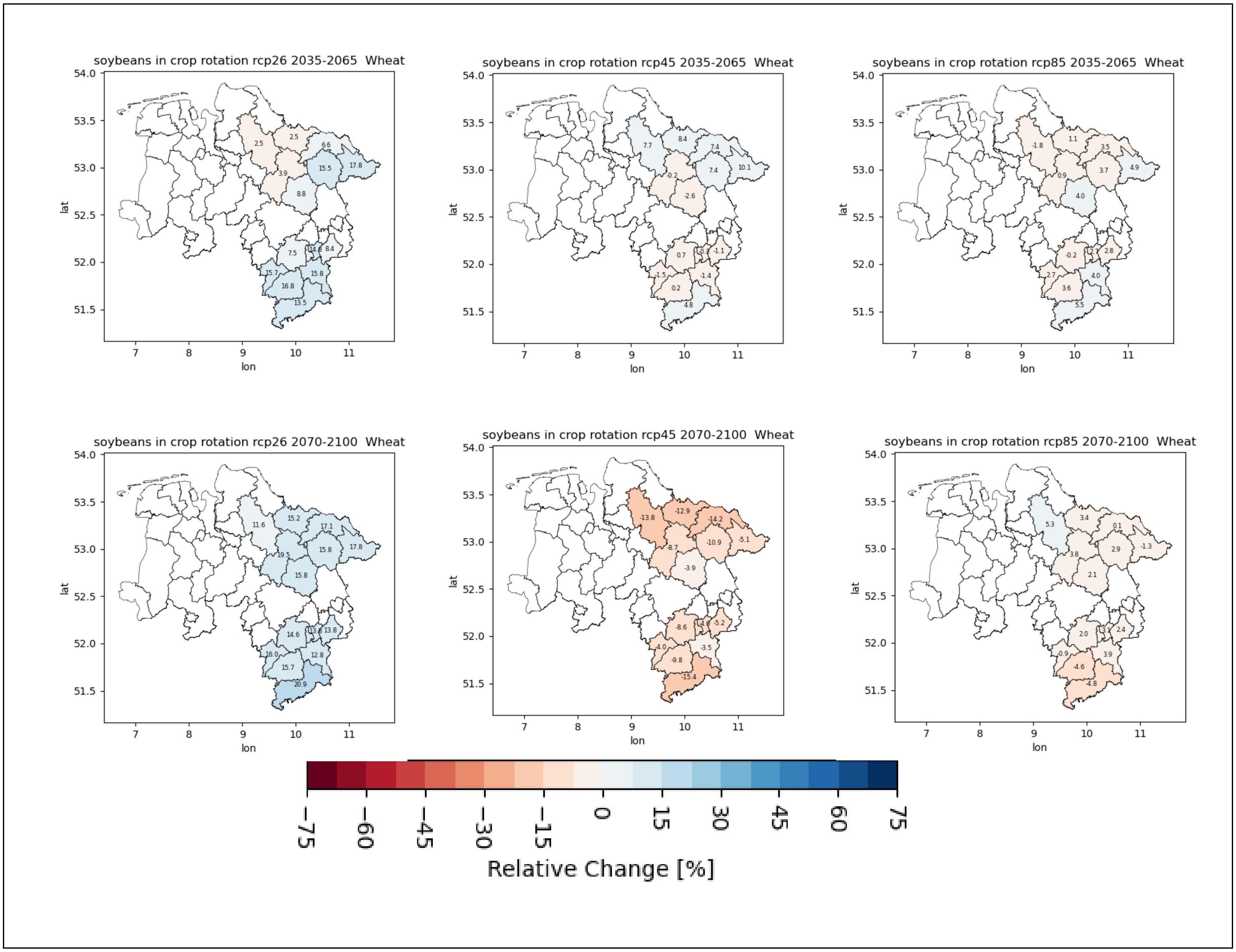


Figure 38 shows the winter wheat relative yield difference between two crop rotation scenarios (With soybeans and without soybeans, BAU). It also indicates both strategies under three different RCP scenarios for the near future (2035-2065) and the distant future (2070-2100).

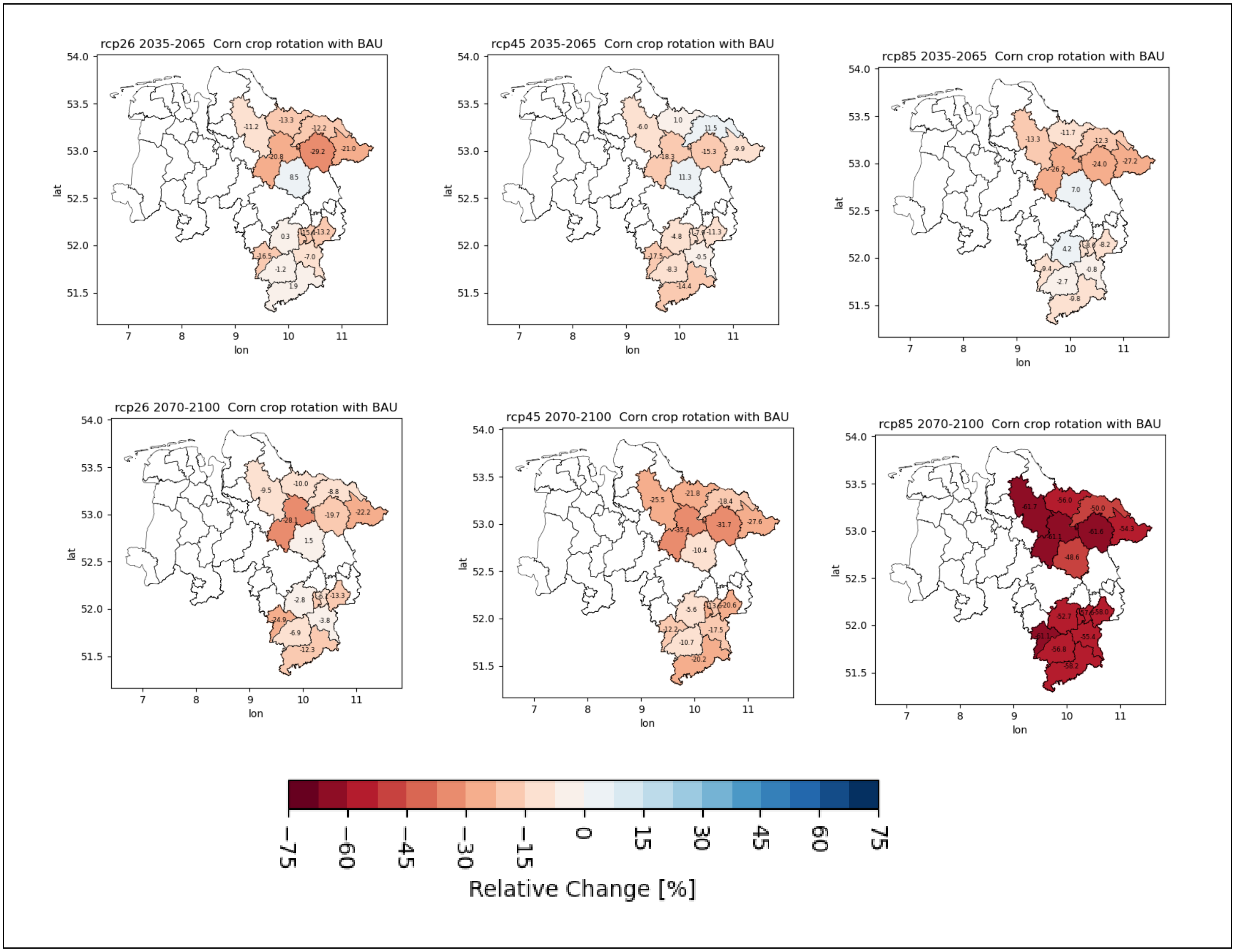


Figure 39 shows the silage corn yield changes compared to the reference period under three RCPs scenarios. It also offers two time periods (near future, 2035-2065; distant future, 2017-2100).

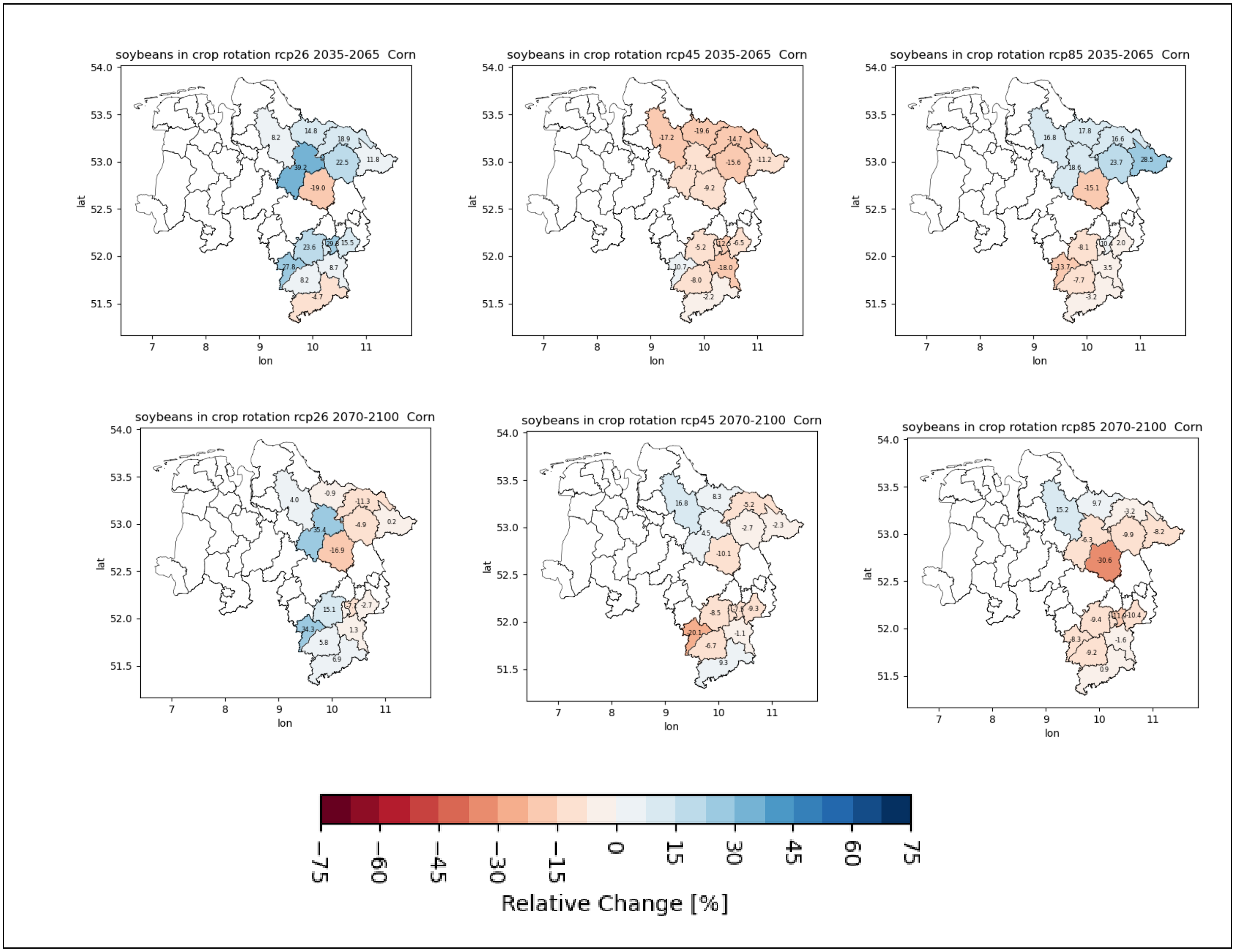


Figure 40 shows the silage corn relative yield difference between two crop rotation scenarios (With soybeans and without soybeans, BAU). It also indicates both strategies under three different RCP scenarios for the near future (2035-2065) and the distant future (2070-2100).

DISCUSSION AND CONCLUSIONS

The projected increase in temperature is highly likely to cause a decrease in crop yields in Lower Saxony[24,26]. For this reason, new methods and studies are needed to assess the effectiveness of various adaptation measures able to provide economic, social, and environmental benefits. In this paper, we have analyzed soybean cultivation to improve soil quality and increase yields. Soybean crops have been used in different regions due to their capability to fixate nitrogen. However, implementing soybean cultivation as an adaptation measure requires careful consideration as it is a highly demanding water crop[112]. In this paper, we have analyzed the long-term effectiveness of soybean in the context of climate change. For this, we have implemented the EPIC crop model to perform several simulations. The model was used to test the inclusion of soybean in crop rotation and see its effect on winter wheat and silage corn.

According to our results, soybean within current crop rotation schemes displays a relative advantage over the BAU scenario. The diminution of soybean yields in the future due to this is also portrayed in our results. This effect means that combining soybeans with other crops, i.e., winter wheat and silage corn, might be sufficiently irrigated with irrigation's existing allowance water use.

In this regard, previous research studies suggest that once the optimum growing temperature is exceeded, the mean crop yields decline and yield variability increases despite similar interannual climate variability(Tigchelaar et al., 2018). These variations could explain the drastic drop in yields for both crops in a more distant future, despite a low difference in temperature variability between the two future periods. This observed behavior in our simulations goes along with the evidence provided by literature about the sensitivity of crops to temperature changes and the importance of understanding them to apply better risk assessments[114].

NELS districts show less variability in precipitation distribution patterns, which plays a crucial role in determining the water availability for the crops. This behavior can be seen clearly for winter wheat for both future periods, even though, from our results, silage corn displays a greater spread in its yields. Warmer temperatures solely are not sufficient to get higher and more stable silage corn yields. More irregular rainfall patterns might affect silage corn more heavily than winter wheat only for scenarios 2.6 and 4.5. If we face climate conditions as in RCP 8.5, then we may develop concrete management strategies related to irrigation and soil improvement to hold more water in the soil.

This study provides an overview of future scenarios, including soybean within the crop rotation. Nevertheless, we used only one bias-corrected model to assess future climate conditions for this research. The lack of ensemble models increases the uncertainty in our results as the climate system is represented narrowly. Similarly, crop models as EPIC may not describe all changes assertively that might occur under climate change conditions as they were developed under reference period conditions. However, we included only increasing temperatures and CO2 concentrations as inputs in EPIC to have more realistic outputs, which allowed us to analyze our results under three different climate scenarios.

One adaptation strategy might not be sufficient to attain sufficient and stable yields in the future on this subject. A balanced combination of several approaches towards water management, soil restoration, efficient fertilization, sustainable crop rotations may benefit even more than a single application to a specific problem. The agricultural system is unique, as it is a natural human-modified system with many interconnections that cannot be studied with one crop model. A more holistic methodology needs to be applied in such research to include the effects of socio-economic aspects and physicochemical ones. Besides, more research is needed that takes a more in-depth look into which strategies could improve field capacity for all districts and further irrigation options.

Acknowledgments

This work was conducted and financed within the Helmholtz Institute for Climate Service Science (HICSS) framework, cooperation between Climate Service Center Germany (GERICS) and Universität Hamburg, Germany.

SUPPLEMENTARY MATERIAL

BASE YIELDS

Table 15 NELS and SLS yields for the reference period 1979-2018

	District	Winter Wheat [t/ha]	Silage Corn [t/ha]
NELS	Celle	5.99	37.46
	Harburg	5.68	36.76
	Lüchow (Dannenberg)	5.73	38.11
	Heidekreis	5.52	36.33
	Uelzen	5.90	37.75
	Rotenburg	5.49	37.00
	Lüneburg	5.92	37.01
SLS	Holzminden	6.48	40.29
	Northeim	6.41	42.71
	Salzgitter	6.81	37.22
	Wolfenbüttel	6.48	40.93
	Hildesheim	7.03	39.75
	Goslar	6.54	38.74
	Göttingen	6.39	41.23

ERA5 WITH HINDCAST COMPARISON

Since we have worked with only one model for this study, we compared BAU scenario yields between ERA5 and hindcast for 1979-2005. In order to see the differences graphically, we have plotted these yields in maps for all districts (Figure 41). The error is calculated based on reported yields for the same period for each district. The results are in Tables 16 and 17 for winter wheat and silage corn, respectively.

Table 16 Winter Wheat yields for all simulated districts using as climate input ERA5 and hindcast of the climate model. Both simulations are for the period 1979-2005. The last two columns refer to relative error to reported yields for the same period

	District	Winter Wheat ERA5 [t/ha]	Winter Wheat hindcast [t/ha]	Error ERA5	Error Hindcast
NELS	Celle	5.83	5.59	-6%	-10%
	Harburg	5.73	5.20	-5%	-14%
	Lüchow (Dannenberg)	5.60	5.46	-4%	-6%
	Heidekreis	5.13	4.73	-11%	-18%
	Uelzen	5.99	5.70	-9%	-13%
	Rotenburg	5.49	5.02	-2%	-10%
	Lüneburg	5.94	5.69	-1%	-5%
SLS	Holzminden	5.85	4.96	-14%	-27%
	Northeim	5.47	5.00	-22%	-29%
	Salzgitter	6.12	4.94	-21%	-36%
	Wolfenbüttel	6.35	4.94	-13%	-33%
	Hildesheim	7.61	5.46	3%	-26%
	Goslar	5.63	5.04	-21%	-29%
	Göttingen	5.29	4.94	-23%	-28%

Table 17 Silage Corn yields for all simulated districts using as climate input ERA5 and hindcast of the climate model. Both simulations are for the period 1979-2005. The last two columns refer to relative error to reported yields for the same period

	District	Silage Corn ERA5 [t/ha]	Silage Corn Hindcast [t/ha]	Error ERA5	Error Hindcast
NELS	Celle	35.98	28.01	-7%	-28%
	Harburg	29.97	32.97	-19%	-11%
	Lüchow (Dannenberg)	36.25	32.27	4%	-8%
	Heidekreis	31.95	29.24	-10%	-18%
	Uelzen	38.41	33.28	-1%	-14%
	Rotenburg	35.20	36.03	-8%	-6%
	Lüneburg	31.93	32.25	-14%	-13%
SLS					
	Holzminden	28.25	30.85	-27%	-20%
	Northeim	33.70	37.58	-15%	-5%
	Salzgitter	32.51	33.16	-22%	-20%
	Wolfenbüttel	34.01	37.54	-17%	-9%
	Hildesheim	34.04	35.13	-9%	-6%
	Goslar	30.97	32.35	-29%	-26%
	Göttingen	32.46	34.49	-21%	-16%

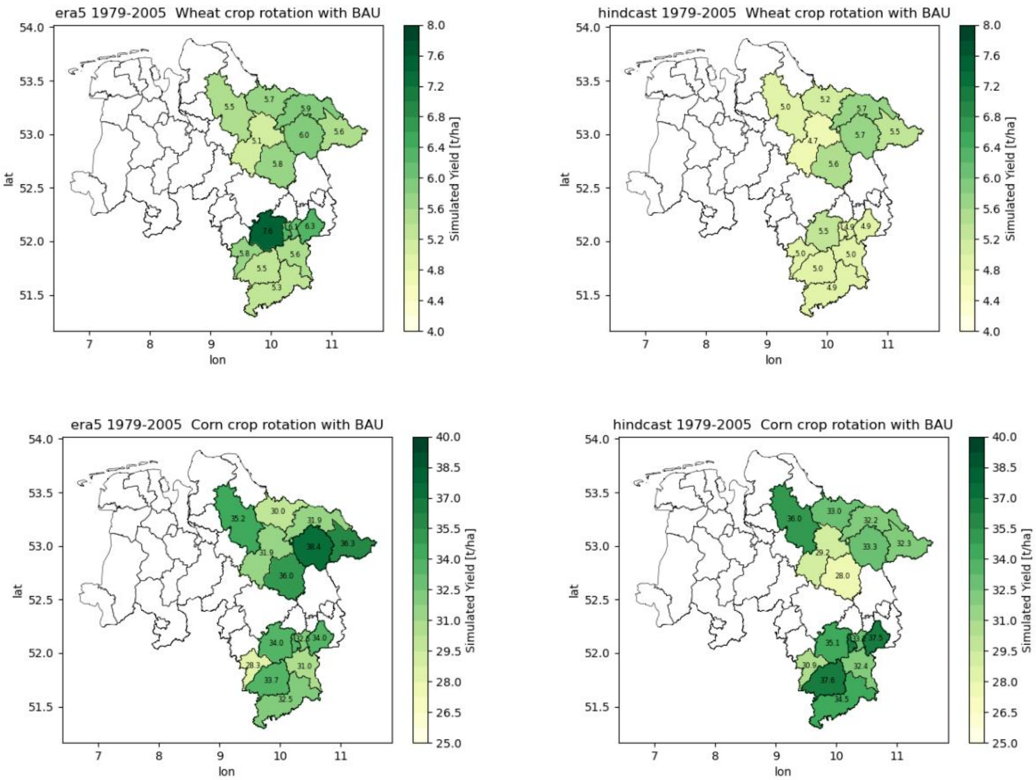


Figure 41 NELS and SLS maps. Upper maps are winter wheat yields and lower ones correspond to silage corn. Left maps are simulated yields with ERA5 and to the right with hindcast. Both climate data are for 1979-

DIFFERENCES BETWEEN HINDCAST AND ERA5

We plotted the relative changes in yields between the simulations with EPIC using hindcast data and ERA5 data for the same period 1979-2005. From figure 42, it can be seen that silage corn yields are underestimated, and for winter, wheat is overestimated.

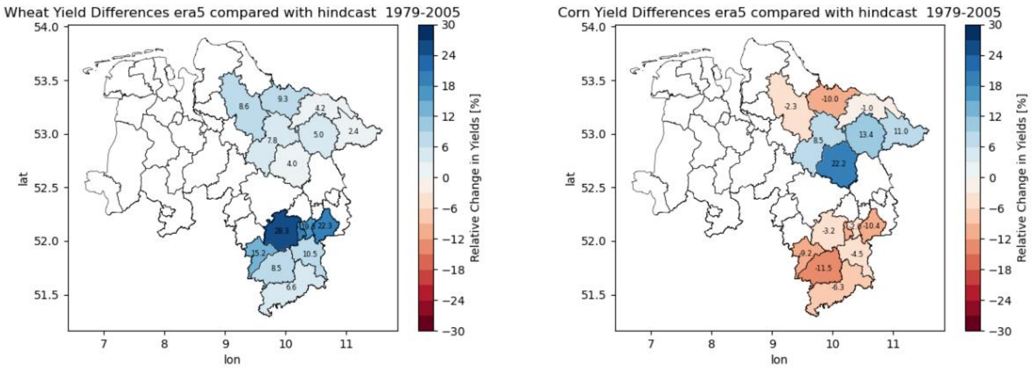


Figure 42 NELS and SLS maps. Left map are winter wheat yields relative differences between results simulated with ERA5 and with hindcast climate data, respectively. The map on the right displays the same, but for silage corn.

SOIL TESTS RESULTS

We changed in the EPIC model the percentages of sand, silt, and clay content only, not other soil parameters that also characterize soil properties regarding water-holding capacity. In the following maps, yield changes are shown compared to simulations with original soil conditions. These simulations are also conducted for the three RCP scenarios split into near and distant future, respectively.

SANDY SOIL

SILAGE CORN

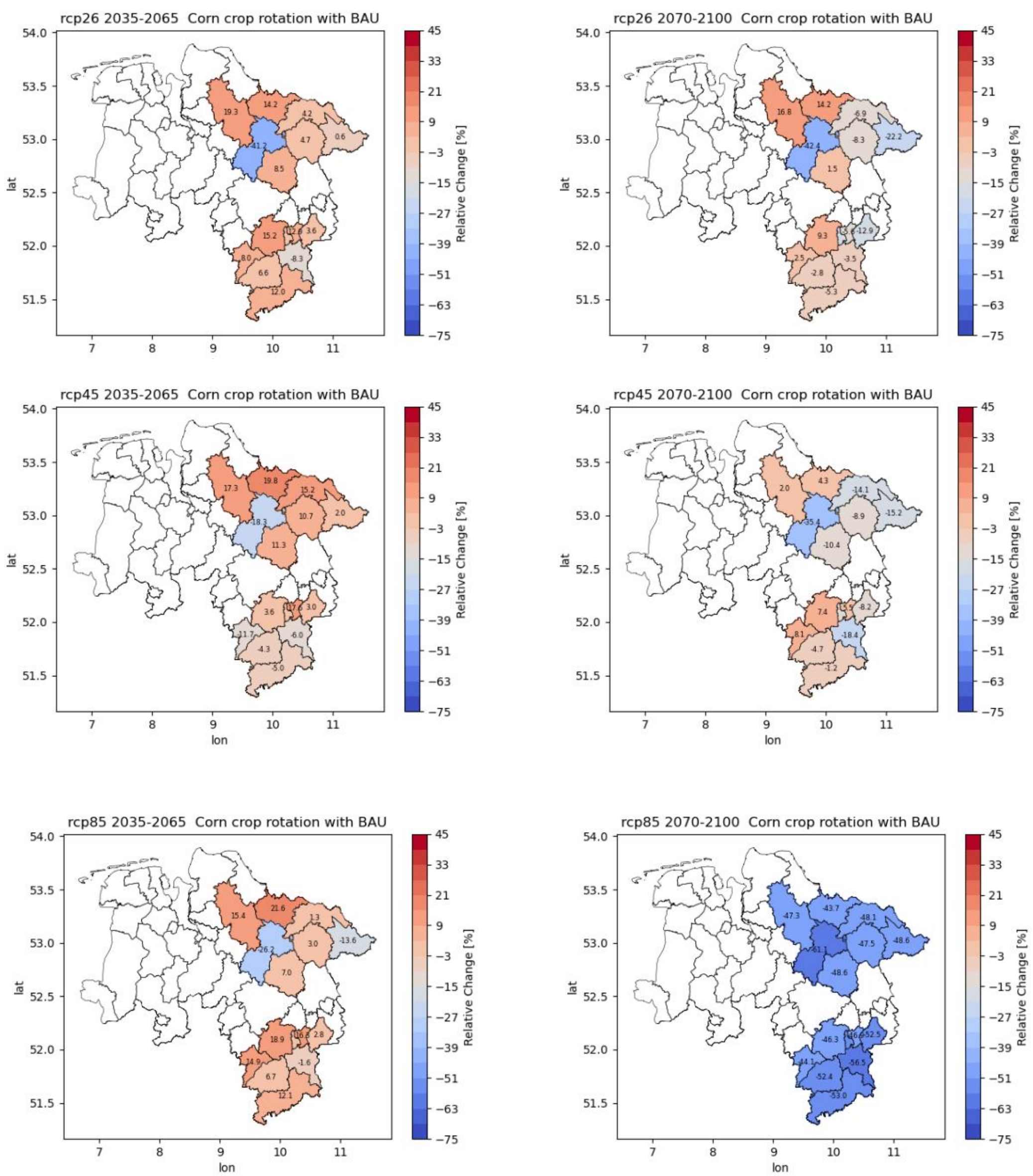


Figure 43 NELS and SLS maps. Left maps correspond to the period 2035-2065. The maps on the right correspond to the period 2070-2100. Upper maps are simulations with RCP 2.6 climate data; middle maps are for RCP 4.5, and lower maps are for RCP 8.5. Relative changes are calculated based on silage corn yields simulated with sandy soil compared with original soil conditions.

WINTER WHEAT

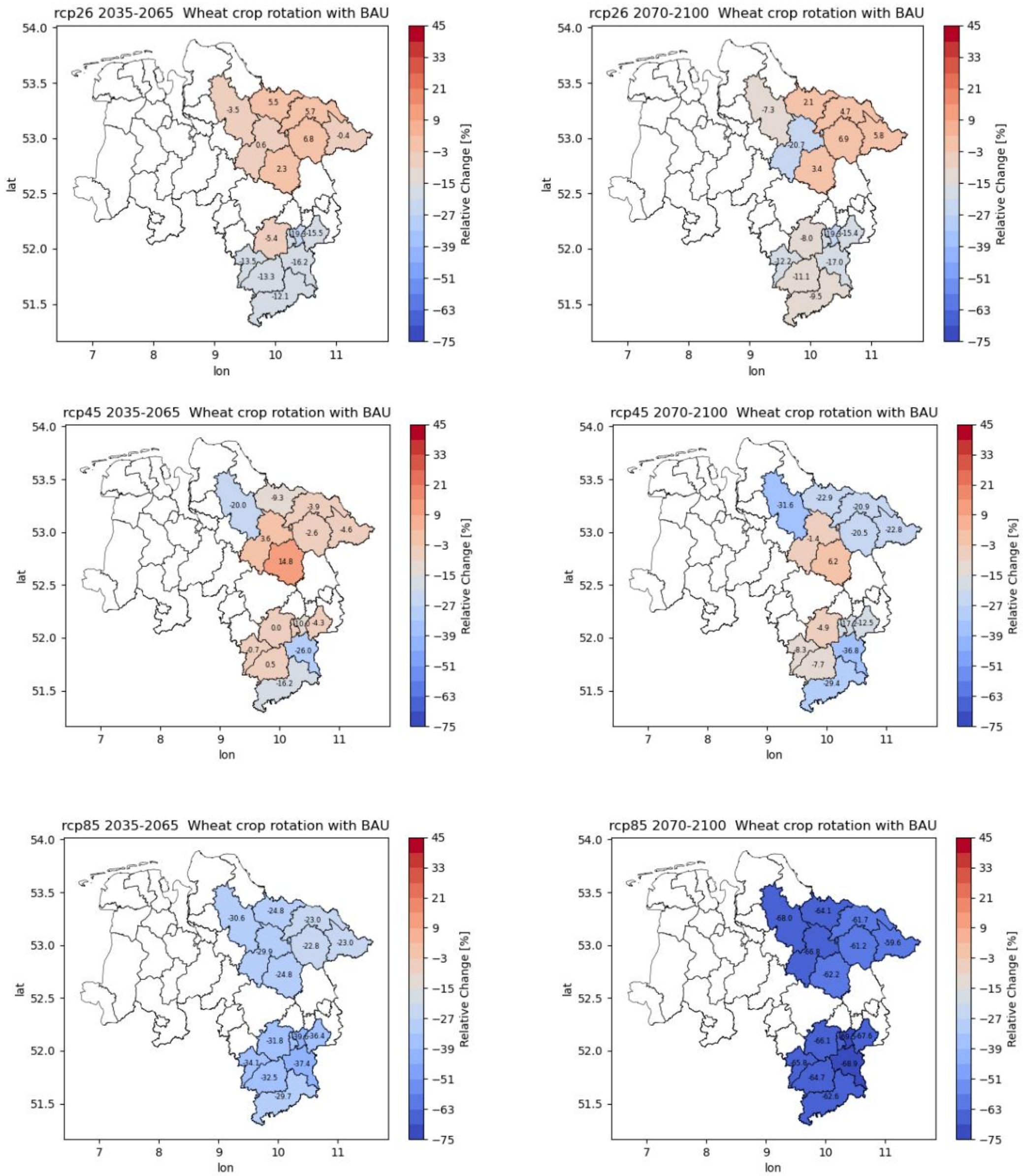


Figure 44 NELS and SLS maps. Left maps correspond to the period 2035-2065. The maps on the right correspond to the period 2070-2100. Upper maps are simulations with RCP 2.6 climate data; middle maps are for RCP 4.5, and lower maps are for RCP 8.5. Relative changes are calculated based on winter wheat yields simulated with sandy soil compared with original soil conditions.

The same procedure was conducted for silt-clay soil texture conditions for silage corn

SILAGE CORN

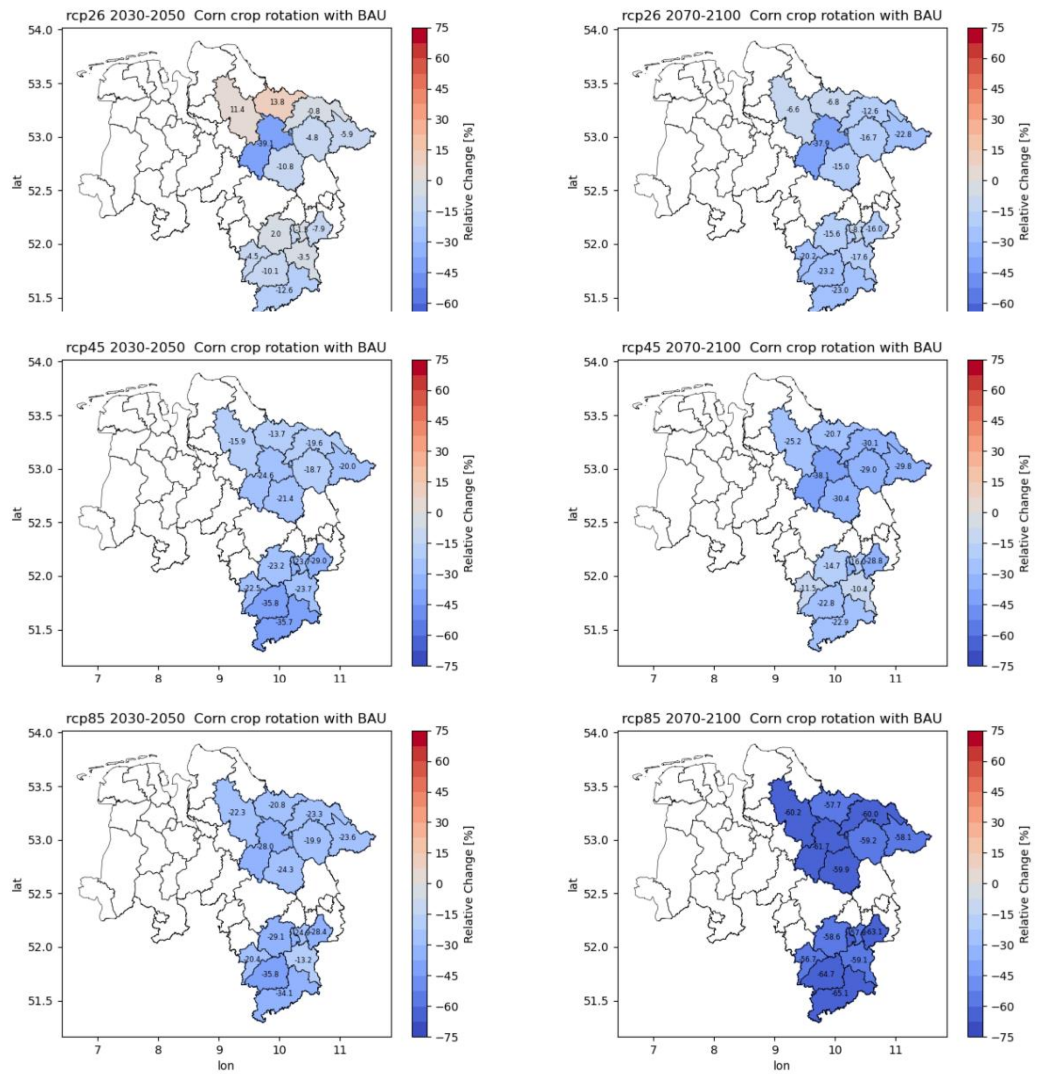
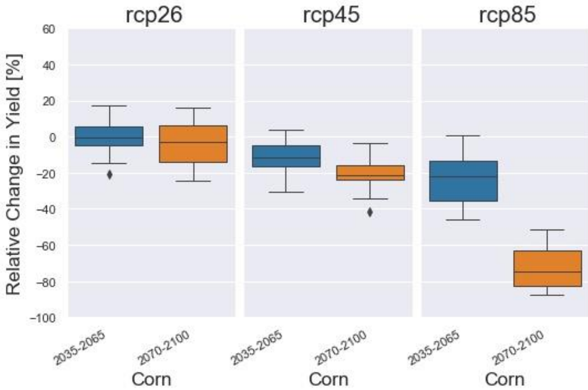


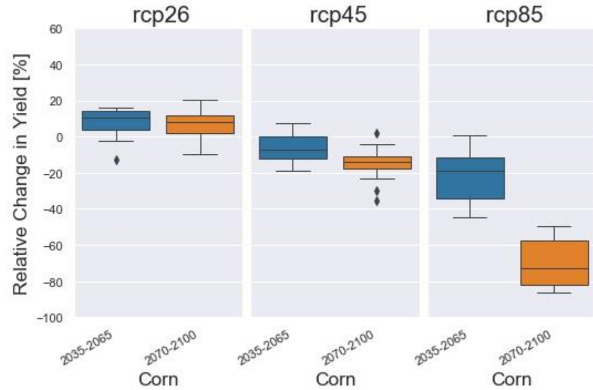
Figure 45 NELS and SLS maps. Left maps correspond to the period 2035-2065. The maps on the right correspond to the period 2070-2100. Upper maps are simulations with RCP 2.6 climate data; middle maps are for RCP 4.5, and lower maps are for RCP 8.5. Relative changes are calculated between reference soil texture and silt-clay texture compared with original soil conditions.

AGGREGATED YIELDS CHANGES

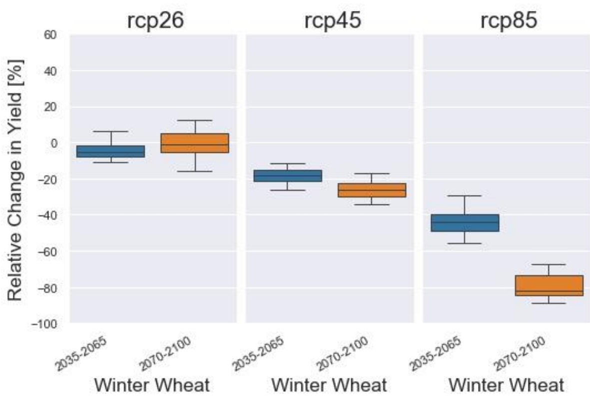
SANDY SOIL TEXTURE

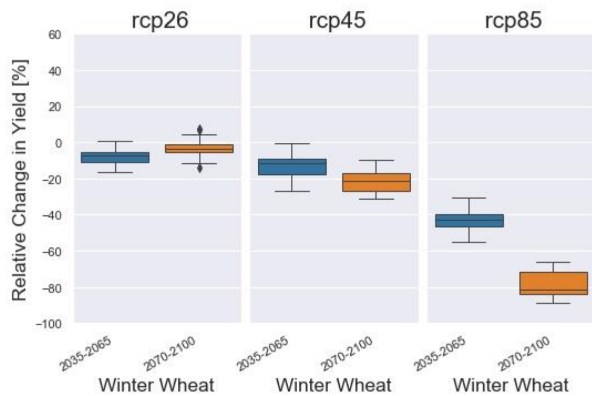


NELS



SLS

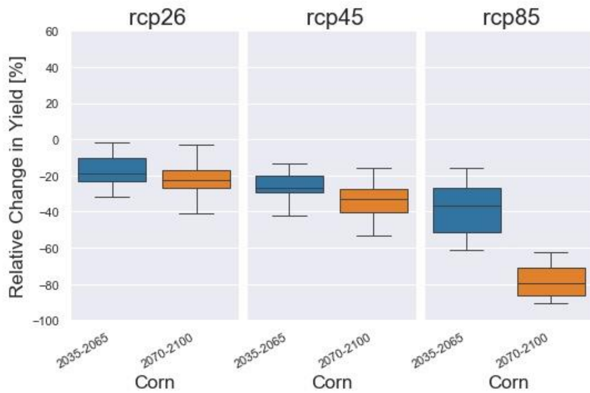




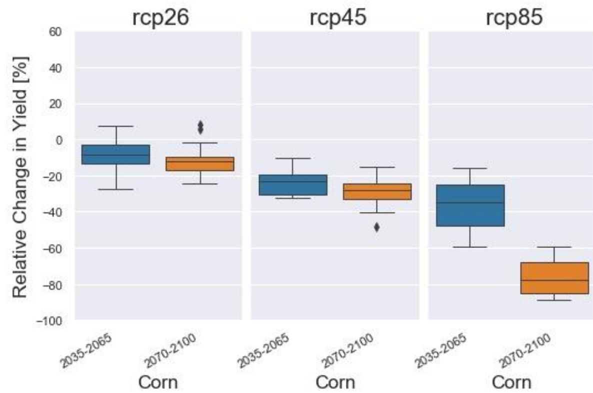
NELS SLS

Figure 46 displays NELS and SLS aggregated boxplots. Left boxplots correspond to NELS districts, which their results are aggregated. Right boxplots represent the same, but for SLS districts. Upper boxplots highlight the changes in silage corn yield under sandy soil conditions. Lower boxplots represent the same as previous, but for winter wheat. Results are split into two future periods for each RCP climate scenario: blue bars for 2035-2065 and orange bars for 2070-2100.

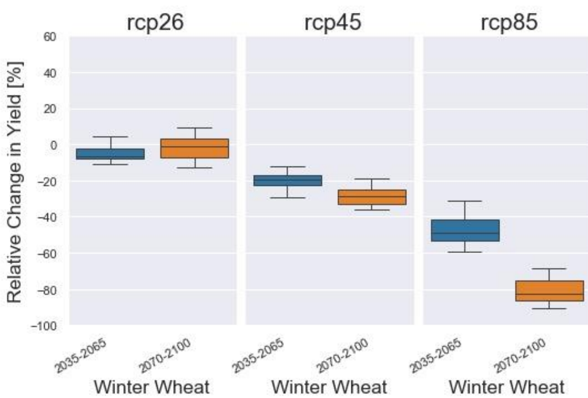
SILT-CLAY SOIL TEXTURE



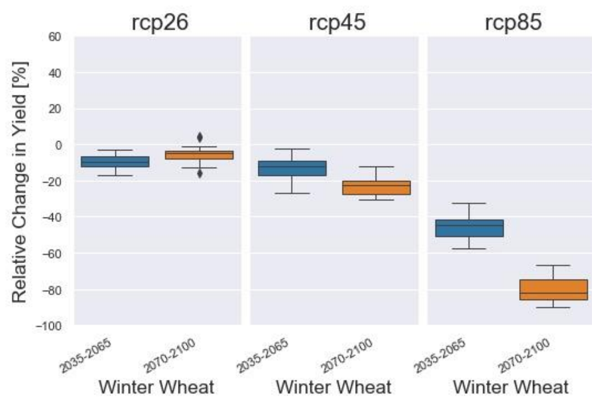
NELS



SLS



NELS

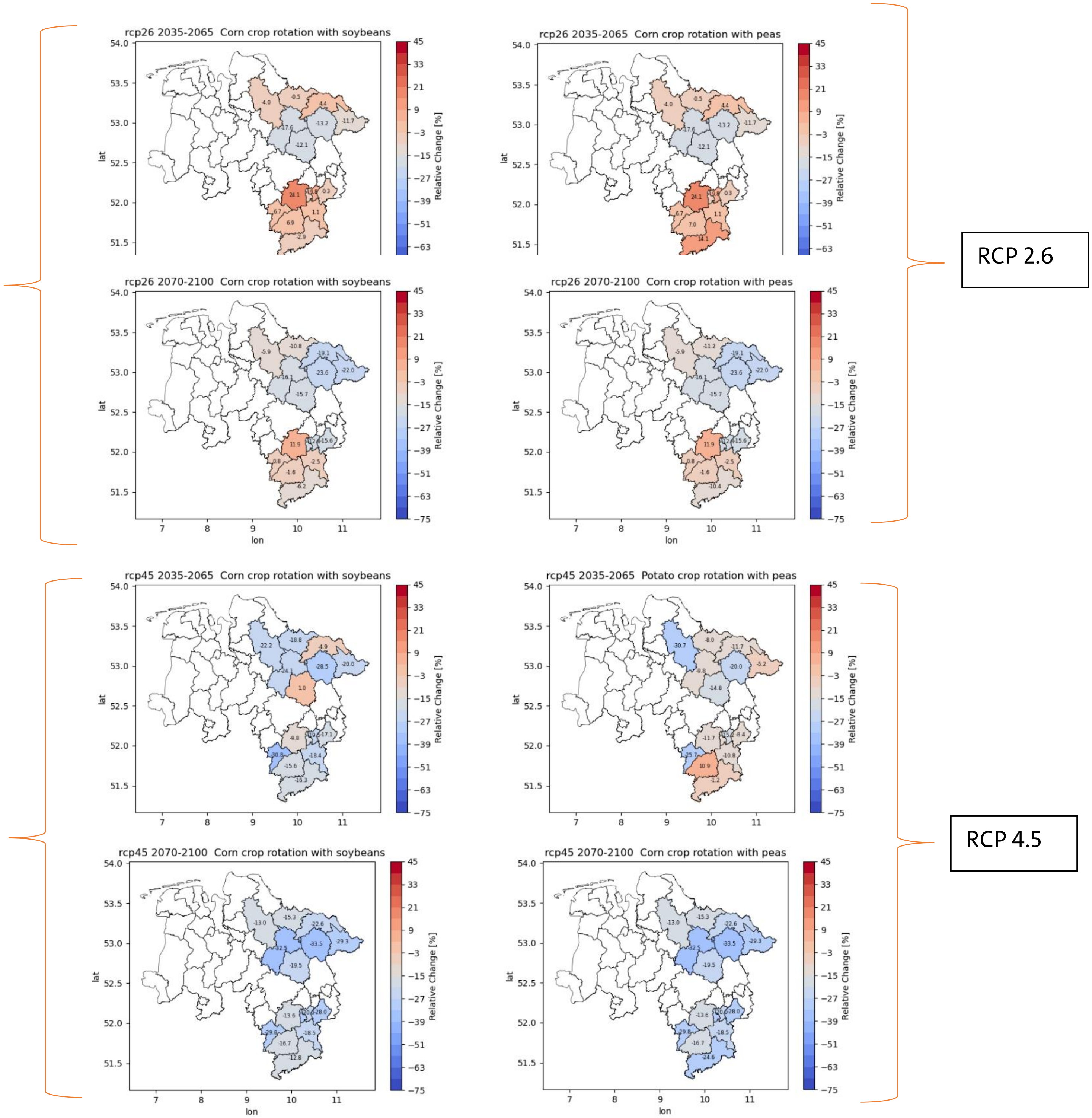


SLS

Figure 47 displays NELS and SLS aggregated boxplots. Left boxplots correspond to NELS districts, which their results are aggregated. Right boxplots represent the same, but for SLS districts. Upper boxplots highlight the changes in silage corn yield under silt-clay soil conditions. Lower boxplots represent the same as previous, but for winter wheat. Results are split into two future periods for each RCP climate scenario: blue bars for 2035-2065 and orange bars for 2070-2100.

Test replacing having legumes (soybeans and peas) before or after silage corn

AFTER CORN



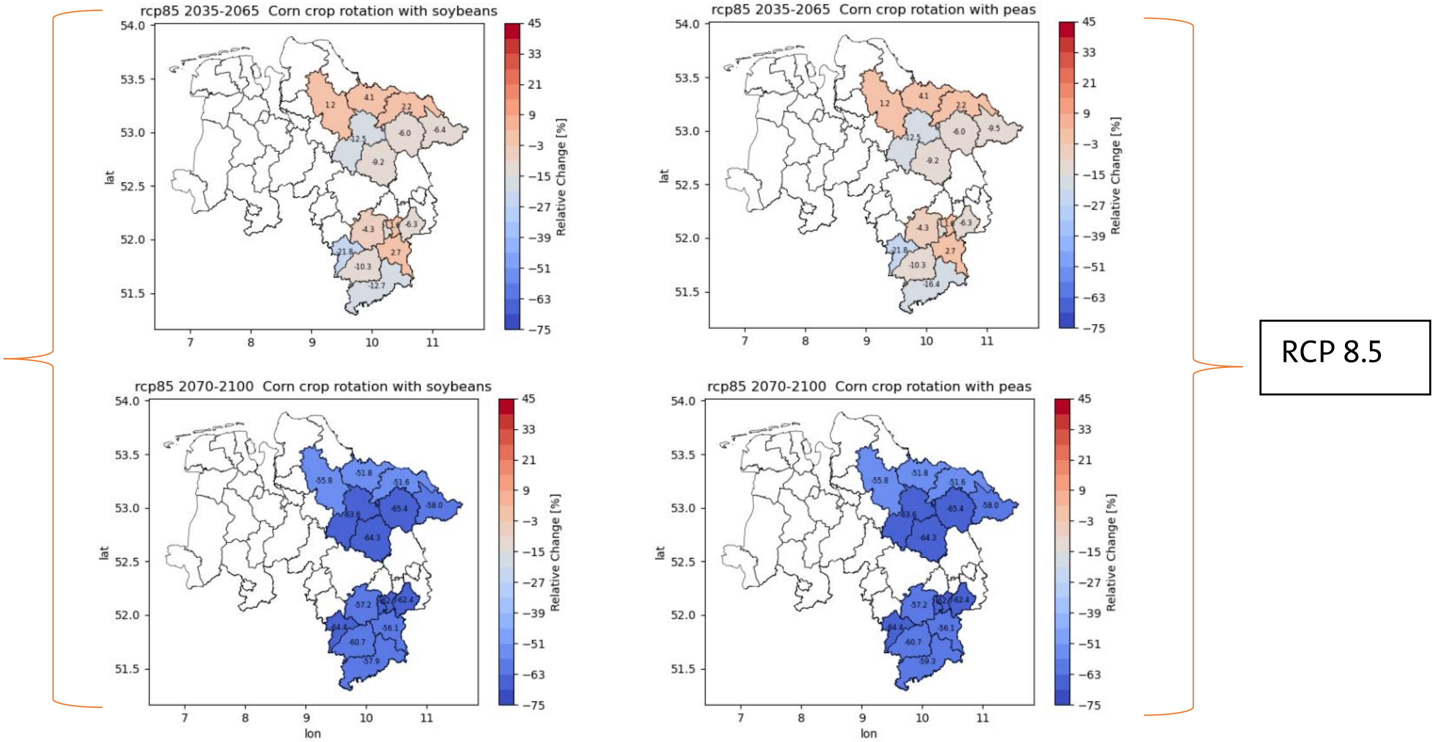
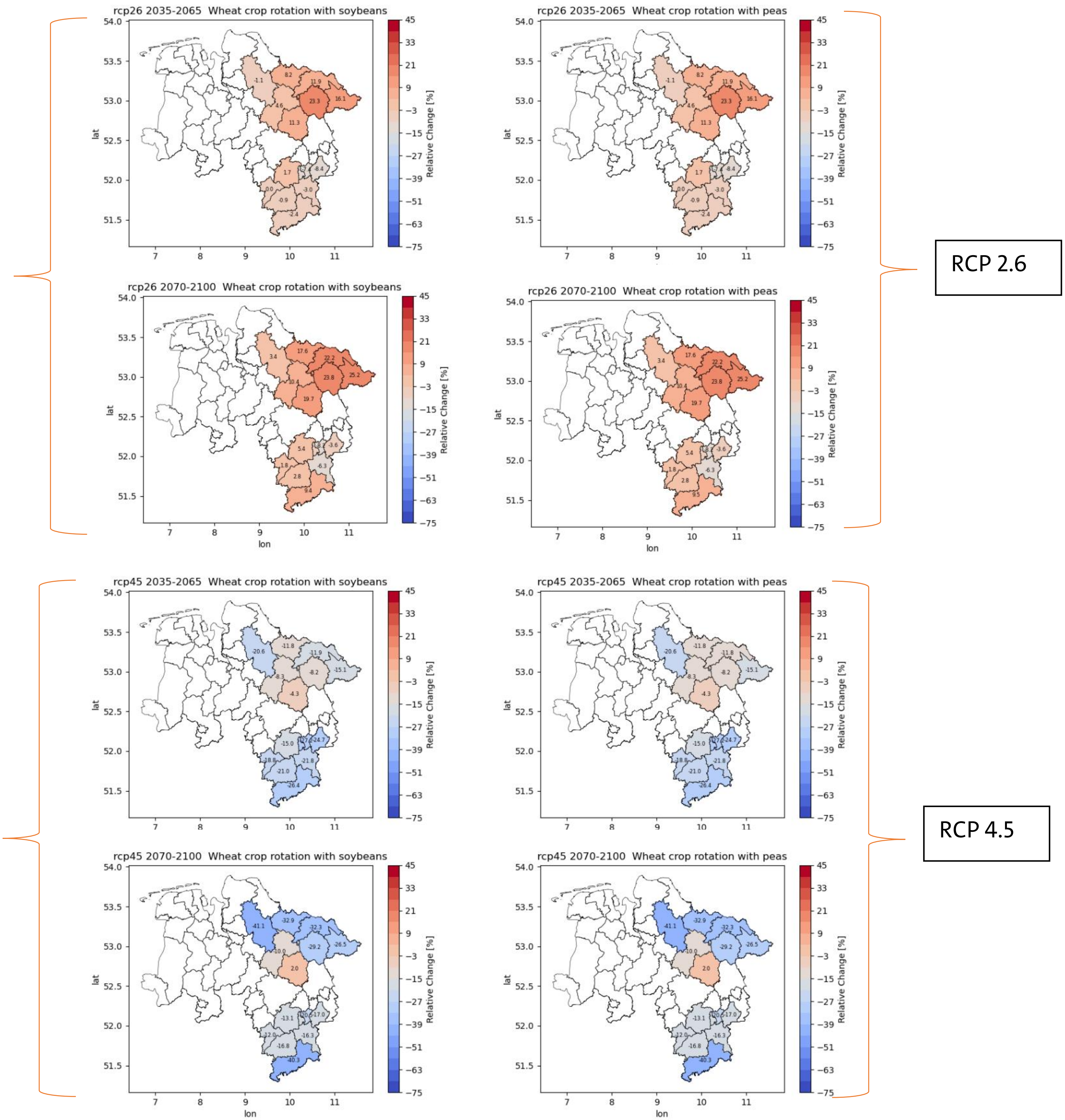


Figure 48 NELS and SLS maps. Left maps correspond to crop rotation with soybeans after silage corn. The maps on the right correspond to crop rotation with peas after silage corn. Maps are categorized by each RCP climate scenario and future period (close – 2035-2065, distant- 2070-2100)


rcp26 2035-2065 Wheat crop rotation with soybeans
rcp26 2035-2065 Wheat crop rotation with peas
rcp26 2070-2100 Wheat crop rotation with soybeans
rcp26 2070-2100 Wheat crop rotation with peas
RCP 2.6
rcp45 2035-2065 Wheat crop rotation with soybeans
rcp45 2035-2065 Wheat crop rotation with peas
rcp45 2070-2100 Wheat crop rotation with soybeans
rcp45 2070-2100 Wheat crop rotation with peas
RCP 4.5
lat
lon
Relative Change [%]

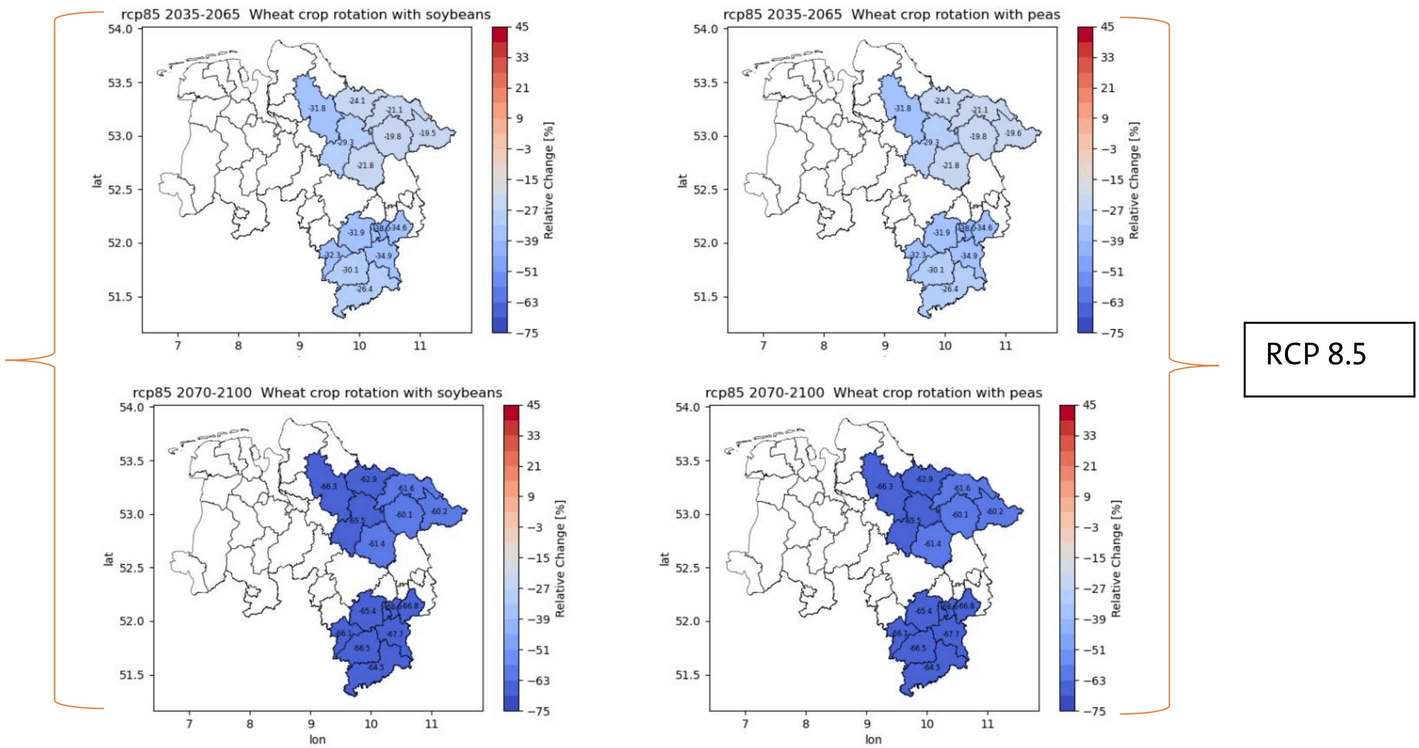
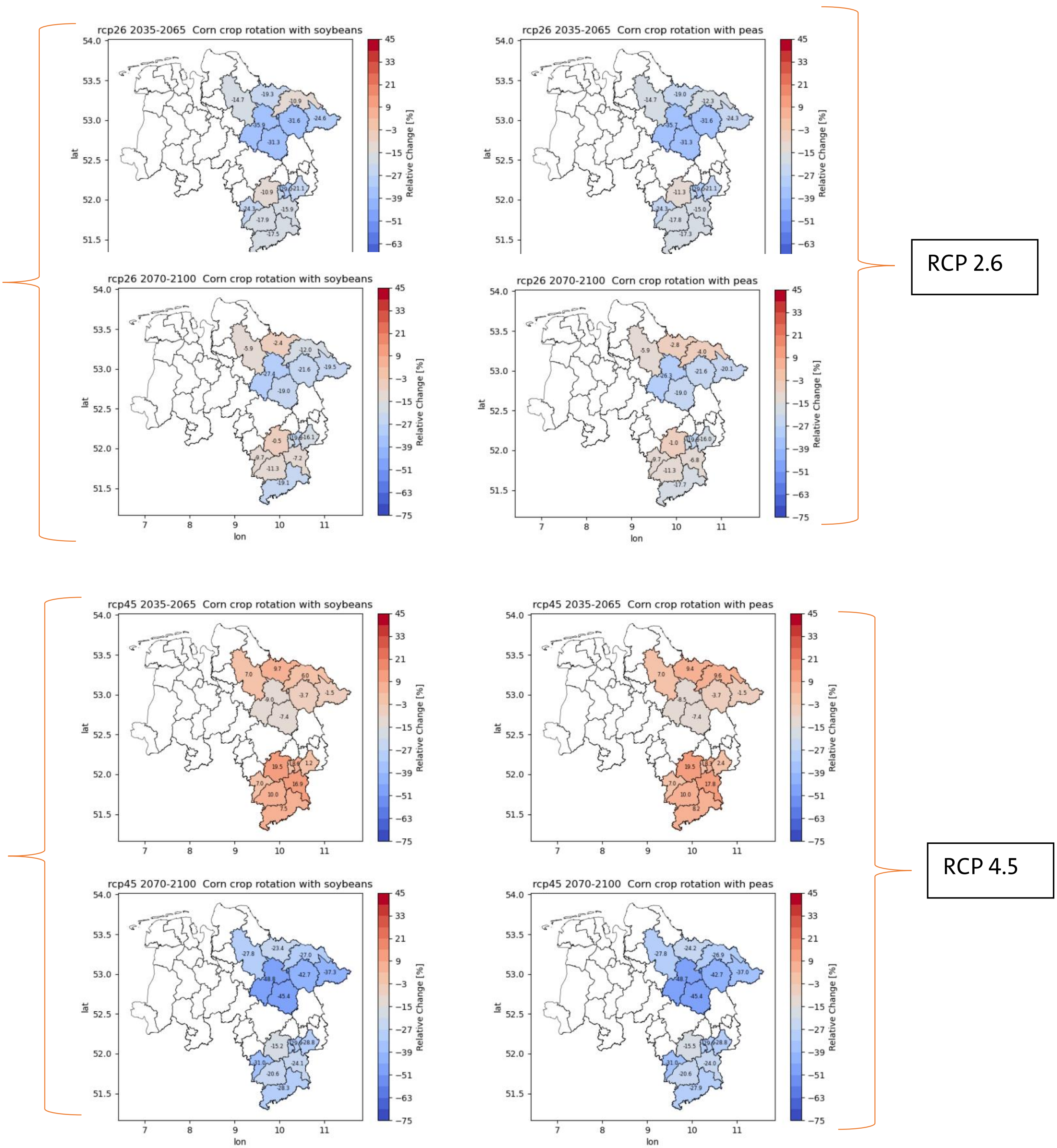


Figure 49 NELS and SLS maps. Left maps correspond to crop rotation with soybeans after winter wheat. The maps on the right correspond to crop rotation with peas after winter wheat. Maps are categorized by each RCP climate scenario and future period (close – 2035-2065, distant- 2070-2100)

LEGUMES BEFORE SILAGE CORN



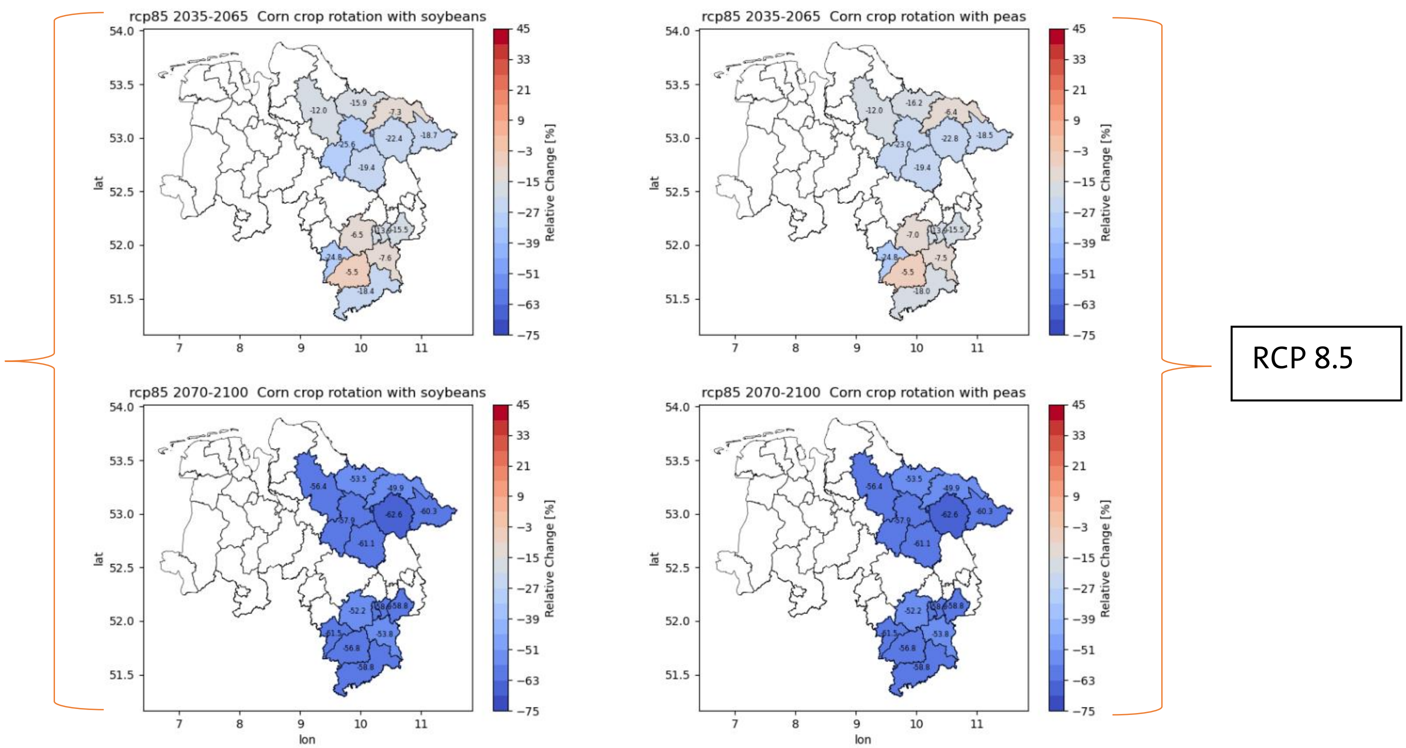
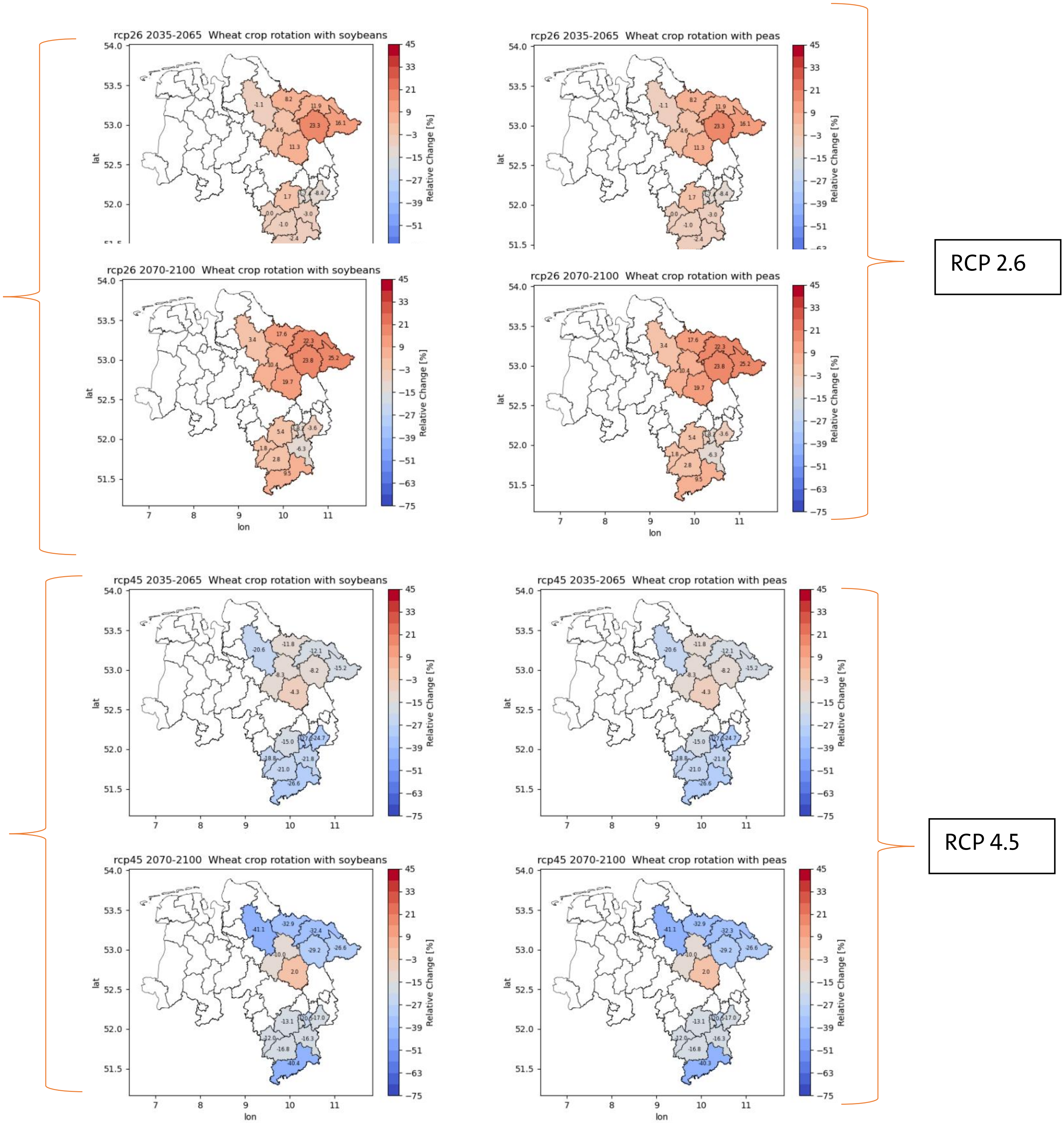


Figure 50 NELS and SLS maps. Left maps correspond to crop rotation with soybeans before silage corn. The maps on the right correspond to crop rotation with peas before silage corn. Maps are categorized by each RCP climate scenario and future period (close – 2035-2065, distant- 2070-2100)

LEGUMES BEFORE WINTER WHEAT



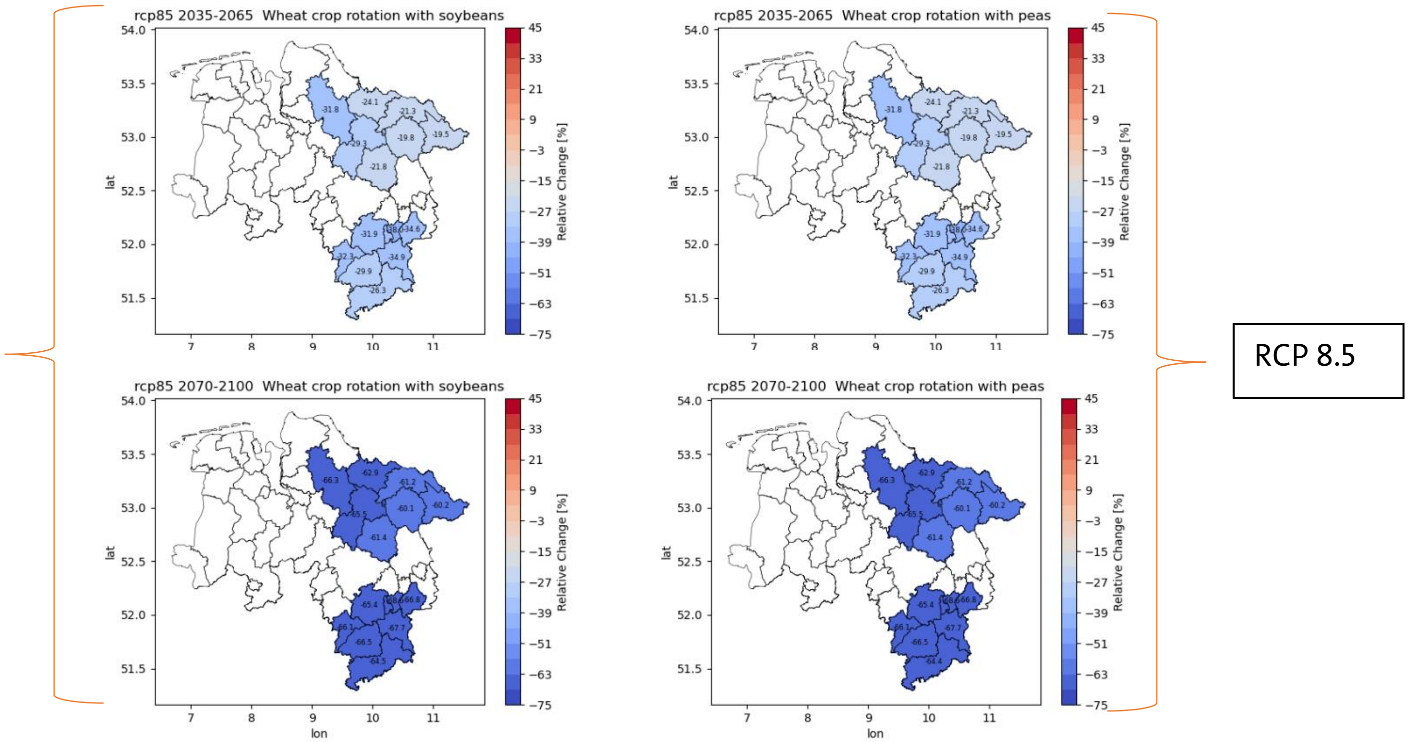


Figure 51 NELS and SLS maps. Left maps correspond to crop rotation with soybeans before winter wheat. The maps on the right correspond to crop rotation with peas before winter wheat. Maps are categorized by each RCP climate scenario and future period (close – 2035-2065, distant- 2070-2100)

Chapter 4

CHAPTER 4

Cropping calendars may partially mitigate yield losses under warmer temperatures with restricted irrigation amount: Case Study in Northern Germany

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ABSTRACT

CONTEXT

Climate adaptation management is a crucial aspect of the resilience of the agricultural sector. The increase in frequency and intensity in drought events, which, according to climate research, will intensify in the coming decades that have unfavorable impacts on farmers' income due to yield losses. Irrigation investments might be the most promising option to attain stable yields for existing crops.

OBJECTIVE

We aim to evaluate which irrigation water amount and which crop calendar may reduce wheat and corn yield losses under three climate change scenarios (RCP) for the German Agriculture sector.

METHODS

We used the process-based crop model EPIC to evaluate yield penalties for wheat and corn in Northern Germany. The management scenarios in the model were five water irrigation amounts based on a fraction of the field capacity (0%- 100%) and crop calendar schemes, including the BAU scenario. These simulations were conducted for three RCP scenarios (2.6, 4.5, 8.5). Future periods were split into the near future (2035-2065) and the far future (2070-2100).

RESULTS AND CONCLUSIONS

Our results show the potential to increase up to 50% of corn yields in warming conditions by planting two months earlier only when there is enough water to avoid stress and drought hazards up to the year 2065. For 2070-2100, crop yield losses may be mitigated up to 10% compared to the BAU scenario for RCP 8.5. These results display the limitation of irrigation and crop calendar application as we can observe that there are still yield losses by applying to reach 60% of field capacity. For winter wheat, yield losses may be mitigated when planted two months later with irrigation of 60% of field capacity. However, this combination of applied strategies is limited due to climate change in plant growth.

SIGNIFICANCE

This study helped understand the potential of several adaptations in mitigating yield losses, nitrogen emissions, and improving water balance. Warmer temperatures and reduced rainfall in future summer periods are likely to shift crop calendars and vary irrigation amounts for varieties that are not modified to be more drought tolerant.

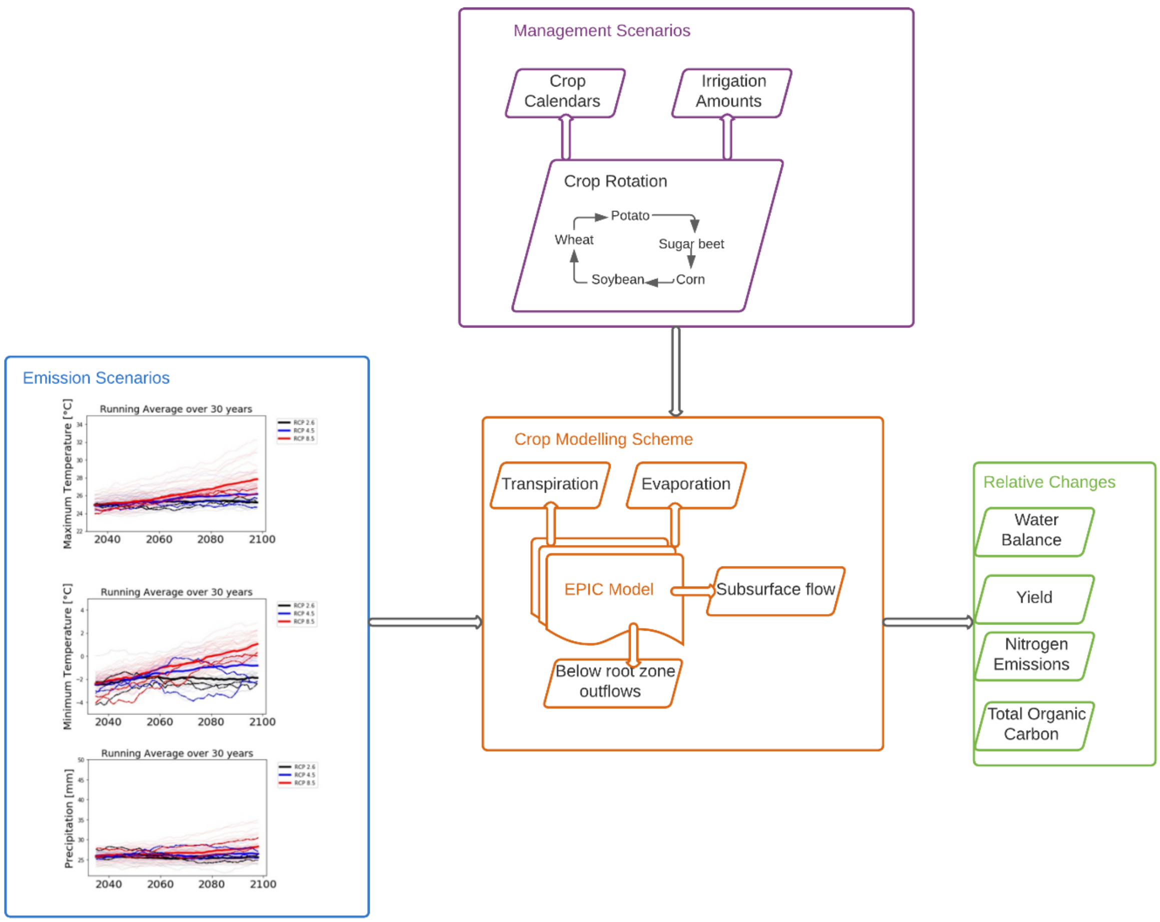
Keywords: irrigation, crop calendars, agriculture, RCP scenarios, crop model, northern Germany

HIGHLIGHTS

- Corn yield losses may be mitigated by planting two months earlier. For winter wheat, the yield penalties are reduced by planting two months later.

- Irrigation is limited as an adaptation strategy due to increased temperatures for the far future (2070-2100).
- Corn may be more affected due to water stress. Reversely, winter wheat is due to temperature stress for both future periods.

GRAPHICAL ABSTRACT



INTRODUCTION

Historically, there have not been significant disputes over water rights between agriculture and domestic use in Northeastern Lower Saxony (NELS), but on nitrate concentration on water sources[115,116].In the 30-year mean from 1971 to 2000, the water balance national average was positive at 185 mm. However, according to the climate report for Lower Saxony, the water surplus will decrease by two-thirds for the period 2070-2100 for the RCP 8.5

scenario[117]. The competition for water as a resource could intensify in Lower Saxony over the next few decades, as agriculture is highly dependent on rainfall quantity and patterns. Due to the sandy soil textures, NELS might be particularly vulnerable to more erratic precipitation patterns [118].

In addition, increasing frequency and intensity in drought events, which, according to climate research, will intensify in the coming decades[119]. Irrigation investments might be the most promising option to attain stable yields for existing crops[120]. Irrigation offers several advantages over rainfed systems. Firstly, it provides an opportunity to use nitrogen fertilizer effectively. Secondly, reducing the cost of fertilizers helps to improve humus soil management. Additionally, the decrease in energy cost may also reduce greenhouse gas emissions[120].

Nevertheless, assessing feasible irrigation strategies requires consistent information on crop processes and how weather conditions and irrigation strategies impact them[121]. Crop models generate data that allows testing various irrigation options and their future implications. This implementation offers an opportunity to save time resources, facilitating this way the decision-making processes.

Process-based crop models like the EPIC Environmental Policy Integrated Climate (EPIC) can assist in such procedures. EPIC is a field-scale model that can simulate homogenous drainage areas in weather, soil, landscape, crop rotation, and management operation parameters5. It can simulate many decades of land management, allowing long-term soil assessments like humus build-up processes. In addition, yield levels, water use, and fertilizer requirements can be tested yearly or seasonally. Previous studies have used EPIC to simulate irrigation processes and their long-term effects in different regions at several scales[122–127]. Although, there is a lack of such studies in Germany, specifically in northern Germany and Lower Saxony.

There is a need to study regional irrigation in Lower Saxony and its potential effects. These include changes in Soil Organic Carbon (SOC), water balance, and the trade-off between crop productivity and water use efficiency (WUE). We have simulated different irrigation levels changing application dates in regards to seasonal water deficit. The simulations use the crop rotation typically used in the region: potato – sugar beet – silage corn-soybean – winter wheat under three emission scenarios (RCP 2.6, 4.5, and 8.5). This research aims to understand how irrigation and management influence soil organic carbon and its contribution to Lower Saxony's nitrogen uptake and losses. Moreover, we investigated the impact of planting and harvesting dates and different water amounts based on the field capacity as irrigation rule on yield and water balance.

Material and Methods

This study used two time periods to assess our results: The near future (2035-2065) and the far future (2070-2100). The research design involved the analysis of different irrigation schedules under three RCP climate scenarios (2.6, 4.5, and 8.5) for several irrigation amounts based on fractions of field capacity (0 to 100%); likewise, the effect of several planting and harvesting timing on yields, water balance elements, and water and temperature stress.

STUDY REGION

The study region is located in the federal state of Lower Saxony (LS) in northern Germany (Figure 1). Agriculture is one of the main economic sectors with one of the largest irrigation areas in Germany, accounting for about 36% of the land irrigated in Germany[128]. Historically, agriculture LS has required additional water due to its low precipitations compared to other areas of Germany. However, the additional water requirements vary greatly depending on the crop and location (Table 18). Besides, climate change is likely to increase the frequency and intensity of drought periods and negative climate water balance during the summer months[129,130]. Consequently, additional adaptation measures to face these new conditions are needed in the area.

The research carried out focused on two districts of Lower Saxony that have different soil textures. Northeastern Lower Saxony (NELS) is characterized by sandy texture soils, while Southern Lower Saxony (SLS) districts have silt-clay texture soils. Lower Saxony is one of the federal districts in Germany with the highest additional water requirements due to low precipitation amount during vegetation periods[131].

Table 18 shows the additional water requirement for selected crops in selected districts in Lower Saxony

Crop	**Additional Water Requirement Range [mm]**
Corn	NELS and SLS 0 – 10
Winter Wheat	NELS 30 – 110 SLS 30 – 70

Figure 52 left depicts the study region for this research and its location in Germany. The map illustrates the range for groundwater recharge. This map gives an overview of the amount of water, which can be stored in the root zone according to BÜK1000 (Soil overview map of the Federal Republic of Germany 1: 1,000,000). This water storage capacity is a crucial soil function, which depends mainly on the soil texture. In our case study, the dominant soil texture in the region is sand, especially in NELS. This differentiation leads to deficient levels in usable field capacity, with NELS having between 150-200 mm of annual water recharge and SLS among 75-200 mm, excepting the southern part of Goslar with levels up to 500 mm/year. Although, these differences are both considered as medium groundwater recharges categories compared to other regions in Germany. Therefore, irrigation is required in the current climatic conditions to ensure yields and quality. According to the calculations of the soil-water balance models, the need for agricultural irrigation will increase in the future with a 25% irrigation potential [26].

Table 19 depicts the total and agricultural area for each district, which shows in terms of percentage that these districts have relevance for the local agricultural sector.

	District	Total Area [km2]	Agricultural Area [km2]	Fraction of Agricultural Area
NELS	Celle	1545	562	36%
	Heidekreis	1874	758	40%
	Harburg	1245	671	54%
	Luechow-Dannenberg	1220	638	52%
	Lueneburg	1323	539	41%
	Rotenburg (Wuemme)	2070	1415	68%
	Uelzen	1454	778	54%
SLS	Goettingen	1753	584	33%
	Goslar	965	275	29%
	Northeim	1267	625	49%
	Holzminden	692	295	43%
	Hildesheim	1206	728	60%
	Wolfenbuettel	722	501	69%
	Salzgitter	224	121	54%

Figure 52 right illustrates the direct runoff on agricultural soils, giving an overview of the average annual amount of precipitation that does not infiltrate. Surface runoff depends mainly on soil and climatic factors. From this map, NELS falls into a lower category than SLS districts. To the left, annual groundwater recharge is presented.

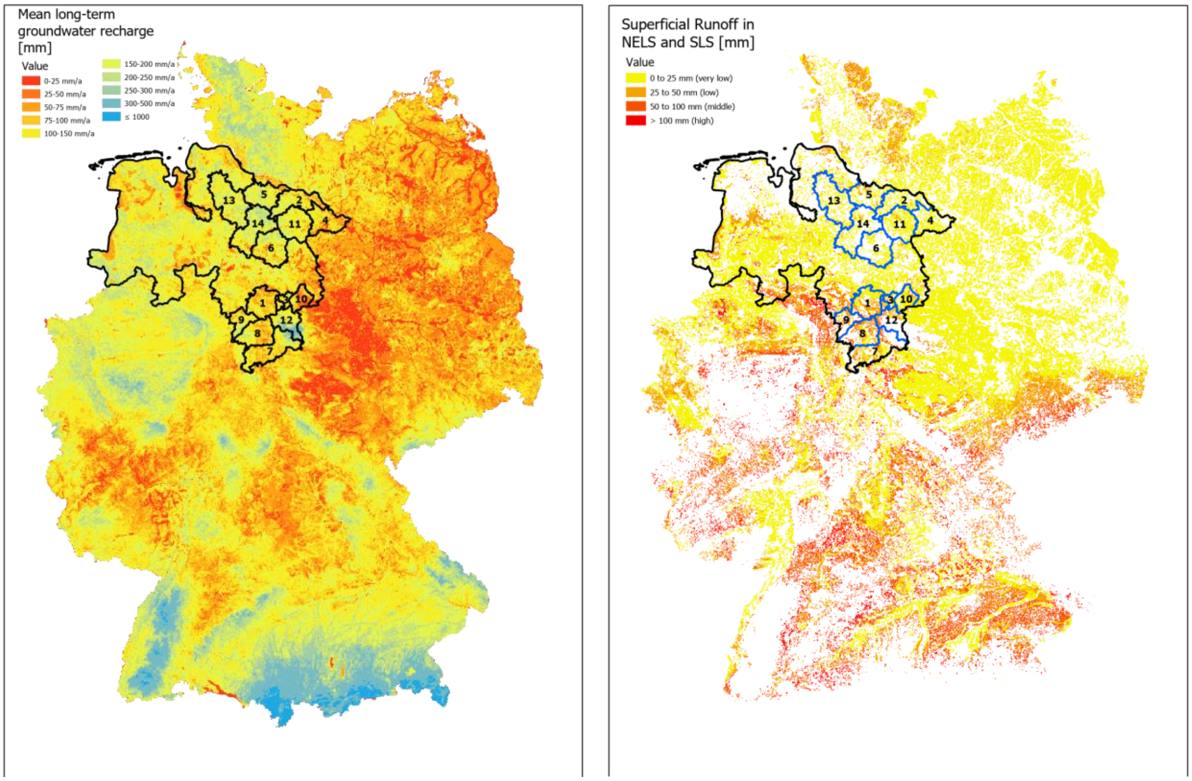


Figure 52 Annual groundwater recharge (left), Superficial runoff on agricultural soils (right) (according to BÜK1000 and DWD). The simulated regions are highlighted within Lower Saxony, which is also highlighted. The numbers represent the districts that we have simulated under the different scenarios. Hildesheim is 1, Lüneburg is 2, Salzgitter is 3, Lüchow-Dannenberg is 4, Harburg is 5, Celle is 6, Göttingen is 7, Northeim is 8, Holzminden is 9, Wolfenbüttel is 10, Uelzen is 11, Goslar is 12, Rotenburg (Wümme) is 13, and Heidekreis is 14.

SIMULATION SETUP

Figure 52 is the simulation setup used for this research. Blue boxes are the general information required for all runs. The green boxes are the tested scenarios for the same crop rotation, which fall into two main categories. Firstly, the three simulated RCPs scenarios (2.6, 4.5, and 8.5). Secondly, irrigation scheduling refers to changing when, according to the water stress suffered by the crop, the EPIC model automatically applies irrigation water during the simulation. We tested different irrigation regimes from no irrigation (rainfed condition) to full irrigation for this work. Within the irrigation tests, we also adjusted at which dates crops are irrigated.

Outputs are the pink boxes. To assess the effects of irrigation on crop yield and soil characteristics, we obtained monthly information on nitrogen fixation, soil organic carbon (TOC), water balance, crop yield, and applied irrigation.

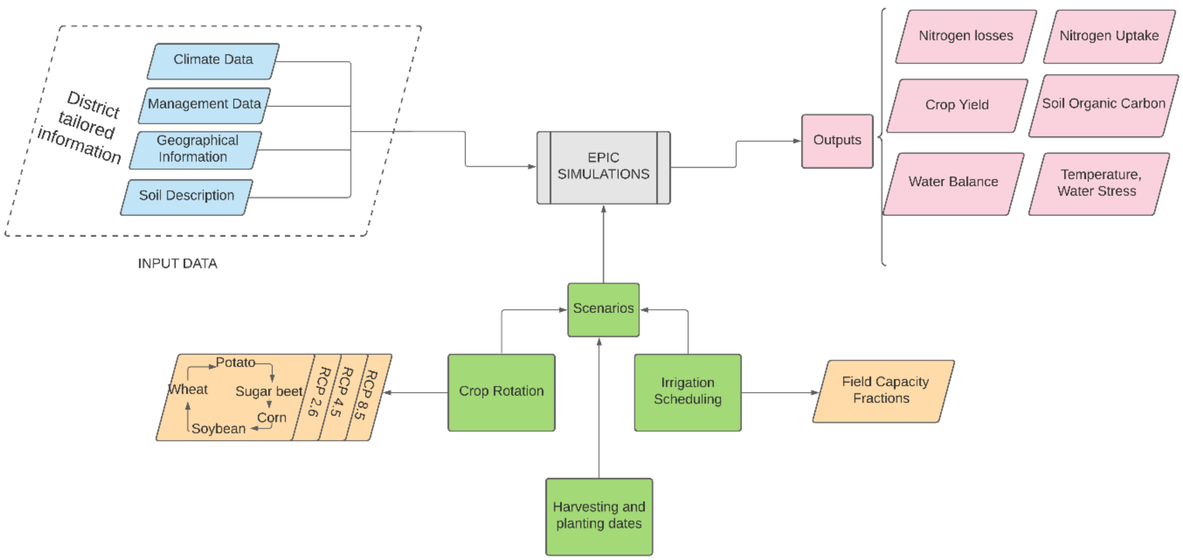


Figure 53 General simulation setup for this study. Pink boxes are the outputs from the EPIC model related to yield, nitrogen emissions, soil organic carbon, water balance elements, and thermic and water stress days. The green boxes are the tested scenarios in this study. Blue boxes are the input information used for the model. The simulations are conducted for the crop rotation described in the orange box. However, the analysis is done only for wheat and corn. The last orange box represents the five irrigation amounts based on a fraction of the field capacity (0% to 100%).

EPIC CROP MODEL

The Erosion Productivity Impact Calculator (EPIC) model was initially developed by the USDA (United States Department of Agriculture) in the early 1980s to simulate soil erosion on crop productivity. It also assesses how agricultural activities affect soil and water resources[32–34]. The model has been continuously expanded to simulate many other processes relevant for land use and agriculture[32,33,36,95]. EPIC is a field-scale model that simulates homogenous areas in weather, soil, landscape, and management operations [132], works in a daily resolution, capable of simulating future conditions.

Based on figure 53, we tested the application of a different amount of irrigation water calculated as a fraction of the field capacity (FC). For this purpose, we used a modified version of EPIC0810, which includes an option to automatically apply irrigation water to a fraction of field capacity set by the user using a new variable here, defined FIR0. Typically, the model calculates irrigation as the amount of water needed to bring the soil water content from the current level to the field capacity. In this study, we set FIR0 from zero to 1, giving the model the ability to apply from 0% to 100% of the water required to bring the soil water content to FC.

EPIC requires five weather parameters as input (Table 20). Precipitation is decisive for agriculture, as past drought caused crop yield reductions in Germany[97,98]. Additionally, extreme heatwaves have also negatively impacted crop yields[99,100]. For this reason, we focussed our weather analysis on precipitation, maximum and minimum temperature, and their influence on potential crop reduction in the future.

We run EPIC for three RCP scenarios (RCP 2.6, 4.5, and 8.5) to test the districts' yield behavior heterogeneity. This research's specific climate projection information is obtained from the Regridded and Corrected Data Sets for the IMPACT2C SlowTrack Models[58]. The RCM-GCM combination is CSC-REMO2009- MPI-ESM-LR for three RCPs (2.6, 4.5, and 8.5)[61,62].

Table 20 shows the input information used for EPIC simulations, including climate, CO2 concentrations for each RCP scenario, topographic characteristics, soil information, and management information for each simulated crop.

Category	Parameters	Reference
Climate: Historical (1979-2018) Lower Saxony Daily data	Maximum daily mean temperature (°C) Minimum daily mean temperature (°C) Relative Humidity (%) (Shortwave) Solar radiation (MJ/m2) Precipitation Quantity (mm)	Copernicus Programme Climate Reanalysis: Run with ERA5 (Re-analysed data)[102]
Climate Projections (2030-2100): RCP2.6 RCP 4.5 RCP8.5 Daily Data		IMPACT2C Quantifying projected impacts under 2 °C warming Report on climate-change information. (2014)[11]) The model used: CSC-REMO2009- MPI-ESM-LR for three RCPs (2.6,4.5 and 8.5)

CO2 Concentration **RCP 2.6** **RCP 4.5** **RCP 8.5**	Yearly CO2 concentration (ppm-CO2-eq) For the daily values, the annual values were repeated for each day in the same year	"GGI Scenario Database" web application is: International Institute for Applied System Analysis (IIASA) GGI Scenario Database Ver 2.0, 2009[103]
Topographic information	Slope Elevation	Digital Elevation Model (DEM) Lower Saxony from high precision DTM dataset of Germany[104]
Soil information	Soil texture Soil type Organic Carbon content Bulk density Carbonate content pH	Soil Map of Germany at scale 1:200,000 (BÜK200)[73]
	Soil albedo	Rosenberg et al. (1983)[105]
	Soil Hydrologic Group	Global Hydrologic Soil Groups (HYSOGs250m) for Curve Number-Based Runoff Modelling[106]
	Soil water at field capacity (1500 kPa)	Bodenbewertungsinstrument Sachsen; Stand 03/2009[107]
Land Use	Agricultural Area	Copernicus CORINE Land Cover Database 2018[72]
Soybean (*Glycine max*) operation information	Seeding Density: 70 grains/m2 Planted May 12th Harvested August 28th Manure 112.05 kg/ha Kali 2.50 kg/ha Phosphorus 4.50 kg/ha	Soybean field tests in Germany: Hiltbrunner et al. (2012)[108] Kunz et al. (2015)[109] Weber et al. (2016)[110]
Sugarbeet (*Beta vulgaris L*) operation information	Seeding density: 11 plants/ha Planted March 16th Harvested: September 5th PK-Solution 450 kg/ha Kali-Mg 140 kg/ha 28-10-10 soluble solution 400 kg/ha	Sugar beet field tests in Germany: Kunz et al. (2015)[109] KTBL-Datensammlung 2018/19[52] Direct operation information from farmers of the region

Wheat (*Triticum aestivum* L.) operation information	Seeding Density: 40 grains/m2 Planted October 25th Harvested July 20th 28-10-10 soluble solution 720 kg/ha Seeding density: 40 plants/m2 Planted March 16th Harvested August 20th 28-10-10 soluble solution 480 kg/ha	KTBL-Datensammlung 2018/19[52] Direct operation information from farmers of the region
Potatoes (*Solanum tuberosum*) operation information	Seeding Density: 40 grains/m2 Planted April 4th Harvested September 18th PK-Solution 500 kg/ha Manure 24.5 kg/ha 28-10-10 soluble solution 400 kg/ha	KTBL-Datensammlung 2018/19[52] Direct operation information from farmers of the region
Corn (*Zea mays* L.) operation information		KTBL-Datensammlung 2018/19[52] Direct operation information from farmers of the region

WATER BALANCE

We describe the water balance (WB) based on indicates the relationship between water inputs and outputs. The inputs are precipitation (PRCP) and irrigation (IRGA); outcomes include the main components of the negative part of the balance, which are actual evapotranspiration (ET), percolation (PRK), and runoff (Q).

$$CWB = (PRCP + IRGA) - (ET + PRK + Q) \quad \textbf{EQUATION 2}$$

PRECIPITATION AMOUNTS

We can establish differences among the three RCP scenarios and the reference period (1979-2018). For RCP 2.6 in 2070-2100, January, February, and September rains are more than for the 2035-2065 period. In the case of RCP 4.5, the rain amounts drop in general for both the near and far future. Although, for May, June, and July increase compared to RCP 2.6. For RCP 8.5, in general, it rains more during winter (December to February) compared to previous RCP scenarios. During summer, compared to RCP 4.5, rainfall quantity drops.

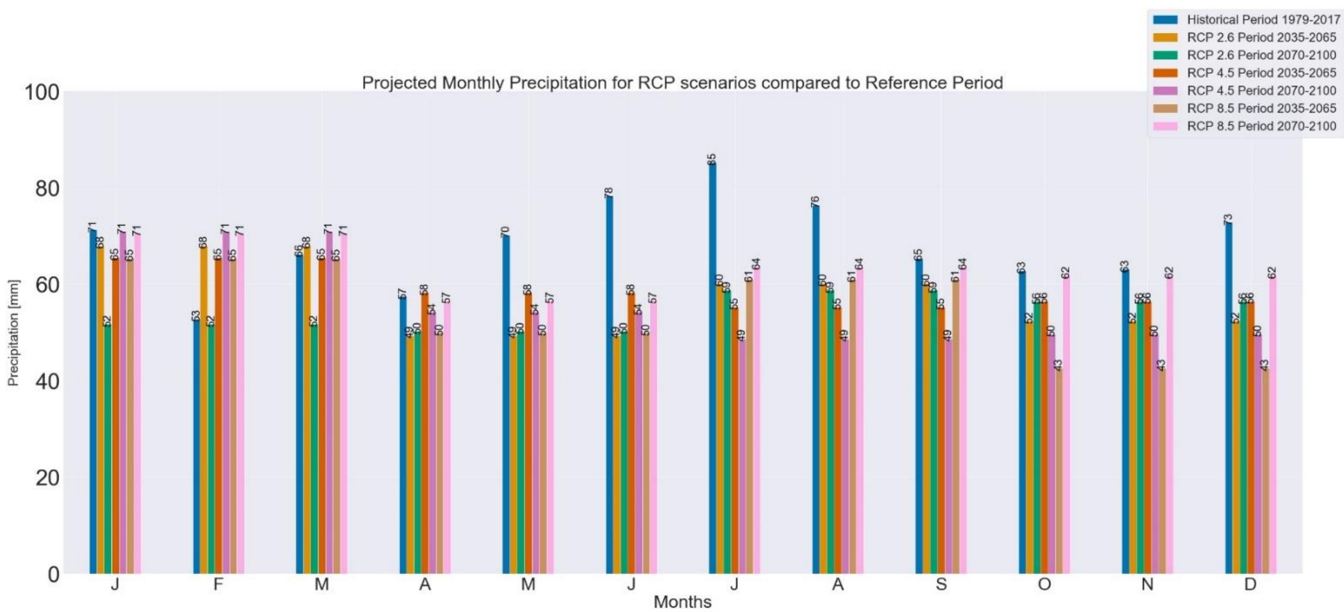


Figure 54 depicts the monthly precipitation [mm] for the three emission scenarios for the two future periods. Blue bars represent the historical precipitation. In general, there is more precipitation in the reference period. Lower rainfall regimes may be observed during future summer periods.

Besides the irrigation amount based on a fraction of field capacity, we included an irrigation trigger based on the water stress factor (WSF) calculated by the EPIC model for each crop every day of the simulated period. The WSF ranges from zero to one and allows the user to set a threshold for the application of irrigation water based on the stress suffered by the crop because of lack of water. The model will automatically apply irrigation water to avoid any stress caused by the lack of water when set to one. In contrast, when WSF is set to zero, the model will not apply any irrigation water. The crop growth simulation will be influenced only by the amount of water provided by precipitation [133] (Table 21). For this research, WSF is set to 0.6 as it represents how generally farmers manage the irrigation in the study area, allowing a more realistic simulation of the actual conditions.

Table 21 shows the applied irrigation tests description based on field capacity fractions (Please refer to figure)53

Irrigation Strategy	FIRO setting	WSF
I1: Automatic Irrigation with FIRGO options	0.0 = 0% FC 0.2 = 20% FC 0.4 = 40% FC 0.6 = 60% FC 0.8 = 80% FC 1.0 = 100% FC	Set to 0.6

PLANTING AND HARVESTING DATES TEST

The exploration of adaptation options included testing several planting and harvesting dates. We explored four possibilities to understand their effect on yields and water balance, irrigation, and evapotranspiration. Furthermore, irrigation amounts, planting, and harvesting management strategies were simulated in EPIC to analyze potential combined benefits, including water stress reduction (Table 22).

Table 22 shows the five crop calendar strategies description, including the BAU scenario. The water stress factor used in this research for all these strategies is 0.6

Planting and harvesting date strategy	Irrigation Setup	WSF
S1: Silage corn, winter wheat, and soybean were planted two months earlier (February and September, respectively) than the BAU scenario. Harvesting dates remain the same as the BAU scenario		0.6

S2: Silage corn, winter wheat, and soybean were planted two months earlier than in the BAU scenario. Harvesting occurs as in BAU.	The annual allowed limit set to 94 mm (Currently allowed limit taking into account extreme years where farmers needed to extract more than usual as 2003 and 2018) together with I1
S3: Silage corn, winter wheat, and soybean were planted and harvested two months earlier than the BAU scenario.	
S4: Silage corn, winter wheat, and soybean were planted two months later (July and December, respectively) than the BAU scenario. Harvesting dates remain the same as the BAU scenario	
S5: Silage corn, winter wheat, and soybean were planted and harvested two months later than the BAU scenario.	

RESULTS AND DISCUSSION

This section shows monthly water balance changes over I1 irrigation strategies and planting and harvesting strategies S1-S4. Likewise, we want to see the effect of each component of water input and outputs on crop yields for each tested scenario. We assess whether the temperature (TS) and water stress (WS) effect on yield could be reduced by applying different irrigation, planting, and harvesting dates. Additionally, we display a time and county average on total organic carbon (TOC) among the other tested management scenarios. Finally, we discuss the potential causes of the variations and impacts on the regions. Effects of irrigation and management on soil organic carbon

We observed TOC changes on each crop calendar and climate scenario (Figure 55). Compared to the BAU scenario, TOC for RCP 2.6 and 4.5 increases by about 5% when planting is two months earlier. For RCP 8.5, there is no difference between BAU and this management strategy. (Trost et al., 2014)[134] reported similar results in Northern Germany related to the impact of irrigation on the potential TOC increase: In a later study, they determined that in arid soils with dry climates, irrigation may have a more prominent role in enhancing TOC into the ground[135]. However, irrigation does not affect TOC as soils may be explained by the low clay and high sand content, which results in low incorporation of stable TOC, which may have counterbalanced the potentially positive effects of increased harvested yields.

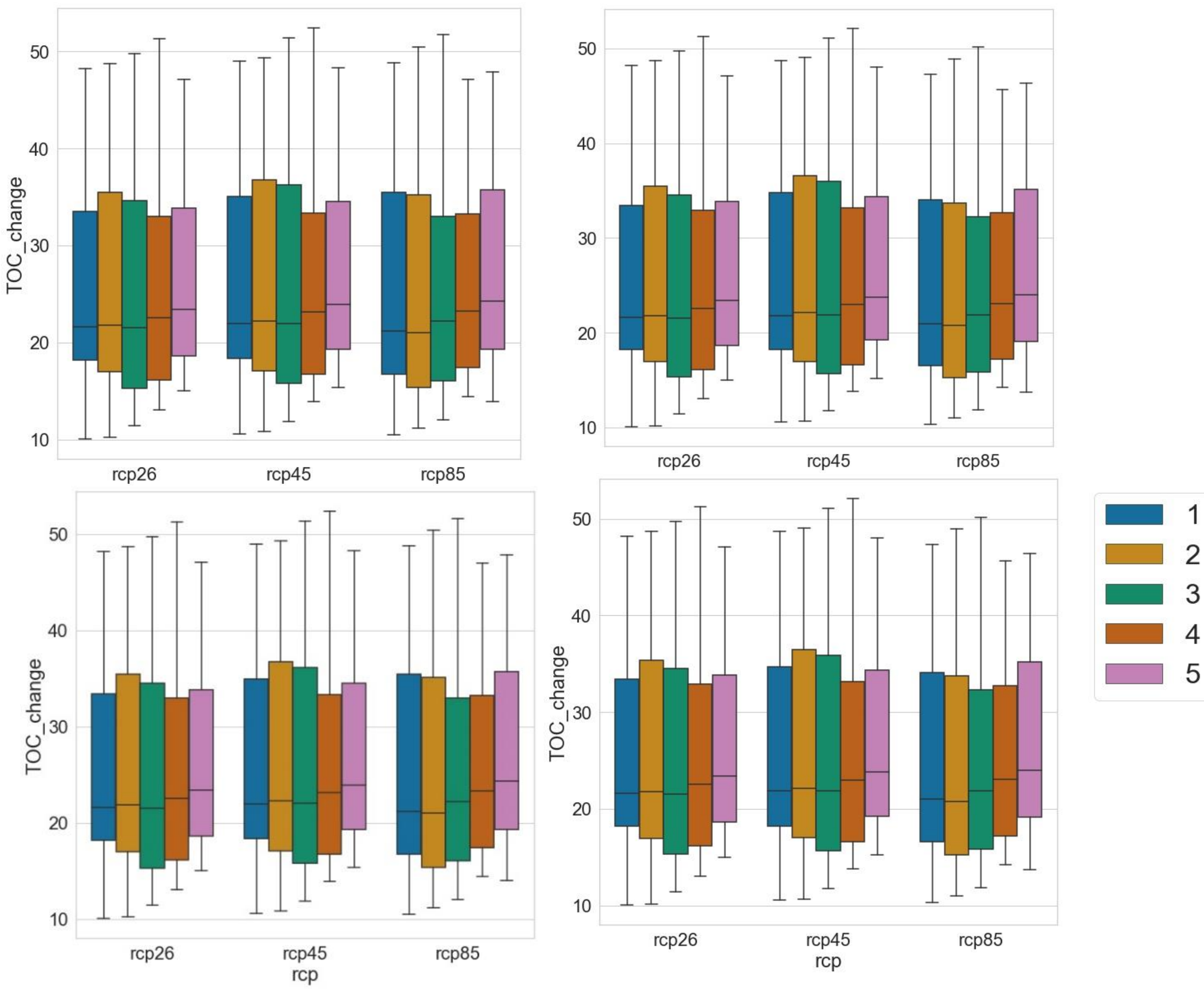


Figure 55 TOC change compared to the reference period (1979-2018) among three RCP scenarios and management strategies: There are no differences among treatments. Numbers 1 to 5 represent crop calendar strategies. 1 is BAU scenario, 2 planting earlier, same harvesting, 3 planting and harvesting earlier, 4 later planting, same harvesting, 5 later planting and harvesting.

SELECTION OF MANAGEMENT STRATEGY

Planting earlier and harvesting as the BAU scenario represents advantages above other strategies regarding more water available to the crop during summer, less evapotranspiration, and less irrigation required. Although, according to our results, an isolated adaptation option may not ensure stable yields in the future. EPIC simulations with no water stress were performed by allowing a maximum application annual rate of 500 mm. A compensation factor of one is not realistic nor applicable in the field. Additionally, temperature stress is still present and influences yields negatively. In this sense, irrigation adaptation potential is limited to temperatures above crops' optimum temperature and water availability.

The studied region has not faced water accessibility conflicts with an extraction percentage in Lower Saxony corresponding to 9% on a national scale, of which about 13% are from groundwater bodies[136]. This lack of conflict is due to irrigation with groundwater playing a minor role in crop production in the region since only 6% of the farmers irrigate this way[25]. However, one of many climate change impacts in the region (Figure 54) is lower rainfall, about 13% during July to August for RCP 8.5 than RCP 2.6 and 4.5. Similarly, for RCP 8.5 rainfall pattern increases by 6% from April to May. These expected changes may make the farmers use more water during the regular growing season and adapt the crop calendars to new climatic conditions.

Climate change will affect the timing of cereal crop growth. In this regard, the model results study indicated the best planting date for silage corn to be mid-February, which corresponds to the planting two months earlier instead of mid-April as in the BAU scenario. Crop simulation studies have shown mid-April to be the best planting dates in current conditions[137,138]. Planting earlier for a C4 plant as corn in a warmer climate allows it to grow more if there is enough water, which similar results were shown on empirical evidence [139]. For this reason, planting earlier would take advantage of higher rainfall amounts in an earlier vegetation period for scenario RCP 8.5, allowing ensuring higher yields. Harvest heating units plots can be found in the supplementary material.

The more water used to irrigate crops, the more water can be lost due to runoff and percolation. For this reason, we were interested in finding out if there was an optimum amount that had a significant effect on yields beyond this amount. For example, for both silage corn and winter wheat, a level of irrigation of 60% of the field capacity may help reduce runoff and percolation without negatively affecting the attained yields (Figure 56 and 60). All applied irrigation amounts results are displayed in the supplementary material.

We describe the crop yield changes and nitrogen uptake by the crop compared to the reference period for these selected irrigation amounts for all tested management strategies. For corn, planting two months earlier and unchanged harvesting dates (Operation B) yield penalties are mitigated by about 10% on average for both periods. Advancing the crop calendars two months later may reduce yields up to around 80% for both future periods. Nitrogen uptake extends up to 150% for the near future for RCP 2.6 and 4.5. This fertilization effect is reduced by 50% compared to the reference period by 2100 for RCP 8.5 (Figure 58 and 62). Consecutively, we can observe a positive effect on mitigating nitrogen losses for corn and wheat (Figure 59 and 63).

Winter wheat sown two months later with unchanged harvesting (Operation D) helps mitigate yield reduction and stability since the heatwave effect of higher temperatures may diminish. (Aurbacher et al., 2013)[140] reported the need to shift the planting date of winter wheat to mitigate the yields assuming no integration of different management approaches.

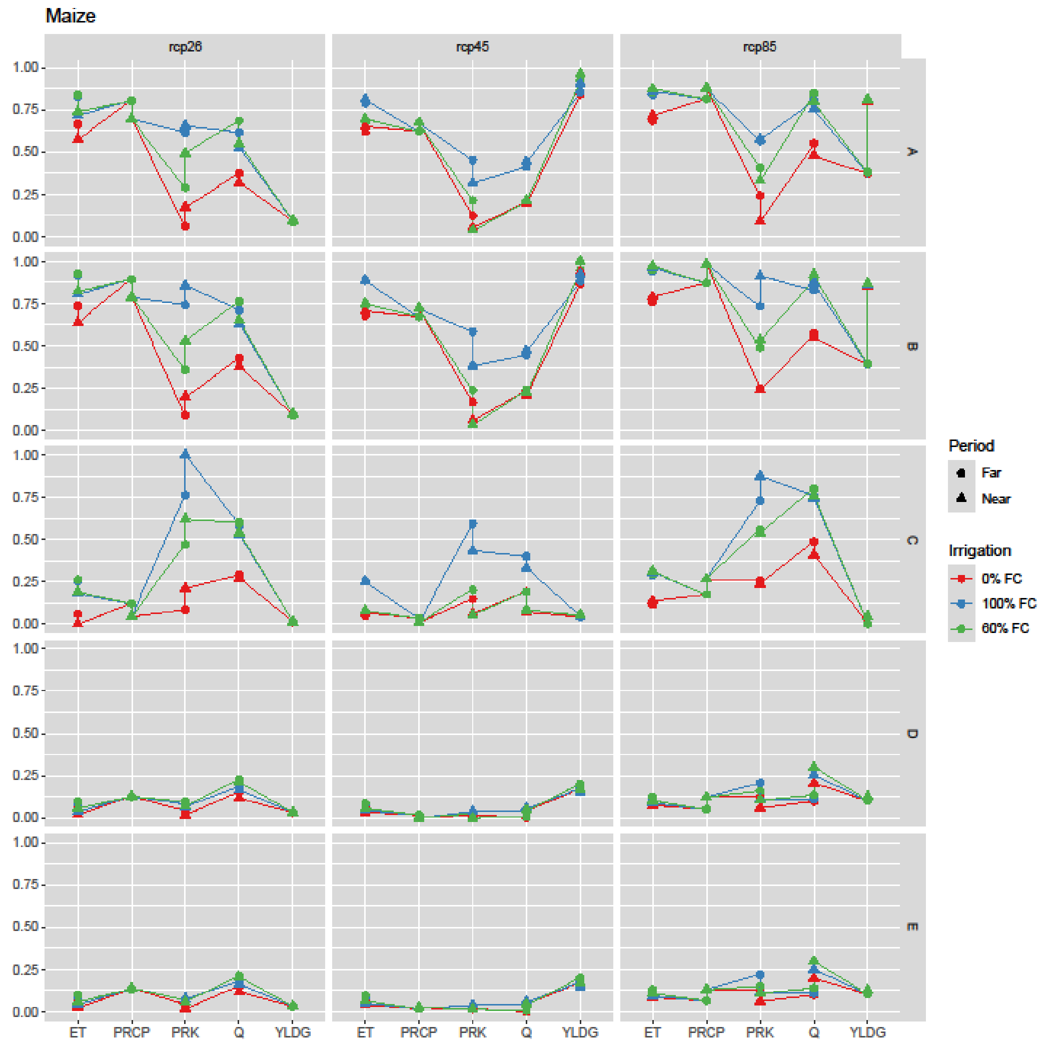


Figure 56 Parallel plot for silage corn: Planting and harvesting later reduce yields (Treatments D and E). Letters A to E represents crop calendar strategies. A is BAU scenario, B planting earlier, same harvesting, C planting, and harvesting earlier, D later planting, the same harvesting, E later planting and harvesting.

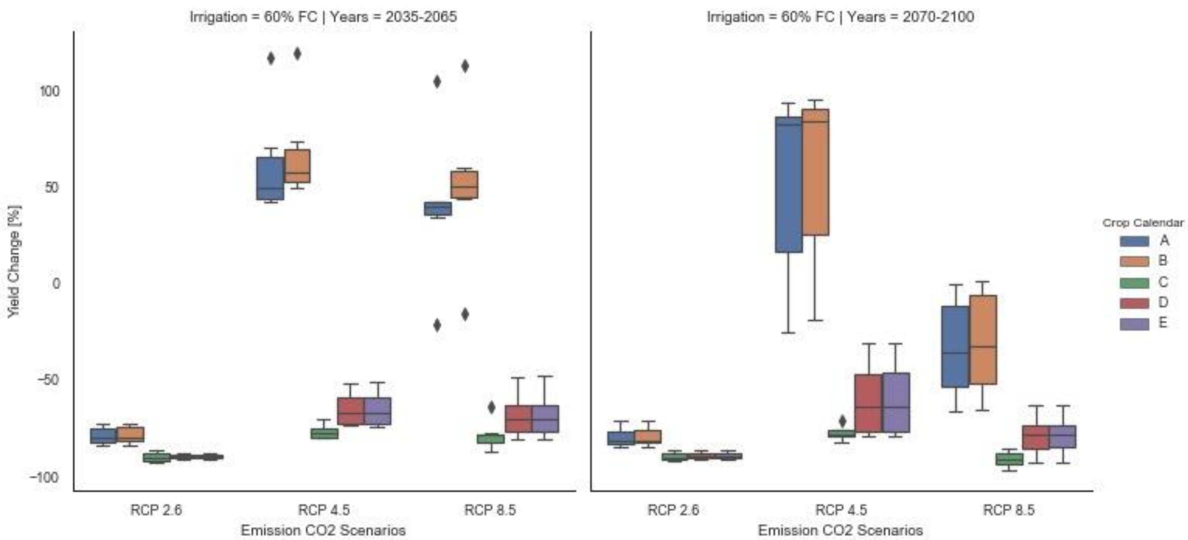


Figure 57 Corn yield change: Planting earlier increases yield by 40% (Treatment B). Letters A to E represents crop calendar strategies. A is BAU scenario, B planting earlier, same harvesting, C planting, and harvesting earlier, D later planting, the same harvesting, E later planting and harvesting.

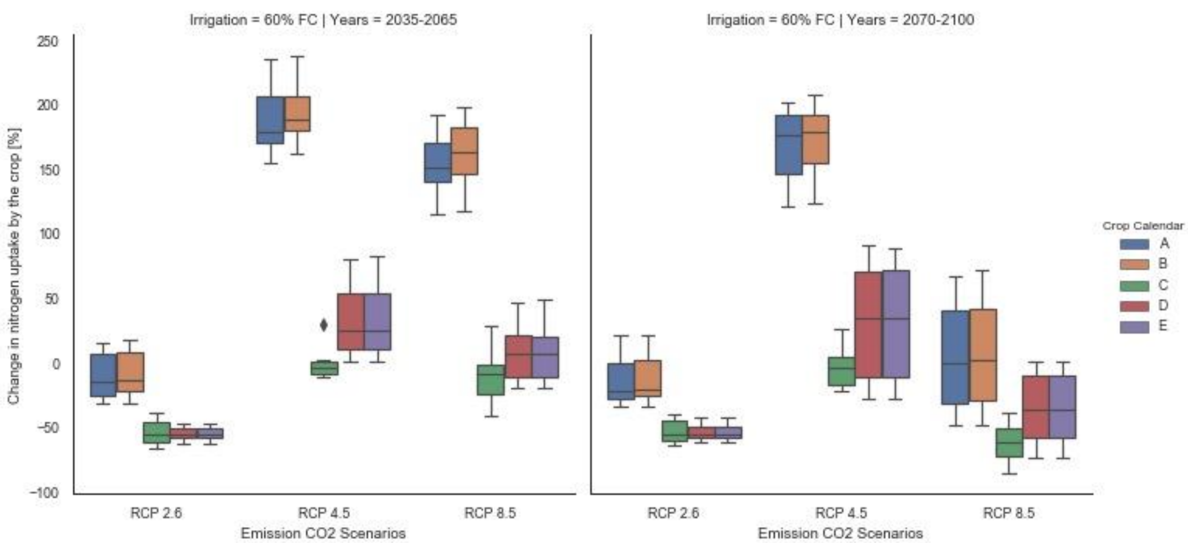


Figure 58 Planting earlier increases nitrogen uptake for RCP 8.5 for the near future. This effect is less apparent for years 2070-2100 than BAU (Treatment B). Letters A to E represents crop calendar strategies. A is BAU scenario, B planting earlier, same harvesting, C planting, and harvesting earlier, D later planting, the same harvesting, E later planting and harvesting.

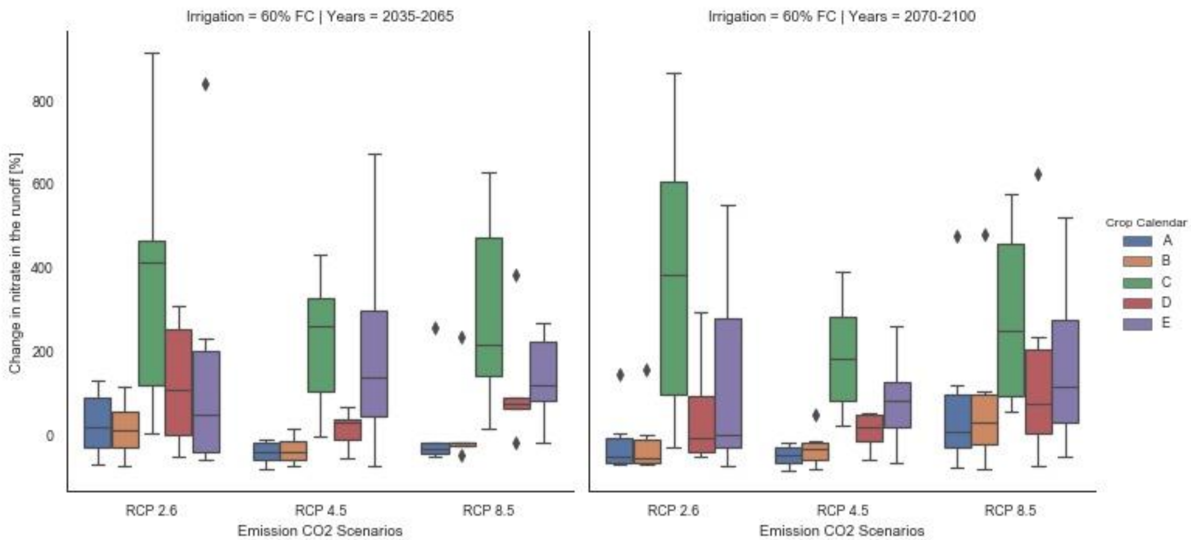


Figure 59 shows that planting earlier decreases nitrate losses for RCP 2.6 for the near future. This effect is less apparent for years 2070-2100 than BAU (Treatment B). Letters A to E represents crop calendar strategies. A is BAU scenario, B planting earlier, same harvesting, C planting, and harvesting earlier, D later planting, the same harvesting, E later planting and harvesting.

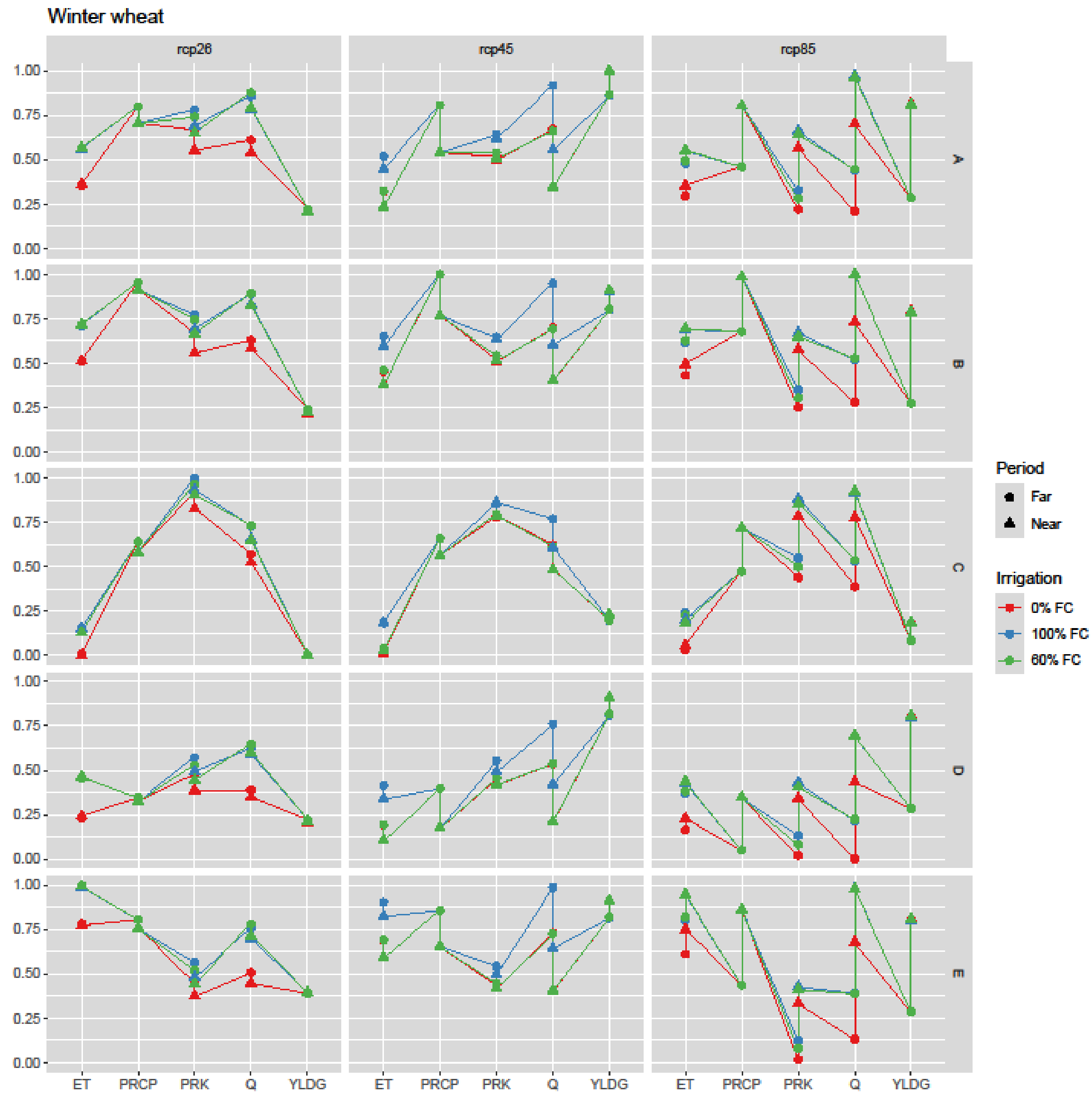


Figure 60 Parallel plot for winter wheat: Later planting and same harvesting reduce water losses and ET increases compared to BAU. Letters A to E represents crop calendar strategies. A is BAU scenario, B planting earlier, same harvesting, C planting, and harvesting earlier, D later planting, the same harvesting, E later planting and harvesting. ET is Evapotranspiration, PRCP precipitation, PRK percolation, Q runoff, YLDG is yield.

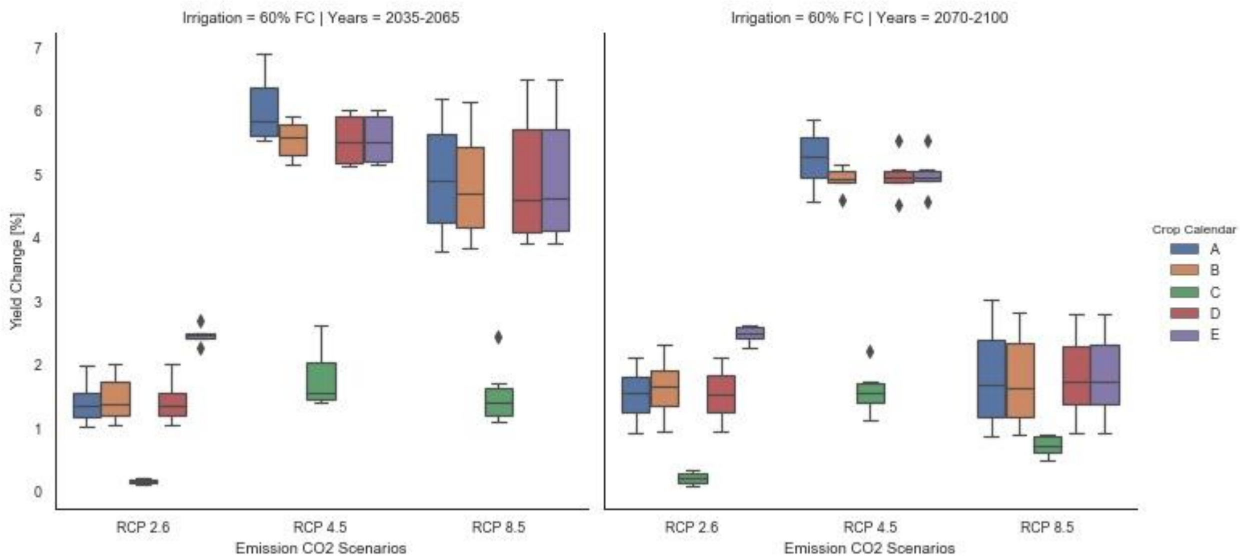


Figure 61 Planting and harvesting later, so planting later only increase wheat yields for RCP 8.5 for both periods. This effect is consistent only for planting and harvesting later for RCP 26. Letters A to E represents crop calendar strategies. A is BAU scenario, B planting earlier, same harvesting, C planting, and harvesting earlier, D later planting, the same harvesting, E later planting and harvesting.

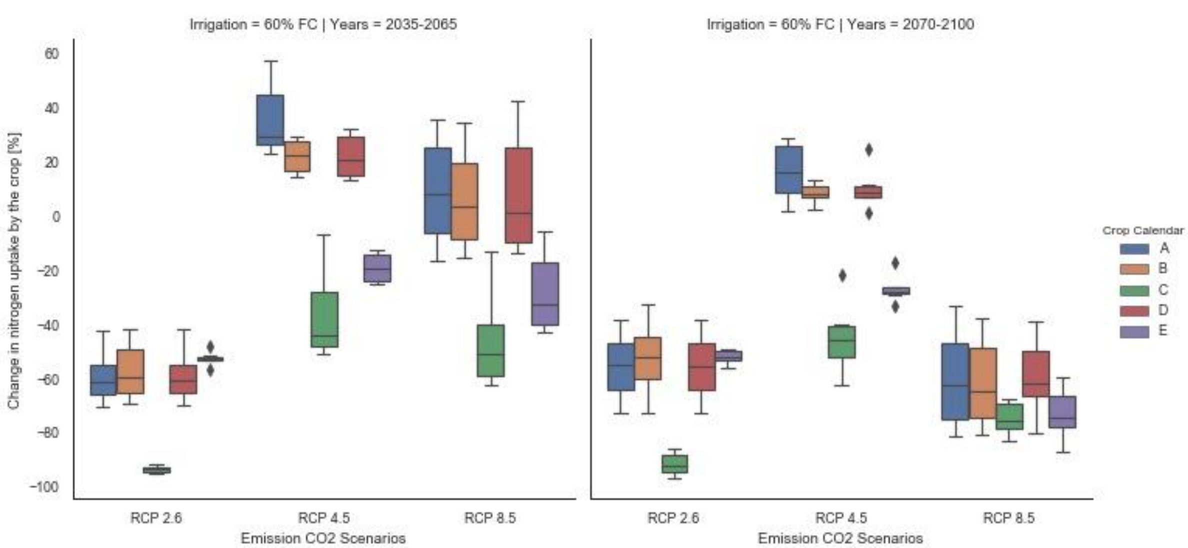


Figure 62 Planting later increases nitrogen uptake for RCP 8.5 for the near future. This effect is less apparent for years 2070-2100 than BAU (Treatment B). Letters A to E represents crop calendar strategies. A is BAU scenario, B planting earlier, same harvesting, C planting, and harvesting earlier, D later planting, the same harvesting, E later planting and harvesting.

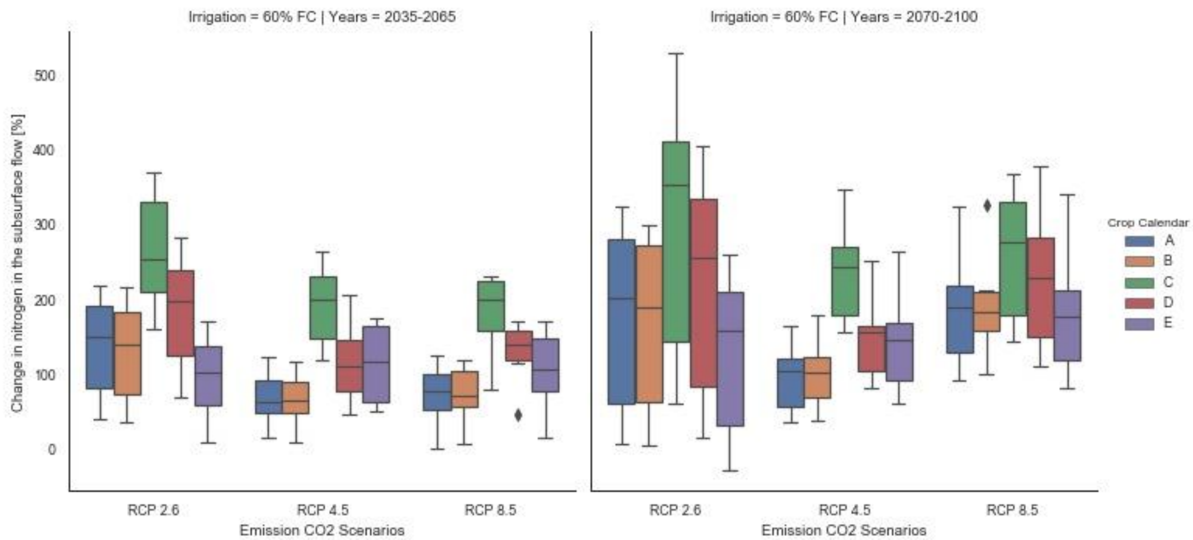


Figure 63 Planting earlier decreases nitrate losses. This effect is less apparent for years 2070-2100 than BAU (Treatment B). Letters A to E represents crop calendar strategies. A is BAU scenario, B planting earlier, same harvesting, C planting, and harvesting earlier, D later planting, the same harvesting, E later planting and harvesting.

THE FUTURE IMPLICATION OF CEREAL PRODUCTION

The shortening of the projected growing period under climatic warming indicated by earlier vegetation may yield reductions than current production levels. To take advantage of warming signals and the variation in precipitation, farmers need to adjust crop calendars to such new changing climate conditions. Thus, this research shows that under the model used, planting two months earlier and adapting the irrigation to about 60% of field capacity may help to reduce such crop yields, especially for silage corn. Similar results were reported by several studies[141–144]. It highlights that the more extended vegetation period must be used as an advantage. However, there is a risk of drought due to enhanced ET during the growing season and insufficient crop available water, especially on sandy soils, characteristic in the NELS region.

SILAGE CORN

Our results show the potential to increase up to 50% of their yields in warming conditions by planting two months earlier only when there is enough water to avoid stress and drought hazards up to the year 2065. For 2070-2100, crop yield losses may be mitigated up to 10% compared to the BAU scenario for RCP 8.5. These results display the limitation of irrigation and crop calendar application as we can observe that there are still yield losses by applying to reach 60% of field capacity (Figure 56). According to the climate model used, we can observe water stress consequences in red for Harburg (located in NELS) and Holzminden (located in SLS). According to the climate model used, their precipitation values are around 40% less during the new shift-growing season than in the rest of the simulated districts (Figure 64). The usage of only one plausible climate projection limits the analysis of our results. Crop assessment methods as EPIC together with climate models perform pretty well on a global or continental scale. However, their applicability in local extensions, as in this study, is uncertain[145–147], leading to opposite results among similar studies. For instance, [148] reported in their research that winter wheat future yields do not decrease using six regional climate models, which does not include the model we utilized. For this reason, they do not suggest planting it later.

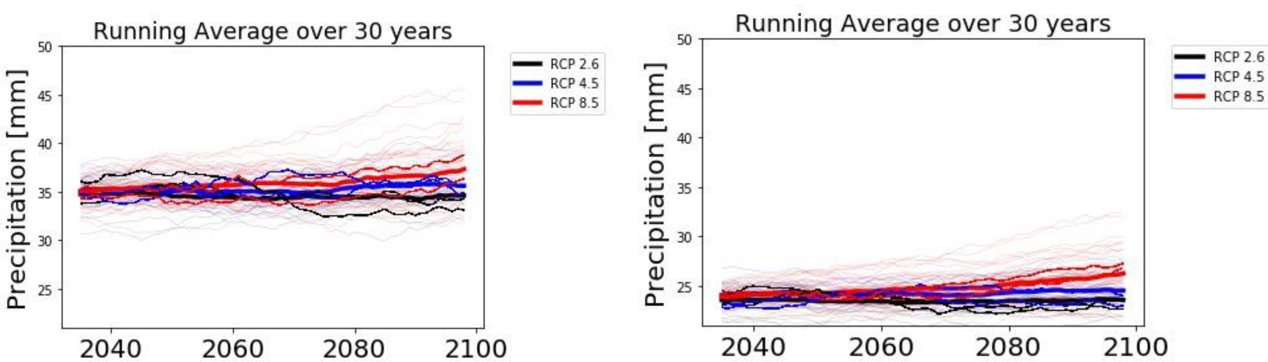


Figure 64 Average yearly precipitation: 88 climate combinations in thin lines for three RCP scenarios. Thickest lines represent the average of all combinations for each emission scenario. Second thick lines are the climate model information used in this study.

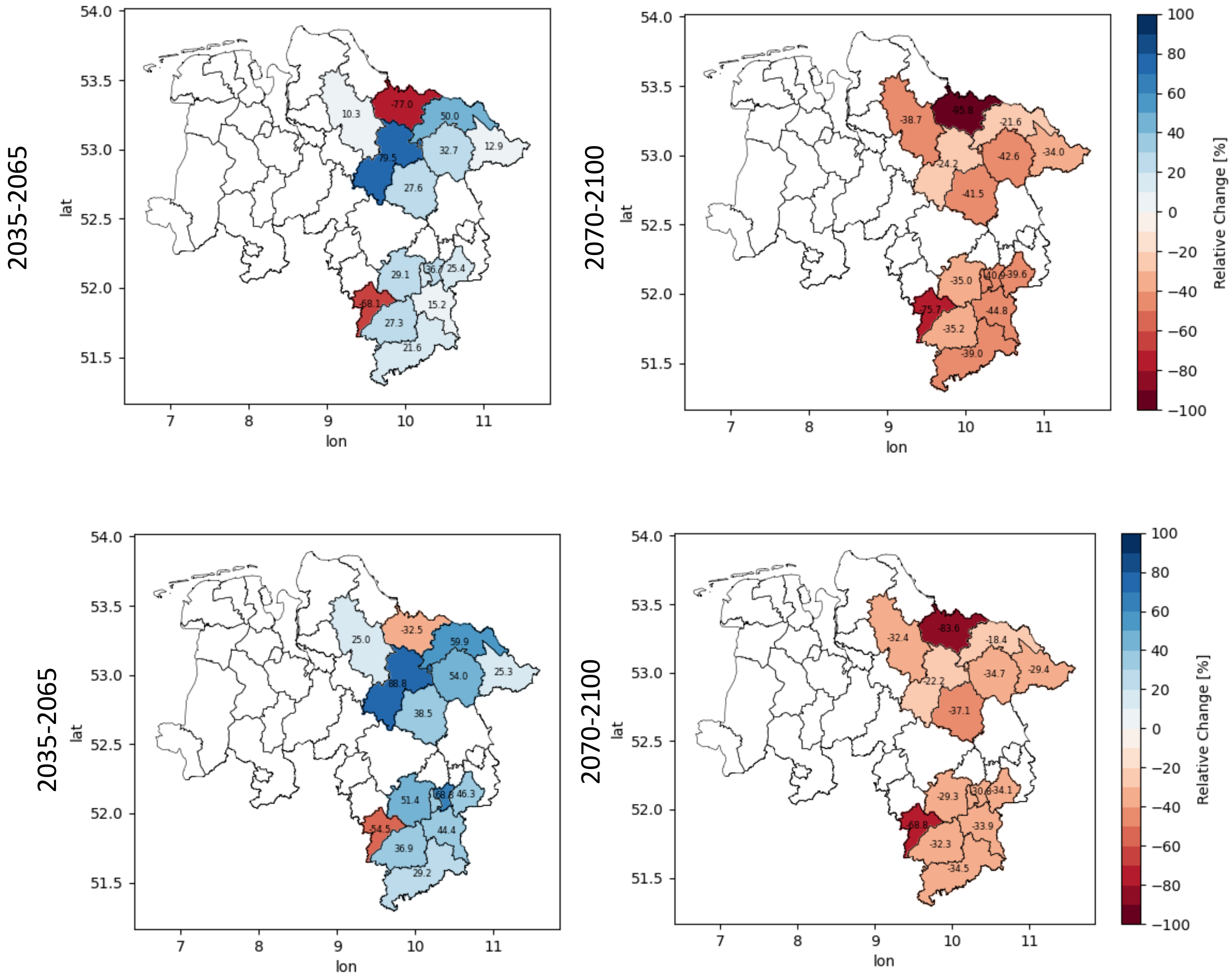


Figure 65 Management Scenario: 60% Field Capacity irrigation amount and planting two months earlier. Near future (Left side) under these conditions increase corn yields for more districts. Right side is far future where corn yields are reduced

WINTER WHEAT

As figure 60 depicts, for winter wheat (*Triticum aestivum L.*), yield losses may be mitigated when planted two months later with irrigation of 60% of field capacity. However, this combination of applied strategies is limited due to climate change in plant growth. Previous authors have reported research on winter wheat detriment growth due to heat stress. Araus et al. 2002 has indicated that higher temperatures are the main abiotic restraints on cereal yield, mainly during the vegetation period. Heat stress is also a primary limitation to wheat production and profitability in many wheat-growing regions of the world[149]. Wheat yields have been more limited due to heat stress [150,151]. Our results show that regardless of advancing planting date, losses may be diminished by 10% for most NELS districts for 2035-2065. For future heat stress constraints, yields reach penalties of about 70% that are not apart from the BAU scenario for RCP 8.5 (Figure 66).

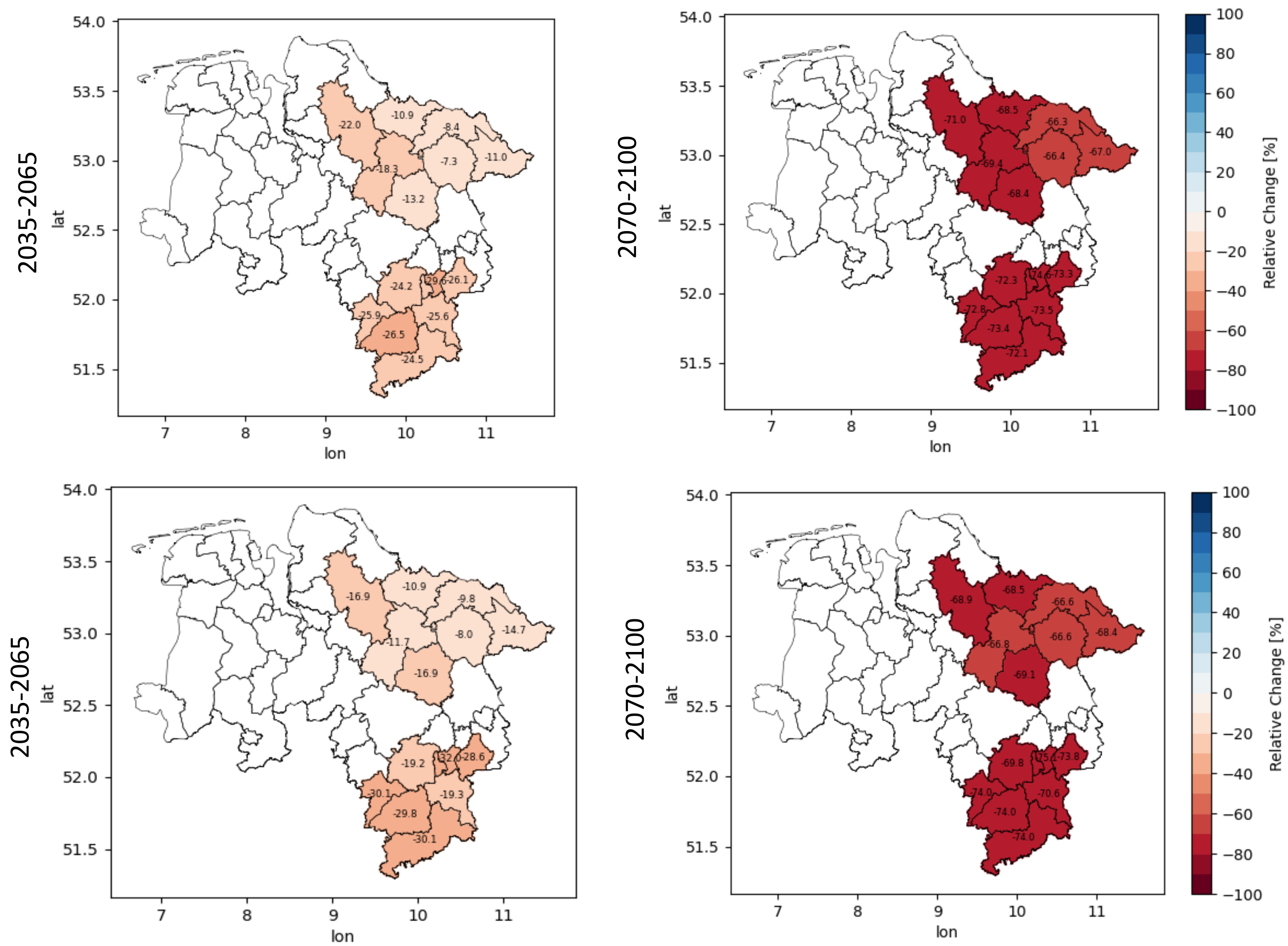


Figure 66 Management Scenario: 60% Field Capacity irrigation amount and planting two months later. Near future (Left side) under these conditions wheat yields losses are mitigated for more districts. Right side is far future where wheat yields losses are up 75%.

WATER AND TEMPERATURE STRESS

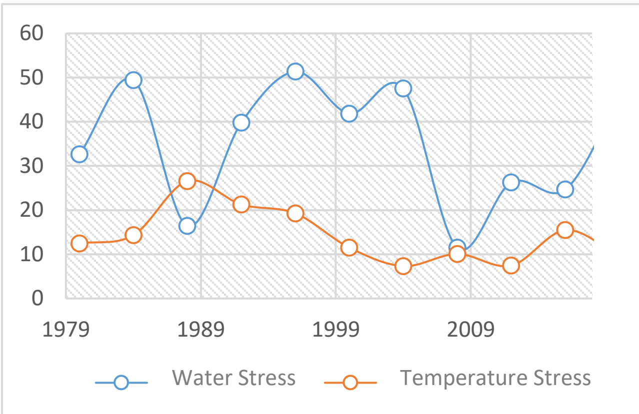
Corn and winter wheat present different behaviors under a similar management combination for both future periods with RCP 8.5. Figures 3.13 and 3.14 depict which of these two types of strains significantly influence crop development for corn and wheat. In the case of corn, we can observe that water stress plays a more prominent role (Figure 3.13). The

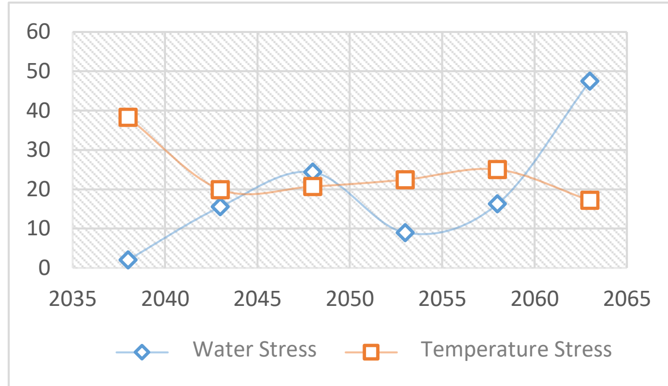
EPIC model computes the number of days the crop suffers stress due to lack of water or deviations from optimum growth temperature. Thus, irrigation may mitigate these negative impacts partially. Likewise, heat stress is mitigated by extending the vegetation period by two months. This strategy is appropriate since corn yield penalties in the future are expected due to a reduction in the length of the crop cycle[152] and augmented water stress as atmospheric water demand increases[153,154].

On the other hand, wheat is more affected by temperature stress than water stress (Figure 3.14). Adjusting its crop calendar is insufficient to avoid yield losses, especially for 2070-2100, in which water stress increases slightly. This intensification will lead to enhanced transpiration during the vegetation period, increasing the risk of drought and associated yield losses on sandy soils[155]. In this sense, cultivating more drought-tolerant varieties would be necessary to keep producing food under new climate conditions with an increasing population and efficient management strategies towards irrigation and crop calendars, as reported in [156] for wheat and [157] for corn.

This increased water requirement may lead to water conflicts in the region, as more water for irrigation will be needed to enhance yield stability in the future. However, irrigation alone may have limitations due to legal restrictions regarding the maximum amount that farmers can use. Likewise, the impact of climate change on the plants due to temperature stress cannot be alleviated by implementing irrigation.

CORN





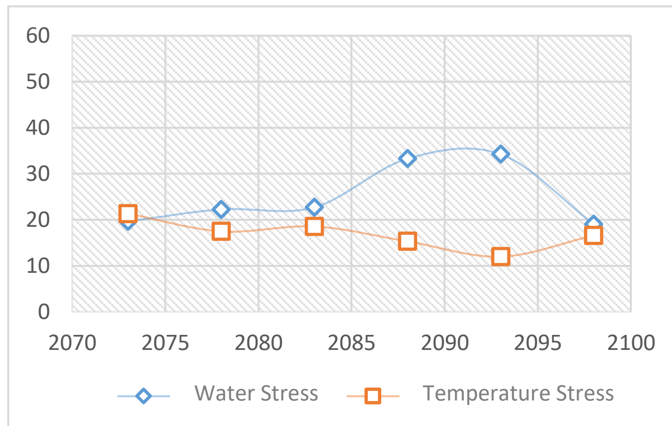
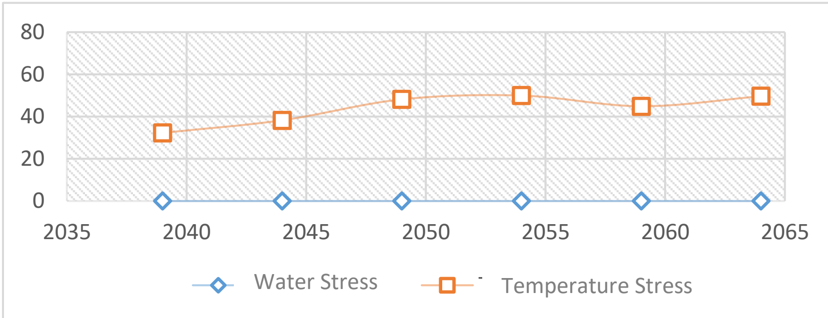


Figure 67 Yearly temperature and water stress days for corn. Left side is the number of days for the reference period. Right side depicts both future periods. Upper plot is near future and lower one is far future. The reference period shows us that corn is about 20 days in average more stress due to water than the future.

WINTER WHEAT



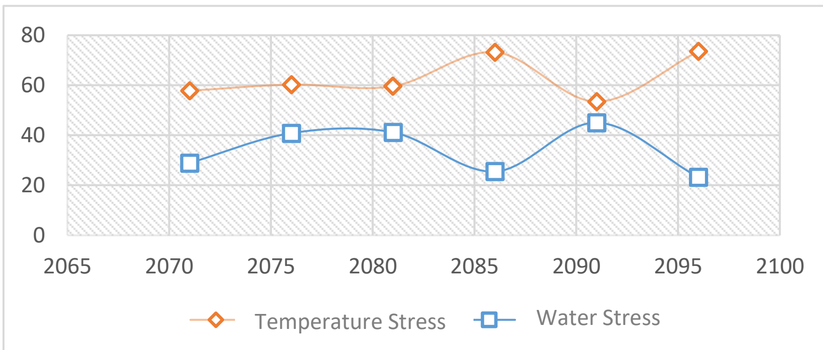


Figure 68 Yearly temperature and water stress days for wheat. Upper plot is near future and lower one is far future. This crop has more days with thermical stress than due to lack of water.

CONCLUSIONS

This study helped understand the potential of several adaptations in mitigating yield losses, nitrogen emissions, and improving water balance. Warmer temperatures and reduced rainfall in future summer periods are likely to shift crop calendars and vary irrigation amounts for varieties that are not modified to be more drought tolerant. Corn may be seeded earlier, while winter wheat could be sown later to advance yield development for the near future and alleviate yield penalties for the far end. Additionally, water availability is also a critical factor in mitigating losses in the distant future. However, this increased water requirement for irrigation may lead to water allocation conflicts in the region. In this sense, we have observed from our results that irrigation poses limitations in yield enhancement since plants will also be stressed due to warmer temperatures during the growing season.

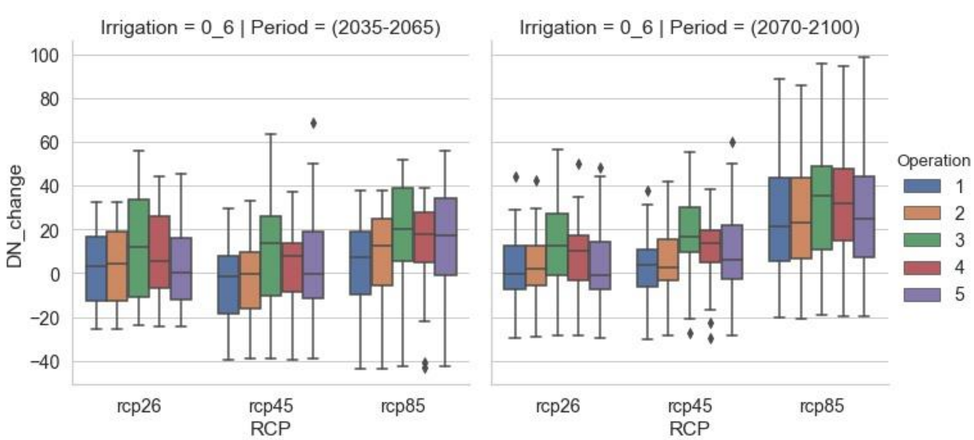
Nevertheless, this is applied indirectly in EPIC by changing specific crop parameters as base temperature, and optimum growth temperature as this crop model is process-based. For this reason, there is a need to conduct further studies to assess these management strategies, including drought-tolerant cultivars for wheat and corn. The question here is whether a crop model like EPIC is the most appropriate tool for such analysis.

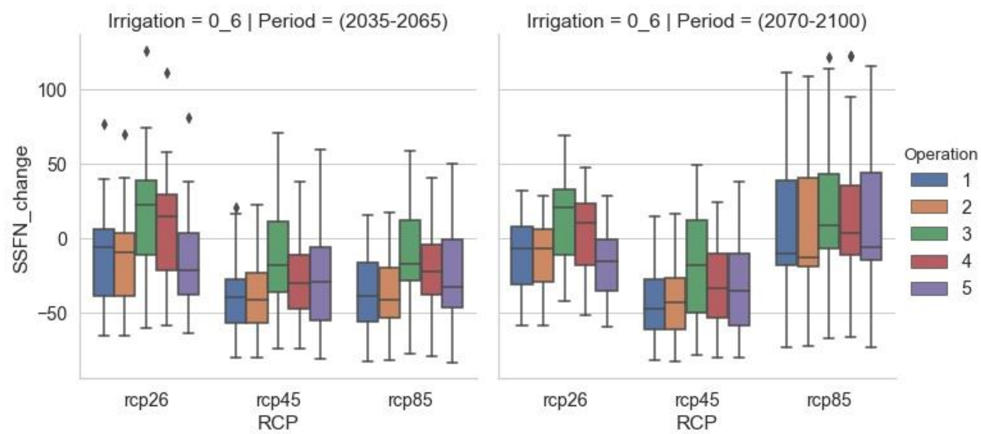
It is essential to highlight that this study's outcomes are based on only one climate model for the three emission scenarios, which shows only one possible future trajectory. For this specific model, two districts have notably less rainfall than the rest of the districts. These climate conditions highlight corn yield penalties regardless of the adaptation-applied strategy whose advantage works for the rest of districts with similar higher precipitation amounts. Thus, it is necessary to conduct simulations including more climate combinations to capture more potential future trajectories that may be lead to other results.

SUPPLEMENTARY MATERIAL

MANAGEMENT IMPACT ON NITROGEN EMISSIONS

Nitrogen balance variations among climate scenarios and management strategies included denitrification (DN), nitrogen in percolation (PRKN), and nitrogen in runoff (SSFN). The following two plots depict these changes for the reference period for the selected irrigation amount.

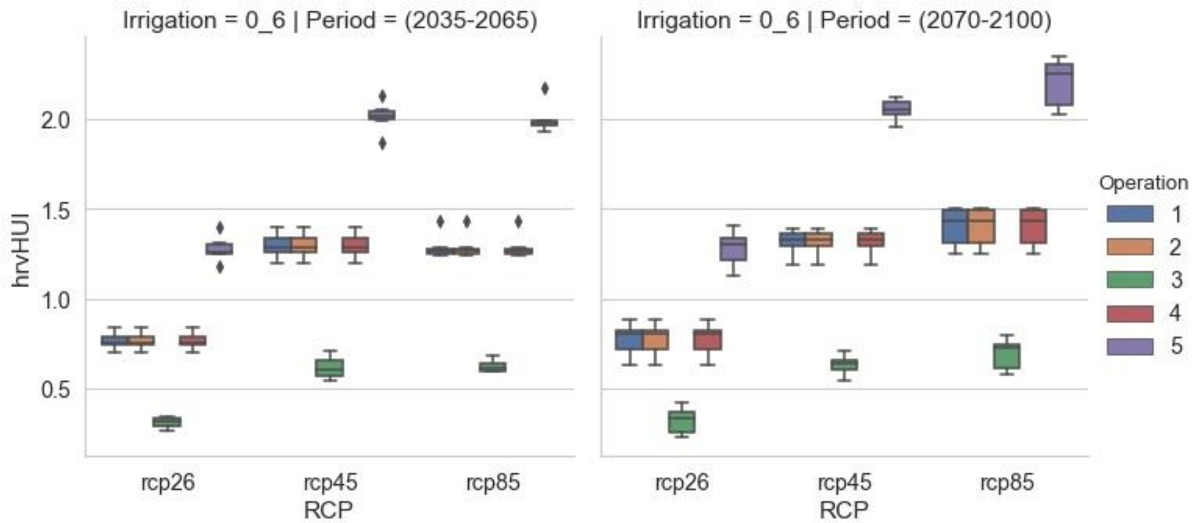


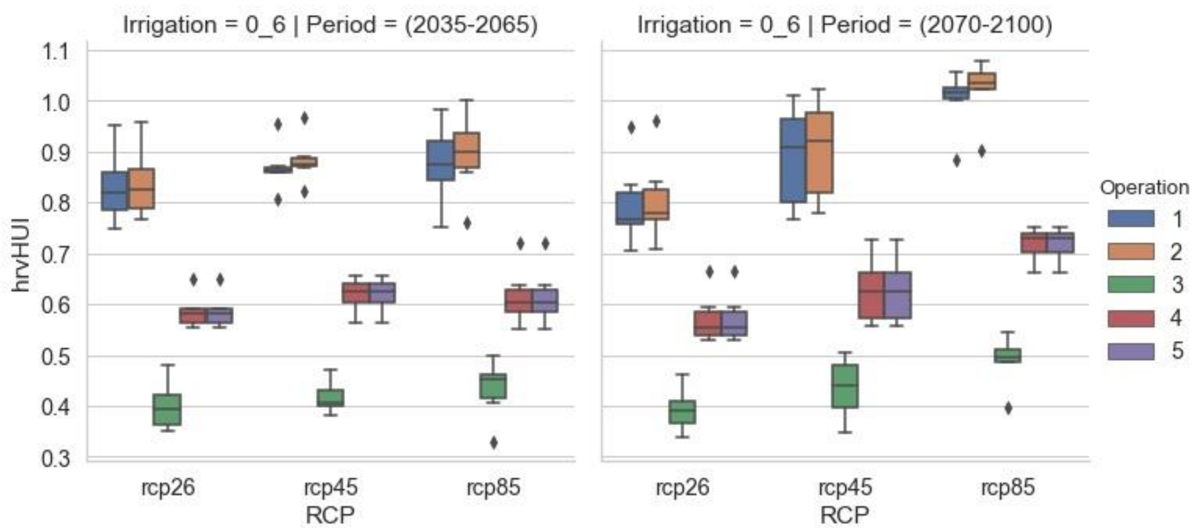


HEAT UNITS AT HARVEST VARIATIONS

Heat Units at Harvest (hrvHUI) is calculated as the ratio between the heat units accumulated by the plant and the potential heat units (PHU). A HUI equal to one means that the crop has reached physiological maturity. A HUI below one indicates that, when harvested, the crop was not at physiological maturity. In contrast, a HUI value above one indicates that the crop was harvested past maturity, which is the case of corn or wheat. They are harvested after physiological maturity to let the kernels dry down on the field.

The following two plots show the variations on hrvHUI for each emission scenario and crop calendar options for the 60% FC irrigation amount for corn and wheat, respectively. For corn, operation 2 increases hrvHUI by about 0.1 for all future RCP scenarios. In the case of wheat, operation four does not change the maturity stage of the crop when it is harvested.


Irrigation = 0_6 | Period = (2035-2065)
Irrigation = 0_6 | Period = (2070-2100)
hrvHUI
2.0
1.5
1.0
0.5
rcp26
rcp45
rcp85
RCP
Operation
1
2
3
4
5


Irrigation = 0_6 | Period = (2035-2065)
Irrigation = 0_6 | Period = (2070-2100)
hrvHUI
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
rcp26
rcp45
rcp85
RCP
Operation
1
2
3
4
5

Chapter 5

CHAPTER 5

Warmer Germany: temperature indices are moderately correlated to yields that may indicate soil water deficit in the future under climate change

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ABSTRACT

CONTEXT

Climate model projections display warmer temperature signals and more erratic rainfall patterns in Germany. These new conditions may represent an increased hazard of agricultural drought events with crop yield losses increment in many regions. Crop models help the understanding of such dynamics to assess the effect of adaptation strategies. However, research has focused on determining drought events using proxies as SPEI (Standard Precipitation Evapotranspiration Index) and their impact on yield losses.

OBJECTIVE

We aim to assess whether soil moisture deficit or climate indices or a combination of two may have a stronger correlation to crop yields for the German agriculture sector.

METHODS

The simulations were conducted using the EPIC crop model under three RCP climate scenarios (2.6, 4.5, and 8.5) for two future periods: near future (2035-2065) and far future (2070-2100) for wheat and corn. We compared the correlation, using copula models, between yield and extreme climate indices for temperature and precipitation and yields with Soil Moisture Deficit to assess which climate predictor can express yield losses more accurately in advance.

RESULTS AND CONCLUSIONS

Both corn and wheat exhibit moderate correlation with temperature climate indexes as the number of summer days, the consecutive number of days with temperatures higher than 30°C and 35°C, especially for RCP 8.5. On the other hand, they are weakly correlated to precipitation climate indexes as the number of consecutive wet or dry days. We also found that corn penalties are more affected due to temperature stress than due to water stress (r2= 0.85 for RCP 2.6, r2=0.91 for RCP 4.5). Wheat yields lack correlation with the number of water stress days for the three selected CO2 emission scenarios. However, it is relatively good correlated with the number of days with temperature stress for climate RCP 2.6 and 4.5. This stronger correlation with temperature over water may explain the weak correlation between yields and soil moisture deficit calculated from the soil moisture content simulated by EPIC.

SIGNIFICANCE

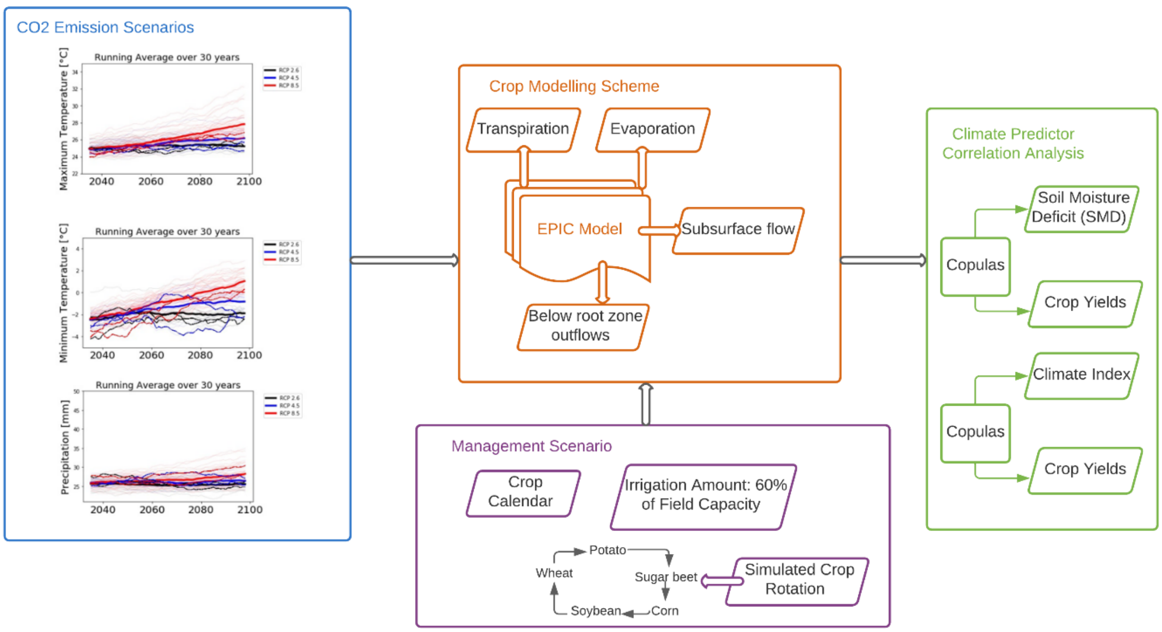
Using copulas, we found that when crops suffer more from thermic stress, their loss trends may be identified using temperature indices and not precipitation indicators, especially for RCP 8.5.

<u>HIGHLIGHTS</u>

- For this study, crop yields are stronger correlated to temperature indicators than with precipitation indicators.

- Under this simulation setup, crops penalties are more correlated to temperature stress days than water stress days.
- Vine copulas that correlate yield to two climate indicators are trivially associated for both corn and wheat under RCP scenarios 2.6, 4.5 and 8.5

GRAPHICAL ABSTRACT



INTRODUCTION

Agriculture is a human activity that is highly sensitive to climate events, especially to temperature and precipitation patterns during the growing season. However, it is still unknown which climate predictor can be more suitable to explain yield losses under changing weather conditions, e.g., droughts.

Typically, proxy drought indices such as SPEI (Standard Precipitation Evapotranspiration Index) describe the lack of rain and warming conditions. Some authors have researched the existent correlation between yields and such proxy indicators [158–160]. However, more direct drought indicators reflect better the effect of extreme weather on yields than SPEI[161].

Accessibility to evapotranspiration information on different climate scenarios is not possible in all regions. Therefore, we compared the correlation that crop yields have between climate indices and soil moisture index to determine which is a better predictor of expected yields in the future. This information is processed already, in contrast to raw climate data, which can be used for many users.

Crop penalties may be caused by a plethora of causes that can be correlated with each other non-linearly. For this reason, the use of copula models is increasing in research about agricultural drought, hydrological studies, and similar. (Das et al., 2019)[162] a proposed non-stationary gamma distribution with climate indices in its location parameter as a covariate using a copula model to assess local drought effects. (Zscheischler et al., 2017)[163] evaluated a bivariate copula model between temperature and precipitation as indicators for climate variability along different temperature-precipitation gradients. (Alidoost et al., 2019)[164] developed a multivariate copula model to assess extreme climate indices' dependence on crop yield, production, and price.

Previously cited literature on copula model application shows multivariate dependence of climate (precipitation and temperature) to crop yields. However, we are also interested in comparing this correlation to the potential relationship between corn and wheat yield with the Soil Moisture Deficit (SMD). This captures climatic conditions and management and soil characteristics where the agricultural operation is taking place. Crop models like EPIC calculate Soil Moisture based on the previously listed human-nature aspects, which can be used to calculate SMD for different scenarios, including CO2 emission pathways, irrigation amounts, and crop calendars.

This understanding is relevant for climate adaptation purposes since countries as Germany, where import one-third of their food since they have a focus on industry, have been affected their crop production by increasing warming events such as the summer of 2018 and 2020 that are expected to increase in frequency [165–167].

With this research, we want to do an exploratory study to assess the grade of dependence of corn and wheat yields with a combination of extreme climate indices for precipitation and temperature using a vine copula model and a bivariate model in the case of SMI and single climate indices utilizing a case study in Northern Germany under three climate scenarios: RCP 2.6, 4.5 and 8.5.

DATA AND METHODS

CASE STUDY

The study region is located in the German federal state of Lower Saxony (52°45′22″N 9°23′ 35″ E) in Northern Europe (Figure 69). The part is highly dependent on agriculture production, with one of the largest irrigation areas in Germany, accounting for about 36% of the land irrigated in Germany [128] due to low precipitation amount during vegetation periods[131]. The simulations in EPIC were carried out at the district level, highlighted in red on the right side of Figure 69.

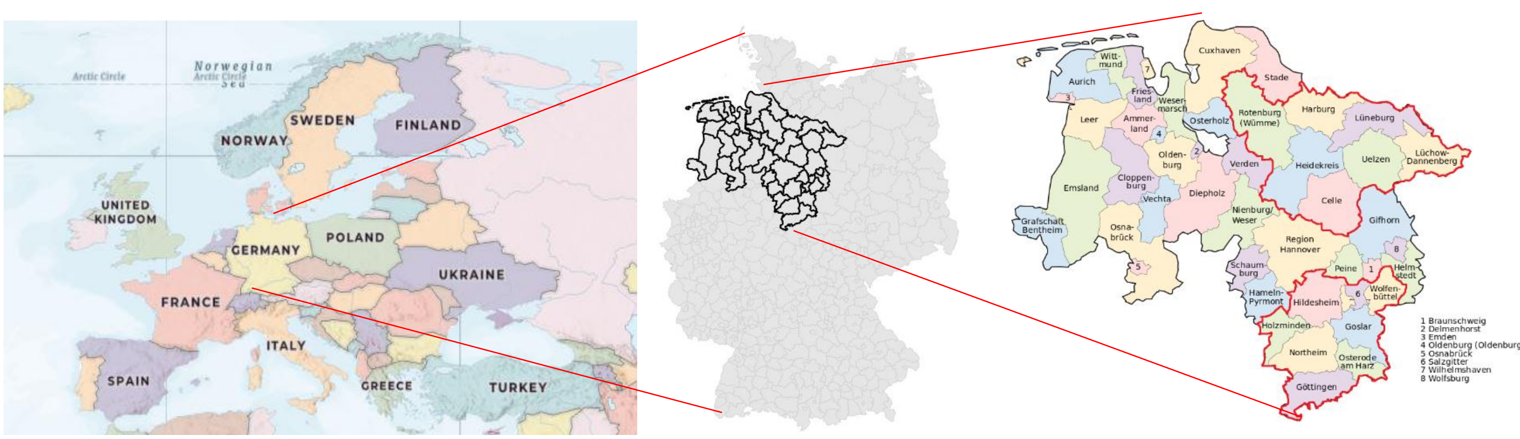


Figure 69 displays the geographical location of the study region. Left side shows the location of Germany in Europe. The middle figure shows where Lower Saxony is located in Germany. Right side is the federal state of Lower Saxony. The red borders highlights the selected districts for EPIC simulations.

AGRO-CLIMATIC INDICES

These indicators are used to characterize plant-climate interactions for agriculture. Agro-climatic indicators help convey climate variability and change in terms meaningful to the agricultural sector.

The indicators utilized in this research are focused on precipitation and temperature since they are the most relevant parameters for crop growth, as described in Table 23 [168].

Table 23 describes the climate indices selected for this study for precipitation and temperature

Precipitation Indicators	Units	Description
Maximum number of consecutive dry days (CDD)	Days	The most extended period of consecutive days when daily precipitation is less than 1mm.
Maximum number of consecutive wet days (CWD)	Days	The most extended period of consecutive days when daily precipitation is higher than 1 mm. This indicator provides information on drought, oxygen stress, and crop growth (i.e., less radiation interception during rainy days).
Maximum number of Heavy precipitation days	Days	The most extended period of consecutive days when daily precipitation is higher than 10 mm.
Temperature Indicators		
Maximum number of consecutive summer days (SU)	Days	The most extended period of consecutive days when Daily Maximum Temperature is higher than 25°C. This indicator indicates the occurrence of heat stress.
Maximum Number of extremely cold days (TN10LT)	Days	The most extended period of consecutive days when Daily Minimum Temperature less than -10°C.
Maximum Number of winter days (TX0LT)	Days	The most extended period of consecutive days when Daily Maximum Temperature less than 0°C.
Number of extremely hot days (TX35GE)	Days	The most prolonged period of consecutive days when Daily Maximum Temperature is higher than 35°C.
Number of hot days (TX30GE)	Days	The most prolonged period of consecutive days when Daily Maximum Temperature is higher than 30°C.

SOIL MOISTURE DEFICIT CALCULATION

The calculation is a modification based on [169] as in equation 3

$$SMD = \left[\frac{5\times(SM-FC)}{(PO-FC)} - 5\right] \textit{EQUATION 3}$$

In this equation, SM (m/m) represents soil moisture, FC (m/m) is field capacity, PO is porosity (m/m). The general assumption for this calculation is that porosity is equal to soil saturation.

$(PO - FC)$ Characterizes the maximum water volume that can be held in short periods [170]. $(SM - FC)$ represents the actual soil water content that is available for the plants.

This equation allows describing drought severity into five categories, as shown in Table 24

Table 24 shows the description of the drought condition based on the soil moisture deficit value obtained from Equation 3.

Drought Condition	**SMD**
Less intense	-1 or more
Moderate	-2 to <-1
High Intense	-3 to <-2
Severe	-4 to <-3
Extreme	-5 or less

EPIC PROCESS-BASED CROP MODEL

We run EPIC for three RCP scenarios (RCP 2.6, 4.5, and 8.5) to test yield dependence on climate indices and SMI. This research's specific climate projection information is obtained from the Regridded and Corrected Data Sets for the IMPACT2C SlowTrack Models[58]. The RCM-GCM combination is CSC-REMO2009- MPI-ESM-LR for three selected RCP climate scenarios [61,62]. Figure 70 summarizes the methodology applied in this study, which includes the general input information used for EPIC simulations.

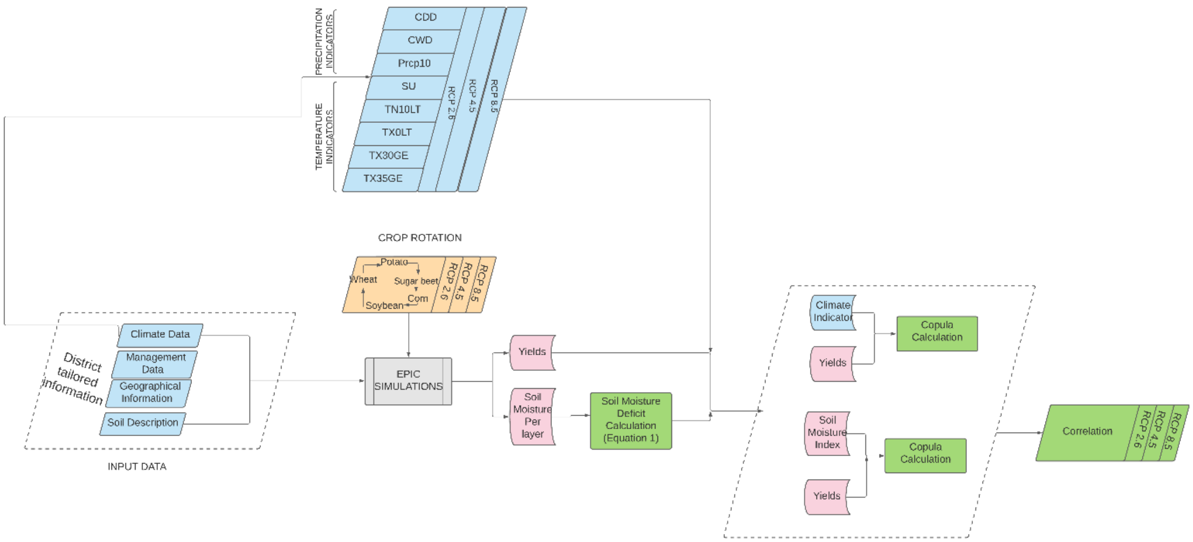


Figure 70 shows the synopsis of the methodology used. Blue boxes are the climate information and indices calculated from it. Pink boxes are outputs from the EPIC model. Green boxes are calculation processes. The correlation between yields and climate indicators and SMI are conducted for the three selected RCP scenarios.

Table 25 describes the input information that was required for EPIC simulations conducted for this study.

Table 25 describes the input information used for the simulations in EPIC, including climate information, CO2 concentration for each RCP scenario, management operations for wheat and corn simulated within the crop rotation, soil characteristics, and topographic information.

Category	Parameters	Reference
Climate: Historical (1979-2018) Lower Saxony Daily data	Maximum daily mean temperature (°C) Minimum daily mean temperature (°C) Relative Humidity (%)	Copernicus Programme Climate Reanalysis: Run with ERA5 (Re-analysed data)[102]
Climate Projections (2030-2100): RCP2.6 RCP 4.5 RCP8.5 Daily Data	(Shortwave) Solar radiation (MJ/m2) Precipitation Quantity (mm)	IMPACT2C Quantifying projected impacts under 2 °C warming Report on climate-change information. (2014)[11]) The model used: CSC-REMO2009- MPI-ESM-LR for three RCPs (2.6,4.5 and 8.5)
CO2 Concentratio n RCP 2.6	Yearly CO2 concentration (ppm-CO2-eq)	"GGI Scenario Database" web application is: International Institute for Applied System Analysis (IIASA) GGI Scenario Database Ver 2.0, 2009[103]

RCP 4.5 **RCP 8.5**	For the daily values, the annual values were repeated for each day in the same year	
Topographic information	Slope Elevation	Digital Elevation Model (DEM) Lower Saxony from high precision DTM dataset of Germany[104]
Soil information	Soil texture Soil type Organic Carbon content Bulk density Carbonate content pH	Soil Map of Germany at scale 1:200,000 (BÜK200)[73]
	Soil albedo	Rosenberg et al. (1983)[105]
	Soil Hydrologic Group	Global Hydrologic Soil Groups (HYSOGs250m) for Curve Number-Based Runoff Modelling[106]
	Soil water at field capacity (1500 kPa)	Bodenbewertungsinstrument Sachsen; Stand 03/2009[107]
Land Use	Agricultural Area	Copernicus CORINE Land Cover Database 2018[72]
Wheat (*Triticum aestivum L.)* operation information	Seeding density: 40 plants/m2 Planted March 16th Harvested August 20th 28-10-10 soluble solution 480 kg/ha	KTBL-Datensammlung 2018/19[52] Direct operation information from farmers of the region
	Seeding Density: 40 grains/m2 Planted April 4th	

	Harvested September 18th	
	PK-Solution 500 kg/ha	
Corn (*Zea mays* L.) operation information	Manure 24.5 kg/ha	KTBL-Datensammlung 2018/19[52]
	28-10-10 soluble solution 400 kg/ha	Direct operation information from farmers of the region

CORRELATION BETWEEN CLIMATE INDICES AND YIELDS

We want to learn the dependency structure between climate and crop yields. To assess the impact of climate extremes on a crop, we analyze the collective behavior of climate extreme indices with crop yields using multivariate distributions by using copulas. We selected the copula approach to adequately treat the distribution's tails, which is critical for assessing climate extreme events[171,172].

The copula captures the dependency between the random variables. The marginals capture individual distributions based on Sklar's Theorem (1959) shown in Equation 4:

$$F_{XY}(x, y) = C(F_X(x), F_Y(y)) \quad \textit{EQUATION 4}$$

Being C the copula function, Fx and Fy are the marginal distributions of x and y, respectively. This approach allows modeling the dependence structure among variables and their marginal values separately.

Vine copulas are multivariate copulas built out of bivariate copulas. For this research, we compare, with the use of vine copulas, the potential correlation between climate indices in Table 1 in pairs to describe wet-cold, wet-hot, dry-cold, dry-hot climatic conditions and yields to assess which condition could affect yields more. Likewise, we analyze the correlation between SMI and yields as in Equation 5:

$$f(x_1, x_2, x_3) = f_{3|12}(x_3|x_1, x_2) f_{2|1}(x_2|x_1) f_1(x_1) \quad \textit{EQUATION 5}$$

Using Equation 4 for the distributions of $f(x_1, x_2)$, $f(x_2, x_3)$ and $f_{13|2}(x_1, x_2|x_3)$ we can define that the pair copula distributions in Equation 5 are as it follows in Equations 6 and 7:

$$f_{2|1} = c_{12}(F_1(x_1), F_2(x_2))f_2(x_2) \text{ EQUATION 6}$$

$$f_{3|12}(x_3|x_1, x_2) = c_{13;2}\left(F_{1|2}(x_1|x_2), F_{3|2}(x_3|x_2)\right)f_{3|2}(x_3|x_2) \text{ EQUATION 7}$$

This copula represents the distribution of (X1, X2) given X3, which is denoted by $c_{13;2}$. In this study, X1 and X2 are extreme climate indices and X3 crop yields.

In this study, we make use of Kendall's tau as a copula-based dependence measure. This parameter offers the advantage that the dependence does not depend on the marginal distribution, elliptical or not. Instead, it is a measure of the rank of the variables (Read Emberechts, McNeil, and Straumann, 1999 for more information). As described in Corder and Foreman, 2009, we categorized the values of Kendall's Tau into five categories as described in Table 26.

Table 26 displays the interpretation of Kendall's Tau obtained from the copula calculation.

Kendall's Tau for a direct relationship	Kendall's Tau for an indirect relationship	Relationship Strength
0.0	0.0	**Trivial**
0.1	-0.1	**Weak**
0.3	-0.3	**Moderate**
0.5	-0.5	**Strong**
1.0	-1.0	**Perfect**

RESULTS

CORRELATION BETWEEN CLIMATE INDICES AND YIELD

After calculating the vine copula distributions of climate indices pair given a crop yield based on their empirical distributions, we plot them with their respective Kendall's tau for each climate scenario. The correlation for wet-cold, wet-hot, dry-cold, and dry-hot combination (namely the vine copulas) is trivial for RCP 2.6 (Figure 71.a, Table 27) for both corn and wheat yields. In the case of wheat, there is a moderate negative correlation with temperature indices TX30GE and TX35GE, but a weak negative one with the number of Summer Days (SU). It exists a weak to moderate positive correlation with TX0LT. Corn shows a similar behavior compared to vine copulas. Likewise, TX30GE and TX35GE indices have an inverse relationship with corn yields. However, with SU index has a moderate positive correlation. Precipitation indices as CWD, CDD, and Prcp10 have for both crop weak negative correlation.

For climate scenario RCP 4.5 (Figure 71.b, Table 27), TX30GE positively correlated with both crops. Conversely, both SU is negatively weak correlated for both crops. TX35GE has a moderate negative correlation with corn yield and weak with wheat. TN10LT is weakly correlated for both crops, but for wheat, this relationship is positive, and for corn, negative. CWD, CDD is weakly correlated for both crops. However, this correlation is positive for wheat and negative for corn. Combinations TX0LT-CDD, TX0LT-Prcp10 for corn, and TX0LT-CDD for wheat are the only vine copulas that have a weak correlation with crop yields. TX0LT-CDD has a negative correlation for both crops, and TX0LT-Prcp10 has a positive correlation with wheat yield.

The worst climate scenario RCP 8.5 (Figure 71.c, Table 27) displays a similar trend to RCP 4.5 for SU for both crops. Temperature indices are more robust correlated to yields than precipitation indices, especially TX30GE, TX0LT, and TX35GE for wheat. TN10LT is still weak negatively correlated for wheat and corn. The significant difference is that TX30GE is weak positive correlated to corn yields. Since it is positively moderately correlated to both crops

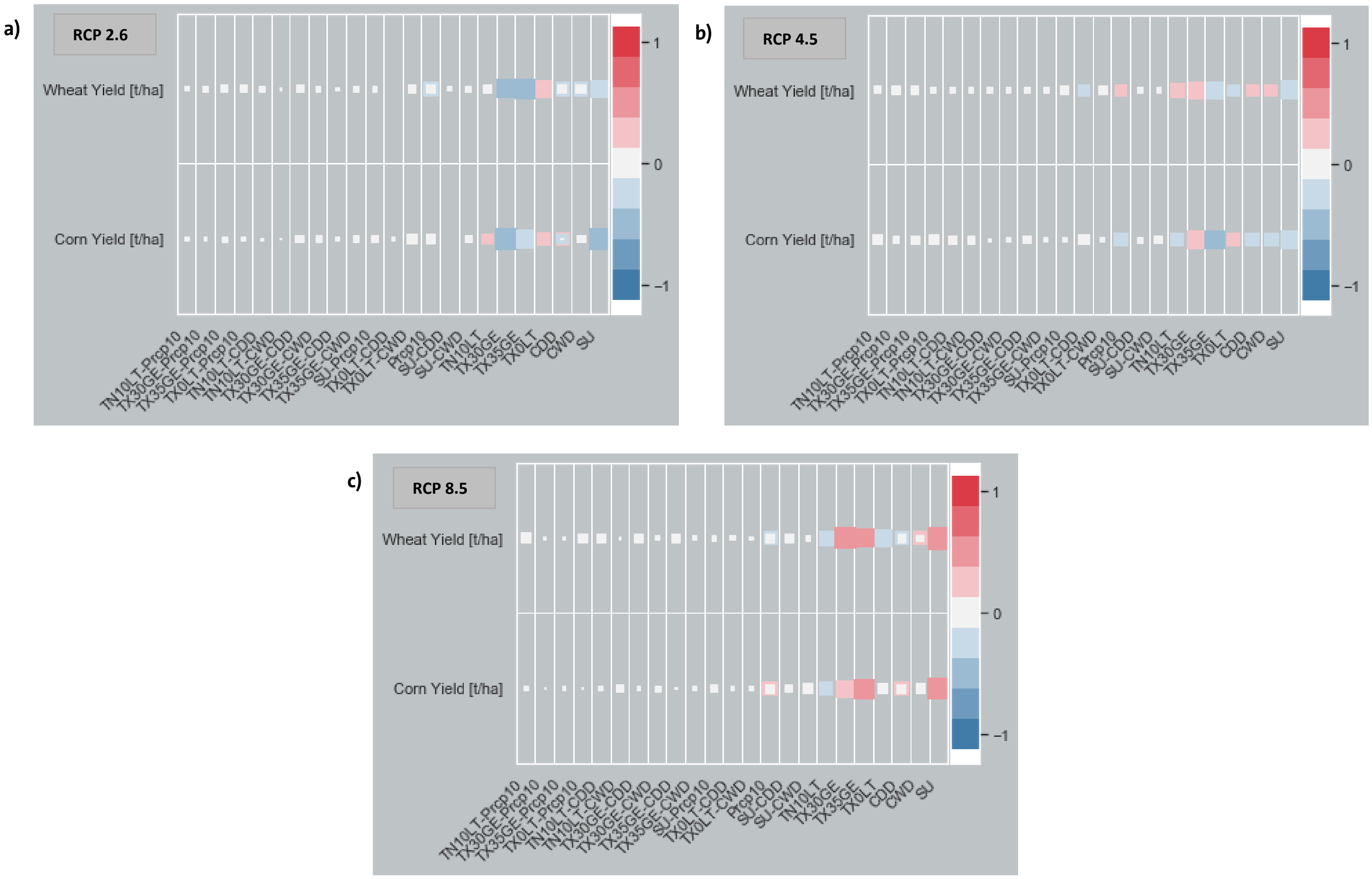


Figure 71 displays the heatmaps ranging from -1 to 1 for Kendall's Tau correlation parameter between corn and wheat yield in the y axis with the selected climate indicators. We show the temperature-precipitation combinations and single climate indices on the x axis. Upper left (a) plot are the results for climate scenario RCP 2.6, upper right (b) is for RCP 4.5 and below plot (c) is for climate scenario RCP 8.5.

Table 27 describes the bivariate distribution between climate indicators and crop yields with a moderate correlation for the RCP 2.6 scenario. Tree 0 corresponds to the bivariate distribution between climate indicator (variable 1) and yield (variable 3) based on Equation 4.

Climate Index	**CO2 Emission Scenarios**	**Yield**	**Tree 0**	**Kendall Tau**	**Interpretation**
TX30GE	RCP 2.6	Corn Yield [t/ha]	1,3 <-> Gaussian, parameters = -0.670707	**-0.468**	Moderate
TX35GE	RCP 2.6	Corn Yield [t/ha]	1,3 <-> Gaussian, parameters = -0.495816	**-0.33**	Moderate
SU	RCP 2.6	Corn Yield [t/ha]	1,3 <-> Gaussian, parameters = -0.696719	**-0.491**	Moderate
TX30GE	RCP 2.6	Wheat Yield [t/ha]	1,3 <-> Gaussian, parameters = -0.507799	**-0.339**	Moderate
TX35GE	RCP 2.6	Wheat Yield [t/ha]	1,3 <-> Gaussian, parameters = -0.531695	**-0.357**	Moderate
SU	RCP 2.6	Wheat Yield [t/ha]	1,3 <-> Gaussian, parameters = -0.47737	**-0.317**	Moderate

Table 28 describes the bivariate distribution between climate indicators and crop yields with a moderate correlation for the RCP 4.5 scenario. Tree 0 corresponds to the bivariate distribution between climate indicator (variable 1) and yield (variable 3) based on Equation 4.

Climate Index	CO2 Emission Scenarios	Yield	Tree 0	Kendall Tau	Interpretation
SU	RCP 4.5	Corn Yield [t/ha]	1,3 <-> Gaussian, parameters = -0.48638	**-0.323**	Moderate
TX30GE	RCP 4.5	Corn Yield [t/ha]	1,3 <-> Gaussian, parameters = 0.469681	**0.311**	Moderate
TX35GE	RCP 4.5	Corn Yield [t/ha]	1,3 <-> Gaussian, parameters = -0.542353	**-0.365**	Moderate
SU	RCP 4.5	Wheat Yield [t/ha]	1,3 <-> Gaussian, parameters = -0.498819	**-0.332**	Moderate

Table 29 describes the bivariate distribution between climate indicators and crop yields with a moderate correlation for the RCP 8.5 scenario. Tree 0 corresponds to the bivariate distribution between climate indicator (variable 1) and yield (variable 3) based on Equation 4.

Climate Index	CO2 Emission Scenarios	Yield	Tree 0	Kendall Tau	Interpretation
SU	RCP 8.5	Corn Yield [t/ha]	1,3 <-> Gaussian, parameters = 0.704306	**0.497**	Moderate
TX35GE	RCP 8.5	Corn Yield [t/ha]	1,3 <-> Gaussian, parameters = 0.580318	**0.394**	Moderate

SU	RCP 8.5	Wheat Yield [t/ha]	1,3 <-> Gaussian, parameters = 0.672115	**0.469**	Moderate
TX0LT	RCP 8.5	Wheat Yield [t/ha]	1,3 <-> Gaussian, parameters = -0.466759	**-0.309**	Moderate
TX30GE	RCP 8.5	Wheat Yield [t/ha]	1,3 <-> Gaussian, parameters = 0.662321	**0.461**	Moderate
TX35GE	RCP 8.5	Wheat Yield [t/ha]	1,3 <-> Gaussian, parameters = 0.521032	**0.349**	Moderate

CORRELATION SMD AND CROP YIELDS

Before the copula model calculation, we observed the distribution of SMD vs. yields (We show only the two extremes climate scenarios RCP 2.6 and RCP 8.5 in Figure 72). For corn, both variables are skewed distributed in the case of RCP 2.6, to the right for SMD and to the left for yield. RCP 8.5 SMD is close to a normal distribution, but corn yield is skewed to the right, yield losses are higher than climate scenario RCP 2.6. SMD vs. wheat yield highlights a slightly more apparent trend than corn, but there is still a weak trend for both shown RCP scenarios.

This is better displayed in Table 30. We calculated a bivariate copula model between crop yields and SMD at 10 cm derived from equation 2 for the three selected RCP scenarios and the corresponding Kendall's Tau correlation parameter. Table 30 shows that, contrary to our central hypothesis, the SMD to wheat and corn yields are weakly correlated in each CO2 Emission Scenario.

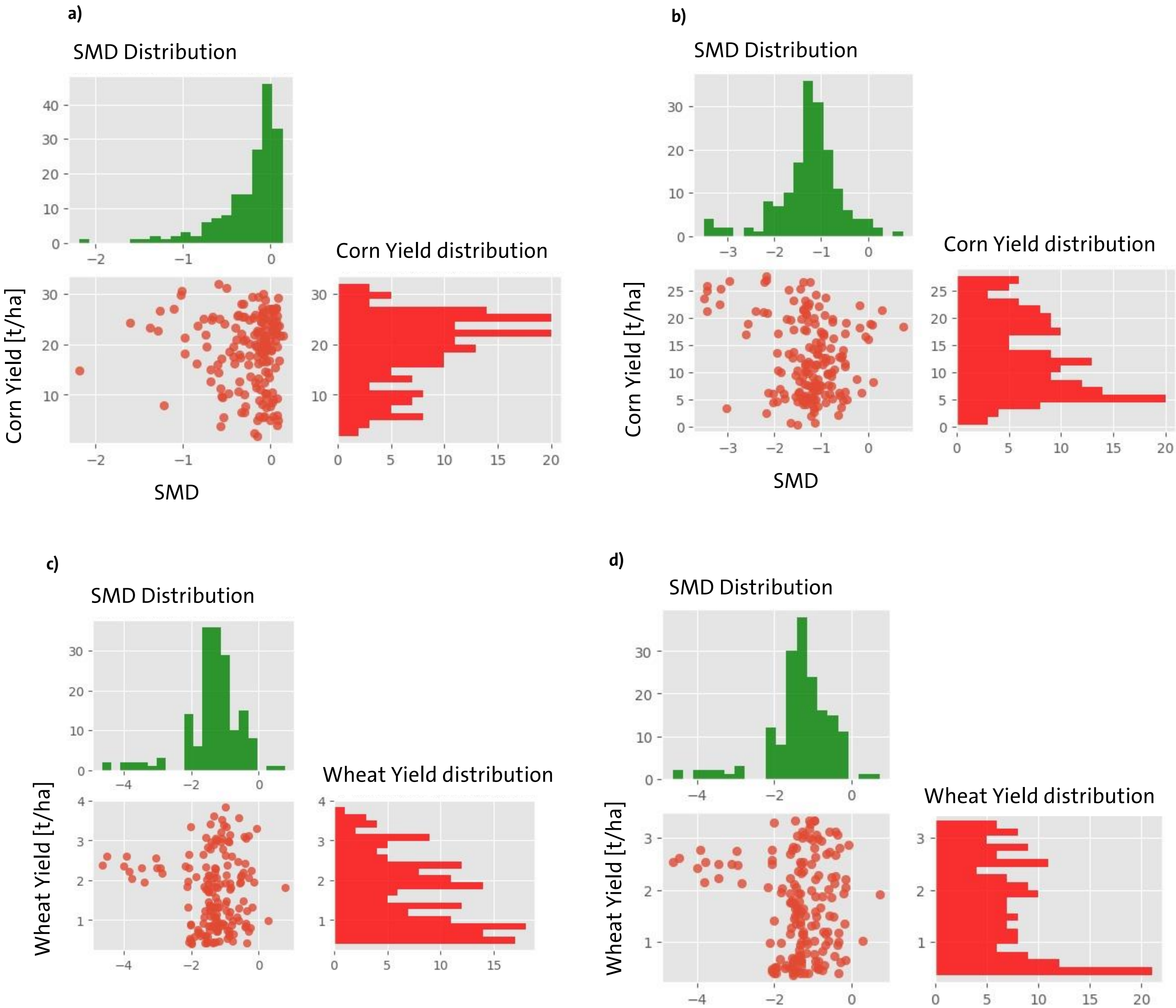


Figure 72 describes the bivariate distribution between climate indicators and crop yields with a moderate correlation for the RCP 8.5 scenario. Tree 0 corresponds to the bivariate distribution between climate indicator (variable 1) and yield (variable 3) based on Equation 4.

Table 30 depicts the correlation between SMD and crop yields for each RCP climate scenario.

SMD Index Depth	CO2 Emission Scenarios	Yield	Kendall Tau	Interpretation
10 cm	RCP 2.6	Corn [t/ha]	**0.07**	Trivial
10 cm	RCP 4.5	Corn [t/ha]	**0.02**	Trivial
10 cm	RCP 8.5	Corn [t/ha]	**0.18**	Weak
10 cm	RCP 2.6	Wheat [t/ha]	**0.12**	Weak
10 cm	RCP 4.5	Wheat [t/ha]	**0.06**	Trivial
10 cm	RCP 8.5	Wheat [t/ha]	**0.03**	Trivial

DROUGHT LEVEL CHANGES

We assessed the potential relationship of the increasing correlation across RCP climate scenarios with crop yields (See Kendall's Tau values from tables 27-30) and drought levels (SMD calculated from Equation 3).

Figure 3.3 illustrates the yearly SMD for each CO2 Emission Scenario. We indicated the years where the drought level is moderate to worse intensity (Table 24). For all years in each RCP, the drought level is moderated excepting the year 2099 for RCP 8.5. However, the SMD values increase gradually from the near future (2035-2065) to the far future (2070-2100) and the RCP climate scenario. This further worsening in drought intensity is featured by the length of each bar in Figure 73. This behavior is consistent with what is expected in the region regarding warming climatic conditions[119,173].

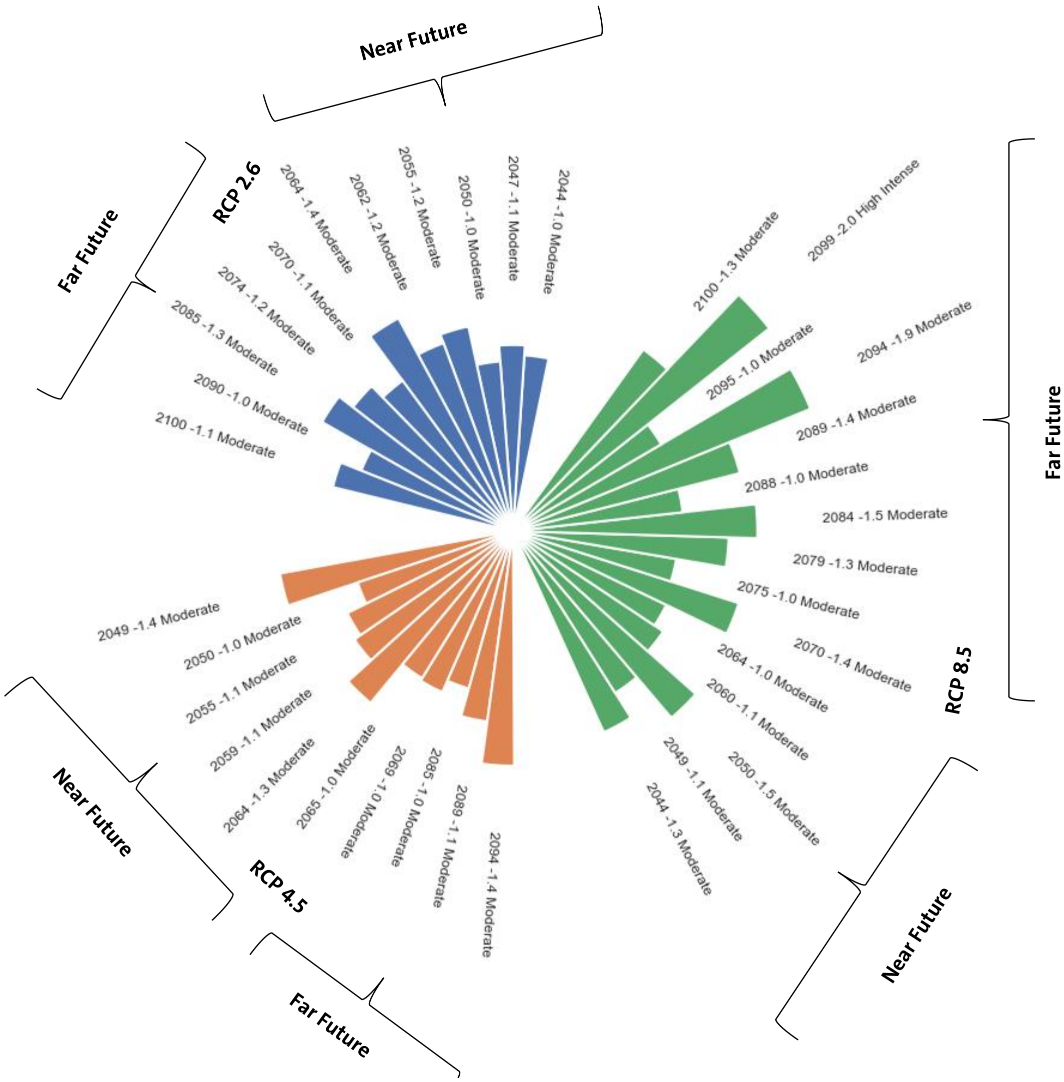


Figure 73 displays the development of yearly moderate drought deficit for each RCP scenario. Blue bars corresponds to RCP 2.6, orange for RCP 4.5 and green for RCP 8.5.

DISCUSSION

SMD calculation (Equation 3) only accounts for potential drought intensity, but not the duration of the soil moisture, including its spatial distribution as in[174,175] where crops like wheat and corn were highly correlated to their own developed standard soil moisture deficit index. [176] Found that the soil moisture deficit is highly correlated to crops like wheat and sorghum with the SWAT model (a river basin scale model that includes a simplified EPIC crop module) in a historical period.

In an entire agriculture system, yield penalties occur due to many environmental stresses and operational decisions. Nevertheless, the EPIC model only considers the significant stress to account for the yields losses for each day. In our case study, crop yields suffer more severe temperature stress (TS) than water stress (WS) (Figure 74). Correspondingly, the temperature stress has, in general, a more significant effect on the yield compared to the water stress, which may explain the low correlation with SMD. However, our study found a weak correlation between SMD and corn and wheat yields in future conditions, but a moderate correlation with maximum temperatures climate indicators SU, TX30GE, and TX35GE. This is significantly more observable for wheat since its yields are not correlated to water stress. In contrast, it can be correlated to the temperature stress in RCP2.6 as r^2 values exhibit for each RCP climate scenario (Figure 75 a and b for corn, figure 75.c, and d for wheat).

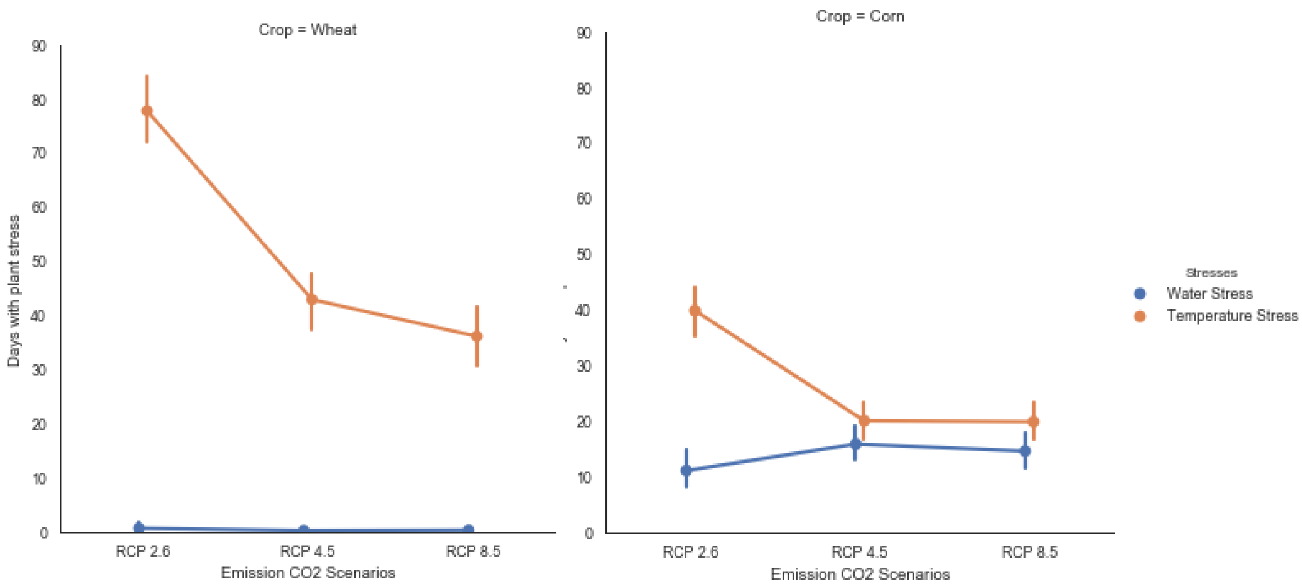


Figure 74 displays the severity of water and temperature stress for both crop yields in terms of the number of days for each CO2 Emission Scenario. Orange Line represents Temperature Stress and the Blue line, water stress.

Those two stresses are directly related to the climate data used as an input for EPIC simulations. This study simulates the agricultural system with only one regional climate model for the three CO2 emission scenarios (Table 25). Further simulations with more climate models will be needed to assess yield development under different potential climatic trajectories. We expected a higher signal between yields and TS and WS. However, for RCP 4.5 for both crops, yields seem to increase the more elevated the WS is. We need to consider that the stress due to temperature is low for days when the number of days with WS is high. Thus, yield penalties are lower since yields are more affected by temperature stress than by water stress. In practical terms, due to climate change, wheat and corn yields in this region may be more restricted to upcoming warming temperatures during cultivation periods than lack of available water.

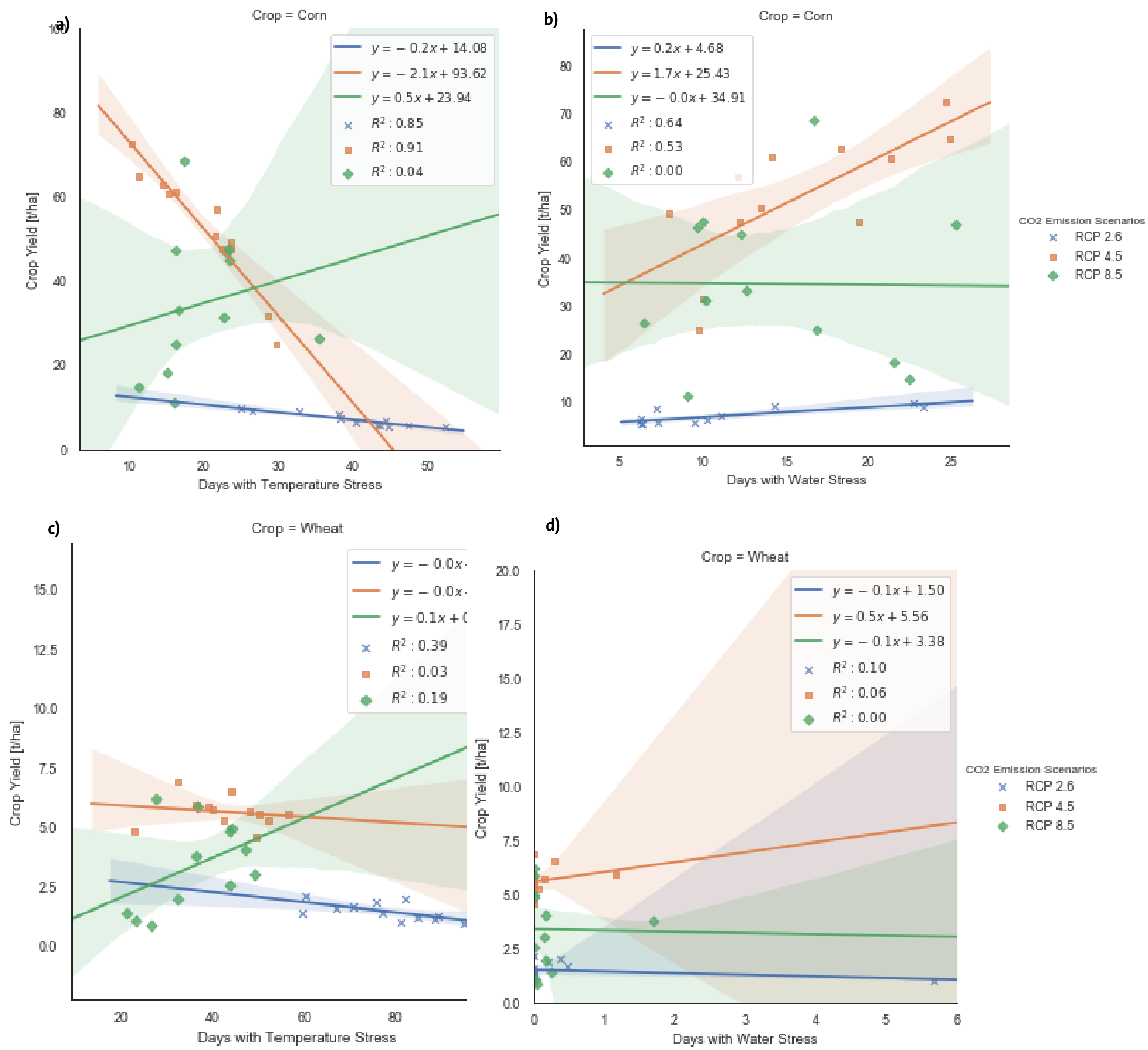


Figure 75 displays the linear regression between crop yields and the number of days where the plant is stressed for each RCP scenario. 8.a) is the linear regression between corn yield and temperature stress, 8.b) linear regression between corn yield and water stress. 8.c) linear regression between wheat yield and temperature stress. 8.d) linear regression between wheat and water stress.

Similar assessments where crops may be more affected by temperature than precipitation, SMD simple calculation may be insufficient to make an initial characterization of plausible future yield penalties, but instead using climate predictors like SU, TX30GE, and TX35GE.

Their correlation strength increases matched with the advancement of SMD intensities for far future years (Figure 75). Additional research in this direction is required, including more climate models with several SMD calculations methods.

This is the first step of this exploratory analysis of climate predictors and their correlation with crop yields. These climate indices are calculated from climate projections that come from their own biases. These uncertainties are extreme for climate extremes (e.g., temperatures or excessive precipitation)[177,178]. For this reason, it is critical to have reliable climate information mainly for precipitation, maximum and minimum temperature to define more robust distributions, primarily when studies are conducted in local scales.

SUMMARY AND CONCLUSIONS

EPIC model is limited when it comes to the attribution of specific stresses to account yield penalties.

Crop yield simulations more affected by temperature than water stress is more substantial than temperature climate indices (SU, TX30GE, TX35GE) than precipitation climate indices (CDD, CWD, Prcp10).

Stronger correlation between yields and SU, TX30GE, TX35GE also correspond to soil moisture moderate deficit in the future.

To use soil moisture deficit instead of climate indices as predictors, we need to conduct more research to include the duration of soil moisture deficits and other calculation methods.

SUPPLEMENTARY MATERIAL

CLIMATE INDICATORS – YIELD COPULA MODEL TREES WITH WEAK AND TRIVIAL CORRELATION.

CLIMATE INDEX	CO2 EMISSION SCENARIOS	YIELD	TREE 0	KENDALL TAU	INTERPRETATION
TN10LT	RCP 2.6	Corn Yield [t/ha]	1,3 <-> Gaussian, parameters = 0.18287	**0.117**	Weak
TX0LT	RCP 2.6	Corn Yield [t/ha]	1,3 <-> Gaussian, parameters = 0.229424	**0.147**	Weak
CDD	RCP 2.6	Corn Yield [t/ha]	2,3 <-> Gaussian, parameters = 0.229424	**0.147**	Weak
CDD	RCP 2.6	Corn Yield [t/ha]	2,3 <-> Gaussian, parameters = -0.17523	**-0.112**	Weak
CWD	RCP 2.6	Wheat Yield [t/ha]	2,3 <-> Gaussian, parameters = -0.202908	**-0.13**	Weak
CDD	RCP 2.6	Wheat Yield [t/ha]	2,3 <-> Gaussian, parameters = -0.202908	**-0.13**	Weak
PRCP10	RCP 2.6	Wheat Yield [t/ha]	2,3 <-> Gaussian, parameters = -0.202908	**-0.13**	Weak
TX0LT	RCP 2.6	Wheat Yield [t/ha]	1,3 <-> Gaussian, parameters = 0.408362	**0.268**	Weak
CDD	RCP 2.6	Wheat Yield [t/ha]	2,3 <-> Gaussian, parameters = 0.191074	**0.122**	Weak
CWD	RCP 2.6	Wheat Yield [t/ha]	2,3 <-> Gaussian, parameters = -0.270229	**-0.174**	Weak
CDD	RCP 2.6	Wheat Yield [t/ha]	2,3 <-> Gaussian, parameters = -0.270229	**-0.174**	Weak
PRCP10	RCP 2.6	Wheat Yield [t/ha]	2,3 <-> Gaussian, parameters = -0.549033	**-0.174**	Weak

CLIMATE INDEX	CO2 EMISSION SCENARIOS	YIELD	TREE 0	TREE 1	KENDALL TAU	INTERPRETATION

CDD	RCP 4.5	Corn Yield [t/ha]	2,3 <-> Gaussian, parameters = -0.171064		-0.109	Weak
PRCP10	RCP 4.5	Corn Yield [t/ha]	2,3 <-> Gaussian, parameters = 0.177278		0.113	Weak
TN10LT	RCP 4.5	Corn Yield [t/ha]	1,3 <-> Gaussian, parameters = -0.250466		-0.161	Weak
CDD	RCP 4.5	Corn Yield [t/ha]	2,3 <-> Gaussian, parameters = -0.171064		-0.109	Weak
PRCP10	RCP 4.5	Corn Yield [t/ha]	2,3 <-> Gaussian, parameters = 0.177278		0.113	Weak
TX0LT	RCP 4.5	Corn Yield [t/ha]	1,3 <-> Gaussian, parameters = 0.23905		0.154	Weak
CDD	RCP 4.5	Corn Yield [t/ha]	2,3 <-> Gaussian, parameters = -0.171064		-0.109	Weak
TX0LT-CDD	RCP 4.5	Corn Yield [t/ha]		1,2 | 3 <-> Gaussian, parameters = -0.169336	-0.108	Weak
PRCP10	RCP 4.5	Corn Yield [t/ha]	2,3 <-> Gaussian, parameters = 0.177278		0.113	Weak
TX0LT-PRCP10	RCP 4.5	Corn Yield [t/ha]		1,2 | 3 <-> Gaussian, parameters = 0.168005	0.107	Weak
CDD	RCP 4.5	Corn Yield [t/ha]	2,3 <-> Gaussian, parameters = -0.171064		-0.109	Weak
PRCP10	RCP 4.5	Corn Yield [t/ha]	2,3 <-> Gaussian, parameters = 0.177278		0.113	Weak
CWD	RCP 4.5	Corn Yield [t/ha]	2,3 <-> Gaussian, parameters = -0.280807		-0.181	Weak
CDD	RCP 4.5	Corn Yield [t/ha]	2,3 <-> Gaussian, parameters = -0.280807		-0.181	Weak
PRCP10	RCP 4.5	Corn Yield [t/ha]	2,3 <-> Gaussian, parameters = -0.280807		-0.181	Weak
TN10LT	RCP 4.5	Wheat Yield [t/ha]	1,3 <-> Gaussian, parameters = 0.281357		0.182	Weak

TX0LT	RCP 4.5	Wheat Yield [t/ha]	1,3 <-> Gaussian, parameters = -0.220884		-0.142	Weak
TX0LT-CDD	RCP 4.5	Wheat Yield [t/ha]		1,2 | 3 <-> Gaussian, parameters = -0.195449	-0.125	Weak
TX30GE	RCP 4.5	Wheat Yield [t/ha]	1,3 <-> Gaussian, parameters = 0.391627		0.256	Weak
TX35GE	RCP 4.5	Wheat Yield [t/ha]	1,3 <-> Gaussian, parameters = -0.406808		-0.267	Weak
CWD	RCP 4.5	Wheat Yield [t/ha]	2,3 <-> Gaussian, parameters = 0.232216		0.149	Weak
CDD	RCP 4.5	Wheat Yield [t/ha]	2,3 <-> Gaussian, parameters = 0.232216		0.149	Weak
PRCP10	RCP 4.5	Wheat Yield [t/ha]	2,3 <-> Gaussian, parameters = 0.232216		0.149	Weak

Chapter 6

6. CONCLUSIONS, LIMITATIONS, AND FUTURE RESEARCH

6.1. Conclusions

The agricultural sector is repeatedly hit by the impacts of climate change in most regions of the world. As occurred in 2018, heatwaves are a tangible example of the threat of yield losses. Climate projections suggest the more frequent occurrence of heatwaves and other climatic extreme events[2,26].

This dissertation focuses on assessing adaptation measures in the long term (near future 2035-2065 and far future 2070-2100) under three CO2 emission scenarios (RCP 2.6, 4.5, and 8.5). The main research tool to make this assessment is the EPIC process-based crop model, we simulated typical crop rotations in northern Germany for fourteen districts: North-Eastern Lower Saxony (NELS): Celle, Harburg, Lüchow-Dannenberg, Lüneburg, Uelzen, Heidekreis, Rotenburg-Wümme and Southern Lower Saxony (SLS): Goslar, Göttingen, Hildesheim, Holzminden, Northeim, Salzgitter, Wolfenbüttel

This methodology tests several strategies simultaneously to analyze the potential long-term co-benefits until the end of the century (as in Chapter 4, where crop calendars and irrigation amounts are co-tested for corn and wheat within a crop rotation, including soybeans). Additionally, Chapter 5 evaluated the potential correlation between crop yields and relevant agro-climatic indices and compared crop development's correlation with soil moisture deficit to explore the impacts of climate extremes on yield changes over time.

Regarding the use of climate information for EPIC, this thesis has also discussed the limitations of using one climate model for impacts studies like this dissertation since each model represents one expected future climate trajectory. However, the conducted analysis helps understand the potential risks that wheat and corn may face by the end of the century under increasing temperatures and shifted precipitation during the vegetation period. Furthermore, this research has also argued that it is required to know about climate data processing and climate models for impact studies like this one.

The innovation in chapter 3 assesses the potential benefits of planting soybeans after corn, within the crop rotation, in northern Europe. The simulations in EPIC showed similar results with field experiments in the Lower Saxony region within the initiatives German Soybean Promotion Council (Deutscher Soja Förderring) and the Soybean Network Project (Projekt Soja-Netzwerk) [23,88,179]. It was also found that soybeans do not improve wheat yields before crop rotation due to the temperature stress that wheat faces under future climatic conditions. This yield increase may be plausible due to higher levels of nitrogen fixation thanks to the potential future soybean growth intensification compared to the reference period (from 2.5 t/ha on average to 4.5 t/ha). Current management strategies might yield crop penalties of about 70% in the worst of the investigated climate change scenario (RCP 8.5). These results agree with the findings of the IPCC report regarding the limited adaptive capacity of the crop system concerning the applied management strategies by the farmers. Regarding soil texture among northern and southern simulated districts (NELS and SLS, respectively), there is no clear trend of which districts enhance higher yields, except for the case of corn, whose yields losses are slightly less in NELS districts. The results showed that corn might benefit more than wheat with the presence of soybeans within the crop rotation under BAU management practices in Northern Germany for all the three tested RCP scenarios.

Chapter 4 further assesses different irrigation amounts and cropping calendar options to test their impact on crop yields, nitrogen emissions, and water balance elements in the future related to climate change. **The innovative part of this research is that we developed a version of EPIC that calculates the amount of irrigation based on a percentage of field capacity to permit a more realistic irrigation scheme to simulate more efficient irrigation in the model. This irrigation option allows allocating water that is limited due to current regulations.** Five irrigation amounts based in the scheme were tested from 0% Field Capacity (no irrigation) to 100% Field Capacity (Full Irrigation) and in between, 20%, 40%, and 60%. This chapter shows that irrigating beyond 60% of field capacity may not lead to extra crop growth for both corn and wheat. However, it was also found that irrigation is limited due to adverse climate impacts on crops. Such behavior means that increasing irrigation efficiency is not enough to attain more stable yields in the future, but planting varieties can cope with higher temperatures during the vegetation period.

Additionally, this study assesses the positive effects on yields when crop calendars are shifted. Particularly if corn is planted two months earlier and wheat two months later, then yields may benefit from it. However, those management measures might not be enough to avoid losses due to climate change in the future, especially for the RCP 8.5 scenario. These results may be explained due to the relationship between yields and crop stresses. Both crops are affected differently by temperature and water stress. Wheat yield penalties are mainly due to temperature stress and corn due to water stress. Planting the former two months later may allow avoiding potential heatwaves. Planting the latter two months earlier may take advantage of more rainfall before summer when corn has been already planted on the field.

Chapter 5 explored the correlation strength between yields and climate indices and between yields and soil moisture deficit and the impact of temperature stress on this correlation. **This study's innovation is a framework based on a copula multivariate distribution model that permitted the correlation strength calculation between yields and climatic conditions.** Two copula types were used: vine copula (multivariate in 3 dimensions) and bivariate Gaussian copula. Vine copulas in a combination of temperature and precipitation pairs are used. These pairs are wet-cold (TN10LT-Prcp10, TX0LT-Prcp10, TN10LT-CWD, TX0LT-CWD), wet-hot (TX30GE-Prcp10, TX35GE-Prcp10, SU-Prcp10, TX30GE-CWD, TX35GE-CWD, SU-CWD), dry-cold (TN10LT-CDD, TX0LT-CDD), and dry-hot conditions (TX30GE-CDD, TX35GE-CDD, SU-CDD). The results show that the correlation between yields and the vine copula is weak for the three RCP scenarios. In the bivariate Gaussian copula, yields are stronger correlated to temperature indicators for maximum and minimum temperatures (TN10LT, TX30GE, TX35GE, TX0LT, and SU) than precipitation indicators. Soil

Moisture deficit showed a weak correlation with both corn and wheat yields. This behavior may be explained due to crops being more severely stressed due to temperature. Further studies should use climate models that include more than one potential trajectory, such as warmer temperatures, less precipitation, and increased precipitation amounts. This set of climate trajectories help to compare the potential correlation strength between yield and climate indices to reduce the biases by using several climate models.

The following table shows the respective answers to the research questions in Chapter 1 (Table 1).

Table 31 shows the research question posed in Chapter 1 (Please refer to Table 1) with their corresponding answers and the main findings.

Research Question	Main Findings
RQ 1. How will climate change affect current crop management systems in Lower Saxony?	The exploratory study in Chapter 3 found that crop losses might increase in the future under current management strategies. Wheat yield changes for each RCP scenario as follows: for **RCP 2.6**, near future: **NELS -3%, SLS -14%**. Far future **NELS -5.1%, SLS is -13%**. For **RCP 4.5**, near future **NELS -7.5%, SLS -6.2%**. Far future **NELS -20%, SLS -13.6%.** Corn yield changes for each RCP scenario as follows: for **RCP 2.6,** near future: **NELS -18%, SLS -28%.** Far future **NELS -15%. SLS -10%.** For **RCP 4.5,** near future **NELS -12.5%, SLS -8.11%.** Far future **NELS -24.3%, SLS -12.7%.** Yield losses may reach up to **65%** for RCP 8.5 for the far future for two district groups due to the increased temperature, leading to a higher number of days in which the crops' stress is due to temperature. In this sense, these first results highlight the importance of applying several adaptation strategies related to irrigation water, planting times to ensure more stable yields in the future.
RQ 2 Will soybean cultivation in Lower Saxony become	Simulations including a crop rotation scheme with soybeans display that expected warmer temperatures for RCP 2.6 and 4.5 might increase soybean yields by 3 t/ha compared to the reference period (1979-2018)

agronomically more viable under climate change in the 21st century?	for both future periods. However, for RCP 8.5 by the end of the century, yields decrease about 2 t/ha since warm temperatures are not the only main driver for higher soybean yields but also the presence of enough water for irrigation. For scenario RCP 8.5, the monthly rainfall is expected to be reduced by 40% (Figure 54, Chapter 4).
RQ 3. How does the integration of soybeans in typical crop rotations impact the performance of companion crops, and how will these impacts vary with climate change?	Although soybeans' presence may lead to a slight increase in yields, this was only shown when soybeans were within the crop rotation and not when soybeans replaced winter wheat or silage corn. Winter wheat yield changes with the presence of soybeans compared to BAU are as it follows: **RCP 2.6**, near future **NELS +8% SLS +11%**. Far future, **NELS +14%, SLS +15%**. **RCP 4.5**, near future **NELS +8%, SLS +1.5%**. Far future **NELS -10%, SLS -7%**. For **RCP 8.5**, near future, **NELS +3%, SLS +3.5%**. Far future, **NELS +3%, SLS + 2.3%.** Corn yield changes with the presence of soybeans compared to BAU are as it follows **RCP 2.6**, near future **NELS +27%, SLS +19%**. Far future, **NELS +15%, SLS +16%**. **RCP 4.5**, near future **NELS -16%. SLS -9%**. Far future, **NELS +15%, SLS -9%.** For **RCP 8.5**, near future **NELS +20.3%, SLS -4.8%.** Far future, **NELS +12.5%**, **SLS -7.2%.** Winter wheat showed more stable yields among the districts than silage corn in the presence of soybeans. However, corn yields increase is higher than wheat, but losses in RCP 4.5 are also higher. The results for the RCP 4.5 scenario are due to the lower precipitation values compared to RCP 2.6 and 4.5 for summer. For the near future, the rainfall is about 10% less than for RCP 2.6 and 4.5. The far future is around 23% less than the other climate scenarios (Figure 54, Chapter 4). Based on these results, the proposed adaptation measure of adopting soybeans within the crop rotation may help increase both wheat and corn yields, but it is limited due to climate change. It is necessary to co-

	apply several management strategies to ensure yield stability under the worst climate conditions expected in the RCP 8.5 scenario.
RQ 4. What co-effects will soybean cultivation have on soil processes and soil properties, and how will these co-effects vary with climate change?	In chapter 3, soil processes refer to nitrification and humus mineralization. The assessment was conducted for each tested climate and management scenario by including soybeans within the crop rotation. These two processes increased in the future for each RCP scenario compared to the reference period (1979-2018). Nitrification changes as it follows: For **RCP 2.6**, near future **NELS: +24%, SLS: +23%**. Far future, **NELS +170%, SLS +150%**. For **RCP 4.5**, near future **NELS +12.5%, SLS +20.1%**. For far future **NELS +67%, SLS +90%**. For **RCP 8.5**, near future **NELS +35%, SLS +45%**. Far future, **NELS +66%, SLS +62%**. Humus mineralization changes are as follows: For **RCP 2.6**, near future, **NELS +46%, SLS +55%.** For far future, **NELS +171%, SLS +56%**. For **RCP 4.5**, near future **NELS +46%, SLS +60%**. Far future, **NELS +66%, SLS +77%**. For **RCP 8.5**, for near future **NELS +65%, SLS +60%**. For far future, **NELS +66%, SLS +65%**. Increased nitrification allows the increment in available nitrate content for the plants. If climatic conditions are also suitable for crop development, the crops can use this additional nitrate. On the other hand, the increase in humus mineralization under higher temperatures, which is a process in which organic substance is converted into an inorganic substance as water and CO2, leads to less available organic content for the crops. This reduction may cause crop losses in the future.
RQ 5. How will irrigation influence soil organic carbon and	In Chapter 4, emissions refer mainly to nitrogen losses through runoff, one of the main issues in the case study region.

nitrogen emissions, and how will these influences vary with climate change?	Compared to the BAU scenario, planting earlier and harvesting dates might help decrease nitrate losses in the runoff in the near future period (2035-2065) by 10% in RCP 2.6. For RCP 4.5 and 8.5, the losses double compared to the BAU scenario. The impact of these modifying crop calendars may be less apparent for the far future (2070-2100). Shifting the crop calendar to two months later also leads to more nitrate losses than the BAU scenario, around 50% for all climate scenarios.
RQ 6. How will rescheduling planting and harvesting dates affect crop yields and soil organic carbon under particular climate developments?	In chapter 4, soil quality is measured only based on total organic carbon. The results of EPIC simulations for both corn and wheat of four different crop calendar treatments display no significant changes for the total organic carbon and across the CO2 emission scenarios. The tested crop calendar treatments, in addition to BAU, are: Planting earlier and same harvesting Planting and harvesting earlier Later planting and the same harvesting Later planting and harvesting Corn yield increases compared to BAU by planting earlier and harvesting the same as BAU as it follows: For **RCP 4.5**, near future **+55%,** far future **+65%**. For **RCP 8.5**, near future **+52%**, far future **-30%**. Wheat yields increase when planted later compared to BAU. For **RCP 2.6** and near-future period is about **+2.5%** and for far future **+3%**. For **RCP 4.5**, the near and far future is around **+5.5%**. For **RCP 8.5**, near future **+4.5%** and far future **+2%**. However, these improvements might be insufficient to avoid yield losses in the future caused by climate change, including increasing in days with temperature stress, especially for wheat.
RQ 7. How strongly are meteorological climate	The study in chapter 5 shows that yields are more correlated to the selected temperature indices than to precipitation indicators like CWD,

indicators correlated with crop yields? Which meteorological indicators are best suited to predict agricultural performance?	CDD, Precp10. Our results suggest warmer temperatures more severely stress wheat and corn than water deficiency, which helps explain the weak correlation to the selected precipitation indices. Correspondingly, corn penalties are more affected due to temperature stress than due to water stress (**r2= 0.85** for RCP 2.6, **r2=0.91** for RCP 4.5). Wheat yields lack correlation with the number of water stress days regardless of the RCP scenario.
RQ 8. How much are yields affected by soil water deficits under current and projected climate states for Lower Saxony?	Crops are severely more affected due to temperature stress than to water stress. This crop penalty behavior may explain the non-existent and weak correlation strength between soil water deficit and yields. In an EPIC simulation setup, as in this study, where temperature stress affects more than water stress, temperature indices could be used to have a first impression of expected yield losses without calculating soil moisture deficit to conduct an exploratory analysis.

6.2. Limitations

This dissertation is an impact research study that used EPIC's process-based crop model to simulate typical crop rotations together with several management strategies under climate change conditions. Among these are planting soybeans, irrigation amounts based on a given field capacity percentage, cropping calendars for three RCP scenarios. This methodology allowed making a first assessment of the potential effect of these management options. However, one RCM was used as climate data input for EPIC in this research, which means one potential climate trajectory is considered. For this reason, to consider model biases and courses of further climate development, it will be necessary to include more climate models. Nevertheless, it may be sufficient to incorporate RCMs that do not belong to the same family to have as numerous potential climate forecasts as possible.

Additionally, EPIC simulations included the CO2 increasing concentration values corresponding for each RCP scenario, allowing for the CO2 fertilization effect. However, in this research, there was no comparison between with and without CO2 concentration increase. This analysis may be helpful to differentiate the impact on yields due to climate variables such as temperature and precipitation, and CO2 levels.

The study area is relatively small, which was helpful, especially for Chapter 5, since it was an exploratory study of the correlation strength between crop yields and several climate indicators. Nevertheless, the climate indicators were selected randomly, as so the type of copula model. For this reason, it may be relevant to compare different copula distributions to identify which one may be a better fit between these variables.

6.3. FUTURE RESEARCH

EPIC requires transdisciplinary knowledge, including climate models, which is not a straightforward process and may slow down the simulation setup.

This research has thoroughly assessed the potential effects of irrigation, crop calendar schemes, and soybeans on crop yields, soil organic carbon, and nitrogen emissions in a typical agriculture system in Northern Germany. To include socio-economic aspects of this analysis, the developed methodology in this research may be coupled with a system dynamics model such as Tinamit[180]. The outputs from EPIC can be used to characterize the system.

Regarding characterizing the system, it will be relevant to conduct simulations with more RCMs, or even it would be worth considering the use of SSP scenarios from the CMIP6 instead of RCPs for the input of the EPIC model. These new scenarios represent different socio-economic developments as well as different pathways of atmospheric greenhouse gas concentrations.

For the further assessment of the correlation strength between yields and climate indicators (as in chapter in 5), it will be required the inclusion of more climate indices as well as the inclusion of climate extreme events in the projections. This selection will allow determining whether yields may be more affected due to temperature or precipitation.

Chapter 7

7. DATA MANAGEMENT PLAN

A Data Management Plan created using DMPTool

Creator: Andrea Catalina Fajardo

Affiliation: Non-Partner Institution

Funder: Climate Service Center Germany in Frame HICSS

Template: Digital Curation Centre

Project abstract:

IMLAND is a collaborative research project between Climate Service Center Germany and Hamburg University. Its main goal is the assessment of several adaptation measures to climate change in the agricultural sector in northern Germany, the Lower-Saxony region. The primary approach of the project is multidisciplinary, including the participation of different stakeholders who play a crucial role in this sector.

Last modified: 05-26-2020

Dissertation in frame IMLAND

Data Collection

What data will you collect or create?

1) What type, format, and volume of data?

Input data for EPIC:

Climate Data: For calibration and validation purposes, I have used reanalysis ERA5 data from CopernicusClimate Data Store (CDS) from 1979 to 2019 on an hourly basis as a reference period.

I downloaded the following parameters for Germany: Maximum Temperature (mx2t, [K]), Minimum Temperature (mn2t, [K]), Solar radiation (ssrd, [J m-2]), Total Precipitation (tp, [m]) (Quantity and not flux), 2 meter air temperature (t2m, [K]) and 2 m dew point (d2m, [K]). These parameters are saved as NetCDF (.nc format) files each for each year and variable. The size of each file is about 21 MB. NetCDF files are a format that allows traceability of the data, especially if after-processing has been done. The horizontal resolution is 0.25°x0.25° (atmosphere), 0.5°x0.5° (ocean waves). Mean, spread and members: 0.5°x0.5° (atmosphere), 1°x1° (ocean waves).

For future simulations (2006 to 2100), bias-corrected and regridded regional climate model (RCM) **CSC_REMO2009_MPI_ESM_LR** - *Original REMO simulations as part of the EURO-CORDEX project were shifted by half a grid* - The climate projections are for three RCPs (2.6, 4.5, and 8.5). These files are also NetCDF saved for each year and each variable -*These files are saved as zip files and then as tar files and are about 5 GB* -Additionally, the hindcast (1951 to 2005) is available for validation purposes. The parameters are Maximum Temperature (tasmax, [K]), Minimum Temperature (tasmin, [K]), Solar radiation (rsds, [W m-2]), Precipitation Flux (pr, [kg m-2 s-1])), and Relative Humidity (hurs, [%])-*this is not regridded as this parameter is more complicated to correct*- The dataset is for Europe available.

Weather Station Data: from the German Weather Service (in German DWD - Deutscher Wetter Dienst). This dataset is not complete. For this reason, it is not used for EPIC simulations. Nevertheless, maximum temperature (TXK, [°C]), minimum temperature (TNK, [°C]), and precipitation (RSK, [mm]) are used to compare the trend of ERA5 and the hindcast mentioned above for the reference period.

The CO2 database from IIASA. The RCP database aims at documenting the emissions, concentrations, and land-cover change projections of the so-called "Representative Concentration Pathways" (RCPs). CO2 concentrations: CO2 concentrations are available from 1918 to 2100 for each RCP utilized in this project.

Soil Data: reliable soil information ensures good results in EPIC. Most of the information used as input source was taken from the Federal Institute for Geosciences and Natural Resources (in German Bundesanstalt für Geowissenschaften und Rohstoffe, BGR) as a combination of a database in Ms. Access and a Map of Germany 1:200,000 (WMS).

The reference system is EPSG:3857.

The areas are divided into several boxes. In order to cover region of interest the following boxes are selected: Helgoland (2005, CC 2310), Neumünster (1999, CC 2318), Emden (2009, CC 3102), Bremenhaven (2009, CC 3110), Hamburg West (2009, CC 3118), Hamburg Ost (2005, 3126), Wittenberge (2011, CC 3134), Braunschweig (1998, CC 3926), Linge -Ems (2008, CC 3902), Bielefeld (2008, CC 3910), Hannover (2006, CC 3918), Kassel (2001, CC 4718), Goslar (2012, CC 4726).

Digital data management provides a detailed, nationwide uniform, and comprehensive information base for land use and soil protection statements across the states. The soil inventories and their spatial distribution on each map sheet's territory are described in legend units structured by soil regions and landscapes.

Each legend unit contains systematic soil information and information about the soil parent material of each dominant and associated soil.

The minimum required parameters for EPIC to run are: soil albedo - *this is obtained from the literature for most common soil textures* – Soil Hydrology group, Maximum number of soil layers after splitting is set up to 10, the number of years of cultivation at start of the simulation is set up to 100. The depth to the bottom layer is set up starting from 0.2 m up to 1 m, depending on the number of layers defined on the soil information database. Bulk density, Sand and silt content, soil pH, organic carbon concentration, saturated conductivity - *it is also obtained from literature* - water content at field capacity - *it is also obtained from the literature*.

Site Data: This study involves as fourteen districts above, which geographical position, area, and general management practices in terms of fertilization and irrigation. The specific information is latitude, longitude - *taken from the shapefile of Germany* - elevation - *taken from the digital elevation model of Germany* -the area only used for agriculture. The mainstream channel (km) and slope (m/m), and channel depth are taken from the information of the Elbe river.

The utilized irrigation is type three, which is irrigation with fertilizer. The depth of the irrigation system - taken from official information from the Chamber of Agriculture Lower Saxony (in German Landwirtschaftskammer Niedersachsen)

Management Data: This is taken mainly from the Board of Trustees for Technology and Construction in Agriculture (In German Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V). The collected information is the most common dates for the different operations: planting, harvesting, tillage, fertilization application, and irrigation schedule.

How will the data be collected or created?

The required data is free of charge to be downloaded as it is described in the following resources:

ERA5 hourly data on single levels from 1979 to present:
https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form

DWD Weather Station Data:
ftp://opendata.dwd.de/climate_environment/CDC/observations_germany/climate/daily/kl/historical/

Climate Projections: This data is available internally at the Climate Service Center Germany (GERICS). Please check https://impact2c.hzg.de/ - *For this project, these data were bias-corrected and regridded* -

CO2 Concentrations:
https://tntcat.iiasa.ac.at:8743/RcpDb/dsd?Action=htmlpage&page=about#rcpinfo

Soil Data:
https://fisbo.bgr.de/app/fisbobgr_produktauswahl/IMap/BUEK200_Arbeitsstand/map/m10000.html

Name conventions:

The climate data coming from NetCDF files must include which district they correspond to, to which climate dataset, and daily, monthly, or wind files(e.g., uelzen_era5.dly, uelzen_rcp26.dly, uelzen_hist.dly).

For the climate data from weather stations, the original names were kept, easy to track to which station/city corresponds to, and which period was initially recorded. For example, reference_produkt_klima_tag_19310101_20181231_00656.txt - *'reference' stands for that* *the file was already edited to include the select reference period, the final '00656' is the station id that can be crossed out with the list of stations to know to which city refers to -*

For the soil files, the name structure is GEN_NR - *this refers to No. of frame/general legend unit the can be crossed over to extra information available on the database* - and then _SoilLayer_ - *this is the code of the soil horizons, which is an abbreviation according to KA4/KA5* -. For example, for Uelzen, the corresponding soil file is GEN_748_3069.SOL

The operation files are named after the initial crop for the corresponding crop rotation following by the nitrogen fertilization level from 0 to 2000 kg/ha. C stands for corn, P for potato, SB for sugar beet, W for wheat, and S for soybean. For example, c_100.OPS

The site files are named after the corresponding simulation unit. Uelzen is the simulation 459, and then 459.SIT is its corresponding site file for that district.

The run files, namely the output files of the simulations, have a general name 'run' followed by the operation id and the site id. For example, for Uelzen is run_1_459.OUT

The whole project is saved on the following path as a zip file: cliccs-c2\A_Users\Andrea\corrected_climate_data.zip

D:\A_Users\Andrea\EPIC_runs\corrected_climate_data\

The main folders inside are divided between input data, scenarios to be tested, runs, plots. The folders are **calibration, dat_files** - *including text files required for EPIC, here EPICCONT.DAT, WDLY0810.DAT, WIND0810.DAT, WPM10810.DAT are specific for ERA5, hindcast, and the RCPs* -, **era5, scenarios** - *inside this folder there is the BAU scenario, which means without soybeans, and the 0-2000 kg/ha N fertilization levels* - **figures, historical, masks, obs_dwd, runs, shapefile, soil_files, site_files**.

All tests that do not make part of the study are saved into OLD in the leading directory's project.

The climate data is compared with the weather station data for the reference period to see similarities in average values over the timeline. With this, it could be seen that ERA5 data can be used for calibration and validation purposes. Likewise, the hindcast can be used only to show some statistics of the behavior of the results from EPIC.

Documentation and Metadata

What documentation and metadata will accompany the data?

The metadata is in the form of a README and updated in Gitlab.

I will be only one README including all aspects about the final data using the format https://cornell.app.box.com/v/ReadmeTemplate

This template is quite complete and captures most of the possible questions that explain the relevant details of the used data.

Ethics and Legal Compliance

How will you manage any ethical issues?

The data I have used is open source and free to use. All required citations and sources are included. In this way, people can download the data directly from the source.

How will you manage copyright and Intellectual Property Rights (IP/IPR) issues?

The bias-corrected data is third-party data. If it is used, it has to be requested directed to the research group who created it.

Please refer to IMPACT2C Project (https://www.climate-service-center.de/science/projects/detail/062848/index.php.en)

Storage and Backup

How will the data be stored and backed up during the research?

The data will be saved on the University server, a copy on Eddy, and a personal backup on the external hard drive.

On this server all process data is: cliccs-c2 (\\cifs-isi03.cen.uni-hamburg.de) :\A_Users\Andrea\corrected_climate_data.zip

How will you manage access and security?

The server and eddy can only be accessed via putty and double password steps.

the other collaborators can access the data only via eddy

Selection and Preservation

Which data is of long-term value and should be retained, shared, and/or preserved?

Since the data is part of my dissertation, I need to preserve it for ten years.

I will keep them on my private external hard drive.

At GERICS, it will be saved as part of the project

What is the long-term preservation plan for the dataset?

Gitlab is the principal repository of the data and scripts.

Data Sharing

How will you share the data?

Through the repository with not only collaborators on the project.

For other colleagues, the repository is also available.

Are any restrictions on data sharing required?

Non-applicable

Responsibilities and Resources

Who will be responsible for data management?

Andrea Catalina is going to be responsible for this. After she leaves GERICS, other colleagues must take this task over.

Contact: andrea.fajardo@climatehubhh.org

What resources will you require to deliver your plan?

Knowledge about working with NetCDF files is required, either with python and cdo.

The data for and from EPIC is mainly text files. Data processing is required.

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