Aus dem Institut für Pflanzenbau und Pflanzenzüchtung
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Between heat death and drought stress, the impact of adverse environmental conditions on critical development stages of agricultural production in the North German Plain

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Diplom Geoökologe Maximilian Oliver Strer
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Dekan: Prof. Dr. Dr. Christian Henning
1. Berichterstatter: Prof. Dr. Antje Herrmann
2. Berichterstatter: Prof. Dr. Henning Kage

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Summary

Changing boundary conditions through environmental shifts, worldwide as well as regional, challenge well- established agricultural production systems. While the extraordinary impacts on crop development through adverse environmental conditions during critical development stages are frequently considered a risk, they are rarely analysed. This is likely due to the complexity of the problem, with interactions and interdependencies between numerous abiotic and biotic factors entangled on various levels.

This thesis investigates these complex interactions between adverse environmental conditions and critical development stages and their impact on agricultural production of the North German Plain. It identifies important, critical development stages, it develops an outlook for the abundance of adverse environmental conditions, and it identifies mitigation strategies for this specific problem by pattern analysis.

A literature study identifies prominent critical development stages that help navigate the topic of adverse environmental conditions and critical development stages in agricultural production. Further, it shows that crop simulation models seemingly lack in capacities to model development-stage specific stress responses.

A modelling study provides an outlook; it finds a consistent increase in abundance of numerous adverse environmental conditions throughout the North German Plain. The inabilities of crop simulation models (DSSAT) are omitted by neglecting modelled yield response and focusing on the evaluation of the abundance of adverse environmental conditions within phenological development stages.

A case study of drought impact on yield variability approaches the problem from another angle. The inventory of drought patterns shows that diversification of production systems is a possible mitigation strategy. Further, it found a starting point for improvements of crop simulation models towards a better assessment of critical development stages in the poorly simulated drought response around flowering. This inventory was derived for various production systems for an example region in the North German Plain.

Zusammenfassung

Widrige Witterungsbedingungen während kritischer Wachstumsphasen können eine außergewöhnlich starke Wirkung auf die pflanzliche Entwicklung haben, z.B. Trockenheit während der Blüte. Dabei reichen die Auswirkungen von Ertragsrückgängen über Qualitätseinbußen bis zum Totalausfall. Es ist anzunehmen, dass die etablierten Produktionssysteme künftig nicht mehr an die veränderten Umweltbedingungen angepasst sein werden und sich solche Konsequenzen häufen werden. Damit geht das Risiko einher, dass die Produktion nicht mehr auf dem gewohnt hohen und zuverlässigen Niveau stattfinden kann. Dies gilt für die Landwirtschaft im Norddeutschen Tiefland wie weltweit. Um diese Risiken für das Norddeutsche Tiefland im speziellen einzuschätzen, wurde in dieser Arbeit eine Übersicht zu kritischen Phasen der pflanzlichen Entwicklung und Ertragsbildung erstellt, eine Perspektive für Risiken der Landwirtschaft im Norddeutschen Tiefland entwickelt und ein systematischer Ansatz zur Verbesserung von Analysemethoden und Werkzeugen getestet.

Kritische Phasen werden schon lange als Herausforderung wahrgenommen. Die Literaturübersicht zeigt, dass je nach Fragestellung zahlreiche spezifische Definitionen genutzt werden, und dass systematische Ansätze zur Analyse der Wirkung von widrigen Witterungsbedingungen auf kritische Phasen selten sind. Zusätzlich wird gezeigt, dass kritische Phasen als Phänologie-spezifische Reaktionen auf bestimmte Umweltbedingungen in Pflanzenwachstumsmodellen, dem Werkzeug der Wahl zur Analyse von Produktionssystemen, kaum entwickelt sind.

Mit dem Pflanzenwachstumsmodell DSSAT (Decision Support System for Agricultural Transfer) konnte, trotz der für Pflanzenwachstumsmodelle typischen Beschränkungen, die Häufigkeit von widrigen Witterungsbedingungen während ausgesuchter Pflanzenwachstumsphasen für drei Zukunftsszenarien abgeleitet werden. Unter der Voraussetzung, dass es zu keinerlei Anpassungen kommt, ergeben sich für das Norddeutsche Tiefland folgende Perspektiven: Die Häufigkeiten für widrige Witterungsbedingungen während ausgewählter Wachstumsphasen nimmt durch alle evaluierten Szenarien durchgängig zu und dies trotz vorteilhafter, phänologischer Entwicklungen wie der Verlängerung der Vegetationsperiode. Darüber hinaus fordert der Klimawandel den etablierten Pflanzenbau im Norddeutschen Tiefland teils auch auf unerwartete Weise heraus, so muss trotz Temperaturerhöhung weiterhin mit Spätfrost gerechnet werden.

Häufig treten widrige Umweltbedingungen nicht vollständig willkürlich auf. Eine Auswertung langer Ertragszeitreihen durch eine Musteranalyse zeigt und klassifiziert die Wirkung von Trockenheit auf die Ertragsvariabilität in Niedersachsen. Neben der Klassifizierung der rezenten Produktionssysteme, die Schlüsse über eine Risiken-vermindernde Gestaltung von zukünftigen Produktionssystemen geben kann, identifiziert die Anwendung der Methode auf modellierte Ertragsreihen Ansatzpunkte, an denen das Pflanzenwachstumsmodell gezielt mittels Phänologie-spezifischer Prozesse verbessert werden kann, z. B. der verbesserten Simulation des Übergangs zur reproduktiven Entwicklung.

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List of abbreviation

Agricultural model intercomparison and improvement project	AgMip
Crop environment resource synthesis	CERES
Crop simulation model	CSM
Diepholz model region	DH
Decision support system for agrotechnology transfer	DSSAT
Fläming model region	FL
General circulation model	GCM
International panel for climate change	IPCC
Nachhaltiges Land Management im norddeutschen Tiefland	NaLaMa-nT
Oder-Spree model region	OS
Representative concentration pathway	RCP
Uelzen model region	UE

Introduction

Success of any agricultural pursuit requires suitable environmental conditions throughout the production process. Adverse environmental conditions, especially during critical production stages, can impact the agricultural pursuit negatively and jeopardise reliable crop production outputs on high levels. Shifting climate conditions in a political setting that demands high yields and yield stability challenge the well-established and long-evolved agricultural production systems at the global and regional scale.

The agricultural production systems of the North German Plain, as elsewhere, are shaped around regional climate patterns to provide optimal boundary conditions for agricultural production (Gömann et al. 2015; BMEL 2019; van Rüth et al. 2019). Each crop has its specific requirements shifting along with its development (Wollenweber 2003; Porter and Semenov 2005; Semenov 2009; Trnka et al. 2011, 2014; Mäkinen et al. 2018; Hoffmann et al. 2018). Some development stages stand out; they harbour the potential for severe yield losses, if demands are not met, or if adverse environmental conditions impact them. The complex issues of adverse environmental conditions and critical development stages certainly is a plague for risk assessment of crop production systems (Porter and Semenov 2005; Tao et al. 2018). It is easy to conclude, that insight in the interaction between adverse environmental conditions and critical development stages can be valuable to assess yield variability of agricultural production systems.

Motivation

Holistic approaches, e.g. the NaLaMa-nT-project (*Nachhaltiges Landmanagment für das norddeutsche Tiefland project*, sustainable land use management for the North German Plain project), show the importance of climate change impact on regional development (Spellmann et al. 2017). While they produce general mitigation strategies, they lack in depths to resolve specific issues, i.e. adverse environmental conditions and critical development stages that can have strong, unforeseen impact on yield variability. Ultimately, not assessing the impact of environmental variability and extremes and using inadequate evaluation tools leads to severe consequences. For example, ill-focused breeding schemes might already have led to a significant depletion of wheats' genetic variability, including resilience to environmental extremes (Kahiluoto et al. 2019). Many valuable and frequently discussed mitigation strategies are neglected in modelling studies because they cannot be tested with crop simulation models (Challinor et al. 2018).

State-of-the-art

The basic concept of critical development stages and adverse environmental conditions, as well as their complex interactions**,** is quite intuitive. On the one hand, some development stages require specific environmental conditions to be successful, e.g. specific temperature ranges to develop reproductive organs (Barnabás et al. 2008; Lizaso et al. 2018). From the production perspective, critical development stages are those that determine the development of the harvestable product such as roots, tubers, or grains, or even endanger the survival of the total crop (Fowler et al. 1996). On the other hand, specific environmental conditions, such as e.g. hail storms, droughts, heatwaves, can hamper crop development; or they can inhibit significant production processes, e.g. high soil moisture reducing machinability (Gobin 2012).

The topic is challenging and intriguing because all these factors stand in correlation, depend on each other, and they can lead to unforeseen consequences when combined (Wollenweber 2003). One could argue on philosophical level that ‘adverse’ and ‘critical’ can only be defined through the duality between crop development and environmental conditions.

The North German Plain is an important agricultural region in Germany (Spellmann et al. 2017). The temperate climates found in Germany support reliable outputs of well-established and long evolved production systems. These systems account for a wide range of environmental variability, e.g. winter frost to occasional summer droughts (Trnka et al. 2011, 2014; Gobin 2012; Spellmann eft al. 2017). Today this generally positive assessment of the region is only disrupted by local conditions, e.g. poor soil properties (Richter et al. 2007).

However, shifts in environmental patterns challenge this picturesque idyll (Barker 2007; IPCC 2014; Gömann et al. 2015). These shifts include an increase of the mean temperature by 1.5 K since 1881 (Barker 2007; IPCC 2007, 2014; Trnka et al. 2011; Gömann et al. 2015; van Rüth et al. 2019), shifts in vegetation period (Menzel and Fabian 1999; Chmielewski and Kühn 2000; Walther 2003; Chmielewski et al. 2004), and an increase in abundance and severity of heat days (van Rüth et al. 2019). The decrease in frost days will not lead to the exclusion of frost in general (van Rüth et al. 2019). Precipitation shifts are not as clear - more winter precipitation is possible (Gömann et al. 2015; Ljungqvist et al. 2016). Water scarcity is likely to increase in summer as the elongated vegetation period increases water demand (Svoboda et al. 2015; van Rüth et al. 2019).

Despite some beneficial developments, shifts will exacerbate environmental stress for agricultural production systems (Chmielewski et al. 2004; Menzel et al. 2006; Estrella et al. 2007; Trnka et al. 2011, 2014; Mäkinen et al. 2018). Yet unprecedented conditions are expected to impact and complicate agricultural production (IPCC 2014; Gömann et al. 2015; van Rüth et al. 2019).

Process-based dynamic crop simulation models are a valuable tool to analyse the response of complex systems like the soil-plant-system to various inputs, e.g. different management schemes (Bindi and Olesen 2011; Trnka et al. 2011; Rötter et al. 2012, 2018a; Gobin 2012; IPCC 2014; Gömann et al. 2015; Martre et al. 2015; Pirttioja et al. 2015; Wang et al. 2017; Wallach et al. 2018). Provided sufficient calibration and validation, they can test general performance of cropping systems in climate change studies over broad ranges of different environments (Jones et al. 2003a; Palosuo et al. 2011; Hoogenboom et al. 2012; Trnka et al. 2014). They are flexible enough to simulate various crops (Palosuo et al. 2011; Kollas et al. 2015), and variable in their application to different topics (Rötter et al. 2012; Pirttioja et al. 2015; Stratonovitch and Semenov 2015). They show reasonable performance in predicting mean yield and mean crop development of various production systems (Palosuo et al. 2011; Rötter et al. 2012; Kollas et al. 2015). However, if not adjusted for the specific problem, they can fail to provide specific responses (Challinor et al. 2009, 2018; Rötter et al. 2018b).

Knowledge gaps

Complexity *per se* is certainly not a knowledge gap; however, every insight can be helpful to navigate the complexity found between environmental conditions and development stages.

Many approaches analysing arbitrarily selected environmental conditions and development stages show that systematic definitions are needed to characterise the problem. Only a broader systematic knowledge base will provide adequate risk assessment (Challinor et al. 2005, 2007, 2018; Rötter et al. 2011; Eitzinger and Thaler 2012; Lizaso et al. 2017).

Risk assessment is needed to identify threats from shifting environmental conditions' impact on local crop production in the North German Plain or other regions. A risk assessment can anticipate calamities and provide mitigation and adaption strategies that will minimize these impacts. An overview of abundances of adverse environmental conditions during critical development stages for the North German Plain can be a useful starting point for this kind of assessment.

Further, there is evidence that the approaches and tools available are insufficient for analysing the development stage-specific response to adverse environmental conditions needed for this kind of risk assessment (Trnka et al. 2011; Gallusci et al. 2017; Challinor et al. 2018). Therefore, new tools and approaches are needed. For instance, analysis of environmental patterns can help to narrow the complexity down and provide starting points to develop new analysis approaches systematically or improve existing tools, i.e. crop simulation models to model specific stress response, more adequately (Gallusci et al. 2017; Challinor et al. 2018).

Research questions

The impact of adverse environmental conditions and critical development stages on agricultural production is an intriguing problem, and the knowledge gaps clearly indicate both general and specific research demands. Here, the impact of adverse environmental conditions and critical development stages of crop production is studied for the example North German Plain. Each of the three identified research questions is answered in a chapter of this thesis.

1. **Which critical development stages are relevant in the context of adverse environmental conditions for the North German Plain?**

Relevant development stages were identified through a literature study. It provides an overview of research about critical development stages and adjacent adverse environmental conditions in agricultural production and for common crops grown in the North German Plain. Further, it assesses crop simulation model capabilities to model critical development stages.

2. **How will the abundance of critical development stages shift in the future of the North German Plain?**

The answer gives an outlook to a potential future for agriculture in the North German Plain by partitioning the problem and focusing on the abundance of adverse environmental conditions during critical development stages. By applying the decision support system for agricultural transfer (DSSAT) crop simulation model, three climate projections are evaluated for the abundance of adverse environmental conditions of various climate elements during selected development stages at four representative sites in the North German Plain.

3. **In which regard are models capable of depicting the specific impact of adverse environmental conditions on crop development?**

Ideally, the study will provide if and where more systematic research on models is needed to simulate adverse environmental conditions and critical development stages adequately. Relative drought impact on observed and simulated yield variability is analysed exemplarily with environmental patterns for the Federal State of Lower Saxony, Germany. The comparison of responses of observed and simulated production systems showcases the model’s sensitivity to drought impacts.

Structure

The **background chapter** provides definitions and context about processes and resources relevant to the conducted research. It includes the establishment of general *definitions* for adverse environmental conditions and critical development, an introduction of the NaLaMa-nT-project (*Nachhaltiges Landmanagment für das norddeutsche Tiefland*, Sustainable land use management for the North German Plain) as the general *framework* for this thesis, and an introduction of the *crop simulation model* used in this study; decision support system for agricultural transfer (DSSAT). This chapter replaces in some regards a classical general methods section by providing background for decisions, e.g. general methods, tools, e.g. DSSAT and resources, e.g. sites, data, climate change projections. Each of the three individual chapters will describe specific methods applied.

Each of the three research questions, established before, is answered by individual research studies that can be found in three chapters: **Chapter 1**, **Chapter 2**, and **Chapter 3**.

General discussion includes a general *synthesis* section that recapitulates the answers to the initial research questions and aggregates them in the overarching context. The *reflection* section discusses the findings in a broader context providing additional perspectives for identifying adverse environmental conditions and critical development stages, handling uncertainties in predicting climate change, and using crop simulation models for this task. It derives mitigation strategies for agricultural production in the NGP, and it develops some solution improving and applying crop simulation around the problem.

Background

Definitions

There is a duality between 'adverse' environmental conditions and 'critical' development stages: one defines the other. This results in the application of various, specific definitions and assessments of these phenomena.

Adverse environmental conditions have always been a concern in the field of agricultural meteorology (Vining 1990). There are many names and specific definitions for adverse environmental conditions, e.g. adverse agroclimatic extremes (Rötter et al. 2018b), '*Agrarrelevante Extremwetterlagen'* (Gömann et al. 2015), adverse environmental conditions (Trnka et al. 2014), or adverse weather conditions (Vining 1990). All share the idea that there are these conditions that have a negative impact on crop production, e.g. yield loss. Adverse environmental conditions must not be considered independent of crops. They have crop and development stage-specific impacts (Daryanto et al. 2017; Strer et al. 2018; Zampieri et al. 2019). In the present work, more specific definitions of Trnka et al. (2014) and Gobin (2012) were followed: environmental conditions are unfavourable events of several days or some weeks that hamper crop development or crop production substantially. Arbitrary short-term events, e.g. hail storms, or fire, are not considered due to their unpredictability. The use of the more general environmental conditions instead of weather conditions opens the definition to other factors, e.g. biotic antagonists.

Critical development stages are phenological stages or production stages that need to be successful for the general crop development or the development of the harvestable crop part. Additionally, the absence of essential production steps, e.g. harvesting due to inadequate soil conditions can hamper agricultural production severely. Development stages are a well-established concept; specific stages have specific requirements to environmental conditions (Porter and Gawith 1999; Barnabás et al. 2008; Meier et al. 2009; Sánchez et al. 2014). Frequently, these requirements are rooted in the development of specific crop organs, e.g. tubers, seeds (Porter and Gawith 1999; Barnabás et al. 2008; Sánchez et al. 2014).

Where necessary specific definitions will be introduced, providing further focus to the assessment of adverse environmental conditions and critical development stages by, e.g. specifically defined thresholds.

Framework: NaLaMa-nT

The *Nachhaltiges-Landmanagement-im-Norddeutschen-Tiefland*-project (NaLaMa-nT, https://www.nalama-nt.de/projekt.html, Spellmann et al. (2017), Figure 7) provides the framework for this thesis. The project aimed at developing a general future sustainable land use management for the North German Plain using a holistic approach that integrates agricultural, forestry, and environmental aspects. However, the approach needed supplementation by an assessment for yield risk of the future North German Plain. The general observation and solutions found by the project left this specific topic unexplored.

While, this thesis - not at least through the highly specific objective - is largely independent of the initial project, the plethora of shared resources and boundaries available through NaLaMa-nT-project made their mark on some decisions and selected approaches. This includes selected sites as well as using the same climate scenarios.

Most evident the geographical definition provided by the NaLaMa-nT -project was used, and the present work focused on the four representative model regions Diepholz, Uelzen, Fläming and Oder-Spree (Spellmann et al. (2017), Figure 7, Supplementary material 1). The North German Plain can be defined geographically, culturally, economically, and in numerous other ways. Indeed, man shaped the region into the highly economized cultural landscapes with agriculture, forestry, settlements, transportation, dykes, etc. that we find today. It is a highly productive agricultural area, dominated by adapted and elaborate agricultural production systems (Spellmann et al. 2017). These have been fine-tuned and developed - over centuries - around the local climate and environmental patterns to generate and ensure high and reliable yield. Various environmental conditions impacted these developments, e.g., the climate gradient from oceanic to continental climate, specific soils that developed on numerous substrates from glacial valley sands to loess accumulations, or the impact of the sea through floods.

The general and regional climatic conditions are especially important in the context of adverse environmental conditions and critical development stages. The region holds a magnitude of challenges from cold periods with occasional freezing and thawing in winter to heatwaves and droughts in summer. Generally, the climate of the North German Plain classifies as Cfb in Koeppen's effective climate classification (Peel et al. 2007). East of the Elbe river the climate is in the transition towards Dfb class climates: with lower precipitation sums, more summer precipitation and larger temperature ranges (Figure 1, Figure 2, Figure 3, Figure 4)

The typical abiotic adverse environmental conditions for crop production are in the North German Plain - alone or in combination – drought and water surplus; frost, especially late frost; and occasional heatwaves (Gömann et al. 2015; BMEL 2017; van Rüth et al. 2019). Various other abiotic and biotic stressors will occasionally impact crop production: numerous diseases, pest, fires and large-scale floods are regularly encountered locally or regionally in the North German Plain. Out of these, especially, droughts and heatwaves are reported to have increased in frequency and severity - indicated by events in the years 2003, 2006, 2015, and 2018, and they are likely to increase even further in future (Gömann et al. 2015; van Rüth et al. 2019).

Table 1 basic statistics fort the model regions (Supplementary material 1, Figure 7)

Region		Diepholz	Uelzen	Fläming	Oder-Spree
Abbreviation		DH	UE	FL	OS
area	[km²]	2000	1500	2100	2200
agricultural	[%]	75	50	40	40
precipitation	[mm]	701	714	663	560

Climate change is expected to have an impact on regional environmental conditions, including shifting weather patterns (Trnka et al. 2011; IPCC 2014).

Widely accepted are temperature-related shifts, they tell a consistent story for the North German Plain: mean temperature increased by 1.5 K compared to 1881 and will further increase (Barker 2007; IPCC 2007, 2014; Trnka et al. 2011; Gömann et al. 2015; van Rüth et al. 2019).

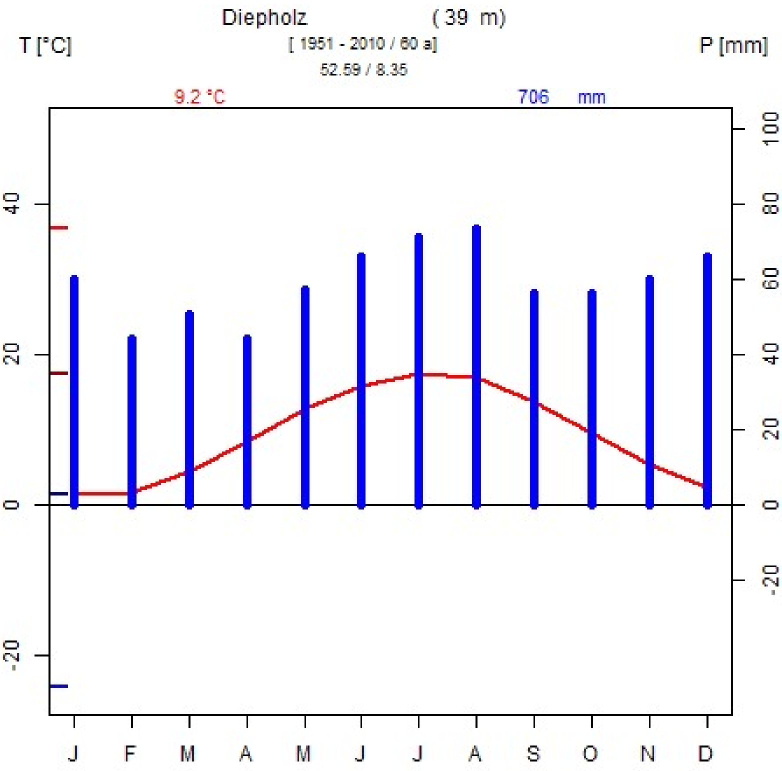

Figure 1 climograph for Diepholz weather stations one of the four NaLaMa-nT model regions

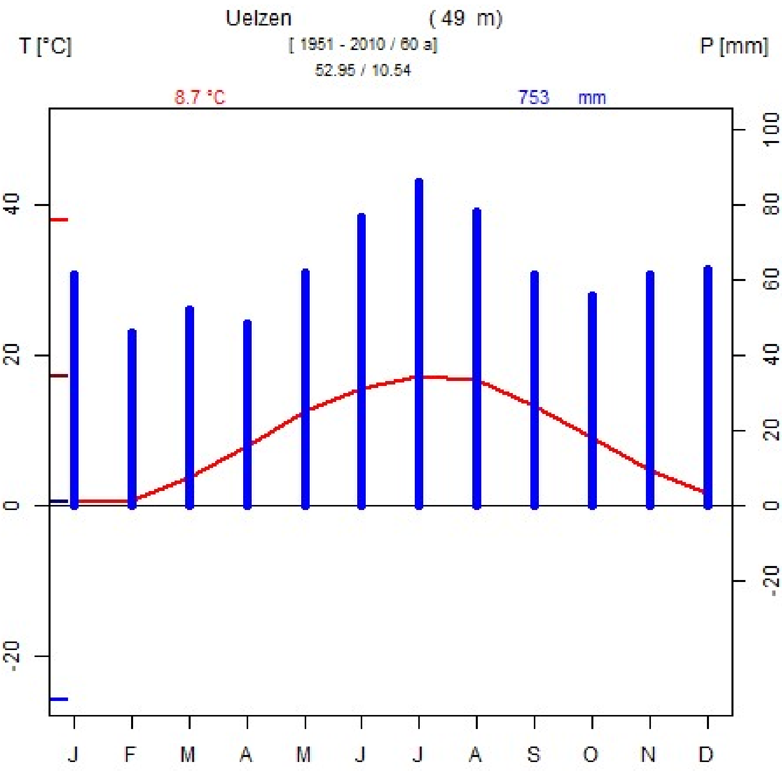

Figure 2 climograph for Uelzen weather stations one of the four NaLaMa-nT model regions

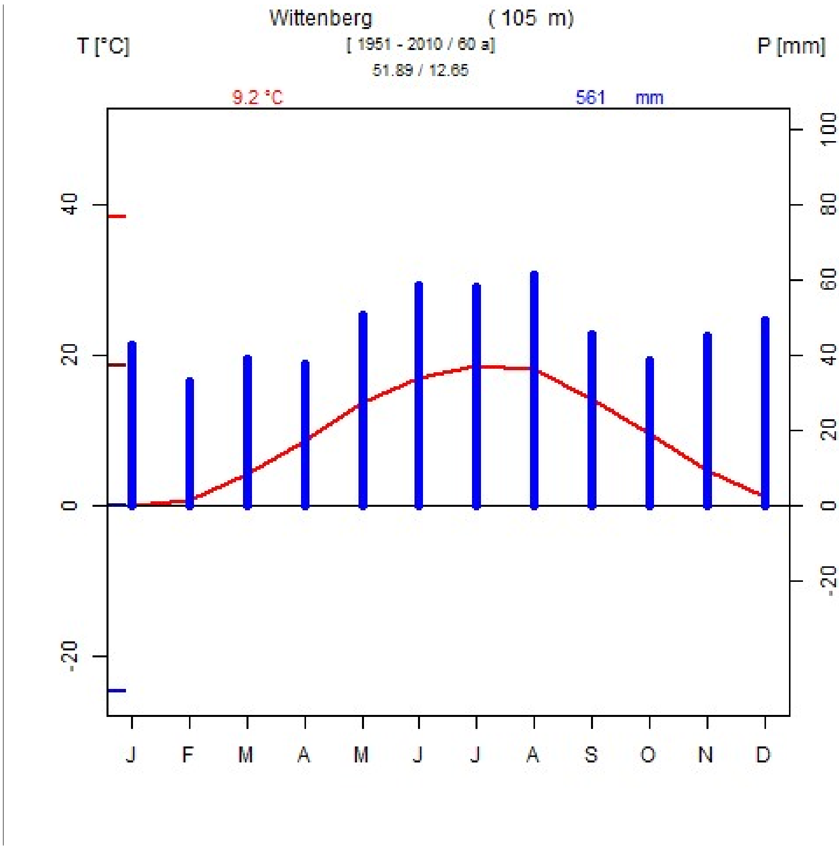

Figure 3 climograph for Wittenberg stations one of the four NaLaMa-nT model regions

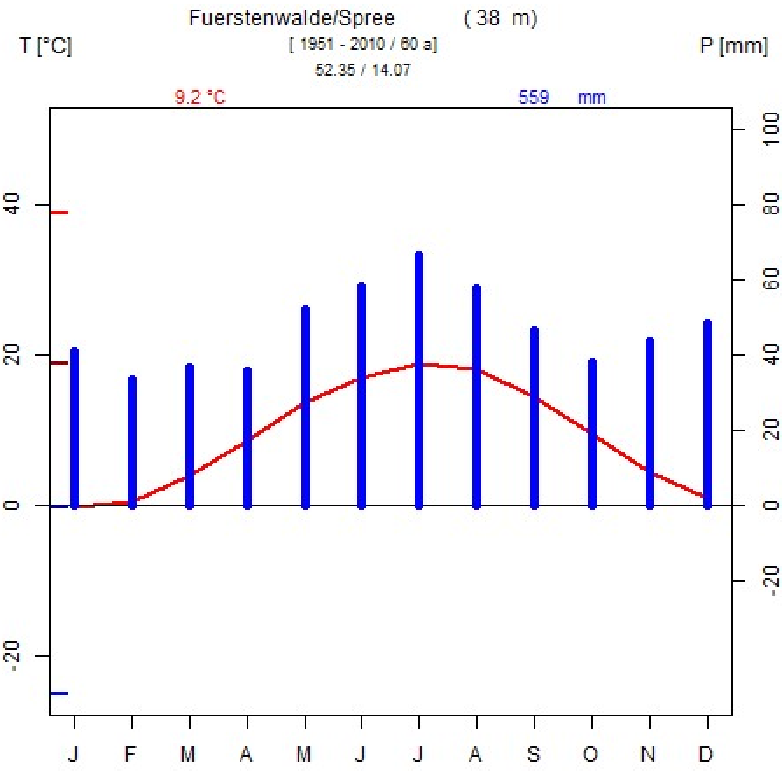

Figure 4 climograph for Fürstenwalde weather stations one of the four NaLaMa-nT model regions

A consequence in terms of crop development is an elongation and earliness of the vegetation period of approx. ten days (Menzel and Fabian 1999; Chmielewski and Kühn 2000; Walther 2003; Chmielewski et al. 2004). In regards to adverse environmental conditions, there is a discussion of a further increase of extreme temperatures in frequency and severity (Jacob et al.; Trnka et al. 2011; Gömann et al. 2015). Heat days will increase in abundance and severity (van Rüth et al. 2019). Frost days will decrease; however, they will not vanish (van Rüth et al. 2019). Some benefits and chances are seen for agricultural production in Central Europe in temperature increase respectively the elongated vegetation period (Menzel and Fabian 1999; Chmielewski and Kühn 2000; Walther 2003; Menzel et al. 2003; Chmielewski et al. 2004; Barker 2007; Estrella et al. 2007; IPCC 2007, 2014; Trnka et al. 2011; Gömann et al. 2015).

Projected shifts in **precipitation** are vaguer. Agricultural production could be challenged by higher water requirements through the elongated vegetation period and precipitation shifts, with more precipitation taking place outside the vegetation period (Gömann et al. 2015; Svoboda et al. 2015). This could make water availability to a potentially limiting factor in rainfed systems of the North German Plain (Simon 2009). Frequently, it is emphasised that regional or local conditions might overrule common trends in precipitation (Gömann et al. 2015; Svoboda et al. 2015; van Rüth et al. 2019).

The main regional climate pattern is the gradient from oceanic to continental climate across the North German Plain. Projections show climate change intensifies along the gradient; with climate change impacts being more pronounced in the East (Trnka et al. 2004, 2011; Gömann et al. 2015).

Shifts in adverse environmental conditions challenge the well-established local agricultural production systems and will have a substantial impact if no mitigation takes place (Trnka et al. 2011; Gobin 2012; Gömann et al. 2015). Exceptional events are expected to increase in abundance and intensity, e.g. heatwaves and droughts not yet reported for this part of Europe (Russo et al. 2015; Hanel et al. 2018).

A primary tool to access these shifts in more detail are climate change scenarios based on global circulation models. They provide reasonable projections of future climate developments. This thesis uses the climate scenario and projections developed for the NaLaMa-nT-project: The Potsdam Institute for Climate Impact Research (PIK) provided three projections for the future climate. They are set in the representative concentration pathways (RCP) 8.5 continuum of the Intergovernmental Panel on Climate Change (IPCC), based on general circulation model and regionalised with a regional statistical model (here STARS). The three different scenarios are: **min** scenario is a run from the INM-CM4 of the IMN, Russia, **med** scenario is a run from ECHAM6 of the Max-Planck-Institute (MPI), Germany, and **max** scenario is a run of the ACCESS1.0 model from CSIRO-BOM, Australia. Each scenario represents a single model run. Supplementary material 1 and Table 2 comprise the range of available climate scenario data and give some overview (Strer et al. 2014).

Crop simulation models

Crop simulation models, here especially dynamic process-based models of the soil-plant-system, are an excellent tool to analyse the response of complex systems, i.e. agricultural production systems to shifting environmental conditions. They can help, as they do in this thesis, to partition and simplify complex systems like agricultural production systems into manageable and analysable parts.

Table 2 mean observed annual temperatures for the period 1990-2010 (obs) and projected by three climate models (**med**, **min**, and **max**) for 2040-2060 at the four model regions. P-values belong to Student's t-test applied to test on differences in means between observation and projection. Asterisks indicate levels of significance (*).

region		DH	UE	FL	OS
obs	[°C]	9.7 ± 0.7	9.3 ± 0.7	10.7 ± 1.2	9.7 ± 0.8
med	[°C]	11.6 ± 0.6	10.9 ± 0.6	12 ± 0.6	11.9 ± 0.6
p-value	[ ]	2.1E-11***	5.7E-10***	7.3E-13***	1.9E-12***
min	[°C]	10.8 ± 0.6	10.2 ± 0.7	11 ± 0.7	11 ± 0.7
p-value	[ ]	1.80E-12***	1.00E-10***	6.10E-13***	5.4E-13***
max	[°C]	12.3 ± 0.9	11.6 ± 1	12.7 ± 1	12.5 ± 1
p-value	[ ]	9.1E-06***	5.3E-05***	2.2E-06***	2.0E-06***

Crop simulation models analyse the response of crops to changing environmental conditions and management schemes (Bindi and Olesen 2011; Trnka et al. 2011; Rötter et al. 2012, 2018a; Gobin 2012; IPCC 2014; Gömann et al. 2015; Martre et al. 2015; Wang et al. 2017; Wallach et al. 2018). They can simulate various crops (Palosuo et al. 2011; Kollas et al. 2015), apply to a wide range of topics including (Rötter et al. 2012; Pirttioja et al. 2015; Stratonovitch and Semenov 2015): water availability (Barlow et al. 2015; Rötter et al. 2018b), phenological development (Lizaso et al. 2017), and stress-specific yield response (Challinor et al. 2007). While they occasionally are tasked with analysing specific stress responses, they developed around solving general crop development issues; with results being especially satisfying in predicting mean yields and mean crop development of generalised production systems (Palosuo et al. 2011; Rötter et al. 2012; Kollas et al. 2015).

Out of many options, the decision support system for agricultural transfer (DSSAT) for crop simulations was selected for this thesis (Jones et al. 2003a; Hoogenboom et al. 2012). It is applied worldwide and presents a well-established bundle of process-based dynamic crop models. It is tested over a broad range of environments (Jones et al. 2003a; Palosuo et al. 2011; Hoogenboom et al. 2012; Trnka et al. 2014) and has shown to have a reasonable performance in yield prediction in model comparison studies (Thorp et al. 2007; Rötter et al. 2012). The modular design harbours the possibility to easily access different crop simulation modules for various crops without the need to manipulate input data (Travasso et al. 1996; Jones et al. 2003a; Soler et al. 2007; Hlavinka et al. 2010; Hoogenboom et al. 2012). Therefore, it seems suitable to analyse the complex correlations between adverse environmental conditions and critical development stages. DSSAT shares sufficient basic traits, concepts, and processes with other models to derive some general insight in model behaviour to this specific problem.

Chapter 1

Manuscript, March 2020

Evaluation of crops and crop models for critical growth stages of major crops in temperate climate conditions – A Review

Abstract

High crop yield and yield stability under varying climatic conditions remains a major challenge for agricultural production, especially in view of climate change. Many crops show a high sensitivity to environmental conditions, such as heat and drought, in specific, critical growth stages. The objective of the current study was to analyse if these specific crop responses are represented by crop growth models commonly applied for risk assessment in climate change scenarios. The focus was on arable crops grown in temperate regions representing the highly productive agricultural areas of Central Europe. A literature survey revealed that for wheat, *maize and rapeseed, flowering and early seed fill are regarded as the main critical growth stage, whereas for potato, stem elongation, tuber formation and inflorescence emergence are crucial, and for sugar beet germination is most sensitive. Although adverse environmental conditions during these critical stages can have a detrimental impact on crop yield, the implementation of these stages in most common process-based crop growth models was found to be non-satisfactory, as shown for the example of wheat models. Therefore, various strategies were identified to account for critical growth stages in a risk assessment context. These are developed either for the purpose of accounting for critical growth stages directly, or for some other use, but are still suitable to add significant improvement to dynamic crop growth models.*

Keywords: *adverse environmental conditions; phenological development; critical crop growth stages; crop modelling*

Introduction

Crop responses to adverse environmental conditions that result in stress to the crop are very complex and variable since they depend on the crop developmental stage and timing of the stress, together with its duration and intensity. Critical growth stages are phenological stages during which crops have specific requirements or are highly susceptible to specific environmental conditions (Porter and Gawith 1999; Sánchez et al. 2014). These requirements are related to the development of sensitive crop organs (Barnabás et al. 2008), or specific processes taking place along critical stages, e.g. meiosis (Porter and Semenov 2005). There are numerous published studies on the physiological impact of stresses during specific growth stages of different crops, e.g. heat during flowering (Ewing 1981; Barnabás et al. 2008; van der

Velde et al. 2012; Stratonovitch and Semenov 2015), drought during anthesis (Saini and Westgate 1999; Ahmadi and Bahrani 2009b; Shrestha et al. 2010), or frost during early development (Rácz et al. 1996). Adverse environmental conditions during these sensitive growth stages, e.g. drought (Trnka et al. 2014), high temperature (Porter and Gawith 1999; Sánchez et al. 2014), or waterlogging can cause substantial yield reduction (Gobin 2012) or even crop failure (Challinor et al. 2005), as in the case of the summer drought of 2003, which resulted in drastic yield losses in Central Europe (van der Velde et al. 2012). Generally, cropping systems are adapted to the environmental conditions prevailing in specific production regions. Climate change, however, will inevitably result in changes in the frequency and distribution of environmental parameters, e.g. rainfall and extremes of temperature, and be accompanied by increased carbon dioxide concentrations (Porter and Semenov 2005; Barker 2007). For Central Europe, it is considered highly likely that distribution will change towards an increased risk of high-temperature events compared with the present conditions (Trnka et al. 2014; Harrison et al. 2014; Pirttioja et al. 2015).

Dynamic crop growth models, simulating crop response to specific environmental conditions, are frequently applied in climate change and risk assessment studies (Palosuo et al. 2011; Rötter et al. 2012). It is only recently, however, that risk assessment studies have started to focus on the impact of adverse environmental conditions on crop growth processes during specific phenological stages (Gobin 2012; Trnka et al. 2014; Pulatov et al. 2015; Liu et al. 2016). Further, there are efforts to improve models to ensure better accountancy of critical growth stages (Challinor et al. 2005; Stratonovitch and Semenov 2015; Ruane et al. 2016). Thus, it may be assumed that crop growth models will differ in their capabilities to reflect interactions of adverse environmental conditions and critical growth stages (Porter and Semenov 2005; Liu et al. 2016; Ruane et al. 2016).

Various development stages can be identified as critical growth stages, and these depend strongly on the prevailing environmental conditions. There is yet no overview, however, for temperate environmental conditions, as represented by Central Europe as an important crop production area. Further, an evaluation of the implementation of these critical development stages in process-based dynamic crop growth models as major tools for risk assessment of cropping systems in climate change studies would be beneficial for assessing the reliability of these tools.

Therefore, the objectives of the current review are (1) to identify critical crop growth stages most commonly regarded to be relevant in crop production, (2) consideration of critical growth stages in dynamic crop growth models and (3) evaluation of these implementations, with respect to risk assessment for crop production in Central Europe under future climate change conditions. Due to the large number of models simulating different crops, the focus in the second and third item is on wheat models.

Methodology

Identification of critical crop growth stages

To identify critical crop growth stages, we conducted a keyword search using scientific databases (Web of Knowledge, Science Direct, Google Scholar). The analysis was restricted to crop species important for Central Europe, i.e. wheat (*Triticum aestivum* ssp aestivum L.), maize (*Zea mays* ssp *mays* L.), rapeseed (*Brassica napus* ssp *napus* L.), potato (*Solanum tuberosum* ssp *vulgaris* L.), and sugar beet (*Beta vulgaris* ssp *vulgaris* L.). Review and research articles were considered for evaluation. The search was restricted to articles investigating yield response to adverse environmental conditions during specific phenological stages. In this respect, the definition for adverse environmental conditions provided by Trnka et al. (2014)

was applied. In detail, the authors considered winter frost without snow cover, late frost, waterlogging from sowing to anthesis, severely dry growing season (sowing–maturity), severe drought events between sowing and anthesis or between anthesis and maturity, heat stress at anthesis or during grain filling. Environmental conditions with a small spatial or temporal resolution, e.g. storms or hail events, were excluded from our study; although they are of importance at a local scale, they have a lower impact at a regional scale (Olesen et al., 2011). Likewise, articles focusing on the effect of salinity were not considered since this is not a key factor limiting crop production in the focus area. Further, articles analysing the impact of biotic factors such as competition, pests or diseases were also excluded.

Phenological growth stages were considered as critical growth stages if they were regarded to be especially susceptible to adverse environmental conditions or to be more susceptible than other stages investigated in the same article. Multiple entries per article are possible if, for example, an article addressed several crops or compared the impact of environmental stress in different development stages. For analysis, principal growth stages were assigned according to Meier (2001). Articles were discarded from the evaluation if growth stages could not be identified appropriately.

Implementation of critical stages in crop models

The second part of the current study focuses on the implementation of critical crop growth stages in dynamic crop growth models. We evaluated the APSIM, APES, CROPSYST, DAISY, DSSAT, FASSET, HERMES, MONICA, STICS and WOFOST models (Table 3), These are all well established and validated (Rosenzweig et al. 2013) but differ with respect to origin and philosophy. The evaluation was mainly restricted to wheat growth modules, which are provided by all the above-mentioned models. Two main aspects were addressed: (i) the types of phenological growth stage scales applied in the different models were identified, i.e. the algorithms and key drivers of phenological development, and (ii) the implementation of adverse environmental conditions was analysed. That is, specific response patterns to environmental stress impacts, such as drought or heat, in specific phenological growth stages. Particular attention was paid to crop growth stages, which had been identified as critical phases by the literature analysis.

Results

Critical growth stages relevant for crop growth

The literature search gave 129 articles fulfilling the search criteria, and a total of about 198 hits were obtained for phenological stages considered to be critical for yield formation. Entries were identified for all crops investigated and for various principal growth stages (Meier 2001). The descriptive graphical analysis revealed that the distribution of entries is not uniform, but differs with respect to crop species and principal growth stage (Figure 5). Regarding crop species, three groups were identified displaying specific distribution patterns: (i) grain crops (wheat, maize, and rapeseed), (ii) potato and (iii) sugar beet.

Grain crops

Grain crops show a common pattern of principal growth stages recognised as critical growth stages (Figure 5). For the early developmental stages of germination and leaf development, there were few entries for critical stages, in particular for rapeseed. For wheat and maize, the number of entries increased slightly in the booting and heading stages. A peak was found for the flowering stage in all grain crops, contributing to about 50% of all entries. In maize and rapeseed, seed filling also seems critical, whereas seed ripening and senescence were of marginal importance. In wheat, the number of entries increased slightly from the seed ripening to the senescence stage.

Table 3 Reference material and supplementary sources, e.g. handbooks and online documentations used for the literature review on the implementation of phenological phases and phenology specific features of dynamic crop growth models. Different production systems e.g. winter and spring are not included, here. Frequently, crops of the same genus are accessible through altered parameter sets. * Minimal number of crops available.

Model	Version	Number of crops*	Reference
APES	V1.0	11	Donatelli et al., 2010
APSIM	7.7	24	McCown et al., 1996; Zheng et al., 2014; Keating et al., 2003
CROPSYST	V.3.04.08	> 10	Stöckle et al., 2003
DAISY	V. 5.19		Abrahamsen and Hansen, 2000; H ansen et al., 2012; Abrahamsen, 2015
DSSAT (CERES)	4.6	42	Jones et al., 2003, Hoogenboom et al., 2012,
FASSET	V.2.0	> 7	Olesen et al., 2002
MONICA	V 1.2	13	Nendel and Specka, 2013; Nendel et al., 2011
HERMES	V.4.26	>8	Kersebaum, 2006; Kersebaum, 2011
STICS	V.6.9	24	Brisson et al., 2003
WOFOST	V.7.1.7	11	Boogaard et al., 2014; Supit et al., 1994

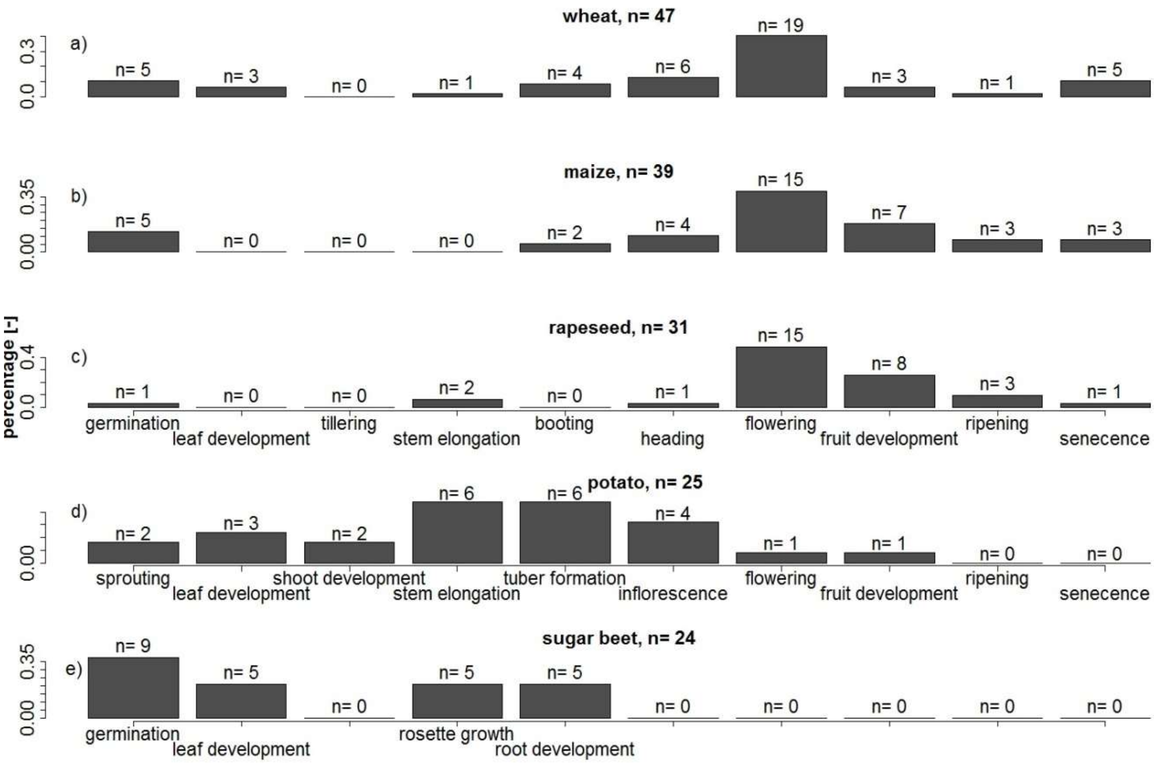

Figure 5 Relative abundance of phenological growth stages identified as critical growth stages in articles, by crop. Crop development is provided as principal growth stages according to the BBCH scale (Meier 2001) for wheat (a), maize (b), rapeseed (c), potato (d), and sugar beet (e), respectively.

The observed pattern suggests that the impact of stress on plant physiological processes and crop development is similar among the three grain crops, with flowering being reflected as the most sensitive stage. Differences in the method of pollination, however, may affect the crop sensitivity at this critical stage. In particular, pollen, when transported by wind over larger distances, is prone to desiccation, resulting in reduced longevity (Fonseca and Westgate 2005). Thus, based on the amount of wind-pollination by crops, a higher susceptibility to heat and drought stress might be expected for maize, which is primarily cross pollinated by wind (> 95%, (Emberlin et al. 1999), while rapeseed is self-fertile and partly cross pollinated by wind and insects (30%, (OECD 1997)), and wheat is characterized by a usually low proportion of cross pollination (1-2%, (OECD 1999)).

For Central Europe, we assume high temperature and water limitation to be the most relevant adverse environmental conditions during flowering (Trnka et al. 2011; Gobin 2012). Cereals have a high requirement for optimal temperature and sufficient water supply in the period from inflorescence emergence to early grain filling (Barnabás et al., 2008). In the subsequent growth stages, crops acquire capabilities to compensate partly for the impact of stress by redistributing resources from vegetative plant parts to storage organs, resulting in a gradual decrease of susceptibility to stress. For rapeseed, a similar response has been reported (Angadi & Cutforth, 2000). Importantly, it is emphasised frequently that grain crop reaction to single as well as multiple stress is related strongly to specific cultivar behaviour (Angadi and Cutforth 2000; Farooq et al. 2014).

Temperature

Crop growth and development is driven substantially by temperature, with each crop being characterized by specific temperature ranges (minimum, optimum, maximum), which may differ among developmental stages (Porter and Gawith 1999; Sánchez et al. 2014). For the developmental phase around wheat anthesis, values of 9.5±0.1°C, 21.0±1.7°C and 31.0°C have been reported as minimal, optimal and maximal temperature for growth (Porter and Gawith 1999). Exposure of wheat to temperatures below -17.2±1.2°C and above 47.5±0.5°C are assumed to cause lethal damage (Porter and Gawith 1999). For maize, values of 7.7±0.5°C (minimum), 30.5±2.5°C (optimum), and 37.3±1.3°C (maximum) indicate a somewhat higher temperature requirement. Similarly, the lower lethal temperature (-1.8±1.9°C) is higher than for wheat, whereas the upper limit (46.0±2.9°C) is similar (Sanchez et al. 2014). Rapeseed is characterized by a relatively wide temperature range of cardinal temperatures (e.g., 4.5±2.5°C, 27.8±2.1°C, 42.6±2.8°C (Suanda 2012)). During flowering, floral sterility may occur when temperatures exceed 27°C (Morrison and Stewart 2000).

Yield loss by heat stress during flowering can be attributed to different physiological processes, e.g. reduction in photosynthesis and transpiration, increase in respiration, or a modified assimilate allocation, which then impairs the development of reproductive organs (Young, Wilen, and Bonham-Smith 2004). Although crops are capable of adapting to high-temperature stress to a limited extent, e.g. by the production of heat shock proteins, and canopy cooling through transpiration (Barnabás et al. 2008), these heat-stress tolerance mechanisms are limited.

The development of ovaries and pollen seems to be highly susceptible to heat stress impact (Saini and Aspinall 1982; Barnabás et al. 2008). High temperature adversely affects fertilisation by reducing the viability and germination ability of pollen and, therefore, of fertilisation success (Barnabás et al. 2008), probably due to the reduced amount of heat shock proteins produced (Masearenhas and Crone 1996). For wheat, a maximum temperature of 20°C was identified for spikelet formation (Porter and Semenov 2005). Temperatures above 30°C during floret formation were reported to lead to sterility in wheat, and male infertility occurs at even lower levels of stress exposure than female sterility (Saini and Aspinall 1982). In rapeseed, heat stress during flowering was found to lead to a decrease in the number of pods (Chauhan et al. 1992) although heat-tolerant cultivars are less affected.

Recent work suggests that plant sugars may serve as a substrate and a signal to control seed set under drought and heat stress (Liu et al. 2013). In maize, for instance, changes in the carbon metabolism were found to be a consequence rather than the cause of seed abortion (Oury et al. 2016). In addition, sugar metabolism contributes to antioxidant protection and heat shock protein synthesis (Liu et al. 2013). Apart from the level of heat stress, the duration of exposure is relevant; for instance in rapeseed, where longer exposure is reported to result in a reduction in the number of fertilized flowers (Angadi and Cutforth 2000). Partial recovery after short stress pulses is possible, whereas long-term stress exposure of several days' duration has a fatal impact. In maize, heat stress additionally can lead to asynchrony between male and female flowering, thereby preventing successful fertilization (Cárcova and Otegui 2001). Thus, during flowering and early grain fill the component of yield most affected is seed number, while in the later growth stages, heat stress mainly reduces seed weight. This is also due to the acceleration of crop development, resulting in a shorter seed fill duration (Barnabás et al. 2008). However, it is emphasised that maize grain filling is elongated under heat conditions. Further, it is suggested that this is explainable by different enzyme types utilized in starch production (Barnabás et al. 2008).

Low temperature generally slows down all plant metabolic processes (Porter and Gawith 1999; Barnabás et al. 2008), and differences in species sensitivity are well documented, with maize being characterized by lower tolerance to chilling than wheat and rapeseed, especially in the early crop developmental stages (Porter and Gawith 1999, Sánchez et al. 2014). Specific organs and processes, however, can remain highly susceptible to the effects of cold temperature (Levy 1985; Ortega and Santibanez 2007). Frost damage is unlikely during the flowering of maize and wheat in the geographical focus area of this study, but it may occur during the flowering period of rapeseed.

Water supply

Quantification of water stress impact is not always straightforward. Various different approaches and quantifications are used to classify water stress, e.g. vapour pressure deficit (Gobin 2012), waterlogging index (Gobin 2012), spectral vegetation index (Moran et al. 1994), water balance (Zirgoli and Kahrizi 2015), and canopy temperature. These different approaches hamper attempts to analyse the impact of water stress. Furthermore, water surplus, as well as water limitation, exerts an impact on crop development and growth.

Water limitation impacts on crop growth and development in various ways (Kumar et al. 2015), and water stress is associated with water-limited conditions in crop production, primarily. The most severe impact of drought is reported to occur between onset of meiosis and early seed formation in cereals (Saini 1997), whereas the impact is less pronounced during later seed fill, but nevertheless is evident. This aligns with Potopová et al. (2015) who conducted statistical analysis for rapeseed and different cereals in temperate climate conditions in order to identify monthly drought patterns affecting yield. The authors found that July/August was most relevant for maize, while May/June and also October (early development) turned out to be the most important months for wheat, and April and May following a dry winter in the case of rapeseed. Water limitation during the flowering of wheat results in a yield reduction of up to 50% (Farooq et al. 2014). Generally, water stress affects the female inflorescence and thus fertilisation, whereas the male inflorescence is less impaired (Barnabás et al. 2008). In contrast, Barnabás et al. (2008) found that water shortage did not affect fertilisation of wheat unless the severity of water shortage was lethal. In maize, drought has a high influence on viability and germination potential of pollen (Barnabás et al. 2008). Furthermore, a drought-induced expansion of the anthesis-silking interval may adversely affect fertilisation and yield (Barnabás et al. 2008). In rapeseed, drought-stress-induced constraints are also well documented. For instance, Zirgoli and Kahrizi (2015) found shifts in yield, flowering duration, days to maturity, pods per plant, seeds per pod, and 1000 seed weight under drought conditions. A flowering duration reduction of up to 10% and yield reduction of 30% were observed following drought during flowering (Zirgoli and Kahrizi 2015). Reduction in the number of seeds per pod caused by drought stress at flowering was attributed to a reduction of the time course between flowering and silique formation (BirunAra et al., 2011). During seed filling, the yield impact of drought was reported to be similar or even stronger than during the flowering stage (Ghobadi et al. 2006). Additionally, seed chemical composition may be influenced by water limitation, with a modified relation of protein to oil (Ghobadi et al. 2006).

Excess water is also regarded as an adverse environmental condition for crop development (Mittra and Stickler 1961; Gobin 2012), and in particular waterlogging has an impact on the physiological development of crops, mainly by the immediate interruption of oxygen supply (Gutierrez Boem et al. 1996). A lower diffusion of oxygen in water, relative to diffusion in air, can result in soil oxygen concentrations of below 2% (Zhou and Lin 1995). Furthermore, crop nutrient uptake is affected. In the case of rapeseed, for instance, Gutierrez Boem et al. (1996) reported reduced N, P, K and Ca contents in aboveground biomass under waterlogging conditions. Generally, the length of flooding correlates with the severity of crop damage. In addition, other environmental factors may amplify the effects of waterlogging. Gutierrez Boem et al. (1996) found evidence that high temperatures can exacerbate the impact of waterlogging by a higher crop metabolic activity. The organs most affected will be those under development at the time when waterlogging occurs, and those with the strongest resource demand (Mittra and Stickler 1961; Gutierrez Boem et al. 1996). Consequently, flowering is a development stage that is susceptible to waterlogging. Significant decreases in grain yield were observed in wheat, barley and maize, when excess water was applied, particularly at anthesis, whereas during grain maturation cereal crops were more tolerant of flooding (Mittra and Stickler 1961). For rapeseed, the findings are less consistent. Stem width, leaf area and overall plant height were found to be reduced significantly (Zhou and Lin 1995; Gutierrez Boem et al. 1996). However, Zhou and Lin (1995) emphasise that the impact of waterlogging is stronger during germination and early seed development than during flowering. Overall, water surplus, especially waterlogging, is a minor problem for the typical well-drained agricultural production sites in the North German plain. Its occurrence requires a combination of specific local soil and topographic conditions and intensive rainfall events.

Multiple stress effects

Although the mechanisms underlying plant response to single stress factors have been studied extensively, the patterns of plant response to stress combinations are still largely unknown (Suzuki et al. 2014). Multiple stress effects, however, cannot be predicted from the plant’s response to single stress exposure (Rizhsky et al. 2004), since adaptation strategies may comprise ‘shared’ or ‘unique’ mechanisms (Pandey et al. 2015). Thus, the overall response can be additive or antagonistic, and there is some evidence that the dominant stressor mainly determines the impact of the stress combination. If heat and drought result in different patterns of growth limitation, the combination of both stresses may result in a greater extent of plant damage, as has been reported for spring wheat, where combined heat and drought stress was found to cause higher yield reduction than heat or drought alone (Prasad et al. 2011). In addition, reproductive organs have been found to be more sensitive than vegetative plant parts. Beneficial effects resulting from multiple stresses have not been reported, although the impact of the stress may be relieved. Yang and Zhang (2006), for instance, found that the impact of the reduction of grain filling duration through water shortage on cereal yield was partly compensated by increased temperature promoting the reserve translocation from leaf and stem to the grain.

Potato

Adverse environmental conditions may affect not only tuber yield but also tuber quality in terms of size, form and constituents, which is crucial for marketing. Stem elongation, tuber formation and inflorescence emergence are regarded as critical stages in potato development (Figure 5).

Frost is known to have a damaging effect on the growth and development of potato plants. Soil temperatures of -1.4°C to -1.9°C at the tuber planting depth were found to lead to increased mortality, and this negative impact will be increased by lower temperatures (Boydston et al. 2006). Therefore, planting is recommended to take place after the frost period, and a minimum soil temperature of 8°C is assumed appropriate. An air temperature range of 15°C to 25°C is regarded as optimal, whereas tuber growth is restricted by air temperatures above 32°C as well as below -1.5 °C (Ewing 1981). Temperatures exceeding 45°C have been reported to be lethal. Heat stress affects tuber yield by different processes, i.e. a reduction of the stimulation of tuberization, an increase in assimilate respiration and a shift of assimilate allocation to aboveground vegetative plant parts. Stimulation of tuberization by ensuring adequate temperatures is crucial for tuber setting (Ewing 1981), and a limitation in tuber initiation can hardly be compensated during further development. The balance between potato haulm and tuber growth is essential for a high tuber yield. Thus, environmental conditions negatively affecting the source-sink relationship will inevitably decrease tuber yield. For haulm development, cardinal temperatures of 5°C, 17-25°C and 30°C (minimum, optimum and maximum) have been reported (Ewing 1981). Lethal low temperature of -1.5°C is similar to that identified for tuber development. However, the lethal upper temperature of 40°C for the haulm is substantially lower than for tubers (Levy and Veilleux 2007). The impact of specific temperatures on the development and viability of different crop parts can be explained by different processes located in specific parts (Struik et al., 1989, 1989a, 1989b). Frost affects potato development in many ways, e.g. by its impact on tuber development. Days with cold temperature and frost have been reported to reduce the available bulking time. The worst-case scenario in terms of economic output would be high temperatures during early development promoting sprouting, followed by cold temperatures forcing increased tuberization, and high temperatures thereafter reducing tuber growth, resulting in many small, deformed potatoes (Reynolds and Ewing 1989). Apart from tuber yield, tuber quality is affected by temperature. Low temperatures, especially low night-time temperatures, are known to promote tuberization and potentially leading to a large amount of small tuber size classes (Struik et al., 1989, 1989a, 1989b). Levy & Veilleux (2007) emphasise that high night temperatures are especially harmful, by promoting metabolization of resources rather than storage. Starch accumulation is regarded to be optimal at a temperature of about 20°C, whereas it stagnates above 30°C (Struik and Wiersema 2012). However, Van Dam et al. (1996) emphasise that temperature impact is not always straightforward and it varies depending on the cultivar.

Potato is characterised by a high sensitivity to water shortage, with the most critical developmental stage being tuber initiation (Gobin 2012). Water use is high during tuber initiation, and drought stress decreases the photosynthetic rate and leaf area, which leads to an increased number and proportion of tubers in the smaller size categories (Dwyer and Boisvert 1990). Based on laboratory and field experiments, Haverkort, Van De Waart, and Bodlaender (1990) reported a linear relationship between the number of tubers initiated and the amount of available water during the first 40 days of development, which comprised mainly the vegetative growth stage. In contrast, phenological development was not affected (Dwyer and Boisvert 1990). Drought effects are less pronounced during later stages of development (Dwyer and Boisvert 1990). Further details concerning the impact of environmental conditions and stresses on different plant organs are reported by (Levy and Veilleux, 2007; Struik et al., 1989; 1989a, 1989b).

Sugar beet

For sugar beet, the development stages which were found to show higher sensitivity to adverse environmental conditions deviate from the pattern detected for grain crops and potatoes. This can be mainly attributed to the biennial life cycle of sugar beet, since only entries for growth stages in the first development year till harvest have been accounted for evaluation. As already mentioned, germination was more often identified as the critical growth stage, whereas the abundance of the remaining stages was similar (Figure 5).

Sugar beet generally shows a relatively high tolerance to heat, drought and salinity (Ober and Rajabi 2010), which is commonly attributed to its progenitor, *Beta vulgaris* subsp. *maritima* ((L.) Arcangeli), being a plant adapted to hot, dry and mildly saline environments (Ober and Rajabi 2010). Nevertheless, heat and drought can have a significant negative impact on sugar beet yield. Furthermore, there seems to be large variability in stress tolerance, and in particular for heat tolerance, among cultivars. The optimal temperature range for growth of 16-25°C is rather wide (Terry 1970). The lethal upper temperature of 42°C is considered to be in the top range for heat susceptibility (35°C -45°C) of arable crops (Jackson and Black 1993). During early stages, growth and development of sugar beet plants are severely limited by low temperatures. Young plants are susceptible to frost (Ober and Rajabi 2010). Cary (1975) identified temperatures in the range -2.5°C to -0.5°C as lethal during early development. Thus, frost during early development is a threat for sugar beet under Central European conditions. Further, early bolting is a specific problem (Stout and Owen 1942) not uncommon in practical cultivation. Normally, the transition from vegetative to generative growth of beets takes place in the second year of crop development under European growing conditions (Meier 2001). However, under specific environmental conditions (i.e., day length and temperature), vernalisation can occur in the year of sowing and initiate early bolting. Consequently, resources are translocated to reproductive organs and yield and yield quality is reduced (Hoffmann, 2010). Mutasa-Gottgens et al. (2010) reported that temperatures below 4°C over 9 days or below 6°C for 18 days would successfully vernalize the crop and induce bolting. Wood & Scott (1974) found a positive correlation between days with minimal air temperatures below 7°C and the proportion of bolted sugar beet plants. In later growth stages, a temperature of 17°C is regarded as optimal for sucrose accumulation (Cary 1975; Ober and Rajabi 2010).

Despite a pronounced drought tolerance, yield fluctuations up to 30% in Central and Western European sugar beet production are attributed to drought impact, resulting in a reduction of sucrose accumulation (Ober 2001; Jones et al. 2003b). Under conditions of increasing aridity, these yield losses are expected to increase (Romano et al. 2012). A modelling study by Qi et al. (2005) found drought to have the same yield-reducing impact as heat. A phenology-specific susceptibility of sugar beet to water limitation is generally not assumed for temperate climates (Hoffmann, 2010; Hoffmann et al., 2009; Ober and Rajabi, 2010; Shrestha et al., 2010). Brown et al. (1987) in contrast, reported younger crops to be more drought-sensitive, which the authors attribute to the smaller root system not being able to fully support the crop in case of stress impact.

Crop development in process-based crop models

The damaging impact of abiotic stress may vary depending on the development stage of the crop. Thus, an accurate simulation of crop phenological development and its adaptation to abiotic stress is a condition for modelling stress impact on yield and quality. In the following section, therefore, our aims are (i) to present the approaches for implementing phenological development chosen in different wheat growth models before analysing, and (ii) to evaluate the representation of stress impact in critical growth stages.

Basic types of representing phenological development in crop growth models

The algorithms describing crop phenology vary depending on the model's purpose. Consequently, we found differences among the models with respect to the number of phenological stages represented and the level of complexity in their representation (Figure 5). Generally, the conceptual stages utilised in the models deviate from those defined in phenological growth scales (Meier 2001). The model algorithms quantifying phenological development always differentiate between vegetative and reproductive growth and mainly focus on temperature, photoperiod and vernalisation as driving factors. The latter is considered in most models (Table 4), but not in all (FASSET, DAISY). It is implemented, for instance, by modifying the developmental rate, as in APES (Streck and Weiss 2003). Only a few models consider the impact of further potential stressors on wheat development, for example, nutrient or water shortage in APSIM.

Basically, the models adopt one of two different philosophies in quantifying crop phenology: thermal time (TT) or development stage variable (DVS) (Table 4, Figure 6).

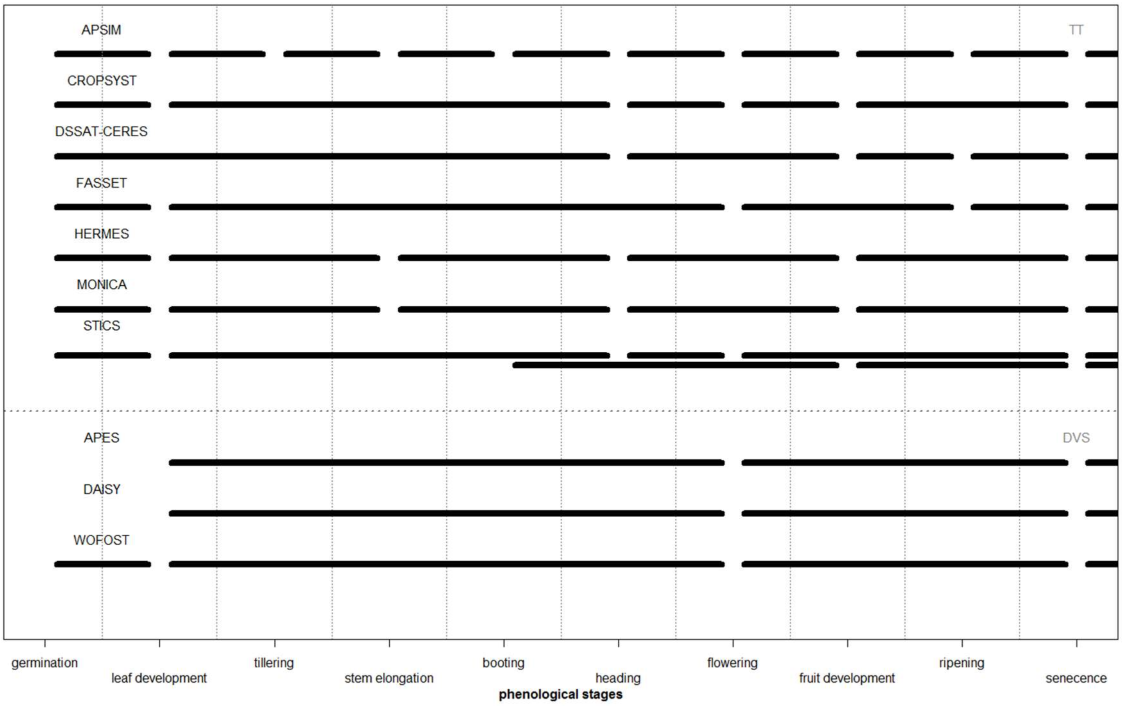

Figure 6 Schematic representations of growth phases in wheat crop growth models assigned to the corresponding principal phenological growth stages (Meier 2001).

Thermal time-based models simulate important development stages, e.g. flowering and grain filling (Table 4), by the accumulation of thermal time and fixed cultivar-specific thresholds per stage. APSIM, CROPSYST, DSSAT-CERES, FASSET, HERMES, MONICA and STICS belong to this group. FASSET differentiates six phenological stages (Laegdsmand 2011), DSSAT-CERES includes seven (Jones et al., 2003), and APSIM up to eleven different stages (Zheng et al. 2014). STICS uses two independent phenological development scales, one for leaf and root and another one for reproductive organs, both of the TT type (Brisson et al. 2003). Photoperiod is implemented in all models belonging to the TT group and, generally, the accumulation of thermal time is reduced by a photoperiod factor or function. APSIM, for instance, uses an empirical, species-specific scaling function, which reduces the effective accumulated temperature, whereas MONICA calculates a daily reduction factor to scale the daily increment of phenological development. Thermal time models utilise an approach adjusted to the actual physiological development in number and type of reproduced development stages, but nevertheless are strong simplifications of most relevant phenological stages, e.g. flowering.

The second group of crop growth models, to which APES, DAISY and WOFOST belong, applies a dimensionless stage variable (DVS) for quantifying phenological development. The development stage variable (*DVS*) is calculated from the sum of a daily increment ΔD, with $DVS_{i+1} = DVS_i + \Delta D$.

The daily increment ΔD is obtained from the development stage rate *d*, which is modified by a temperature $f_T(T)$ and a photoperiod function $f_d\ (DL)$:

$$\Delta D = d\ f_T(T)\ f_d\ (DL)$$

The DVS system distinguishes between two main growth phases - vegetative and reproductive growth - i.e. sowing (DVS = 0) to flowering/anthesis (DVS =1) and flowering and maturity (DVS = 2) (Figure 6). Following the assumption that basic processes act in the same way during crop development, the DVS system focuses on the representation of these. Consequently, this group utilises fewer conceptual growth stages (basically: vegetative, reproductive). Flowering is considered in each of the models in some way. Further, the DVS approach allows for additional processes to be considered by scaling factors or scaling functions, for instance, when implementing heat stress or vernalisation. However, these aspects are rarely considered (Table 4).

Table 4 Implementation of phenological development in wheat growth models and of stress impact during critical growth stages (a actual, p- potential, T –transpiration, E- evaporation). * utilises two development scales for vegetative and reproductive development. ** Identifies conditions and gives warning

Model	Phenology						
	Number	Type	Temperature	Photoperiod	Vernalisation	Specific heat mortality	Water stress implementation on biomass development
APES	2	DVS	yes	yes	yes	no	ETa/ ETp
APSIM	11	TT	yes	yes	yes	anthesis	Available soil water
CROPSYST	6	TT	yes	yes	yes	no	Ta/ Tp
DAISY	2	DVS	yes	yes	no	no	Available soil water
DSSAT-CERES	7	TT	yes	yes	yes	no**	Ta/ Tp
FASSET	4	TT	yes	yes	no	no	ETa/ ETp
HERMES	6	TT	yes	yes	yes	no	Ta/ Tp
MONICA	6	TT	yes	yes	yes	anthesis	ETa/ ETp
STICS	5|4*	TT	yes	yes	yes	no	Available soil water
WOFOST	3	DVS	yes	yes	no	no	Available soil water

Evaluation and comparison of the two basic approaches (TT and DVS) are complex due to various, different and specific functions implemented in each model. Generally, phenological development is well represented in dynamic crop growth models. All models have shown that they are capable of predicting phenological development under various environmental conditions (Asseng et al. 1998; Rötter et al. 2011; Palosuo et al. 2011). Furthermore, they are capable of producing high-quality predictions of phenological development when appropriately parameterised (Asseng et al. 1998; Pohanková et al. 2013). In larger ensemble studies comparing various crop models under standardised settings; however, differences in model accuracy became evident (Palosuo et al. 2011; Rötter et al. 2012). These inaccuracies were, in part, attributed to simplifications inherent in the structure of the models (Brisson et al. 2003). Asseng (2014) regarded minor inaccuracies in predicting phenological development to have a negligible impact on yield prediction. This is in contrast to Liu et al. (2016) who found for several wheat models (DSSAT-CERES, DSSAT, NWheat, APSIM, WheatGrow) accurate prediction of phenological development to be a prerequisite for predicting crop yield.

The representation of phenology response to temperature is mostly simple (Parent and Tardieu 2014). In TT systems (e.g. CERES-wheat), a linear temperature response is most common, whereas more complex temperature response functions - bilinear (e.g. STICS, CropSyst), trilinear (e.g. APSIM-maize) or others (GECROS (Parent and Tardieu 2014)) - are more likely to be found in the DVS systems. This, however, is a highly simplified categorisation. In many cases, the simple description of phenology is the starting point for model improvement. More complex temperature response functions require a larger set of parameters, but obviously, seem better suited to predict crop phenology with higher precision (Kumudini et al. 2014). For instance, Li, McMaster, Yu, & Du (2008) improved their wheat model by implementing a temperature response function that slows down the development for both supra- and suboptimal temperatures, which improved prediction of wheat flowering. Pulatov et al. (2015) compared different potato models and found linear temperature response functions to be sufficient for predicting development under temperate conditions. However, they emphasised non-linear functions to be more appropriate under increasing temperature environments, because they account for critical thresholds. Universal effects on crop development, such as lethal temperature limits, are frequently implemented in crop growth models. Temperature thresholds show immediate impact and are applied, for instance, in STICS (heat) or DSSAT (freezing). Such temperature thresholds can affect simulations in different ways. In DSSAT, for example, leaf growth is hampered if a first threshold is exceeded, while crop growth and development is terminated as the lethal temperature is reached (Jones et al., 2003).

Although water and nitrogen supply can have strong effects on phenological development (Wang and Engel 1998), their impact is rarely implemented in crop growth models. Models are exceptions that include more environmental factors than temperature and photoperiod (Table 4). APSIM, being one of these models, incorporates a water stress function (Zheng et al. 2014), which delays the phenological development by reducing the daily temperature sum. Moreover, in the phase from sowing till germination, soil moisture has a stronger impact than temperature.

With respect to climate change scenarios, the potential impact of CO_2 concentration, either directly or indirectly via its impact on canopy temperature, might also be of importance for crop development (Hussain et al. 2013). With respect to wheat, however, the studies available so far do not reveal a clear effect (Oehme 2012).

Models show various ways to implement general water limitation. Some utilise actual transpiration in relation to potential transpiration, while others utilise evapotranspiration or vapour pressure deficit thresholds (Table 4). DAISY uses - oversimplified - the ratio between actual and potential evaporation to scale down potential photosynthesis to a water-stress hampered one. A similar approach is delivered by APSIM, water-stress sensitive processes, e.g. photosynthesis and leaf expansion, are influenced by water demand index calculated from general water parameters (Zheng et al. 2014). The index scales the photosynthesis in the model by reduction of daily biomass accumulation rate. Phenological development is also impacted in APSIM. General stress impact is evaluated as sufficient, and model comparison studies show reasonable results, for instance, in predicting mean yield (Palosuo et al. 2011; Rötter et al. 2012).

Process-based crop models as tools for risk assessment of critical growth stages

Climate variability is generally considered important for risk assessment of cropping systems under climate change conditions. Ray et al. (2015) found that a third of the world's annual crop yield variability is caused by climate variability. In this respect, the interactions of crop-specific critical growth stages and the occurrence of adverse environmental conditions have to be taken into consideration. Crop models, frequently applied for risk assessment, should be interpreted as an abstracted representation of reality; they are purpose-built, and consequently, their complexity varies according to the application, data availability, and objective of the model (Motha 2011).

Generally, process-based crop growth models achieve reasonable results in reproducing crop growth and crop development, i.e. prediction of yield and phenology, and various other plant parameters. This applies particularly to models successfully validated and calibrated for a specific region and problem (Jones and Thornton, 2003; Palosuo et al., 2011; Pirttioja et al., 2015; Rötter et al., 2012; Ruane et al., 2016). The reasonable performance is achieved despite rather basic simulations of phenological development (Table 4). In terms of risk assessment, they are frequently used to evaluate the impact of adaptation strategies, e.g. modifications of crop management to circumvent specific environmental conditions. Pulatov et al. (2015), for instance, identified a reduction of risks for potato yield stability through earlier planting.

A number of other process-based dynamic crop models are applied at various scales and in various regions with different climates, and they produce reasonable results (Jones and Thornton, 2003; Kollas et al., 2015; Palosuo et al., 2011; Pirttioja et al., 2015; Pulatov et al., 2015; Rötter et al., 2012), such as the models tested in the AGMIP crop model comparison network. APSIM, for instance, originally developed for Australian conditions, has been validated for various regions and climates (Trnka et al. 2004; Palosuo et al. 2011). The same holds true for DSSAT, which is applied to improve crop production all over the world (Jones and Thornton, 2003). Essential, however, is the impact of typical environmental conditions for a specific region, which may jeopardise yield stability and crop development (Eyshi Rezaei et al. 2015; Stratonovitch and Semenov 2015) and this should not remain unaccounted for if a model is transferred to a new region-specific problem. Nevertheless, specific regional stress adaptations in a model can be useful, when transferred to other regions.

Weaknesses of process-based models in considering critical growth stages

Despite the generally satisfactory model performance concerning the simulation of phenological development, yield and yield stability, further, development is required to remedy the weaknesses and deficits, which for instance became evident in model ensemble comparisons (Palosuo et al. 2011; Rötter et al. 2012; Asseng et al. 2013; Pirttioja et al. 2015).

Commonly, the divergence in model performance is attributed to differences in model purposes (Rötter et al. 2011). An agronomic focus of model development will favour holistic approaches, acknowledging the interdependencies of weather, soil and plant. But even in this group, we find models customised for specific research questions, such as nutrient fluxes (e.g. HERMES, MONICA). Therefore, these models represent only a small portion of the soil-crop system in an appropriate way. At the same time, vital features of critical growth stages are neglected, because they are of minor concern for the primary purpose. Thus, process-based crop models may result in a biased evaluation of potential risks (Rötter et al. 2011).

With respect to specific stress reactions in critical growth stages most process-based crop models are less well-equipped than for dealing with general stress impact on crop growth, i.e. independent of phenology, such as drought or nutrient deficiencies, which are implemented for instance by thresholds. Phenological development specific impact is implemented only occasionally, e.g. temperature response functions accounting for specific reactions during specific growth stages by specific high and low-temperature limits, as found in APSIM. It thus might be concluded that simplification and abstraction of specific reactions in dynamic crop growth models seem not to be a disadvantage for larger-scale problems such as yield development of a region (Jones and Thornton, 2003). When dealing with other issues, for instance analysing the performance of cultivars or suitability of plant functional traits for target environments, the shortcomings of process-based models in accurately representing the response of crops during specific growth stages, become clearer. Lobell et al. (2012), for example, identified weaknesses of CERES and APSIM in predicting senescence of wheat under high-temperature conditions in India. Consequently, APSIM was improved for the critical stage impact on grain number and grain filling (Lobell et al. 2015).

Apart from model algorithms quantifying crop stress response, calibration procedures have an impact on the suitability of crop growth models to cope with climate variability (Ruane et al. 2016). In most models, calibration of parameters comprises the minimization of the difference between modelled and measured yield. Thus, the focus is on the mean yield as an indicator of model performance, which may entail a lower sensitivity to variation in environmental conditions (Ruane et al. 2016).

Solution strategies to better represent critical growth stages by crop models

Although rare, some approaches have been developed for enabling a better representation of the impact of adverse environmental conditions in critical crop growth stages (Table 4), which will be exemplified for the stage of flowering. An advantage of process-based crop models is that they can be modified to suit a new problem by modifying existing processes or introducing new processes - provided sufficient knowledge and resources are available (Challinor et al. 2005; Pulatov et al. 2015).

The implementation of high-temperature effects during specific developmental stages was shown to improve the quality of prediction (Challinor et al. 2005; Lobell et al. 2012; Wang et al. 2013; Ruane et al. 2016). MONICA follows the approach described (Challinor et al. 2005) to model heat stress response during flowering by a specific temperature function reducing biomass accumulation. Stankowski et al. (2015) improved yield prediction by the inclusion of empirically derived heat-sensitive grain number simulation. APSIM uses a stress module active during the simulation of flowering. Here, a temperature response function is used. This hampers temperature accumulation up to termination of development and reduces biomass accumulation (Zheng et al. 2014). A further attempt is suggested by Lobell et al. (2015), APSIM is modified to simulate the specific impact of heat on grain number and weight for a sophisticated evaluation of wheat and yield losses under climate change in Western Australia. It is reasonable to assume that application in other regions and climate change scenarios will benefit from the implementation of specific environmental processes during specific stages.

Another critical issue refers to a cultivar-specific stress response, which applies to general stress reactions and stress reactions during critical growth stages. Breeding for abiotic stress tolerance or resistance, e.g. heat tolerance during flowering, and identification of the corresponding plant functional traits have been identified as key to increase yield stability under climate change conditions (Stratonovitch and Semenov 2015; Liu et al. 2016). Thus, another approach would be to include cultivar-specific stress responses. Commonly, a genotypic response is not sufficiently implemented in dynamic crop growth models (Challinor et al. 2007; Rötter et al. 2011; Liu et al. 2016), but it would improve risk assessment by providing the opportunity for testing different plant functional traits (Rötter et al. 2011).

Acclimation is a crucial mechanism in crop development which enables crops to cope with adverse environmental conditions (Yordanov et al. 2000). Risk assessment studies could be improved substantially by crop growth models, including acclimation effects. A sudden late frost, for instance, affects crop development and survival considerably (Gutschick and BassiriRad 2003; Pulatov et al. 2015). The same below-zero temperatures during winter after gradual cooling might have little or no effect on the crop's viability and development. Thus, including information on the immediate or historical environmental experience of crops will improve the prediction of risks arising from sudden adverse environmental conditions (Gutschick and BassiriRad 2003). Crop growth models, however, rarely include such mechanisms (Gutschick and BassiriRad 2003). In DSSAT, winter hardiness is simulated by a stepwise decrease of lethal minimal temperature during germination and emergence to account for higher temperature sensitivity during early development of wheat. Acclimation for water deficit, achieved, for instance, in plants by the accumulation of solutes (Yordanov et al. 2000), is not accounted for in dynamic crop growth models.

A general criticism concerning the consideration of heat impact refers to the database underlying model calibration. Weather data mainly comprise temperature, radiation, precipitation and some other well-established, standardised environmental variables, easily accessible with climate stations (Thimme Gowda et al. 2013). These, however, describe only a small part of the environmental conditions experienced in cropping systems. Consequently, their suitability may be limited for assessing the impact of specific adverse environmental conditions during critical stages. Siebert et al. (2014), for instance, reported an improved model prediction when using canopy temperature instead of air temperature for an actual risk assessment of heat stress on wheat productivity.

Drought as an agricultural phenomenon is hard to identify in the first place. Not only is drought often hidden by slow onset, but there is also a lack of a clear definition of drought (Wu 2003). Thus, various environmental parameters are used to identify drought, for instance, the ratio between actual and potential evapotranspiration, precipitation shortage, or soil moisture deficit. General drought limitation of growth processes is implemented in most crop growth models by reducing the potential production by a water-limitation factor (Van Ittersum et al. 2003). Realistic implementation of drought, however, should account for the susceptibility of crops at different development stages. Available approaches are rare and rather generic (Geerts et al. 2008). CropSyst, for instance, includes drought stress as an accelerator of general phenological development (Stöckle et al. 2003), while STICS utilises a drought factor to accelerate maturity and senescence for specific stages (Brisson et al. 2003). In APSIM, a temperature stress factor is accumulated, which affects water availability ratio and prolongs phenological development up to growth termination.

Findings on drought response of quinoa (*Chenopodium quinoa Willd., 1797*), a crop known to alter phenological development to exploit favourable environmental conditions, have been implemented in AquaCrop (Geerts 2008; Geerts et al. 2008, 2009). The authors found that pre-anthesis drought stress delayed phenological development, whereas post-anthesis stress led to its acceleration. Furthermore, they showed that these relations are well quantifiable by drought indicators. Corresponding model modifications improved model performance, but require sufficient experimental data to analyse such mitigation strategies.

Multiple stresses are well known to have an impact on crop growth as well as crop development (Rizhsky et al. 2004; Barnabás et al. 2008), and crop model predictions would most likely benefit from an implementation of these. However, the implementation of multiple stresses in dynamic crop growth models is restricted by the knowledge gap on the interactions between stress factors (Rizhsky et al. 2004; Barnabás et al. 2008). Nevertheless, dynamic crop growth models are highly non-linear and therefore, able to access different feedback mechanisms.

Alternative modelling approaches

Functional-structured plant models (FSPM) have been developed in recent years (Prusinkiewicz and Rolland-Lagan 2006; Vos et al. 2010; Parent and Tardieu 2014). This type of model connects some decisive physiological processes with a 3D plant structure, localising selected organs and their exposition to the environment, e.g. leaf position within a canopy structure. FSPM models analyse individual plant development and physiological plant processes (Vos et al. 2010; Dejong et al. 2011). Therefore, they seem to enable a more adequate simulation of critical growth stages than process-based dynamic models which focus mostly on general processes of crop growth and development. This higher level of detail in FSPM is achieved at the cost of data requirement. Yield and yield variability, however, are not yet a primary topic of FSPM. Nevertheless, they can be of value to access the problem of risk assessment. Thus, Parent and Tardieu (2014) proposed to include at least sub-models of this type to explore drought and temperature impact on crops and to analyse genetic traits by crop models.

Ensemble studies are another way to omit the shortcomings of crop models in dealing with specific conditions important in climate change risk assessment (Rötter et al. 2012; Nendel et al. 2013). The concept underlying ensemble studies is that different approaches utilised in the models equalise their strength and weaknesses. Primarily, they are applied to compare different modelling concepts, to identify traits to improve the models on various sites and to obtain more reliable yield estimates and risk assessments. Despite the success of ensemble studies, at first sight, the aspect of crop response in critical development stages is widely neglected in process-based crop models utilised in the ensembles.

Conclusion

Although the quantity and distribution of resources relevant for crop growth are mostly adequate in temperate Central Europe, there is a considerable variation in environmental conditions, e.g. yearly temperature amplitude of 40°C and more. Consequently, adverse environmental conditions may coincide with particularly sensitive crop growth stages. In the context of risk assessment of climate change impact based on process-oriented, dynamic crop growth models, it is essential to reflect crop response reliably in these critical growth stages. The current study identified critical growth stages for the most important crops grown in

Central Europe. These relatively clear-cut critical phases, however, are implemented insufficiently in crop growth models. While principle stress reactions, for instance, caused by drought conditions, definitely are available, most models lack a profound representation of crop stress response in critical growth stages. Also, the models differ substantially in the representation of phenological development, which is often designed in such a way to serve the main model purpose best, e.g. analysing nutrient flows. Yet, in most cases, they were not intended to reflect the development of organs specifically sensitive to environmental conditions, which determine yield variability.

Users of crop growth models should carefully check if variability is reliably reflected, for instance, using a sensitivity analysis. Where appropriate, models have to be supplemented by further study to complement risk assessment or need to be extended by processes that have been lacking. For recipients of climate-change risk assessments, we recommend that the original purpose of a given model should be taken into consideration when interpreting results. Furthermore, it should be critically examined to determine if sensitivity analyses, calibration and validation are available and in which range statements concerning yield variability are feasible.

Chapter 2

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By:

Maximilian Strer: *Institute of Land Use Systems, Leibniz Centre for Agricultural Landscape Research, Eberswalder Straße 84, 15374 Müncheberg, German*.

Nikolai Svoboda: *Research Platform "Data", Leibniz Centre for Agricultural Landscape Research, Eberswalder Straße 84, 15374 Müncheberg, Germany*.

Antje Herrmann: *Grass and Forage Science/Organic Agriculture, Christian-Albrechts-Universität Kiel, Hermann-Rodewald Str. 9, 24118 Kiel, Germany.*

Abundance of adverse environmental conditions during critical stages of crop production in Northern Germany

Abstract

Background: *Understanding the abundance of adverse environmental conditions, e.g. frost, drought, and heat during critical crop growth stages, which are assumed to be altered by climate change, is crucial for an accurate risk assessment for cropping systems. While a lengthening of the vegetation period may be beneficial, higher frequencies of heat or frost events and drought spells are generally regarded as harmful. The objective of the present study was to quantify shifts in maize and wheat phenology and the occurrence of adverse environmental conditions during critical growth stages for four regions located in the North German Plain. First, a statistical analysis of phenological development was conducted based on recent data (1981-2010). Next, these data were used to calibrate the DSSAT-CERES wheat and maize models, which were then used to run three climate projections representing the maximum, intermediate and minimum courses of climate development within the RCP 8.5 continuum in the years 2021 to 2050. By means of model simulation runs and statistical analysis, the climate data were evaluated for the abundance of adverse environmental conditions during critical development stages, i.e., the stages of early crop development, anthesis, sowing and harvest.*

Results: *Proxies for adverse environmental conditions included thresholds of low and high temperatures as well as soil moisture. The comparison of the baseline climate and future climate projections showed a significant increase in the abundance of adverse environmental conditions during critical growth stages in the future. The lengthening of the vegetation period* *in spring did not compensate for the increased abundance of high temperatures, e.g., during anthesis.*

Conclusion: *The results of this study indicate the need to develop adaptation strategies, such as implementing changes in cropping calendars. An increase in frost risk during early development, however, reveals the limited feasibility of early sowing as a mitigation strategy. In addition, the abundance of low soil water contents that hamper important production processes such as sowing and harvest were found to increase locally.*

Keywords: *critical growth stages, modelling shifts in phenological patterns, maize, wheat, risk of crop production for the North German Plain, heat and frost stress*

Background

The crop yield attained in the field and its variability are both influenced by a range of climate factors, such as radiation, ambient CO_2 concentration, precipitation, temperature, and soil conditions. Variation in environmental conditions from year to year and in response to climate change may result in substantial shifts in the beginning, duration and end of crop developmental stages. Adequate assessment of these shifts by means of crop modelling will promote understanding of the processes affecting the threats to crop production for specific regions and allow the development of adaptation strategies for climate change.

For the North German Plain, an agricultural highly productive region, climate change is assumed to have a substantial impact on crop production (Maracchi et al. 2005; Bindi and Olesen 2011). Shifts in crop phenology, e.g., by a lengthening of the vegetative period due to changes in management or variation of cultivars exploits more favourable conditions– and has beneficial effects on the yield (Menzel 2002; Chmielewski et al. 2004; Menzel et al. 2006; Estrella et al. 2007; Trnka et al. 2011; Svoboda et al. 2015). The extent to which yield will be increased may vary regionally; while the western part of the North German Plain yield may stay at a similar level as today, the eastern regions might benefit from temperature and radiation changes (Wolf and Van Diepen 1995; Olesen et al. 2007; Trnka et al. 2011). In this respect, climate variability is of great importance (Harrison et al. 2014; Lesk et al. 2016), since 30% of wheat and up to 50% of maize yield variability observed in Western Europe can be attributed to climate variability (Ray et al. 2015). Adverse environmental conditions, such as temperature stress, that occur during critical growth stages may result in severe yield loss and negatively affect yield stability (Semenov and Shewry 2011; Trnka et al. 2014). Shifts in adverse environmental conditions are expected for temperate Europe, e.g., heat stress during flowering periods (Gobin 2012; Trnka et al. 2014) and changes in precipitation distribution (Metzger et al. 2005; Trnka et al. 2011).

The impact of adverse environmental conditions depends on a crop's susceptibility in a given growth stage, which is indicated by, e.g., stage-specific temperature thresholds (Porter and Gawith 1999; Sánchez et al. 2014). Consequently, an assessment of shifts in regional phenological development resulting from climate change – as found in various arable crops grown in Germany (Menzel 2002; Chmielewski et al. 2004; Menzel et al. 2006; Estrella et al. 2007) - is fundamental for the assessment of risk to crop yields. Iglesias et al. (2012) reported varying risks through shifts in crop phenology for different European regions. Trade-offs stabilising yield variability could also be conceivable, e.g. bringing forward of specific growth stages may reduce the probability of heat stress (Harrison et al. 2014). Typically, process-based dynamic crop growth models are utilised in assessment studies (Jones and Thornton 2003a; Palosuo et al. 2011; Iglesias et al. 2012). These models mostly focus on basic crop growth and development processes; however, within they are only capable to focus on a few development-stage specific responses to environmental stress.

Recent studies have mainly focused on the patterns and impact of adverse environmental conditions (Gobin 2012; Trnka et al. 2014; Harrison et al. 2014; Gömann et al. 2015). Trnka et al. (2014), for instance, performed a general analysis of the abundance of various adverse environmental conditions on European crop production but did not consider critical growth stages. Gobin (2012) provided an analysis of shifts of critical growth stages, but the study was restricted to Belgium. For the North German Plain, no study has yet comprehensively analysed the impact of adverse environmental conditions during critical growth stages under the pressure of climate change.

The objective of the current study, therefore, was to identify and evaluate shifts in patterns of adverse environmental conditions during critical growth stages on the North German Plain, as a prerequisite for assessing risks and developing management strategies to improve cropping systems under climate change conditions. The work was conducted within the framework of an interdisciplinary project (https://www.nalama-nt.de (Spellmann et al. 2017)), assessing threats of climate change and globalisation and developing a basis for an integrated and sustainable land management for the benefit of the environment and society on the North German Plain.

In the current study, an inventory of the abundance of adverse environmental conditions during critical growth stages was created for wheat and maize grown in four regions representing the North German Plain. The study was based on recent (1981-2010) phenological and weather data. These data furthermore served to calibrate and validate the dynamic crop growth model DSSAT, which than allowed the assessment of shifts in phenological development and in the abundance of adverse environmental conditions in different climate projections for the period 2021 to 2050.

Material and Methodology

The study area comprised four regions of the North German Plain: Diepholz (DH), Uelzen (UE), Fläming (FL), and Oder-Spree (OS) (Figure 7). The regions largely correspond to local administration districts - allocated from west to the east along 52°N latitude corridor. The North German Plain is characterised by a temperate oceanic climate (Cfb) in the west and a humid continental climate in the east (Dfb) following the Köppen climate classification (Metzger et al. 2005). It provides a major fraction of German crop production (BMEL 2015; Spellmann et al. 2017). In the western regions, fertile silty-loam soils dominate, cultivated with wheat, maize, rapeseed and sugar beet (Richter et al. 2007). In the eastern part, shallower sandy to silty-loam soils, are dominant, in which wheat, maize, rye and rapeseed are grown (Richter et al. 2007). In the present study, we only considered grain wheat and maize production, common in all regions and of have high economic relevance. They represent a winter annual and a summer annual crop, respectively.

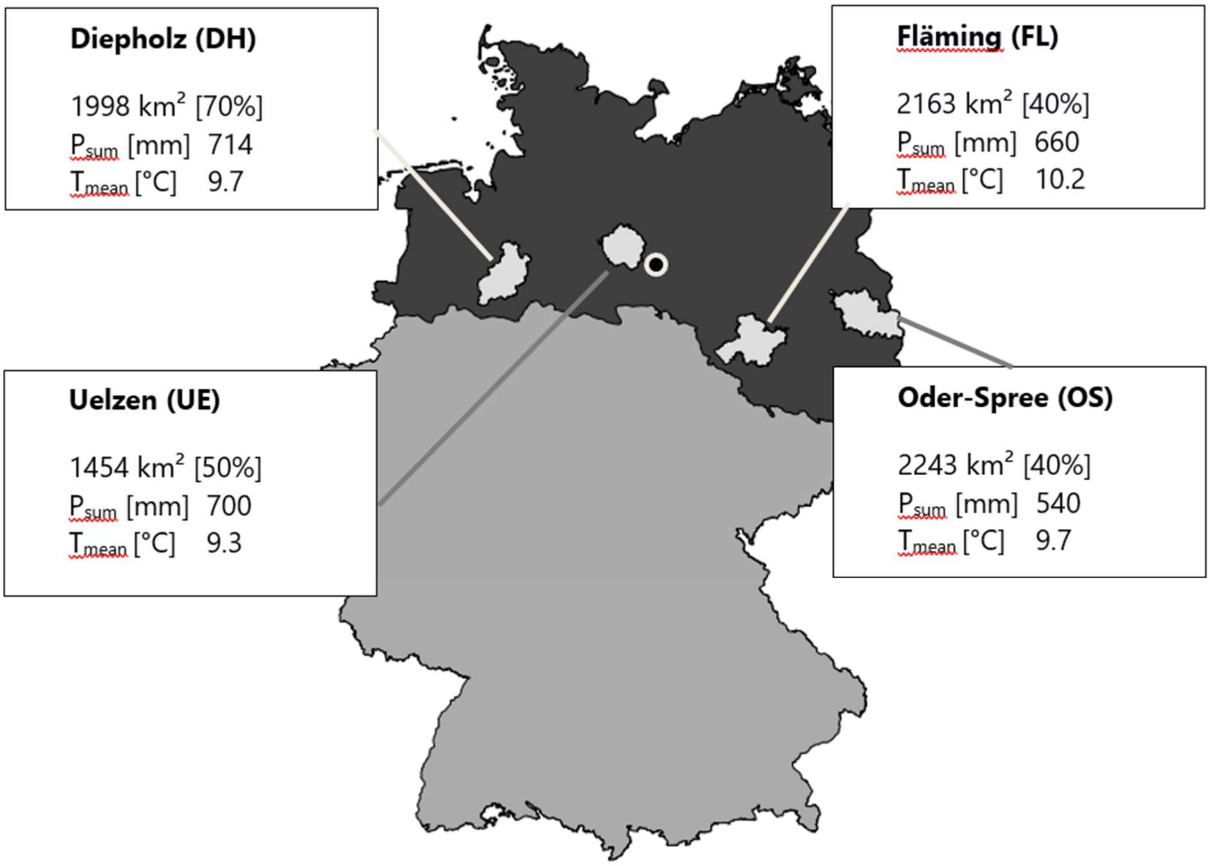

Figure 7 Regions (light grey) located in the North German Plain (black); characterised by total area, cultivated area in percentage of total area (in brackets), average annual precipitation sum (Psum [mm]) and annual average temperature (Tmean [°C]) (Black dot - weather station Salzwedel) (Spellmann et al. 2017).

Weather and phenological data

Weather data from representative weather stations in each region were provided at a daily resolution by the German Weather Service (DWD). Phenological data were obtained from DWD database. It comprises sowing dates, the beginning of various phenological stages of wheat and maize in several repetitions for each district in the baseline period (1981-2010) (Figure 7).

Three climate projections were utilised for future climate evaluation in the projection period from 2021 to 2050 (IPCC 2014; Spellmann et al. 2017). Ensemble comprised 21 GCM; all were set in the scenario RCP 8.5. For the present study, we selected 3 out of 21 GCM on the basis of their performance in the baseline period and their representation of mean temperature increase in the projection period (2021- 2050): a minimum increase of mean temperature to baseline by 1°C (min, INM-CM4, Russia), an intermediate increase of 1.5°C (med, ECHAM6, MPI Hamburg, Germany), and a maximum increase of 2°C (max, ACCESS1.0, CSIRO-BOM, Australia). The utilisation of three different GCM in the RCP 8.5 continuum (IPCC 2014) ensures a wide range of climate change manifestation in respect to e.g. mean temperature or precipitation distribution. Climate data were provided by the Potsdam Institute for Climate Impact Research (PIK). The regionalisation of the GCM output was realised by the statistical analogue resampling scheme (STARS by PIK) at weather station sites.

Modelling

The Decision Support System for Agro-Technological Transfer (DSSAT) (Jones and Thornton 2003a; Hoogenboom et al. 2012) was used to assess crop phenological development in future climate projections. Calibration for obtaining crop parameter sets was performed on phenological data averaged for the North German plain (Figure 7, dark grey, Supplementary material 2), while validation was based on averaged phenological data within each region (Figure 7) with weather, soil, and management given as input. The calibration model was set to fit the general environmental conditions of the North German Plain for both crops. The selected phenological time series were prepared by averaging phenological data at various sites throughout Northern Germany for each year to obtain a time series for each phenological growth stage. Weather data for calibration of crop parameter sets was obtained from the centrally located Salzwedel weather station to represent the North German Plain. Soil properties were set to generic medium silty clay (

Supplementary material 3). Such soil types are frequent in fertile alluvial areas throughout Northern Germany (German soil survey (BUEK1000n), (Richter et al. 2007)). Crop parameters sets were estimated for maize and wheat by minimisation of the root mean square error (RMSE) between simulated and observed phenological data. In addition, goodness of model fit was evaluated in terms of the coefficient of determination (R^2).

For validation, crop parameter sets were tested on averaged phenological development time series (DWD) available for each region for the baseline (Figure 8, 1981-2010). General production system settings were identical with the calibration procedure. Changes, however, were made to reflect the region-specific environmental conditions, i.e., soils (DH, UE: Supplementary Material 3, FL, OS: Supplementary Material 4, BUEK1000n, (Richter et al. 2007; Spellmann et al. 2017), weather conditions (stations of the DWD representative for each of the region, see Figure 7). Validation was assessed by the coefficient of determination and RMSE for each phenological development stage.

Data analysis

First, the phenological data were analysed to provide a general description of phenological development for the baseline (1981-2010) and the projection period (2021-2050). For this purpose, linear regression models were fitted to the time series of phenological development with the year as the independent variable and the beginning (day of year) of prominent phenological growth stages of maize and wheat as the dependent variable. The correlated linear model gives information over trends of phenological development in the considered period. Trends were characterised by the slope of the linear regression for each crop in each region. All regression slopes were tested for significance against zero. Statistical analysis was performed utilising GNU R (R Development Core Team 2013). Generally, significance levels are denoted as follows: "." for $p<0.1$, "*" for $p<0.05$, "**" for $p<0.01$, and "***" for $p<0.001$.

Second, the abundance of adverse environmental conditions during critical growth stages of maize and wheat was quantified for the baseline period (1981-2010) and the projection period (2021-2050) in each region. Critical growth stages were defined according to Porter and Gawith (1999); Porter and Semenov (2005); and Sánchez et al. (2014) as phenological development stages especially susceptible to adverse environmental conditions. For wheat and maize, the critical stages are provided Table 5. Adverse environmental conditions were utilised here in the sense of Trnka et al. (2014) and Gobin (2012) as abiotic environmental events of a relevant length, i.e., days or weeks, that are harmful for crop growth and development. In the present study, we focused on temperature and water limitation, where heat, drought, and frost were analysed on a daily level and heatwaves were analysed for longer periods of time (2 days and more). Furthermore, we included an analysis of high soil water content during sowing and harvest, which is known to be a limiting factor for soil trafficability. Short-term and narrowly localised events exerting mostly rapid physical damage to crops, such as storms, or hailstorms, were excluded from the analysis. The beginning and end of the critical growth stages in question were obtained from DSSAT model runs, and weather data during these stages were evaluated for days exceeding temperature or soil water thresholds as indications of adverse environmental conditions (Table 5). Furthermore, the abundance of drought was evaluated by an assessment of the number of days with soil water content falling below a threshold (Table 5). The percentages of abundance refer to mean growth stage length at each site and each period respectively the pre-set number of days evaluated for each crop or around sowing respectively maturity in the 30-year period for soil moisture (Table 5).

Table 5 Types and limits of adverse environmental conditions, critical growth stages, and sites especially susceptible to these environmental conditions (T_{min} – minimum daily temperature, T_{max} – maximum daily temperature, T_{lethal} – lethal temperature for crop development).

Stage	Expected Adverse Environmental Condition	Problem	Sites	Thresholds / Limits	References
MAIZE					
Sowing	soil moisture	trafficability	western regions	45% of water content (gravimetric)	trafficability limit 30% water content (Frielinghaus and Schindler)
Emergence Stem Elongation	late frost	damage organ tissue	eastern regions	T_{min} < 0°C T_{lethal} < -1.9°C	(Sánchez et al. 2014)
Flowering	heat	damage reproduction	all	T_{max} 37.3°C (Anthesis)	(Sánchez et al. 2014)
	heat days		all	T_{max} > 30°C and T_{min} > 20°C	DWD
	heat spells	following days above limit	all	T_{max} > 30°C	DWD
Harvest	soil moisture	trafficability	DH/ UE	45% of water content (gravimetric)	trafficability limit 30% water content (Frielinghaus and Schindler)
WHEAT					
Sowing	soil moisture	trafficability	western regions	45% of water content (gravimetric)	trafficability limit 30% water content (Frielinghaus and Schindler)
Stem elongation – Heading	frost	frost damage	all	T_{min} < 0°C	(Porter and Gawith 1999)
Heading – Flowering - Milking	heat	heat	all	T_{max} = 31.0°C following days above limit	(Porter and Gawith 1999)
			all	T_{max} > 30°C and Tmin > 20°C	DWD
(Heading –Milking)	heat spells	following days above limit	all	T_{max} > 30°C	DWD
Harvest	soil moisture	trafficability	DH/ UE	45% of water content (gravimetric)	trafficability limit 30% water content (Frielinghaus and Schindler)

Results

Model performance

Crop parameter sets for maize and wheat were successfully fitted to mean phenological development data (Figure 8, Supplementary material 2). Simulated phenological growth stages for maize and wheat mostly lay within the limits of the standard deviation of observed data, e.g. 84% of cases for wheat anthesis and 89% for maize milk ripening (Figure 8), and the goodness of model fit depended on the phenological development stage. For maize, R^2 values for comparison of simulations and observations over 30 years tended to decrease from sowing to maturity (sowing: R^2= 0.94 (RMSE =2.5), emergence: R^2 = 0.83 (RMSE =3.8), end of juvenile development: R^2 = 0.46 (RMSE= 15.2), flowering: R^2= 0.54 (RMSE = 9.2), maturity: R^2 = 0.61 (RMSE= 18.7). For wheat, R^2 values remained relatively constant (stem elongation: 0.53 (RMSE =2.9), inflorescence emergence: 0.59 (RMSE = 3.9), and milk ripening: 0.59, RMSE = 3.8). The onset of maturity, however, was better reflected (R^2:0.75, RMSE = 3.0).

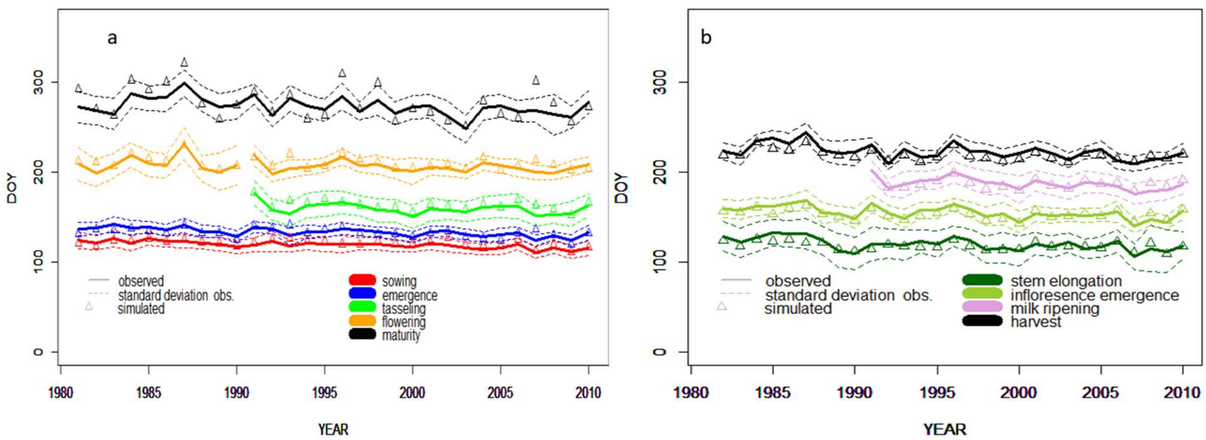

Figure 8 Calibration of phenological development; observed (averaged over the North German Plain) and simulated beginning of specific phenological developmental stages for maize (a) and wheat (b) on the North German Plain.

The model validation revealed comparable results as the model calibration for both crops (Table 6, Table 7). Phenological development was predicted reasonably but varied depending on the region, phenological developmental stage and crop, partly due to differences in the amount and quality of data. Restructuring of administration in the course of the German re-unification led to occasionally missing data in the eastern regions. The smallest deviation between observed and predicted values was found for the centrally located UE region. For maize, the developmental stage of tasselling showed an inferior model fit at sites UE and OS (Table 6), while for wheat, simulation of maturity stage was closer to observations than stem elongation, inflorescence emergence and ripening. Simulated maturity at days of the year > 300, which occurred in a few year-region combinations, was due to simulation termination rather than achievement of maturity.

The deviation between observed and modelled dates in the sowing of maize indicated by a relatively low R^2 (0.8) in DH and FL is due to the comparison of sowing dates as the means from observed, regional data (Table 6) and the actual, natural numbered input data for the simulation.

Table 6 Model validation for the beginning of different phenological developmental stages of maize, specified as day of year. Goodness of model fit is provided as the coefficient of determination (R^2) and root mean square error (RMSE).

	Sowing		Emergence		Tasselling		Flowering		Maturity	
	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
DH	0.80	2.54	0.80	3.02	0.40	13.96	0.57	6.08	0.90	14.86
UE	1.00	0.25	0.56	3.42	0.17	17.78	0.38	8.43	0.87	21.95
FL	0.80	2.31	0.39	5.18	0.46	7.18	0.60	4.14	0.61	11.96
OS	1.00	0.29	0.57	5.84	0.18	10.92	0.84	11.77	0.45	17.37

Table 7 Model validation for different phenological developmental stages of wheat, specified as day of year. Goodness of fit is provided as the coefficient of determination (R^2) and root mean square error (RMSE).

	Stem Elongation		Inflorescence Emergence		Ripening		Maturity	
	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE
DH	0.36	7.06	0.58	4.11	0.36	9.07	0.68	7.11
UE	0.6	4.48	0.63	4.13	0.63	5.02	0.73	6.13
FL	0.53	5.18	0.53	4.85	0.64	7.81	0.90	12.27
OS	0.21	7.46	0.47	5.95	0.07	14.9	0.66	3.76

Shifts in phenology in the recent data set

The observed phenological data showed shifts to earliness for various phenological stages of both crops. In maize, tendencies towards earlier occurrence – indicated by the slopes of linear regression models - were identified for nearly all developmental stages (Figure 9, Table 8). An exception was emergence in OS (0.09 ± 0.13 d/y or 1.2 ± 1.7 d/°C), where R^2, i.e. the portion of the phenological time series development described by the linear trend was very low (<0.01), as well as tasselling in UE (0.27 ± 0.18 d/y or 3.47/± 2.25 d/°C, $R^2 < 0.01$) and in DH (0.09 ± 0.17 d/y or 1.3± 2.15 d/°C, $R^2 < 0.01$). Generally, the number of significant trends identified was higher in DH and UE, i.e. three out of five trends. In contrast, in the OS region only one out of five trends was significant (Table 8). This might be attributed to smaller sample sizes caused by less observation sites in these areas and a more fragmentary data structure.

For wheat, phenological development shifted forward several days at all sites. The linear trends, however, were not always significant, which, as seen in maize, is probably due to the availability and quality of phenological data. For instance, in DH and UE, eight out of the twelve significant trends had three times larger sample sizes than corresponding data sets for the eastern sites. Slopes derived for the eastern regions, however, were comparable to those obtained for western regions. The period around anthesis, i.e., the most critical growth stage, became shorter, as indicated by trends for inflorescence emergence of 0.28 ± 0.99 d/y (OS, respectively 3.7 ± 13.4 d/°C) and -0.23 ± 0.20 d/y (FL, respectively -2.3 ± 2.0 d/°C) and for milk ripeness of -0.84 ± 1.22 d/y (OS, respectively -11.4± 16.5 d/°C) and -2.01 ± 0.725 d/y (FL, respectively -20.1± 7,25 d/°C), respectively (Table 9).

Shifts in phenology in the projection period

The shifts in phenology found for the future climate projections are presented in detail for region DH (Supplementary material 6, Figure 9, and Figure 10). The response patterns quantified for the remaining regions were similar and were strongly correlated to the temperature increase of the projections, i.e. growth stages show similar behaviour for the temperature levels in the projection period in each region (Supplementary material 6 to 12). Phenological development in the DSSAT-CERES model was influenced by temperature. Consequently, critical growth stages of maize and wheat occurred earlier, and the duration shortened in the projection period. Shifts were consistent with those identified in the baseline period.

Table 8 linear regression parameters quantifying the changes in maize phenological development for the observed phenological data of the four regions during the baseline period.

	DH			UE			FL			OS		
	Estimate	R^2 / n	p-value	Estimate	R^2 / n	p-value	Estimate	R^2 / n	p-value	Estimate	R^2 / n	p-value
	[d]			[d]			[d]			[d]		
	[d/y]	[]	[]	[d/y]	[]	[]	[d/y]	[]	[]	[d/y]	[]	[]
Sowing	119 ± 7	0.14		122 ± 7	0.02		118 ± 7	0.1		120 ± 7	0.01	
	-0.35 ± 0.05	258	4.3E-10 ***	-0.14 ± 0.07	187	5.1E-02 .	-0.46 ± 0.20	55	2.2E-02 *	-0.1 ± 0.21		6.3E-01
Emergence	134 ± 8	0.17		134 ± 8	0.06		131 ± 7	0.12		133 ± 6	0	
	-0.4 ± 0.06	255	9.1E-12 ***	-0.24 ± 0.08	177	2.0E-03 **	-0.52 ± 0.19	56	9.0E-03 **	0.06 ± 0.18		7.4E-01
Tasselling	192 ± 12	0		194 ± 15	0.02	1.4E-01	202 ± 23	0.16		198 ± 15	0.16	
	0.09 ± 0.13	168	4.8E-01	0.27 ± 0.18	125		-1.21 ± 0.31	81	0.0E+00 ***	-0.84 ± 0.25		1.0E-03 **
Flowering	201 ± 10	0.05		206 ± 9	0.06	1.6E-02 *	201 ± 7	0		199 ± 17	0.01	
	-0.36 ± 0.16	108	2.6E-02 *	-0.45 ± 0.18	90		-0.06 ± 0.22	50	7.9E-01	-0.28 ± 0.59		6.4E-01
Harvest	280 ± 17	0		271 ± 18	0.01	1.7E-01	262 ± 15	0.08		262 ± 11	0.03	
	-0.07 ± 0.13	259	5.8E-01	-0.24 ± 0.17	196		-0.8 ± 0.39	54	4.4E-02 *	-0.4 ± 0.34		2.5E-01

Table 9 Linear regression parameters quantifying the changes in wheat phenological development in the four regions during the baseline period.

	DH				UE				FL			OS		
	Estimate [d] [d/y]	R^2 / n []	p-value []		Estimate [d] [d/y]	R^2 / n []	p-value []		Estimate [d] [d/y]	R^2 / n []	p-value []	Estimate [d] [d/y]	R^2 / n []	p-value []
Stem Elongation	118 ± 13	0.09			123 ± 16	0.01			126 ± 9	0.07		129 ± 42	0.02	
	-0.48 ± 0.12	162	0.0E+00	***	-0.23 ± 0.14	202	9.3E-02	.	-0.52 ± 0.41	25	2.2E-01	-1.26 ± 2.19	18	5.7E-01
Flowering	155 ± 9	0.13			156 ± 11	0.13			155 ± 12	0.02		157 ± 33	0	
	-0.41 ± 0.08	169	1.3E-06	***	-0.49 ± 0.09	218	4.2E-08	***	-0.23 ± 0.20	56	2.6E-01	0.28 ± 0.99	22	7.8E-01
Milk Ripeness	191 ± 14	0.35			187 ± 13	0.05			187 ± 14	0.34		172 ± 20	0.05	
	-1.34 ± 0.22	69	9.1E-08	***	-0.52 ± 0.23	104	2.2E-02	*	-2.01 ± 0.73	17	1.4E-02	-0.84 ± 1.22	12	5.1E-01
Harvest	224 ± 12	0.2			224 ± 12	0.11			221 ± 14	0.01		214 ± 11	0	
	-0.66 ± 0.10	180	4.0E-10	***	-0.51 ± 0.10	224	4.2E-07	***	0.32 ± 0.63	25	6.2E-01	0.07 ± 0.38	30	8.5E-01
Sowing	289 ± 16	0			287 ± 12	0.08			285 ± 9	0.05		286 ± 18	0	
	0.08 ± 0.16	175	5.8E-01		-0.43 ± 0.10	224	2.8E-05	***	-0.43 ± 0.42	23	3.2E-01	-0.23 ± 0.64	31	7.3E-01
Emergence	299 ± 33	0.01			301 ± 15	0.08			301 ± 10	0.03		299 ± 19	0	
	-0.44 ± 0.32	164	1.8E-01		-0.54 ± 0.13	210	3.2E-05	***	-0.39 ± 0.46	23	4.1E-01	-0.1 ± 0.68	30	8.8E-01

For maize, a forward shift of several days was found for sowing and each consecutive growth stage in all projections at all locations (Figure 9). A tendency was found for the acceleration to be larger in later growth stages because the temperature effect is cumulative, and the maximum projection which was to chosen as to show the highest temperature increases generally showed the strongest effects compared to the baseline period. Duration and earliness of anthesis were clearly correlated with the mean temperature increase in each of the three projections (Supplementary material 6, Figure 9). For maturity, earliness adds up to more than 2 weeks for the max projection (Supplementary material 6, Figure 9). The determination of maize harvest, respective to maturity stage, was generally accompanied by larger uncertainties.

For wheat, a forward shift of phenological stages was also found for all regions (Supplementary material 10, Figure 10). As expected, this response was correlated to the increase in mean temperature in the projections. In intermediate and minimum, the shift was only a few days in the maximum projection maturity occurred up to two weeks earlier compared to the baseline (Supplementary material 10, Figure 10). Like maize, the forward shift was most pronounced for maturity. The length of the critical growth stage around flowering was reduced by 1 day, with the maximum projection showing the largest effect (Supplementary material 10). Only UE deviated from this pattern, where we found an increase of 3 days for the projected rather than a decrease (Figure 10). Additionally, the interval of stem elongation to inflorescence emergence in wheat increased by approximately 6 days in the projection period. An explanation is that photoperiod hampers degree day accumulations that propels phenological development. Thus, despite increased mean temperatures, phenological growth stages are elongated.

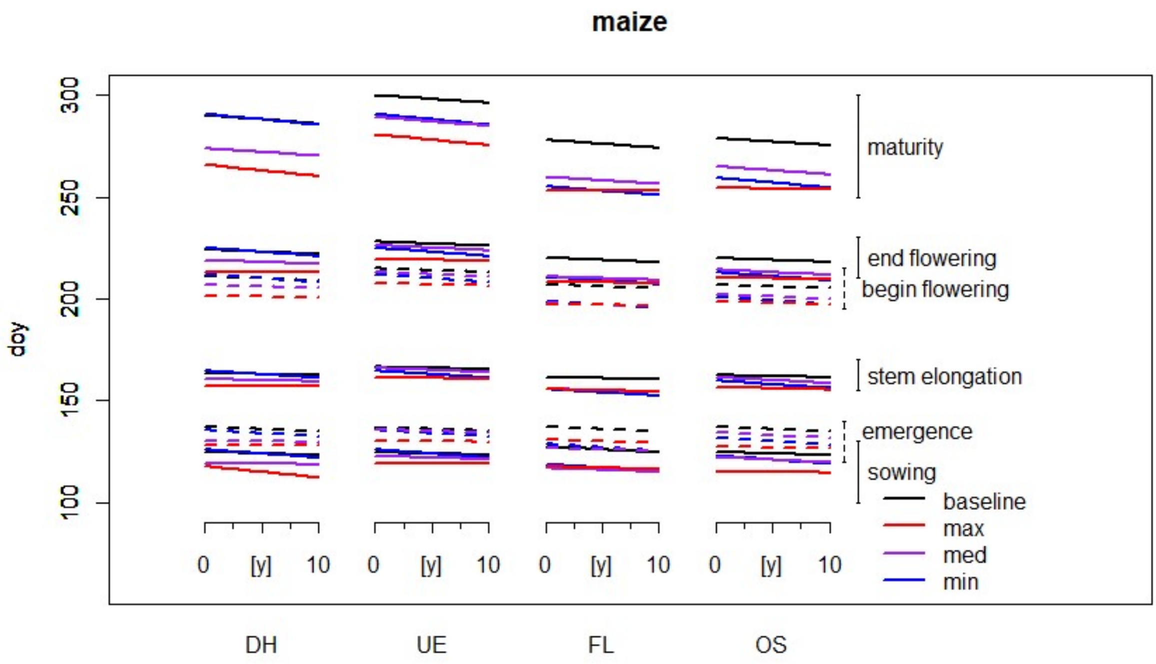

Figure 9 Changes in maize phenological development during the projection and baseline periods as linear trends in the four regions (dashed/ solid lines and brackets for differentiation of overlapping clusters of phenological stages; see also Table 10, and Supplementary material 6 to 12).

Adverse environmental conditions

The abundance of adverse environmental conditions increased during critical growth stages in the future projections (Table 10, Table 11). All regions showed similar general behaviour in the earliness of phenological development and shifts in the abundance of various adverse environmental events (Table 10, Table 11). However, some specific features, e.g., soil moisture and number of hot days, indicate differences between west and east.

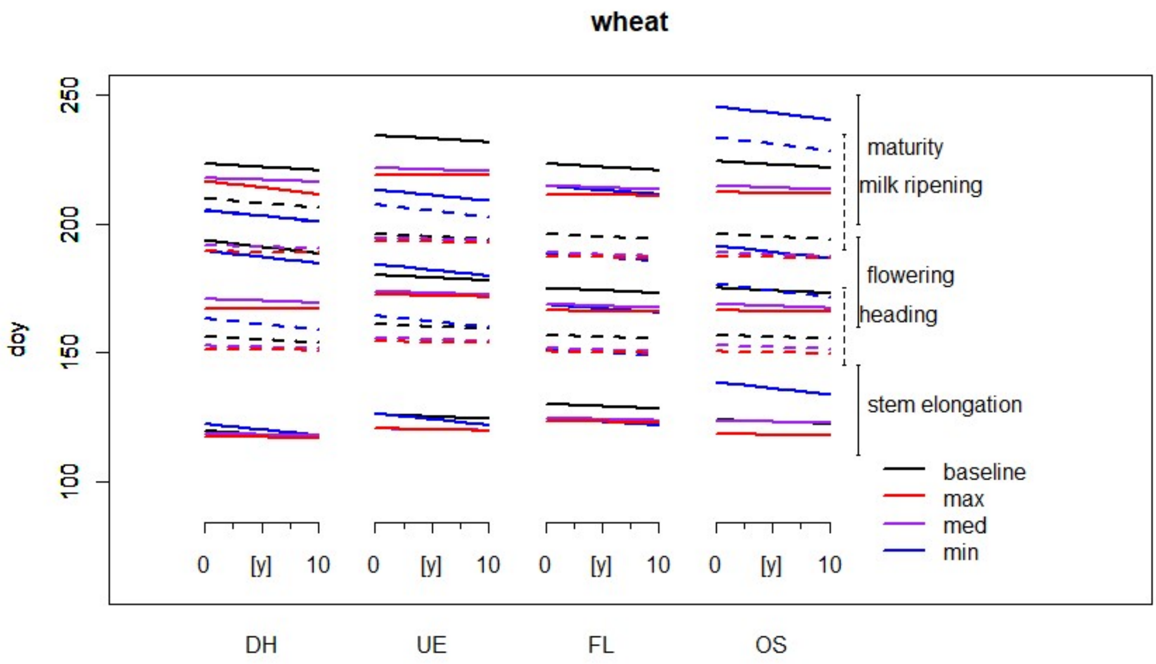

Figure 10 Changes in wheat phenological development during the projection and baseline periods as linear trends in the four regions (dashed/ solid lines and brackets for differentiation of overlapping clusters of phenological stages; see also Table 11, and Supplementary material 6 to 10).

High temperature

Generally, climate change projections with larger temperature increases caused a greater abundance of high temperature events, whereas the length of critical growth stages for maize and wheat decreased (Table 10, Table 11). The occurrence of high temperatures during maize anthesis and in the post-anthesis phase, however, was rare. In particular, daily maximum temperature exceeding 37°C (Sánchez et al. 2014) did not occur around anthesis, neither in the baseline period nor in the projections (Table 10). Only several days into the post-anthesis phase did the temperature exceed 36°C (data not shown). Similarly, only very few hot days, i.e., days with T_{max} > 30°C and T_{min} > 20°C were detected around anthesis for the baseline period. For the projections, an increase in high temperature events was found, which correlated with the projections' mean temperatures (Table 11). For instance, the abundance of hot days in the post-flowering phase of maize (BBCH 71-99) increased from 0.06% in the minimum projection to over 0.14% in the intermediate projection to 0.2% in the maximum projection for DH. Additionally, hot days during anthesis were rare in the western regions, DH and UE, with only a few days in the baseline and minimum projection in DH, whereas in eastern regions, there were 10 hot days recorded in the baseline period. Moreover, this period was shortened by approximately one day.

For wheat, an increase in the exceedance of almost all investigated temperature thresholds was found during the critical growth stage between flowering and milk ripeness (Table 11), with the risk increasing with mean temperature increase in the projections. The number of heat spells in the interval between inflorescence emergence and milk ripeness increased from the baseline to the projection period throughout all sites and for all heat spell lengths. Additionally, for FL, heat spells > 6 days were detected, which had not yet been recorded (Table 11).

Low temperature

Temperatures below the base temperature for maize (10°C) occurred with similar or lower frequency between sowing and tasselling in the climate projections (Table 10). Temperatures below 0°C between sowing and inflorescence emergence were rare in the baseline. For instance, we found three underruns in DH in the baseline period and approximately 15 in the projections (Table 10). Underruns of the minimum temperature thresholds never occurred in the interval between stem elongation and tasselling at any site (Table 10). In the projections, some isolated frost days (1 or 2 each) only occurred at the UE site.

Similar results were found for frost during the early development of wheat. In the baseline, frost was rare or non-existent between stem elongation and inflorescence emergence for all regions (Table 11). In the climate projections, frost occurred approximately 5 times more frequently for wheat. Two days, for instance, were found in the baseline period compared to a range of 7 to 15 days in the projections (Table 11). While a clear difference was found between the baseline and projection periods, the extent was arbitrary among the projections, where no direct relation between projection temperature and number of frost days was detected. Obviously, higher probabilities for extreme temperature are promoted despite beneficial shifts in mean temperature. This contrasts with the high temperature threshold exceedances and heat days, where mean projection temperature increase was correlated to the abundance of high temperature events.

Table 10 Abundance of adverse environmental conditions (fraction, number of days) during specific development stages of maize denoted by BBCH stadium (Meier et al. 2009) in the four regions for the baseline (base, 1981-2010) and projected projections (max, med, min; 2021-2050) and the abundance of heat spells with certain lengths (Indicators as given in Table 5).

Stage		DH				UE				FL				OS			
BBCH		base	max	med	min	base	max	med	min	base	max	med	min	base	max	med	min
"01-30	Tmin < 0°C	0.2	1.2	1.3	1.3	0.5	2.5	1.4	1.9	0.2	1.4	1.7	1.3	0.3	0.9	0.9	1.4
	Tmin <10°C	68.0	63.0	60.0	64.0	66.0	64.0	61.0	65.0	60.0	62.0	61.0	60.0	55.0	56.0	54.0	56.0
	øn [d]	42.7	43.4	41.0	41.6	44.0	42.9	42.5	42.3	40.8	40.8	41.4	40.4	39.7	40.4	40.5	40.7
31-60	Tmin < 0°C	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Tmin <10°C	18.0	18.0	20.0	16.0	19.0	22.0	22.0	19.0	16.0	17.0	17.0	16.0	13.0	11.0	12.0	11.0
	øn [d]	46.1	46.1	46.3	45.2	48.1	46.3	48.3	46.7	44.4	43.1	44.0	44.2	45.0	42.1	43.4	43.6
61-70	Tmax>37.3 °C	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Heat	0.3	0	0	0.3	0	0	0	0	1.1	0.3	0.3	0.3	2.6	1.8	1.2	1.5
	Drought	5.8	14.7	15.5	9.4	5.9	9.6	9.3	8.2	7.8	3.4	5.6	5.3	2.1	3.4	4.8	6.3
	øn [d]	12.3	13.1	12.4	13.2	12.6	12.9	12.7	13.9	12.1	11.5	12.1	11.9	11.8	11.4	11.8	11.9
70-99	Tmax>36°C	0.2	0.6	0.3	0.1	0.1	0.1	0.1	0.0	0.5	1.2	0.5	0.6	0.3	1.1	0.2	0.0
	Heat	0.1	0.2	0.1	0.1	0.0	0.1	0.0	0.0	0.5	1.2	0.5	0.2	0.8	2.1	1.4	0.7
	øn [d]	60.5	50.6	49.5	53.6	66.4	53.4	56.4	62.2	52.5	41.5	44.5	47.4	54.9	42.2	45.3	47.1
61-70	Heat spell 1	15	16	15	13	12	13	17	12	20	22	19	14	12	15	17	18
	Length [d] 2	4	4	11	4	4	5	3	3	5	7	8	12	8	9	12	7
	3	3	3	1	3	2	3	1	1	3	5	3	3	-	2	1	3
	4	2	3	-	-	1	2	1	1	-	1	1	2	-	2	1	2
	5	2	1	-	-	1	-	1	-	-	-	1	2	1	-	1	-
	6	-	-	-	1	1	-	1	-	1	1	1	-	1	-	1	-
	7	1	1	-	-	-	-	-	-	-	-	-	1	1	-	-	.

Table 11 Abundance of adverse environmental conditions (fraction, number of days) during specific development stages of wheat denoted by BBCH stadium [31] in the four regions for the baseline (base, 1981-2010) and projected projections (max, med, min; 2021-2050)

Stage		DH				UE				PM				OS			
BBCH		base	max	med	min	base	max	med	min	base	max	med	min	base	max	med	min
31-50	Tmin<0°C	0.3	0.7	1.5	1.1	0.6	1.5	1.5	1.0	0.0	0.3	0.5	0.3	0.2	0.3	0.3	0.9
	øn [d]	21.9	33.3	33.4	33.5	22.0	33.5	33.9	34.0	17.2	26.7	26.7	26.8	20.8	31.5	27.2	31.6
51-60	Tmax>25 °C	21.0	28.0	30.0	27.0	16.0	23.0	24.0	20.0	25.0	39.0	35.0	31.0	22.0	36.0	33.0	27.0
	Tmax>31 °C	1.5	3.1	3.9	3.5	0.6	1.6	2.2	1.6	2.6	3.2	5.7	6.2	1.8	3.5	4.0	4.4
	øn [d]	18.0	17.5	16.9	16.7	18.1	17.5	17.2	17.3	17.3	16.0	16.2	16.1	17.1	15.9	16.3	16.4
51-75	Tmax>31 °C	3.9	4.6	4.6	4.0	1.3	3.2	2.6	2.2	5.9	6.3	6.7	5.6	4.2	4.9	5.6	4.3
	Heat DWD	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.1	0.1	0.7	0.7	0.5	0.1
	Drought	14.5	24.7	13.1	14.3	14.4	27.9	21.9	13.9	12.2	12.4	14.8	12.5	10.7	11.7	10.1	12.1
	øn [d]	39.0	37.9	38.2	38.0	34.2	38.1	39.1	39.0	37.4	35.8	36.4	36.6	37.3	35.4	36.2	36.6
	Heat spell 1	17	24	24	25	5	17	12	12	20	20	26	29	17	24	28	23
51-75	Length [d] 2	5	3	4	5	2	7	3	2	12	8	10	1	7	5	10	7
	3	2	5	5	3	1	-	1	2	3	3	6	-	3	2	1	-
	4	-	-	1	-	-	1	1	1	1	2	1	1	1	1	1	2
	5	1	1	-	-	-	-	-	-	-	1	-	-	-	1	-	-
	6	-	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-

Soil water

For the analysis of soil hydrological conditions, the exceedance of modelled soil water content (>45% in top soil to a depth of 30 cm) was evaluated for each projection and each site (Table 12). The analysis was set to a period of ±5 day around sowing date for each year separately as well as ± 10 days around harvest, which was provided by the model as maturity date. Soil water content never limited trafficability in the FL and OS regions (data not shown).

For maize, high soil water contents at sowing rarely occurred in the baseline, whereas in the projections, the number of days with soil water content >45% increased up to 29 in DH as well as in UE. Furthermore, a clear gradation became apparent among the projections, with the maximum projection leading to the smallest number, and the minimum projection leading to the largest number of days with high soil water content. This differs from the pattern found for maturity, where the baseline and projections were generally equivalent. The abundance of the actual date and the time span around that date were similar for sowing and maturity.

For wheat, days with high soil water content at sowing were similar for both sites, i.e., approximately 60% out of the 29 years in the baseline (Table 12), while for maturity only approximately 30% of days were above the threshold. The projections revealed generally the same pattern as for maize, with the maximum projection having the lowest abundance and the minimum projection showing the most days above the threshold. The baseline was similar to the minimum and intermediate projections.

The evaluation of low water content as an indicator of drought at the four regions (Table 10, Table 11) shows high variability between baseline and projections for maize and wheat (Table 5). The western regions showed an increase of percentage of days below the soil water threshold during flowering in the med and max projections, in particular at sites DH and FL.

The eastern regions revealed an opposite trend. This was partly due to single severe drought events as the year 2003 which had strong impact on the abundances identified. The comparison of wheat and maize revealed a more pronounced increase of drought conditions for wheat, in particular between inflorescence emergence and milk ripe.

Table 12 Soil water conditions (abundance of days with water content, θ, over 0.45 in the top 30 cm of soil, n - gives the number of days evaluated for each crop on or around sowing respectively maturity for the 30 year period) predicted for sowing and harvest.

Crop	Stage		DH				UE			
	[BBCH]	n	base	max	med	min	base	max	med	min
Maize	01	30	0	11	27	29	1	18	25	29
	01 ± 5 d	300	0	107	302	310	12	182	273	309
	99	30	25	22	22	26	24	24	25	28
	99 - 9 d	300	247	221	216	265	252	236	233	269
Wheat	01	29	18	12	17	19	21	13	14	20
	01 ± 5 d	290	194	139	117	207	218	161	127	232
	99	29	11	4	11	17	12	4	13	8
	99 - 9 d	290	57	15	56	164	63	22	70	33

Discussion

Phenology

The shift in the phenological development documented for maize and wheat in the baseline period is in accordance with various studies conducted for Germany and Europe (Menzel and Fabian 1999; Chmielewski et al. 2004; Menzel et al. 2006; Estrella et al. 2007; Vučetić 2011). Menzel et al. (2006), for instance, reported a 2.5 days/C° earlier occurrence of phenological stages in the spring, translating to 2.5 days per decade for various crops grown in Europe. Similarly, a 2 to 2.9 days per decade earlier phenological development was found when analysing statistical data from 1960 to 2000 for Germany (Chmielewski et al. 2004). For wheat, e.g., the beginning of inflorescence emergence was found to advance by 2 days per decade in Germany, which is considerably less than our finding of 3 to 5 days per decade (Table 9). For maize, full flowering on average was found to shift forward by 0.47 days per decade (Estrella et al. 2007) in Central Europe, which is in good agreement with our study, where a shift of 2 to 3 days earlier was documented over 30 years (Table 8). Comparability among studies is limited due to differences in the evaluated time spans, phenological data availability and regional context. Warming patterns are regarded as the main cause for phenological shifts (Menzel et al. 2006). Other factors influencing crop development, however, cannot be disregarded, such as management (Chmielewski et al. 2004; Estrella et al. 2007) or shifts in cultivars.

The lack of significance in some of the identified trends, especially during the baseline period of the OS and FL regions can be attributed to discontinuous time series and small sample sizes. The lack of significance in the trend for the sowing date of wheat in DH probably is due to limited machinability in late summer/ early fall caused by water-saturated soils (Gobin 2012). Furthermore, labour shortages can lead to rigid schemes for sowing. This is the case especially for smaller farm sizes (BMEL 2015).

The shifts in phenological development identified for the projection periods in the current study are comparable to those reported by other studies for European conditions (Schröder et al. 2014; Trnka et al. 2014). Schröder et al. (2014), for instance, found an advancement of phenological stages in the first half-year of up to 10 days, based on simulations by 10 climate models for the period 2031 – 60 (temperature projection + 3.7°C in 2100) for Hessen, Germany.

Model performance

Phenological development was reasonably well predicted for all regions of the North German Plain. Deviations between simulated and measured values were mostly within the standard deviation (Figure 8, Table 6, Table 7). This is in agreement with Palosuo et al. (2011), who found DSSAT to be capable of reproducing the anthesis (EC 61) and yellow ripeness (EC 90) dates of European wheat production, with comparable RMSE of approximately 6 days for anthesis and 8 days for yellow ripeness. For maize, Vučetić (2011) found satisfying results in predicting the phenology of maize in Zagreb, Croatia, predicting silking with $R^2 = 0.71$ and maturity with $R^2 = 0.66$, which is within the range documented in the present study (Table 6). Somewhat larger discrepancies became evident for the maize harvest, as indicated by high standard errors of up to 3 weeks (Table 6, Table 7). Most likely this is due to the underlying database, where harvest was not differentiated among different production types, i.e., silage maize, corn cob mix and grain maize. The harvest date provided by DSSAT maize is physiological maturity, but the phenological data recorded in the North German Plain will contain a considerable proportion of maize harvested at silage maturity. In this respect, the different maturation behaviour of silage maize with respect to the maturity group and the maturation of stover compared to cob may have further contributed to larger deviations between the observed and simulated data. Nevertheless, the calibration parameter set can be regarded as valid to describe the phenological development of maize and wheat in the four regions. This is particularly true since other environmental factors, such as local water and nutrition supply, are generally not considered for phenological development in crop models (Hoogenboom et al. 2012).

Adverse environmental conditions

Thresholds are commonly used in crop models as indicators of adverse environmental conditions. Physiological stress, however, is not a result of threshold exceedances, but a complex interaction of the environmental history of a site finally leading to effects on plant growth processes. In this respect, interactions of abiotic stress factors (Barnabás et al. 2008) or acclimatisation effects (Porter and Semenov 2005) may substantially vary the extent of the environmental impact on growth and development processes. It has also been shown that abiotic state variables are not necessarily highly correlated with plant response mechanisms (Siebert et al. 2014). Thresholds, however, are easily accessible, and the difference between abundances in the baseline period and the projections is a suitable indicator for changes in environmental patterns (Gobin 2012; Trnka et al. 2014).

The increased abundance of environmental conditions exceeding thresholds in the current work is similar to other studies reporting an increase of heat and drought stress all over Europe (Gobin 2012; Trnka et al. 2014). For maize, however, heat stress around anthesis seems less relevant in the North German Plain, since the threshold value was not exceeded in either the baseline or the projection periods. Although there was an increase in hot day events in the projection period, these days were still beneath the anthesis lethal temperature threshold of 37°C (Sánchez et al. 2014). It should also be considered that despite increased mean temperatures, we found shifts in the distribution of temperatures that would increase the probability of low temperature abundance (Figure 11). With respect to low temperatures (< 0°C), the current study documented a four-fold higher abundance of frost occurrences in the projections compared to the baseline for the period from sowing until stem elongation in maize. The same pattern was found for wheat.

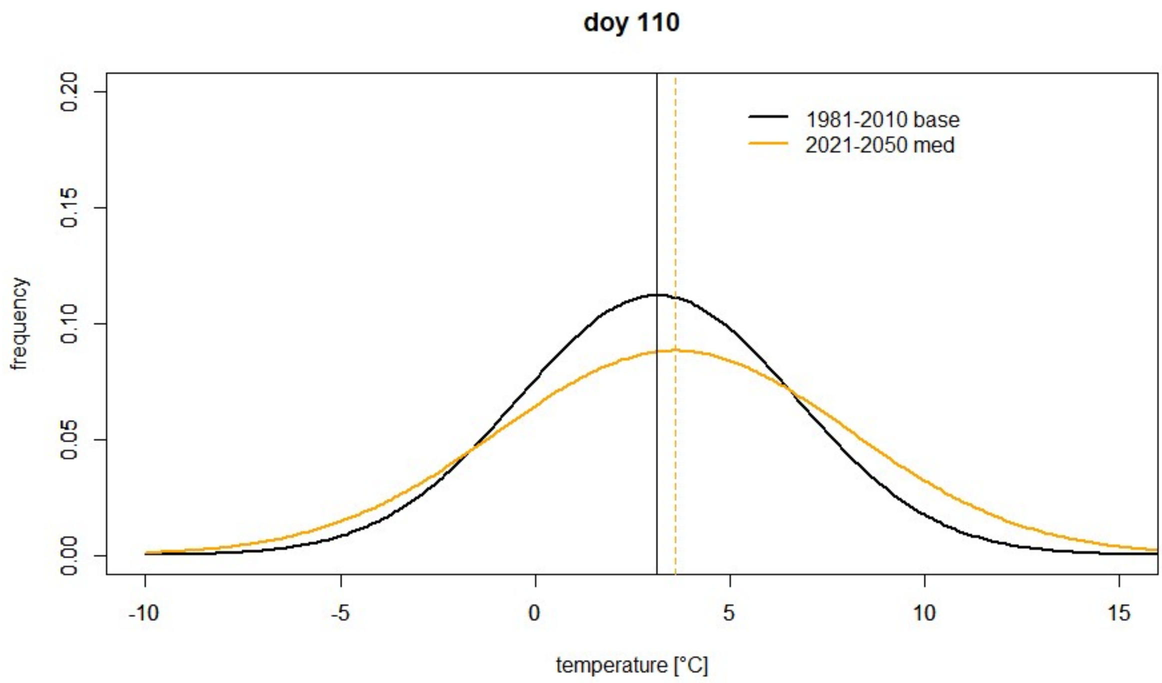

Figure 11 Example of normal distributions fitted to de-trended low temperatures at the DH site for the baseline 1981-2010 and the projection period at doy 110.

While low temperatures can have a significant impact on the development of maize, the impact of low temperature *per se* should be less pronounced for wheat (Porter and Gawith 1999; Sánchez et al. 2014). The increased abundance of lower temperatures can be explained through the earlier phenological development in both crops. While increased mean temperatures promotes an earlier phenological development in the crop model, shifts in temperature distributions in the projected climate can increase the abundance of lower temperature (Figure 11). Additionally, photoperiod and frost effects in the crop model hamper the accumulation of degree days and lengthen specific phenological stages, especially in winter wheat production, which is completely exposed to the period with short day length in Northern Germany. This suggests that frost conditions can be a reasonable threat in future German cropping systems. Similarly, Trnka et al. (2014) identified an increased abundance of late frost for wheat production systems at several investigated sites, and increased winter frost abundance at continental sites in Europe. In contrast, Gobin (2012) reported maize and wheat to benefit from earlier planting in Belgium. However, late frost abundance was not investigated in that study.

An evaluation of the impact of adverse environmental conditions on crop growth and development, whether it be for historical or future periods, is always afflicted by uncertainty, since adverse environmental conditions are rare events and thus a general source of error (Gömann et al. 2015). Despite the use of 30-year time slices, small case numbers inhibited further statistical analysis for significance, and the analysis therefore was only descriptive. However, temperature-related effects were consistent.

Table 13 Mean annual precipitation sums for the baseline and the projection periods at the for regions (percentage gives ratio of precipitation for the April to September period).

Region	baseline [mm]	min [mm]	med [mm]	max [mm]
DH	705 (52%)	739(0.48)	746 (47%)	705 (48%)
UE	732 (53%)	758 (50%)	742 (48%)	728 (48%)
FL	542 (56%)	578 (50%)	560 (48%)	545 (47%)
OS	551 (59%)	576 (51%)	562 (49%)	564 (47%)

Soil trafficability during sowing and harvest can be a limiting factor in crop production, but it strongly depends on local soil properties. In the current study, shifts in soil water conditions were small and arbitrary. We were not able to identify clear trends between the baseline and projection time periods for most sites. If a change occurred, it was an increase; however, changes were inconsistent over the three evaluated projections. This is in contrast to Gobin

(2012), who found that the number of water-logged days at the time of planting for summer crops as well as for the harvesting of maize declined from 1947 to 2008 in Belgium.

Our analysis of drought abundance during critical development stages of maize - indicated here by days with soil water content falling below a threshold - gives only an overview on the complexity of precipitation distribution in a climate change context. The abundance of drought events was correlated to single severe drought events as in the year 2003 which had strong impact on the abundances identified. The utilisation of accumulative methods quantifying drought, or other standardised indicators including precipitation and evapotranspiration (Vicente-Serrano et al. 2010; Gobin 2012) would clearly improve the assessment of drought in itself. The model, however, is not yet validated for evapotranspiration. In addition, the impact of carbon dioxide concentration on crop transpiration is not included in the model (Nendel et al. 2009). However, some features are reasonably explainable. Wheat drought abundance in FL and OS is in accordance to the climate change scenarios, where higher annual precipitation together with a shift to more winter rainfall resulted in nearly constant summer precipitation (IPCC 2014, Table 13). The reduced drought abundance detected in maize can be attributed to typical heavy rain events in the summer replenishing soil water (Metzger et al. 2005; Trnka et al. 2011), especially in the more continental Eastern regions.

Temperature shifts can be explained consequently throughout the regions by the mean temperature increase given by climate scenarios (IPCC 2007). The STAR scheme has proven to be reliable to break down general circulation models (GCM) to regional levels (Gerstengarbe et al. 2013). However, precipitation provided in the climate models is regional and within each projection highly variable. GCM shows a higher variability in predicting hydrological aspects than in predicting temperature (Wentz et al. 2007; Ljungqvist et al. 2016). Similarly, Ljungqvist et al. (2016) emphasized that precipitation as provided by GCM is highly variable and should be considered as random manifestation rather than to be interpreted in a context of expectable shifts.

Conclusion

The increased abundance of temperature-related stress in all projections indicates the necessity of improving cropping systems to minimise the risk for crop production in the North German Plain. This particularly applies to the eastern North German Plain, where a stronger impact of climate change may be expected, and requires the development of adaption strategies. Apart from breeding for more stress-tolerant genotypes – primarily heat tolerance around anthesis in wheat and cold tolerance for germination and early development in maize, there is potential for earlier sowing of summer-annual cultivars to avoid high temperatures and drought during critical development stages, i.e., flowering in early summer. For maize, earlier sowing, however, could result in a trade-off due to the risk of frost damage. For winter-annuals, such as wheat, earlier maturing genotypes might be an option to ensure that reproductive development will occur under more favourable environmental conditions. Changes in soil water content affecting trafficability were small but should not be ignored.

The methodological approach applied in the current study is easily transferable to other adverse environmental conditions, e.g., by selecting indicators of moisture-limitation. A methodological challenge exists because of small sample sizes, which are a consequence of the moderate climate in the region, and, in the case of critical development stages, of the fine-tuned and specifically adapted production systems. Another challenge lies in the crop models' capabilities of predicting phenological growth stages. Generally, crop growth models have proven to be suitable for predicting the phenological development of various crops for this region. However, predicting phenological development under stress conditions, e.g., heat, drought, and multiple stresses, is still a challenge in crop modelling. A refined implementation of stress reactions in crop growth models, i.e., water and heat stress, would allow for a more reliable assessment. For the input site, the quality of the global circulation models is crucial, particularly the aspects related to precipitation.

The method applied in the current study is easy transferable to other regions - provided an adequate set of climatological and phenological data and a suitable crop growth model are available- and gives a reasonable overview on local cropping systems and the abundance of adverse environmental conditions as an indicator for risk assessment.

Chapter 3

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Drought patterns shape yield variability: An assessment for crop production in Lower Saxony, Germany.

Abstract

Droughts impact and have impacted agricultural pursuit in Lower Saxony, Germany as well as worldwide. Challenges through drought are likely to increase under climate change. Therefore, a classification of the typical succession of drought events, i.e. *drought patterns, can be a valuable tool for shaping future agricultural production systems to provide reliable and high yields. We use the potential of drought patterns to find differences between observed and simulated yields and in this way, identify starting points for improvements for crop simulation models; the main tool for analysing agricultural production systems.*

First, an inventory of annual correlation patterns of drought impact on yield variability is provided between a monthly drought index and observed yields for generalised agricultural production systems, i.e. barley, maize, oats, potato, rapeseed, rye, sugar beet, and wheat all common in the federal state of Lower Saxony, Germany.

Second, this inventory is compared to modelled annual correlation patterns finding substantial differences between both. Here, maize and wheat time series are modelled with DSSAT-CERES.

We found distinct specific drought patterns for crops and crop production systems. In regards to the mitigation of climate change impacts, these patterns indicate that diversification of crops and production systems can level the effect of drought on yield variability. The model study was not able to reproduce these drought patterns one to one; the deviations found indicate that crop models need targeted improvements to simulate drought impact, more adequately. We consider that phenology stage-specific drought response can provide this improvement.

***Keywords**: drought patterns, yield variability, Lower Saxony, standardised yield residual series SYRS, standardised precipitation evapotranspiration index (SPEI), crop simulation models, DSSAT*

Introduction

Doubtless, drought can have an extraordinary impact on yield, especially when occurring during critical phenological development stages, e.g. flowering, or tuber initiation. Because of recent heat and drought episodes in north-western Germany, drought patterns have to be reconsidered and re-evaluated. Classifying their current impact on crop production can be the first step to identify perspectives for agricultural production systems in shifting environmental conditions, and to initiate well- targeted improvements for analysis tools and methods, e.g. crop simulation models.

The impact of environmental patterns in the temperate region of Germany is probably most evident in clear, predictable, and distinct seasons (Metzger et al. 2005; Gömann et al. 2015; van Rüth et al. 2019). Agricultural production is quite successful in minimising risk imposed by such patterns in Lower Saxony. It evolved around these patterns to produce high and reliable yields. Additionally, there are adverse environmental conditions that underlie higher variability and are not as obvious to detect that can jeopardise the agricultural pursuit, severely. These complex interactions between adverse environmental conditions and critical development stages are a plague for risk assessment (Porter and Semenov 2005; Tao et al. 2018). Certainly, drought is such a condition that takes place occasionally to regularly and can have a substantial impact (BMEL 2019). In recent years, heat and drought episodes were more frequent in all of Germany, with memorable events taking place in 2003, 2006, 2015, and 2018 (Gömann et al. 2015; Russo et al. 2015; Hanel et al. 2018; van Rüth et al. 2019).

Usually, crop simulation models are the tool to go to for simulating environmental impacts on agricultural production systems. They are well suited to simulate mean yields (Palosuo et al. 2011; Rötter et al. 2012; Kollas et al. 2015; Wallach et al. 2018). However, they are limited when simulating yield variability (Porter 2005; Challinor et al. 2005; Rötter et al. 2011). Typically, there is a gap between modelled and observed results. This gap is always a concern when working with crop simulation models, but it is of most importance when analysing the impact of shifting environmental conditions, e.g. drought (Rötter et al. 2011).

Therefore, a classification of drought patterns and their impact on agricultural production systems for a region can be a valuable method for further analysis of various topics around risk assessment, e.g. sensitivity of crop simulation models to simulate drought impact and drought patterns, or the development of mitigation strategies for climate change.

The typical succession of environmental conditions aggregates to environmental patterns at a site. Plant development and agricultural production systems have developed around the necessity of local environmental patterns and conditions to match specific crop requirements (Barnabás et al. 2008; Ober and Rajabi 2010). This development includes the evolution of particular organs, ensuring ideal conditions for sensitive processes to succeed, as well as the development of strategies in crop management, e.g. sowing dates to omit predictable unfavourable conditions like late frost events (Trnka et al. 2011). Climate change-related shifts in environmental patterns challenge these well-established agricultural production systems (IPCC 2014; van Rüth et al. 2019).

Continuous water availability is crucial for crop development (Vining 1990). Water limitation from light water scarcity to intense drought stress induces constraints on the development of various crops (Saini 1997; Ober and Rajabi 2010; Zirgoli and Kahrizi 2015). A wide range of physiological responses can be triggered depending on the level, duration, intensity of water limitation, and the impacted development stage (Malik et al. 2011; Perata et al. 2011; de San Celedonio et al. 2014; Xu 2015). For instance, for cereal yield, severe impacts of drought are reported between the onset of meiosis and early seed formation (Porter 2005; Barnabás et al. 2008; Mäkinen et al. 2018).

On the other side, water surplus can be regarded as an adverse environmental condition for crop development, too. The oxygen-depleted soil environment hampers crop development and management processes by impacting soil machinability (van der Velde et al. 2012; Gömann et al. 2015). High water content alters soil heat balance having an impact on the development of subterranean crop parts, e.g. roots and tubers (Pendleton 1950; Hoffmann and Jungk 1995; Jacobsen 2006). Water availability is likely to be reduced during the vegetation period, and temperature increases might, in turn, increase water use in Germany (Barnabás et al. 2008; Ahmadi and Bahrani 2009a; Ober and Rajabi 2010; Malik et al. 2011; Perata et al. 2011; van der Velde et al. 2012; Gömann et al. 2015).

Drought patterns are a way to classify more regularly occurring droughts. Drought patterns as introduced by Potopová et al. (2015) use annual correlation patterns between standardised yield residual time series (SYRS) and the standardised evapotranspiration index (SPEI) as a classification for drought impact on crop production (Vicente-Serrano et al. 2010; Beguería et al. 2014; Stagge and Tallaksen 2014; Potopová et al. 2015). SPEI has shown to be sensitive to shifts in environmental conditions through climate change (Vicente-Serrano et al. 2010). The high degree in the standardisation of these patterns allows high comparability, e.g. of regions, of numerous crops, and observed and modelled yields (Stagge and Tallaksen 2014; Potopová et al. 2015).

Crop simulation models are a tool that provides a long-term risk assessment of agricultural production systems and the development of mitigation strategies against climate change. They analyse the response of crops to changing environmental conditions (Bindi and Olesen 2011; Trnka et al. 2011; Gobin 2012; IPCC 2014; Gömann et al. 2015). They are flexible enough to simulate diverse crops (Palosuo et al. 2011; Kollas et al. 2015), variable in their application to different topics (Rötter et al. 2012; Pirttioja et al. 2015; Stratonovitch and Semenov 2015; Strer et al. 2018), e.g. including water availability (Barlow et al. 2015; Strer et al. 2018; Rötter et al. 2018b), and they show excellent performance in predicting mean yield and mean crop development (Palosuo et al. 2011; Rötter et al. 2012; Kollas et al. 2015; Wallach et al. 2018).

The DSSAT-CERES simulates various crop simulation tasks. It has proved to predict crop yield in the North German Plain, satisfyingly (Rötter et al. 2012; Hussain et al. 2018).

However, crop simulation models are limited in reproducing yield variability, and their predictions are only valid in specific ranges (Palosuo et al. 2011; Rötter et al. 2012; Kollas et al. 2015; Wallach et al. 2018). A problem that comes with these limitations is a bias towards only a few mitigation strategies of the many discussed being tested with models (Challinor et al. 2018; Rötter et al. 2018a).

There are many challenges of drought patterns' impact on agricultural production systems and for their analysis.

Shifts in environmental patterns including the abundance, severity, and length of drought events jeopardise the well-established agricultural production systems of Lower Saxony. A classification of drought patterns on yield variability is needed to identify problems of the recent production systems and develop mitigation strategies for drought risks that ensure high and stable yields in future.

In regards to crop simulation models, the questions arise: if they are capable of resolving development stage-specific response to environmental patterns adequately or if there is a gap between modelled and observed patterns that need to be closed. The implementation of development stage-specific processes can be a suitable strategy to close this gap and to increase crop simulation model's accuracy in predicting yield variability by improving them, significantly (Porter and Gawith 1999; Siebert et al. 2014; Sánchez et al. 2014; Wang et al. 2017). Such improvements certainly need a focus. We do believe that the evaluation of annual correlation patterns for drought impact can inspire this systematic research to improve crop simulation to more accurately predict yield variability under stress (Asseng et al. 2011; Palosuo et al. 2011).

We set the following objectives:

To derive an inventory of annual drought patterns' impact on yield variability for crops produced in Lower Saxony, Germany. Such a reference for production crops, *i.e. barley, maize, oats, potato, rapeseed, rye, sugar beet, and wheat* can be a valuable assessed for the analysis of local production systems given risks through shifting environmental conditions and for the development of mitigation strategies for these systems.

To compare observed and modelled annual correlation patterns and identify the gap between observation and simulation, here by the example of DSSAT for maize and wheat production. This comparison evaluates a crop simulation model for its suitability to simulate adverse environmental conditions' impact on critical development stages.

Material and Methods

Method

Annual correlation patterns derived between yield time series and climate time series provide a classification for environmental impact on agricultural production systems. We follow closely the approach presented by Potopová et al. (2015) to establish such annual correlation patterns between standardised yield residual series (SYRS) to describe yield variability, and the standardised precipitation evaporation index to describe drought (SPEI). Latter is a measure for water balance anomalies in monthly to annual resolution. The method allows for comparison between various crops, production systems, years and sites. The high grade of standardisation allows high comparability. This standardisation includes de-trending of yield and environmental time series to omit the impact of long-term shifts and developments (Potopová et al. 2015).

Region

Lower Saxony has a highly productive agriculturally dominated landscape, providing a significant fraction of German crop production. A temperate oceanic climate dominates the region (Cfb, classification Köppen (Metzger et al. 2005; Peel et al. 2007)). We selected Diepholz (centrally located) as a representative site for this region (Metzger et al. 2005). It is characterised by mostly fertile soils, mainly cultivated by maize, winter barley, summer barley, rye, potato, sugar beet, oats, and rapeseed (Richter et al. 2007). Except for regional specialised production systems, e.g. vegetables and some local soil properties, drought was generally not regarded as an imminent risk for the local agricultural production systems until, recently. Therefore, local agricultural production relies heavily on rain-fed systems.

Data preparation

Standardised yield residual series (SYRS) are prepared from observed yield data. Supplementary material 15 to Supplementary material 23 give a general overview of the available yield time series. The focus of data preparation was on de-trending the time series. In regards to this goal, standard functions can quantify yield trends for specific crops (Table 14). The adjusted coefficient of determination and Akaike information criterion (AIC) selected the crop-specific de-trending functions. The resulting residuals acquired from the de-trending process are standardised (Interpretation guidance: Table 15 b).

The focus here was to provide a de-trended time series for each crop. Arguably, functions applied here, do not meet requirements to describe physiological crop responses, e.g. growth limits.

Table 14 Functions applied for describing yield time series (b – intercept; a, c – coefficients; d – tipping point; K – capacity; k - exponential growth rate; A - initial value).

Model	Function
linear	$f(t) = a \cdot t + b$
linear plateau	$f(t) = \begin{cases} a \cdot t + b, & t \leq d \\ d, & else \end{cases}$
bi-linear	$f(t) = \begin{cases} a_1 \cdot t + b_1, & t < d \\ a_2 \cdot t + b_2, & t \geq d \end{cases}$
exponential	$f(t) = A \cdot e^{k*t}$
logistic	$f(t) = K \cdot (1 + Ae^{kt})^{-1}$

Additionally, the calculation of the standardised precipitation evapotranspiration index (SPEI) uses a time series of *monthly* mean temperature and *monthly* precipitation sums (1946-2015). The Thornthwaite approach derives evapotranspiration needed for the calculation of the SPEI (Begueria and Serrano 2015). This study aggregates lags for SPEI of one, two, and three months. A linear model was sufficient to de-trend temperature and precipitation time series. Table 15 comprises interpretation guidance for SPEI and SYRS.

Inventory

Spearman's rho correlation coefficient determines the strength of the association between SYRS and SPEI. These correlation coefficients are calculated for each combination of month and crop respectively production system, i.e. maize, winter barley, summer barley, rye, potato, sugar beet, oats, and rapeseed. Additionally, using different time lags provides insight on longer-term impact (one month, two months, three months).

Modell study

A modelling study provides simulated yield time series for maize and wheat. A comparison between observed and modelled patterns identifies the potential of the model to reproduce annual correlation patterns at the site. The analysis was restricted to maize and wheat, being important production crops and representing summer and winter cropping in Lower Saxony.

Table 15 categories to interpret moisture [a)] and yield [b)] by accessing SPEI and the SYRS according to Potopová et al. (2015).

a)

Moisture categories	SPEI	
	from	to
Extremely wet	>= 2.0	
Severely wet	1.5	1.99
Moderately wet	1.49	1
Normal	0.99	-0.99
Moderate drought	-1	-1.49
Severe drought	-1.5	-1.99
Extreme drought	<=-2.00	

b)

Yield variability	SYRS	
	from	to
High yield increment	>= 1.5	
Moderate yield increment	1	1.49
low yield increment	0.5	0.99
Normal	0.49	-0.49
Low yield loss	-0.5	-0.99
Moderate Yield loss	-1.0	-1.49
High yield loss	<=-1.5	

The model was set up in DSSAT as follows: we used p*henological data* sets to establish typical production schemes from sowing to maturity. Input climate data were daily weather time series in the period 1981 to 2010. Soil type was set typical for the study area as a medium silty loam accordingly to the German soil survey (Richter et al. 2007, Supplementary material 24). Model parameters are estimated by the minimisation of root mean square error (RMSE) between simulated and observed phenology and yield data (Figure 15, Figure 16).

Crop simulation models can provide sophisticated methods to determine water balance (Jones et al. 2003a; Hoogenboom et al. 2012). Nevertheless, we choose to derive evapotranspiration after Thornthwaite for better comparability with the observation procedure (Vicente-Serrano et al. 2010; Begueria and Serrano 2015). The parametrisation of crop models for maize and wheat in the period 1981-2010 was successful based on the available data (Figure 15, Figure 16). A subset of observed annual correlation patterns provides a reference for comparison that matches the model period (1981-2010 instead of 1948-2015).

Data

The present study utilises comprehensive agro and agroclimatic data compiled from the Federal Statistical Office of Germany, State Statistic Bureaus and the German Weather Service (DWD).

Yield data comprise yields of different crops from agro-data sets published by statistical bureaus in Germany 1948 to 2015. These include yields of various production crops in Lower Saxony. Supplementary material 15 to Supplementary material 23 illustrates a general overview of the available yield time series.

The climate data used falls into the following three categories.

First, climate data utilised for the calculation of SPEI are available from the German weather service DWD. It comprises in *monthly resolution* temperatures, and precipitation means respectively sums for the years 1948 to 2015.

Second, climate data to model yield time series of maize and wheat in a *daily resolution* is available for the time frame 1981 to 2010. Data comprise weather data of the weather station in Diepholz operated by DWD. Data include daily mean, max and min temperatures, as well as daily precipitation, wind speeds and solar radiation.

Third, data on phenology comprises dates for numerous phenological stages of wheat and maize for the period 1981-2010 obtained from the German weather service.

Results

Data preparation

Yield development differs strongly between each crop (Supplementary material 15 to Supplementary material 23). De-trending was possible based on the trend functions and allowed to derive standardised yield residual time series. We found long-term trends in yield development. The visualised functions suited our criteria best; having the highest adjusted R^2 (Supplementary material 15 to Supplementary material 23); respectively, the lowest AIC (Data not shown). The standardised precipitation evapotranspiration index (SPEI) evaluating monthly drought conditions at the site in Diepholz, Germany shows a constant alteration between drought and wet periods (Figure 12). While most months play out between moderately wet and moderately dry, there are several examples of extreme events of moist and dry conditions (Figure 12). For instance, this includes 31 months with less than 20 mm precipitation in 70 years. This and the alterations in SPEI indicate the importance of short-term weather variability in the region. Aggregated to annual lags, the SPEI shows fewer changes (Figure 12), with a noticeable, predominantly moister period from 1975 to 1990 (Figure 12).

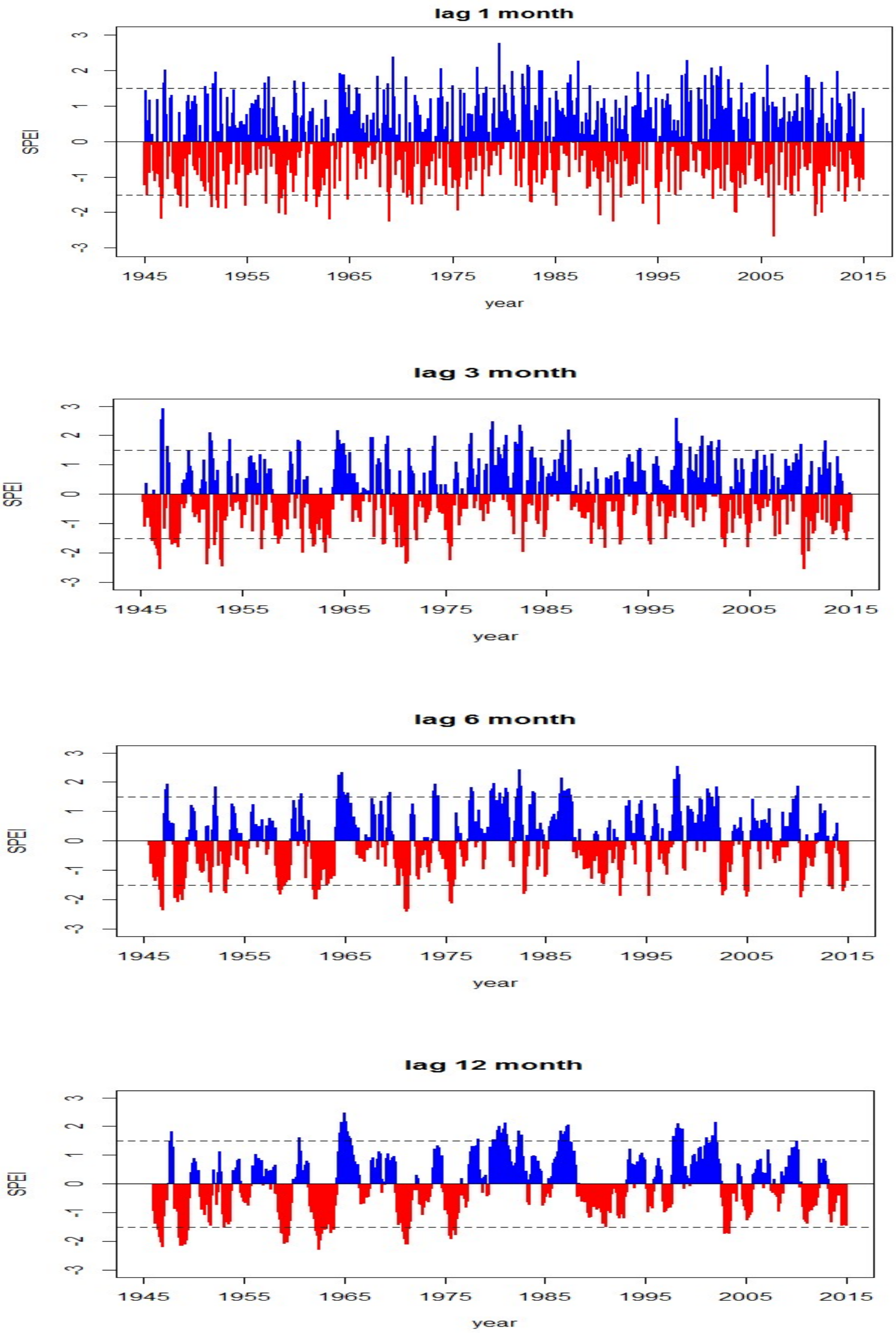


Figure 12 SPEI for different time lags of one month, three months, six months, and twelve months from 1945 to 2015 at DH, Germany.

Reference: drought / wet pattern

We provide a basic characterisation of drought / wet conditions impacting agricultural production through annual correlation patterns derived for the reference period (1948-2015) in Lower Saxony (Figure 13). Spearman's rho correlation coefficients aggregate to these patterns (correlation coefficient hereafter). Correlations include three different time lags of the SPEI (one month, two months before, three months before, Figure 13). Positive correlation coefficients indicated a negative effect of drought on yield variability, i.e. dry and low yields, or reverse high moisture condition leading to high yields. Generally, negative correlation coefficients are more frequent and have larger absolutes, with correlation coefficients reaching down to -0.4. The positive correlation coefficient rarely reaches more than 0.2.

Shifts of correlation coefficients over the three lags of a specific month are rare; indicating that generally immediate monthly impact of environmental conditions prevails compared to longer effects. While each crop shows its specific annual correlation pattern (Figure 13), some factors, e.g. crop type, and production scheme, share overarching patterns.

Maize, oats, and summer barley as typical summer crops in the region - with sowing in spring and harvest later in the same year – share features in patterns. There is a cluster of negative correlation coefficients in early spring at planting (March, and April in barley and May, and June in maize and oats); generally stronger in higher time lags (Figure 13). Months with positive correlation coefficients, i.e. drought resulting in reductions of yield - follow this negative cluster from approx. May to July. This is typically the time where the shift from vegetative development to reproductive development takes place.

In regards to production systems, summer barley shows specific patterns comparable to summer crops and winter barley shows patterns similar to winter crops. This direct comparison emphasises the importance of management of a production system on yield variability (Figure 13).

Wheat, rye, winter barley, and rapeseed are typical winter crops in the region. For these sowing takes place in fall, they are dormant through winter and harvest is in second year's summer or fall. We identified the following general annual correlation pattern (Figure 13). While the first production year with young crops shows positive correlation coefficients (high moisture being rather beneficial for yield development), the second-year shows negative correlations, predominantly. Variability found in correlation coefficients is generally higher in the second year. Noticeable is rapeseed and winter barley, where we see only small positive correlations in the early development in the first year. Rapeseed, and rye show increases in correlation coefficients towards the summer month. In contrast, wheat and winter barley show arbitrary alterations between positive and negative correlation coefficient in the first half of the second year with a cluster of predominantly positive correlation coefficients found from February to April.

Sugar beet's annual correlation pattern is distinct: It starts with strong negative correlation coefficients at sowing and increases monthly until it reaches positive values in summer and ends highest on positive values before harvest (Figure 13). The negative correlation shows higher absolutes approx. 0.4 then the positive correlation approx. 0.1. There is some variability found between positive and negative correlations for the different time lags between late spring and early summer (June and July). The general pattern shifts from dominantly negative to dominantly positive correlations in this time.

In contrast, **potato** shifts from slightly negative correlation coefficients between June and July to positive correlation coefficient for the rest of the vegetation period (Figure 13). Around planting, positive correlation coefficients are found, e.g. in March and April. In July to September at the harvest time correlation coefficients are positive, too. Negative correlations are found only in June. Correlation coefficients' signs are widely stable throughout the time lag range.

Pattern subset for comparison

The subsets of annual correlation patterns derived for the comparison period (1981-2010) deviates in some features from the reference period (1948-2015, Figure 13, Figure 14). These changes can indicate the impact of shifts in management and climate (Van Ittersum et al. 2013). The ranges of absolute correlation coefficients found are more significant in the shorter period of 30 years. Especially, positive correlation coefficients are more accentuated (Figure 13, Figure 14) indicating higher drought risks through changes in climate and management. Negative correlation coefficients are on similar levels as those in the reference period (1948-2015).

In **maize,** the general pattern is similar: negative correlation coefficients after sowing, predominantly positive correlation coefficients follow for about two months and slightly negative ones after that. Noticeable is the shift to earliness of positive correlation coefficients from June, July to July, August (Figure 13, Figure 14) that aligns with shifts to earliness found in phenology.

Wheat shows a more complex picture. While, the general course over the year is similar to the longer period, i.e. positive correlations after sowing, turning negative over winter (November, December, January), followed by positive correlations in spring (February, March) and negative correlations in the month before harvest. In some cases, patterns deviate strongly, e.g. negative correlation coefficients found in December and Mai are not apparent in the reference pattern (Figure 13, Figure 14).

Modelled time series

The parametrisation of the crop simulation model was successful for maize and wheat for the entire 30-year-span (1981-2010). The models reproduce crop yields, sufficiently (Figure 15, Figure 16). Mean yields and general yield variability predicted for maize is in good agreement with the observations (Figure 15). The wheat model overrates mean yield by approx. 0.6 t/ha. Phenological development stages as far as implemented in the model are reproduced sufficiently for both crops (Figure 15).

The maize model performs well in predicting the first half of the time series (Figure 15). It repeatedly matches single years accurately and reproduces some features in the further course of the time series, e.g. heat year in 2003 (Figure 15). Wheat model performance is weaker besides predicting several years accurately and reproducing the general trend; we find outliers and higher variability in the simulated yields (Figure 16). These outliers, predicted in 1983, 1989, 1990, and 2005, increase the mean yield onto the elevated level and contribute to the more substantial variability (Figure 16).

Based on these modelled yield time series, we derived annual correlation patterns between SPEI and SYRS for modelled yield, accordingly to the observed ones (Figure 14). The annual correlation patterns given by both production systems show amplification of correlation coefficients: modelled yield time series show higher ranges. Notably, negative correlation coefficients are more pronounced in the modelled time series (Figure 14).

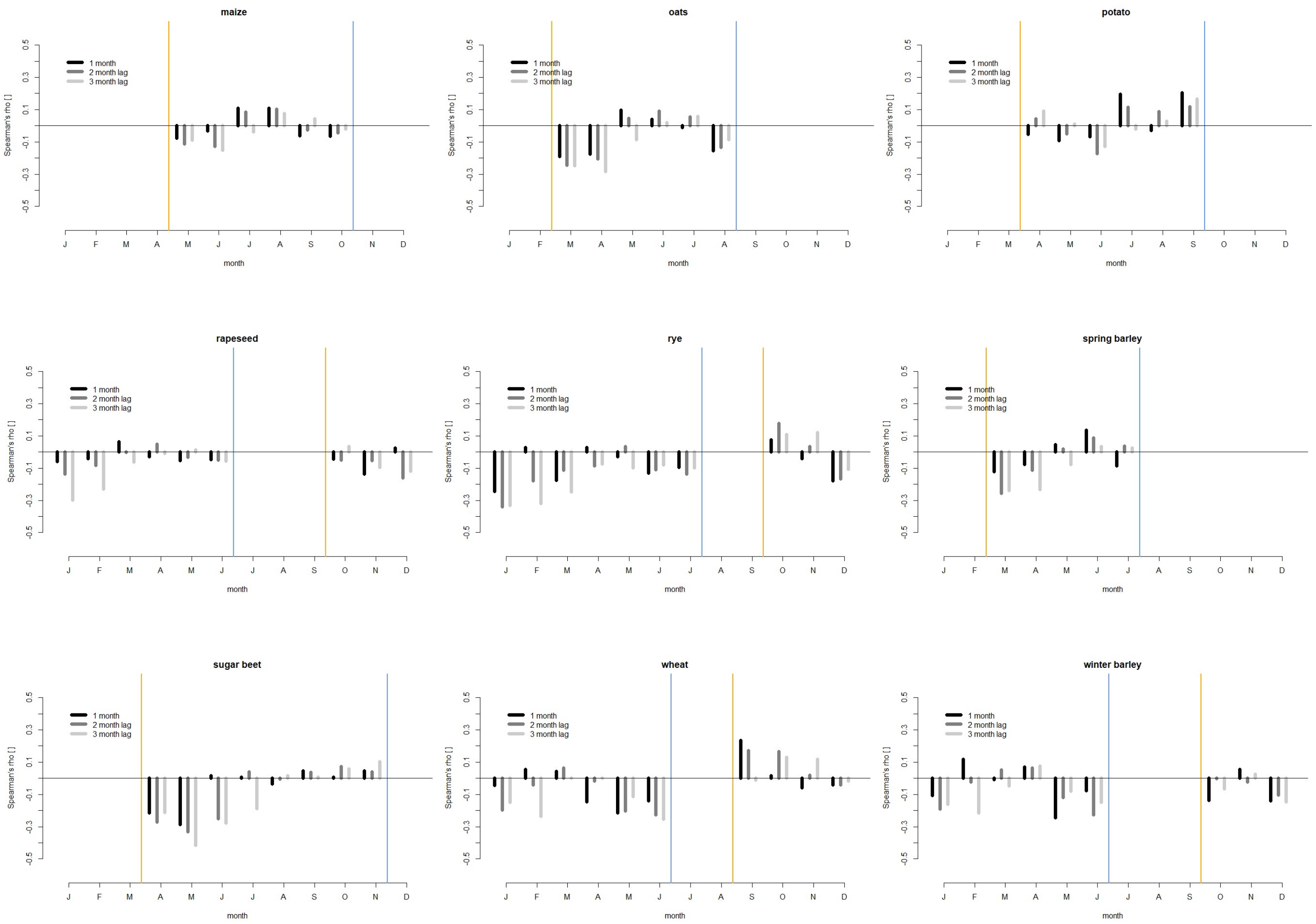


Figure 13 Spearmen's rho correlation coefficient annual pattern between SPEI (DH-Weather data) in 1 to 3 months lag and SYRS for selected regional annual production crops (maize, oats, potato, rapeseed, rye, summer barley, sugar beet, wheat, winter barley; yellow line general sowing time; blue line general harvest time).

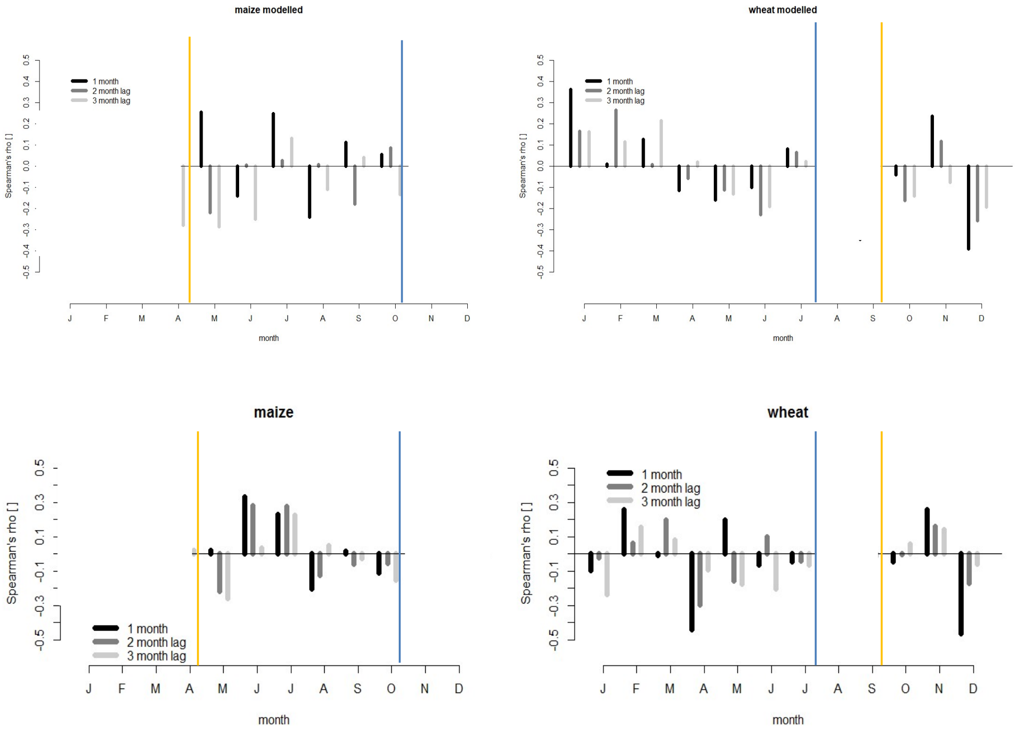


Figure 14 modelled and comparison period annual patterns of Spearman's correlation coefficient between SYRS and SPEI for maize and wheat in 1981-2010.

The annual correlation pattern derived for maize deviates from the observed annual correlation pattern (shorter subset) in some crucial points. In June maize correlation coefficients were negative. Observed annual correlation patterns do not show this behaviour (Figure 14). *Vice versa* modelled patterns do not show the predominantly negative correlation coefficients in the observed patterns from August to October. These differences show that the model is not able to reproduce the drought pattern entirely and that the drought impact along critical stages of approx. flower initiation to ripening is not met by the model, yet.

Modelled and observed annual correlation patterns (shorter subset) for wheat show similarities (Figure 14). Both, annual correlations patterns follow the same course in the first year: neutral to negative coefficients in September, positives in October and negative in November, showing the model's capabilities to simulate this early development. There are deviations in the further course of development. These show the model's difficulties in predicting specific drought impacts. Most prominent is the positive correlation coefficient in May, indicating the negative drought impact around the critical development stage of flowering that is not reproduced by the model. The shift from positive to neutral correlations in January and February in the simulation appears not until February March in the observed annual correlation pattern. The prominent negative correlation coefficient for observed April is stronger than those found in the simulation data (Figure 14).

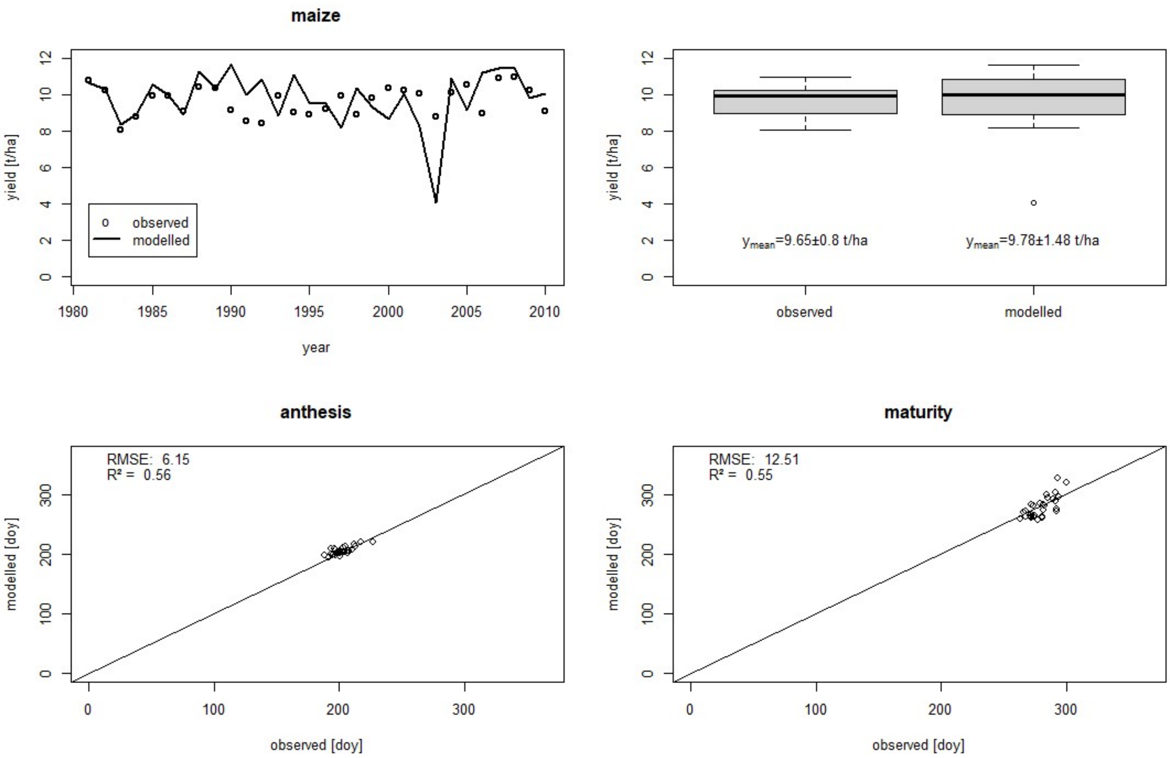


Figure 15 maize comparison of modelled and observed time series for Lower Saxony, Germany (1982-2010).

In regards to identifying differences between model and observation, we found substantial discrepancies and similarities comparing modelled and observed annual correlation patterns indicating issues that can be targeted by improvements and potential of models to reproduce specific responses that should be kept.

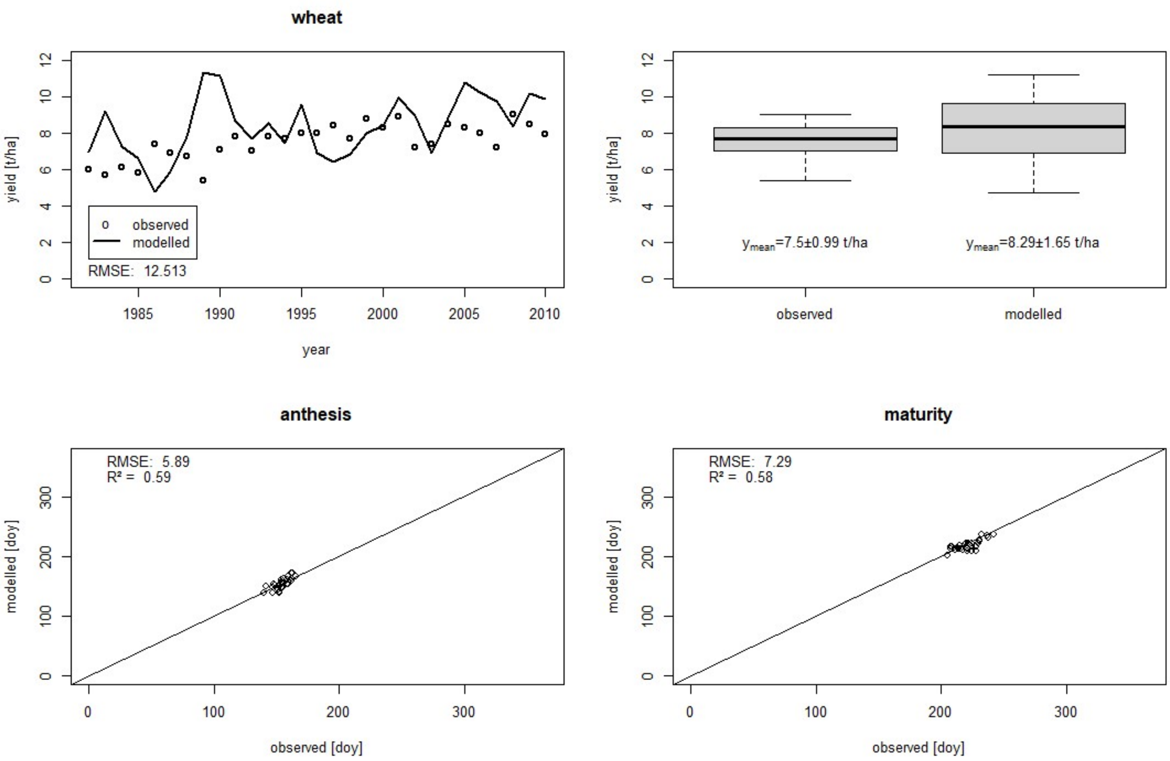


Figure 16 wheat comparison of modelled and observed time series for Lower Saxony, Germany (1982-2010).

Similarities speak for the quality of the model to reproduce the monthly impact of on production system. Both show a positive correlation after sowing (Figure 14). Notably, the annual correlation patterns provided for the first year of wheat production aligns well in the first production year after planting (Figure 14). In terms of model improvement, these features need conservation.

Some outstanding features of the annual correlation patterns in our model example were not matched, reproducing these, however, is a necessity in assessing agricultural production systems in regards to challenges from climate change. We found various deviations, inversions in annual correlations patterns for some month in the model. These can be interpreted as insufficiencies of the model to capture specific temporal features, e.g. specific development stage related stress reactions of a production system—for instance, the positive correlation coefficient not reproduced by the model for wheat around anthesis (Figure 14).

Discussion

Data transformation and data preparation

SYRS

Providing the standardised yield residuals series was successful. While aspects of the identified trend functions might describe developments reasonably, they are limited in their significance through the focus on accurate description for trend adjustment. Consequently, trends are not necessarily derivable from these functions (Lobell et al. 2009; Van Ittersum et al. 2013).

SPEI

The standardised precipitation evapotranspiration index provides a relative assessment of drought and wet conditions. The variability in monthly precipitation sums is small over the year (Metzger et al. 2005); drought spells are rare (Trnka et al. 2011; Gömann et al. 2015). Occasional months with less than 20 mm precipitation have been reported (31 in 70 years). This finding is in agreement with droughts being rather rare in the general temperate oceanic climates of western central European (Peel et al. 2007; Trnka et al. 2011). Drought conditions found here will match moist conditions in regions were drought indices are typically applied (Vicente-Serrano et al. 2010). However, probabilities for some adverse environmental conditions, i.e. water scarcity during vegetation growth through shifts of precipitation into winter seem to increase drought risks in North-Western Germany and parts of Europe (Gobin 2012; Trnka et al. 2014; Gömann et al. 2015).

Inventory of drought patterns

Generally, the impact of adverse environmental conditions on yield variability is highly complex (Estrella et al. 2007; Gobin 2012; Trnka et al. 2014; Gömann et al. 2015). The correlation coefficients do not indicate drought impact absolutely (Potopová et al. 2015). A positive correlation coefficient shows the drought condition's negative impact on yield. However, the reverse is valid as well, moist conditions contributing positively to yield. Eco-physiological context is needed to identify the processes behind key traits of major annual correlation patterns.

Grain crops, including cereals, maize, and rapeseed, share some traits. Germination to emergence and the transition between vegetative and reproductive development until fruit set are typically considered critical development stages. The success of germination requires specific environmental conditions, and the young crop is vulnerable and limited by its reduced access to resources (Barnabás et al. 2008; Gobin 2012).

Reproductive processes require optimal environmental conditions to succeed, and success typically determines the development of the harvested yield components (Barnabás et al. 2008). Drought can have a severe impact on fertilisation, e.g. maize needs ideal conditions of temperature and water supply to produce viable pollen (Barnabás et al. 2008). Further drought can shift the development of female and male reproductive organs; jeopardising cross-fertilisation success (Barnabás et al. 2008). The positive correlation coefficient found in spring/ summer aligns with the transition from vegetative to reproductive development in most of the grain crops produced in Lower Saxony (Figure 13).

The specific annual correlation patterns found for spring and winter barley shows the importance of specific production systems on yield variability. Spring and winter barley pattern align in a way that they balance each other. In a scenario with both systems in place, a severe single drought event at any given time would only impact one system, negatively. Diversification is a classic and relatively easy mitigation strategy; it works well, especially for highly unpredictable environments (Olesen et al. 2011; Kollas et al. 2015; Challinor et al. 2018). Whether this is a viable strategy depends on the socio-economic context. For instance, spring barley is used widely for brewing only, and might not be substituted easily in the necessary quality.

Potato tuber formation is regarded as the most sensitive stage to adverse environmental conditions. Potato production needs relatively high and reliable water supply to be successful (MacKerron and Jefferies 1986; Walworth and Carling 2002; Gobin 2012). Drought impacts quantity and quality parameters of tuber development, negatively. It can have an impact on the number of tubers and their size (Haverkort et al. 1990; Ojala et al. 1990). Tuber initiation of potato has a beneficial response to dryer conditions (Haverkort et al. 1990; Ojala et al. 1990). We found negative correlation coefficients up to three months after planting. Water surplus might negatively impact tuber development in this stage, possibly through altered heat balances in the soil. Correlation coefficients are positive in later year (July, August) aligning with the lower sensitivity to dryer conditions expected during bulking and late development (Struik et al. 1989c; Walworth and Carling 2002).

Root development determines the yield of sugar beet. While sugar beet is not regarded as overly sensitive to some water deficit (Kirda et al. 1999), more severe drought can be an issue hampering yield development (Ober and Rajabi 2010). Kirda et al. (1999) report droughts have the most substantial impact during emergence and early growth periods under arid climate conditions of Anatolia, Turkey. Generally, the consistently small positive correlation coefficients show sugar beet's requirements are well covered under the recent climate of

Lower Saxony. On the other side, moist soil conditions can hamper the development of sugar beet by, e.g. postponement of sowing, lack of aeration, and altered soil heat balance (Pendleton 1950; Hoffmann and Jungk 1995; Jacobsen 2006). The high soil moisture found after the typical restock of water storage after winter can explain the strong negative annual correlation patterns found in early development. Small correlation coefficients in the later development of sugar beet (June) indicate some negative impacts of dryer conditions.

We were able to compare these patterns with those of a study applying the approach to statistical yield data in the Czech Republic, e.g. maize shows positive correlation coefficients in the summer month, too (Potopová et al. 2015). However, correlation coefficients found in Lower Saxony, have generally smaller ranges and various crops show less pronounced and in parts deviating patterns. These deviations are especially the case for rapeseed (Potopová et al. 2015). These differences can be a result of data used. While Potopová et al. (2015)s' evaluations rely on a range of sites, i.e. 304 weather stations and several sites providing yield, here regionally aggregated data is evaluated against a selected representative weather station. Additionally, the Czech Republic is characterised by a more continental climate with more pronounced heat and drought episodes that might lead to stronger accentuated patterns (Metzger et al. 2005).

Modelled time series

We were able to derive a reasonable calibration for maize and wheat production systems with DSSAT-CERES. They emphasise phenology before yield. Further, we assume that differences between observed and modelled yields are alone due to the different responses. We are aware that various factors account for variability between model and observation. While crops respond to a plethora of environmental conditions, crop models work only on a subset of certain climate elements. The selection and composition of these boundary conditions have an impact on the model results. For instance, canopy temperature improved model results compared to mean temperatures (Siebert et al. 2014). Arguably, the setup and parametrisations of the model used in this study are rather general and simple. We used rigid production schemes to model yield, not utilising available knowledge about changes in production, e.g. cultivars, machinery, or shifts in climates, e.g. earliness and extension of vegetation period, or shifts of land use (Estrella et al. 2007). The differences found here between reference, and the shorter comparison subset of annual correlation certainly indicates some shifts.

Additionally, regionalisation is very coarse. The model is set up around one representative site with specific environmental conditions certainly not recapturing all features found in Lower Saxony. Tapping more data sources can provide a more detailed picture and improve the overview (Potopová et al. 2015). We find stronger absolute ranges in the modelled correlations. This stronger variability can be a result of higher variability of a specific site compared to the more balanced spatial means in observed statistical yields (Zhao et al. 2015). Also, the monthly resolution is too coarse to represent individual phenological development stages (Meier et al. 2009; Strer et al. 2018). These stages are frequently only several days in length (Meier et al. 2009). A higher resolution can provide an evaluation of actual development stages. However, this requires crop models, phenology and weather data that can resolve the problem on this level (Rötter et al. 2011, 2018a).

Despite, steady progress in improving crop simulation models, they show already a bias towards modelling only few mitigation strategies because they can be modelled and preferring some crops before others (Challinor et al. 2018; Rötter et al. 2018a). Therefore, tools like crop simulation models that are essential in long-term risk assessment for agricultural production have to improve further to simulate specific challenges, e.g. shifting environmental patterns in a climate change setting (Gömann et al. 2015; Strer et al. 2018; van Rüth et al. 2019).

We see two applications for the method to improve crop simulation models: for parameter estimation aiming at providing abiotic stress processes, more adequately (Rötter et al. 2018b), and for the identification abiotic stress processes that cannot be modelled with crop simulation models. Solving the optimisation problem not or not only for the goodness of fit parameters and mean yields, but for pattern might improve the model towards modelling more accurately the response to drought (Rötter et al. 2011, 2018a; Martre et al. 2015). This certainly needs some more work on details. An advantage is that no additional data were required to calculate annual correlation patterns compared with those anyway needed for setting up the crop simulation model. An extension of the approach on other adverse environmental conditions that are index-able is a possibility to account for many more environmental factors that impact yield development. Many improvements for crop simulation models are available: new approaches that include phenology specific responses of the crop simulation model to stress have improved yield response, significantly (Challinor et al. 2005; Lizaso et al. 2017). These improvements are typically highly specific. Any systematic identification, e.g. through pattern analysis, can help to focus resources on specific improvement. For example, a point we identified to be improved is drought specific response around flowering of grain crops (Figure 14).

Conclusion

The annual correlation patterns found for lower Saxony show that relative droughts have already impacted the agricultural production systems in the recent past. Despite some similarities, these patterns are specific for each crop and even for each production system.

The inventory provided here allows developing specific mitigation strategies that reduce the impact of the patterns on yield variability. A path that came up is spreading the risk by implementing a diverse range of crops and production schemes with balanced annual correlation patterns; stabilising the yield variability on a high level.

Models should improve to reproduce drought response more, adequately. In terms of analysis of model results by annual correlation patterns, we see the identification of starting points as a way for well-targeted instead of arbitrary improvements. Additional refinement is needed to analyse phenology-stage-specific response for drought. Nevertheless, we are hopeful that this can help to resolve certain common biases in crop simulation model application, e.g. mitigation strategies that are accessible with recent models being over-represented.

The stage-specific impact of adverse environmental conditions on agricultural is a complex and intriguing problem. Better understanding together with the improvement in analysis tools, can be a part in developing suitable mitigation strategies for agricultural production systems in Lower Saxony as well as worldwide. Especially, given that agricultural production is challenged by an ever-growing demand of higher and stable yields to ensure world nutrition, and by shifting environmental conditions through climate change.

General discussion

Synthesis

The understanding of the impact of adverse environmental conditions on critical development stages of crop production is still limited (Mäkinen et al. 2018). By answering the initially stated research questions, this thesis contributes to deepening this understanding by identifying critical development stages, analysing recent environmental patterns and assessing risk for the North German Plain under climate change.

Chapter 1 analysed literature to identify relevant development stages in crop development and contrasts this with an overview of the implementation of phenology and development stage-specific stress impact in common crop simulation models, answering:

1. **Which critical development stages are relevant in the context of adverse environmental conditions for the North German Plain?**

Chapter 2 identified the abundance of adverse environmental conditions during critical development stages of maize and wheat, for four sites in the North German Plain and projects them into the future (2021-2050); answering:

2. **How will the abundance of critical development stages shift in the future of the North German Plain?**

Chapter 3 identified the gap between observed and modelled yield response to annual drought patterns in Lower Saxony; answering:

3. **In which regard are models capable of depicting the specific impact of adverse environmental conditions on crop development?**

Which critical development stages are relevant in the context of adverse environmental conditions for the North German Plain?

Critical development stages pose a remarkable problem. The impact of adverse environmental conditions and critical development stages can have very specific and hardly predictable outcomes for crop production. The literature study provides some insight into this complexity and variability. Chapter 1 shows an overview of the perception of critical development stages in the scientific community. It evaluates research articles for critical development stages of production crops common in the North German Plain. However, it falls short in providing a general systematic definition of the problem.

Critical growth stages have been considered in agronomy for a long time. There is a consensus to define critical development stages by the potential loss of the harvestable crop component or by the loss of total crop vitality. For instance, in cereals, flowering determines grain development, with flowering requiring a narrow corridor of environmental conditions to succeed, or in sugar beet unfavourable conditions can induce unwanted developments, e.g. early sprouting redistributing resources away from storage in the root. Systematic research on specific stress process is needed to provide a better understanding of fundamental processes and to navigate the complexity that critical development stages provide (Hlaváčová et al. 2018).

In contrast to the highly diverse perceptions in experimental and basic research on the topic, the response to adverse environmental conditions is implemented rather simple in crop simulation models (Rötter et al. 2011, 2018a; Hlaváčová et al. 2018). Crop simulation models are limited to a small range of phenological development. Some distinguish only between vegetative and reproductive development (Chapter 1). Development-stage-specific processes are even rarer. Solutions for such specific stress impacts are considered frequently, but it lacks in their systematic implementation. Such model adaption improving prediction of crop development processes significantly include a wide range from new structural attempts for models to the implementation of new stress-sensitive processes, e.g. heat-specific responses by temperature ranges for pollen fertility, or sophisticated temperature response functions (McMaster et al. 2005a; Challinor et al. 2005; Wang et al. 2017; Lizaso et al. 2018).

Despite these limitations, process-based dynamic crop models can be a valuable tool for analysing the response of complex systems to environmental conditions. This requires adequate application concepts, calibration and validation based on systematic research for specific environmental stress impact on crop development.

For instance, Chapter 2 and Chapter 3 show approaches that use models to identify and assess adverse environmental conditions and critical development stages. Chapter 2 relies on the overview provided in Chapter 1. It focusses on the abundances of various adverse environmental conditions during selected critical development stages, with phenological stages being predicted well. It finds that these abundances are likely to increase in the North German Plain. Chapter 3 aims to identify critical development stages for drought by an analysis of environmental patterns. The patterns certainly provide hints where drought might impact development strongest.

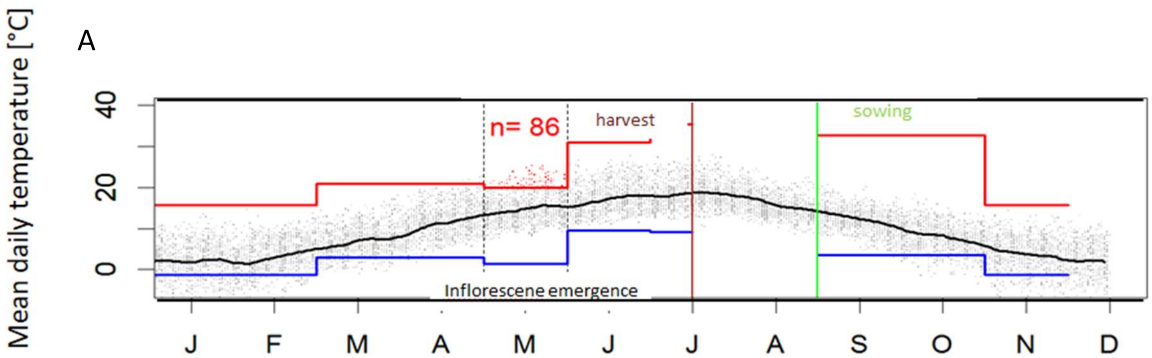
How will the abundance of critical development stages shift in the future of the North German Plain?

Shifts in environmental patterns due to climate change are likely to lead to an increase of the abundance of adverse environmental conditions along critical growth stages in the North German Plain.

The abundance of adverse environmental conditions is assessed through the evaluation of threshold exceedances of, e.g. climate elements for maize and wheat production at four representative model regions Diepholz, Uelzen, Fläming, and Oder-Spree in the North German Plain, Germany (Figure 17). A model (DSSAT-CERES) was set up to simulate general maize and wheat production, including phenology. The models' drawbacks in simulating specific impacts during critical development stages were bypassed by focusing on the abundance of adverse environmental conditions and neglecting yield (Figure 17).

The general procedure is straightforward. Figure 17 depicts it for the example of inflorescence emergence of wheat. Figure 17 (A) shows the initial situation: threshold exceedances during this phenological development stage in the reference period (red dots: daily mean temperatures above threshold). Agrometeorological data for the reference period were used to demark the length of mean phenological stages. Overlaying the scenario temperatures illustrates the increase in abundance of adverse environmental conditions during inflorescence emergence (Figure 17 B). To refine the approach, DSSAT is used to determine phenological stages dynamically for each year (Chapter 1). Three specific general circulation model projections were evaluated representing a minimal, medium and maximal temperature increase within climate change RCP 8.5 continuum for the period 2021-2050 (Figure 17).

Generally, the abundance of adverse environmental conditions is likely to increase in future. Despite some earliness in phenology, threshold exceedances of high-temperature are more frequent in 2021 to 2050 than in 1981 to 2010. On the opposite frost will still occur in future and potentially impact early development stages, negatively. This counterintuitive contradiction is due to shifts of variability. These shifts follow general expectations of temperature shifts through climate change (Figure 11, Houghton et al. 1990; Porter and Semenov 2005; Barker 2007; IPCC 2014).



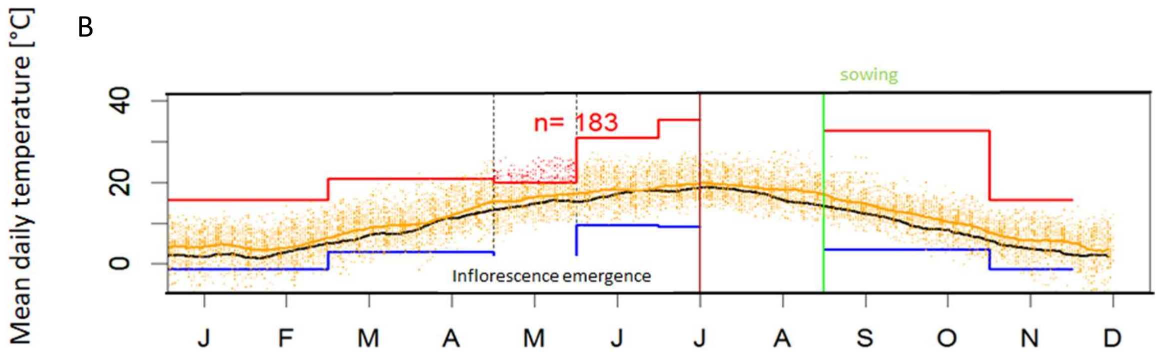


Figure 17 procedure applied to identify adverse environmental conditions, e.g., temperature by exceedance of thresholds. Plots are based on Diepholz weather stations data (DWD), mean phenology (DWD), and medium climate scenario (Supplementary material 1, Table 2). Phenology specific thresholds for wheat, according to Porter et al. 1999 (blue – minimal temperature thresholds, red - maximum temperature thresholds). (A) Reference period from 1981 – 2010 (grey – daily mean temperature, solid black line – seasonal temperature curve of mean temperature). (B) Scenario period 2021-2050 (orange – daily mean temperature, solid orange line – seasonal temperature curve of mean temperature).

Water balance - here indicated as water content - shows that both droughts, as well as water surplus, have to be considered in future for some development stages. However, water balance is challenging to evaluate, since its strongly depends on local soil properties.

Chapter 3 supports these findings. Where drought patterns were analysed for a more recent period (1981-2010), this subset showed shifts in environmental patterns' impact on yield variability compared to the general, longer evaluation period (Chapter 3). However, the high level of aggregation does not allow to distinguish between pure environmental and other shifts, e.g. management.

In which regard are models capable of depicting the specific impact of adverse environmental conditions on crop development?

The comparison of drought pattern impact between observed and modelled yield variability has shown that this yield response cannot be reproduced sufficiently by crop simulation models, yet. Amongst, others this has a major implication for the analysis and development of climate change mitigation strategies for cropping systems using crop simulation models.

In many regards, e.g. by using only one model and by limitation to an exemplary site, this research study has rather the character of a case study that tests a novel application for annual correlation patterns. Nevertheless, an inventory of annual correlation patterns between standardised evapotranspiration index and yield residuals was compiled for major production systems of Lower Saxony. These annual correlation patterns provide a systematic overview of drought impact on yield variability.

Most patterns found were explained reasonably by eco-physiological processes, e.g. sensitivity to drought of cereals after sowing. The method can be a valuable technique to categorise different regions and production systems and to identify suitable adaption to climate change. Therefore, a broader inventory for different cultivars, regions, environments, and production systems seems to be a desirable goal. Possibly, allowing the identification of suitable agricultural production systems and management strategies used elsewhere.

Adequate yield response is a prerequisite for many model applications. The comparison between observed and modelled responses showed that DSSAT was not able to reproduce these patterns for wheat and maize, sufficiently.

Chapter 1 supports this finding. The literature review showed that despite the consideration of some process describing critical development stages, their handling in crop simulation models is somewhat neglected or arbitrary in selection. An improved sensitivity analysis using patterns might provide better ranges in which crop models can be used for the assessment of adverse environmental conditions and critical development stages.

Despite, the claim for systematic improvements in models, this thesis lacks in providing actual improvements. It omits yield response in Chapter 2 and only approaches improvement by identifying mismatches in drought patterns in Chapter 3. It leaves the implementation of novel processes that describe the stage-specific stress response found in the context of modelling to future studies.

Reflection

The thesis answered the initial research questions by identifying critical development stages, providing a partial risk assessment for crop production under climate change for regions in the North German Plain, and identifying deficiencies in crop simulation models to simulate the stage-specific impact of adverse environmental conditions. Certainly, each answer generates new perspectives and new questions. There is a demand for more systematic concepts to identify critical development stages, an examination of climate change expectations, and ideas for improvements and optimised applications of crop simulation models to assess the impact of adverse environmental conditions on critical development stages on agriculture.

Determining what adverse environmental conditions and critical development stages are is crucial to their understanding and for systematic research of the topic. The many definitions presented, analysed, and applied in various research studies show that there is a need for clarity and comparability. The thesis uses two very different pathways to approach the problem: one top-down approach partitioning the problem in manageable bits and one bottom-up identifying regional adverse environmental conditions' impact on agricultural production.

There are many expectations for climate change. These expectations and their implication need a thorough consideration not only because they add an additional layer of uncertainty. They have consequences for the development of climate change mitigation strategies, too.

There is no doubt about the potential of crop simulation models to analyse challenges and risks for agricultural production through shifts in environmental conditions. The thesis showed with two approaches that a thoughtful application of models could identify adverse environmental conditions and predict some of their impact on crop development. However, it also showed that model capabilities are limited in providing an adequate stage-specific response. It is necessary to discuss how to improve models to resolve the problem more adequately—well knowing that some limitation will remain due to basic concepts in crop simulation models that are contrary to simulating rare and specific events.

A prerequisite for research on critical development stages and potential improvements of crop models is the availability of validation and calibration data. Large amounts of suitable data of adverse environmental events are needed to analyse phenology-specific stress response, improve crop simulations, and provide general understanding through systematic research (McMaster et al. 2008; Rötter et al. 2011, 2018a). Therefore, long consistent meteorological, and crop physiological time series are needed. However, these time series are challenging to acquire in a sufficient extent that allows for statistical evaluation of extreme events.

Systematic research can help to acquire data on various scales where it is not available yet. Of interest are especially the analysis of basic processes in controlled laboratory experiments focussing on individual plants or even specific plant organs. In terms of the development of a risk assessment for an entire region like the North German Plain, upscaling of basic processes is necessary. This upscaling can include on an intermediate level field experiments with controlled environmental factors, e.g. rain-out shelters bridging the gap from basic processes to the field level. Furthermore, methods are needed, like remote sensing, that are well-suited to make the step to describing larger spatial scales.

Identification of critical development stages

The problem around critical development stages and adverse environmental conditions is intuitive. It is widely accepted that environmental stressors impact crop development and that some stressors can have an extraordinary impact during specific development stages (Gobin 2012; Trnka et al. 2014; Gömann et al. 2015; van Rüth et al. 2019). It is a complex problem that depends on numerous, interacting factors, e.g. crop properties (Fowler et al. 1996), management of production systems (Gobin 2012); duration of environmental conditions (Barnabás et al. 2008; Lizaso et al. 2018); local environmental properties, or daily timing of environmental conditions (García et al. 2016). Doubtless, more profound knowledge and a systematic classification of adverse environmental conditions and critical development stages can provide valuable insight in yield variability and crop risks of agricultural production systems: starting from suitable approaches to identify critical development stages over basic research tools to evaluate and analyse the problem's different aspects to a precise definition describing the complex duality between adverse environmental conditions and critical development stages.

The literature study in this thesis showed that the topic had been considered in various forms for various crops and numerous environmental conditions (Chapter 1). All assessed critical development stages differently; however, all based on reasonable considerations. Typically, development stages were *critical*, if requiring general or specific environmental conditions (Barnabás et al. 2008); environmental conditions were *adverse* if they triggered unwanted crop development (Ober and Rajabi 2010), or production steps were hampered substantially (Gobin 2012). The definitions, applied in these studies, are very specific and sometimes only sufficient enough to resolve the actual research question. More systematic approaches are rare (Wollenweber 2003).

On a level, the problem is a philosophical one that cannot be resolved in its entirety. The duality between environmental conditions and development stages defines if they are *adverse* environmental conditions and *critical* development stages or something else. Therefore, nearly all development or production stages contain the potential to be critical development stages, and all environmental conditions bear the potential to be adverse environmental conditions, with possibly only small difference qualifying between beneficial and harmful. For example, high humidity is beneficial for water efficiency through lower vapour pressure deficit, but ideal for the development of pests (Vining 1990).

Three elements on different levels appear to be relevant in assessing critical development stages:

Potential critical development stages are: (1) all stages of crop development that determine the development of the harvestable product, (2) all stages of crop development that substantially jeopardise the general crop development, and (3) all stages of the production process that are crucial to the success of the agricultural pursuit.

Additionally, for adverse environmental conditions applies that they have the potential to substantially hamper the crop development or the production process through setting inadequate boundary conditions for agriculture, e.g. by suboptimal resources availability.

A point not considered in depth in this thesis, but important for the assessment is: what perspective is taken; how are *adverse* and *critical* defined? In this thesis, the assessment of *adverse* and *critical* comes from a limited human viewpoint: it focuses on yield alone. Other perspectives are imaginable. For instance, general survival and reproduction are of higher importance for crops than yield *per se*. Stress responses are diverse, e.g. adjusting the number of kernels, or shifting development processes (Hoffmann 2010a; Ober and Rajabi 2010). Such strategies guarantee the reproduction sometimes on the coast of overall yield.

Approaching critical development stages

Based on these general assumptions and the findings of the literature study, this thesis follows two approaches analysing adverse environmental conditions' impact on critical development stages.

One top-down approach that uses crop modelling to partition the problem into manageable and analysable bits (Chapter 2). Many risk assessment studies involving crop simulation models follow such top-down approaches that start with an environmental scenario and use the model to derive a local impact by comparison to a reference (Beveridge et al. 2018). Indeed, *crop simulation models* harbour the potential to analyse the response of complex agricultural production systems to adverse environmental conditions by breaking down the complex interactions and focusing on essential processes (Rötter et al. 2011). It was possible to derive reasonable and consistent likelihoods for adverse environmental condition throughout three different scenarios. While the single processes and the derived results are rational, the approach is highly arbitrary because of its usage of preselected critical development stages. The findings in Chapter 3 and the evaluation of the implemented phenological process in Chapter 1 suggest that crop models – here for the example DSSAT CERES - have difficulties in simulating core aspects of critical development stages, e.g. reproduction of yield response to drought, yet. They can be improved; supplemented processes and alternative application methods have shown to be very useful to simulate and analyse phenology-specific stress (Chapter 2, McMaster et al. 2005b; Gobin 2012; Trnka et al. 2014; Challinor et al. 2018).

The other approach uses *environmental patterns* (Chapter 3). It is a more regional-based bottom-up approach to analyse the impact of adverse environmental conditions on critical development stages. It is based on the actual systematic analysis of local, or regional conditions that can be upscaled or aggregated to an overall picture. It allows linking regional conditions and knowledge to a broader perspective (Beveridge et al. 2018).

Annual correlation patterns provide a reasonable inventory of adverse environmental conditions impact on yield development (Chapter 3). The approach is limited. The temporal resolution is too coarse to resolve phenology. A contextualisation of patterns is necessary to interpret the results. However, the approach was able to successfully identify a mismatch between observed and modelled responses to drought patterns. Improvements are needed to close the gap between the understanding of abiotic stress physiology of crops and its incorporation into eco-physiological models to more accurately quantify the impacts of extreme events (Rötter et al. 2018b).

In their own right, both approaches achieve their objectives well. Nevertheless, the contrast between these two pathways - the top-down and bottom-up - seems irreconcilable (Beveridge et al. 2018). Certainly, an integration of both philosophies, like the iterative and interdisciplinary workflow described by Beveridge et al. (2018) might provide a more holistic perspective for the problem.

Multiple stresses

This thesis does not consider multiple stresses. Simultaneous or sequential impact of multiple stressors without the systems chances to regenerate can be even more critical for the agricultural pursuit than single events (Wollenweber 2003). Exactly these interactions are yet not well understood and therefore not yet fully implemented in models (Hlaváčová et al.

2018). Trade-off effects, on the site of physiological processes, can hamper or amplify the impact of adverse environmental conditions (Vining 1990; Barnabás et al. 2008).

Additionally, pests, diseases, or intraspecific and interspecific competition can exceed additional stress. Their impact increases even further under limited resources. Handling several interacting development models, e.g. for the crop-soil-systems, competitors, or pests comes with an increase in complexity and needs thorough considerations (Pandey et al. 2015, 2017; Strer et al. 2016). It is an intriguing problem in general and for the simulation with models.

It is reassuring that the hurdles for a substantial impact by adverse environmental conditions usually are quite high. Only if prolonged stress, multiple stressors or extraordinary stresses co-occur with susceptible development stages, a terminal effect on crop health will be imminent (Wollenweber 2003). But, a significant impact on the quality and quantity of the harvestable product can take place much earlier under less unfavourable conditions (Barnabás et al. 2008).

Climate change projections and expectations

Climate change expectations

There are certain expectations for climate change in the North German Plain. The Background chapter has already established these major environmental shifts due to human-made climate change. These shifts come in a broad range of manifestation and will impact crop production of the North German Plain (Trnka et al. 2011; IPCC 2014; Gömann et al. 2015; van Rüth et al. 2019). Generally, adverse environmental conditions are likely to increase in Europe (Trnka et al. 2011; Gömann et al. 2015). This includes the increase of exceptional events in abundance and intensity in the North German Plain, e.g. severe environmental episodes like droughts or heatwaves as seen in 2003 or 2018 in Germany (IPCC 2014; Gömann et al. 2015; Russo et al. 2015; Hanel et al. 2018; van Rüth et al. 2019).

This thesis findings support the general expectations projected for the North German Plain. Chapter 2 identified an increase in the abundance of adverse environmental conditions by evaluating threshold exceedances, and Chapter 3 found shifts in annual correlation patterns when evaluating more recent data subsets. There are parallels between findings in this thesis, and other studies for future conditions in the North German Plain (Trnka et al. 2014; Gömann et al. 2015; van Rüth et al. 2019). Admittedly, it has to be considered if these agreements are genuine or if they are because they are based on the same sources using the same framework and the same GCMs (Chapter 2, IPCC 2014; Spellmann et al. 2017). Nevertheless, the findings were consistent throughout all three projections, analysed here (Chapter 2). While the results for recent developments in Chapter 3 are based on observation, its high degree of aggregation and generalisation allows not to differentiate between climate change and management change impact on the production systems.

Given these expectations and challenges through climate change and adverse environmental conditions for the North German Plain, mitigation and adaption strategies are necessary to secure reliably high yields.

Mitigation strategies

Developing climate change mitigation strategies that consider adverse environmental conditions are necessary to adapt to the expected challenges through climate change in the North German Plain and world-wide. A plethora of mitigation strategies and adaption mechanisms for agricultural production to climate change is imaginable, available and frequently discussed, e.g. irrigation against drought, breeding of stress-resistant cultivars possibly by genetical engineering, companion planting of resilient cultivars or epigenetic traits, insurances against weather caprices, altering crop rotations, nanoparticle soil additives tweaking soil properties to improve soil nutrient and water supply, autonomous robots caring for individual crops, or diversification to compartmentalize risks. However, all beneficial techniques and strategies can come with trade-offs (Vining 1990). These trade-offs can be unforeseen, reaching from higher costs to long-term devastations, e.g. by soil salinization.

Additionally, to climate change, the agricultural pursuit is under pressure from socio-economic processes, e.g. fluctuating market prices. A reliable socio-economic framework that provides sufficient planning security might be as important as climate change mitigation strategies and will shape the future of production systems maybe even more than recommendations based on research (BMEL 2019). This pressure might lead to investments in infrastructure not yet common: For instance, today, irrigation is rare in the North German Plain. It can be found where vegetable production is common, e.g. Uelzen. Recent history shows that irrigation was of higher importance in the eastern parts of the North German Plain before the collapse of the German Democratic Republic. It was widely applied because it was politically wanted to secure high yields (Wechsung 2008; Spellmann et al. 2017).

Certainly, the agricultural sector is innovative and industrious in finding methods to increase efficiency and to secure high yields. Doubtless, mitigation strategies and adaptions will be found that secure, reliable yields on high levels in the long-term, if the right focus is set. Problems of environmental variability and extreme weather have – certainly in parts due to their complexity - not been in the line of light, yet. A focus is needed to avoid consequences that already occur. Ill-focused breeding might have led to a significant depletion of genetic traits for resilience to environmental variability and extremes throughout Europe. For instance, Kahiluoto et al. (2019) identified only a few genetic hotspots of wheat remain away from main agricultural production areas.

A mixture of various strategies should be expected and applied - one individual all resolving technique is not realistic (Beveridge et al. 2018). However, a framework for future development can be useful. It is somewhat likely that production systems will be adapted by many slight changes based on various individual mitigation strategies applied using local knowledge for local adaption pathways (Beveridge et al. 2018).

If there are mitigation strategies that arise from the results of this thesis, they are diversification of crops and flexible response to adverse environmental conditions. Diversification compartmentalises specific risks and is a well-established and a widely applied risk mitigation strategy; from agriculture to stock markets. For instance, this diversity could include especially resilient cultivars or especially resilient epigenetic traits (Gallusci et al. 2017). Given the challenges identified in the diversity of critical development stages (Chapter 1), abundances and diversity of adverse environmental conditions (Chapter 2), and the variations in crop-specific annual correlation patterns (Chapter 3), makes relying on one or few crops and production schemes a gamble that can jeopardise the total agricultural pursuit. Consequently, a diverse mix of crops and production systems might be the first simple step to reduce this risk. Trade-offs have to be expected, e.g. a decrease of mean yields, a production of larger portion crops that are potentially less economically valuable, a more complex logistic and more required resources (Vining 1990; Trnka et al. 2011).

Further, patterns can identify knowledge and techniques to improve local production systems. This includes adapting production schemes, e.g. modifying crop calendars and using cultivars with a phenological development that omits adverse environmental conditions under the expected climate regime. This valuable insight is potentially driveable by a pattern analysis (Chapter 3). For instance, summer and winter cropping systems of barley have shown significantly different responses to drought. An overlay of both barley production systems levels the risks. The periods with increased drought risk for one production system are beneficial conditions for the other and *vice versa* in terms of drought (Chapter 3). Production schemes identified by the annual correlation pattern can be applied elsewhere. This includes crop rotations and crop calendars elaborated for other regions where the expected environmental conditions can already be found. A transfer like this requires an inventory of sufficient patterns for various environmental conditions, e.g. precipitation distributions, heatwaves and for different production schemes.

Climate change models

General circulation models (GCM) are frequently used to analyse future developments through climate change (Chapter 2). They are mathematical models that simulate the earth's atmosphere and oceans. Different frameworks and scenarios provide boundary conditions for modelling the future development, e.g. the RCP of the IPCC. While climate projection models, as well as the framework behind them, are steadily improved, they are far from being impeccable.

Combined with crop simulation models in applications for climate change impacts, they certainly add an additional layer of uncertainty to the calculation. Many uncertainties and general processes are quite universal in modelling. Critical examination and discussion are needed when working with models. This holds true for climate models as well as crop simulation models and especially for their combination.

Although Tao et al. 2018 found that uncertainty by GCMs is smaller than that of adjacent crop models, it is necessary to consider this uncertainty. Corbeels et al., (2018) investigated the feasibility of crop simulation models to provide adaption strategies using 17 individual GCM runs with one crop simulation model (APSIM), finding high seasonal precipitation variability that led to arbitrary yield in the crop simulation model. Similar observations led in this thesis to neglect yield and its variability, and focus on the abundance of environmental events during specific development stages in Chapter 2.

The reliability of GCMs depends on the considered climate elements. While temperature, especially mean temperature, is generally well understood and confidently projected in scenarios, hydrological components are not. Ljungqvist et al. (2016) analysed long-term hydrological data and compared it to climate model results. They found that they performed poorly in replicating hydrological patterns. Another challenge is regionalisation. Global circulation models work on grids of 50 km x 50 km to 200 km x 200 km and have to be regionalised to finer grids or extrapolated for a specific site. Regionalisation is difficult; it has to consider site-related properties, e.g. soil, types vegetation, altitude, or topography to calculate local manifestation of climate. This regionalisation issue adds to those for crop models in this thesis, where individual sites have to represent entire landscapes (Chapter 2 and Chapter 3).

Ranges for the model are needed, in which the model can provide validated results for a specific question. A way is the use of model ensembles in climate as well as in crop modelling. Using ensembles developed into a standard in handling climate change scenarios and in crop modelling (Rosenzweig et al. 2013; Makowski et al. 2015; Ljungqvist et al. 2016; Corbeels et al. 2018). Research in the climate modelling community showed that the performance of model ensembles was better not only because of error compensation but also because of greater consistency and robustness of results (Hagedorn et al. 2005; Knutti and Sedlacek 2013). Various runs of distinct models capture a wide range of outcomes. For example, the study presented in Chapter uses an ensemble of three climate projections all being set in the RCP 8.5 climate pathway continuum in the IPCC framework provided by three independent institutions. The ranges given through the three distinct GCMs show a consistent image for crop production in the North German Plain (Chapter 2). The issues around modelling do not miraculously disappear by using ensembles; in the best case, they get a bit more assessable (Challinor et al. 2018).

Analysing risk through adverse environmental conditions with crop models

The nature of models is to simplify and generalise complex processes. Therefore, all models rely on three conceptual paradigms:

(1) They are a simplified representation of a natural or artificial original.

(2) Models are reduced in the number of attributes with a focus on those that seem relevant. In consequence, they are limited and provide only a selection of simplified processes to describe the complex reality.

(3) Models are set in a particular context: designed for a specific use, e.g. decision support, to resolve a specific problem, e.g. nutrient flux simulation, and valid only within certain limits, e.g. specific periods or parameter sets.

It is advisable when working with crop simulation models to remind one that they only shed light on some aspects in a narrow range, defined by calibration and validation. Consequently, the application of crop simulation models in risk assessment studies needs a thorough consideration of the model's sensitivity to resolve the research question.

In regards to the abundance of development stages and environmental conditions, crop simulation models seem limited. Depending on their purpose, CSMs can differ significantly in their treatment of key processes and in predicting response to environmental conditions (Challinor et al. 2018). For instance, they rarely distinguish more than two to five phenological development stages and rarely provide stage-specific stress responses (Chapter 1, McMaster et al. 2008; Rötter et al. 2011; Lizaso et al. 2017). Certainly, model responses are complex, but the complexity, diversity and abundance of development stages considered being *critical* and environmental conditions considered being *adverse* exceed the implementation of phenology and phenology-specific stress response by far (Chapter 1). Especially, the stage-specific stress response is evaluated not as satisfyingly (Wallach et al. 2018). This *per se* does not mean that crop simulation models are not capable of assessing stress-specific responses. But they certainly require an analysis of their sensitivity. This is supported by the model validation performed Chapter 3 that identifies: yield response to drought conditions of maize and wheat is simulated inadequately by the example model DSSAT. The model as parametrised for mean yields is not able to reproduce significant elements found in the observed drought patterns.

A consequence that can result out of these issues and limitations is a bias when using crop simulation models. Challinor et al. (2018) report that only a few (4) of the many adaption strategies discussed are examined regularly with models and Rötter et al., (2018a) found that maize and wheat while certainly important production crops are overrepresented in scientific crop modelling studies. These examples show that evaluation is skewed towards a few strategies that can be simulated with crop simulation models, rather than covering what is relevant in the broader socio-economic, or environmental contexts (Beveridge et al. 2018; Challinor et al. 2018; Rötter et al. 2018a). This problem also applies to this thesis; e.g. it is modelling only maize and wheat.

Given these issues, crop simulation models need improvement and new ways of application to provide an adequate risk assessment that includes adverse environmental conditions and critical development stages for a region under climate change like the North German Plain. An advantage of models is that they can be improved. This requires as a first step finding insufficiencies in simulating yield response.

Possible improvement

Rötter et al. (2018b) aggregated recent challenges and developments in crop modelling. These challenges include modelling of adaptations and mitigations, modelling the response to stress, e.g. heat stress, closing gaps in understanding by linking experimentation and modelling, integrating crop and economic modelling for more practical relevance, and assessing agricultural impacts using ensemble modelling. In terms of adverse environmental conditions and critical development stages, mid-to long term developments need to include adequate modelling of multiple stresses and yield quality. For some crops, yield quality response to specific stressors can be valuable information. Stress impacts yield quality, e.g. baking capability of flour which shifts under heat stress especially during ripening stage (Castro et al. 2007; Ober and Rajabi 2010), or the sugar content of sugar beet (Barnabás et al. 2008; Ober and Rajabi 2010).

One path to improve crop simulation models is a general overhaul of crop simulation models to improve on risk assessment by providing amongst others more adequate stage-specific responses (Challinor et al. 2007; Rötter et al. 2011; Ferrise 2017; Lizaso et al. 2017). Many approaches are possible for the implementation of phenology and phenology specific processes. McMaster et al. (2008) proposed a theoretical framework for a new variable model structure implementing phenological development and development specific processes. The crop simulation model IXIM is an example of a development in this direction for maize. Integration of phenological development and stage-specific processes results in significant improvements of predictions. Therefore, the model includes new thermal time calculation, a heat stress index, the impact of pollen-sterilizing temperatures, and the explicit simulation of male and female flowering as affected by the daily heat conditions (Lizaso et al. 2018).

Given the general complexity, implementation of all possible growth and development processes in a single crop simulation model is improbable. More frequent and more likely in crop modelling are improvements of single specific stress response for a specific problem (Challinor et al. 2005; Hlaváčová et al. 2018). Many of these arbitrary improvements for crop simulation models can be found, e.g. more refined temperature response functions (Wang et al. 2017), temperature response during critical development stages (Challinor et al. 2005), or a complete paradigm shift by using other environmental factors as drivers for the simulation, e.g. canopy temperature (Siebert and Ewert 2012).

The general overhaul based on systematic research is preferable; arbitrary improvements are more probable due to, e.g. limited data availability. All these approaches require processes to be identified. In this context, approaches identifying environmental patterns for production systems as in Chapter 3 can provide a focus and starting point for well-targeted improvement, including more systematic approaches in the long-term (Rötter et al. 2011).

Furthermore, other thoughtfully applied strategies for crop simulation models can compensate for the lack of capabilities. For instance, Chapter 2 omits disadvantages in stress response by focusing on the prediction of phenological development. It focused on the evaluation of shifts in the abundance of adverse environmental conditions neglecting yield impact and was able to provide valuable insight into a part of the problem.

Certainly, this thesis lacks in providing proof for all this in the form of an actual implementation of an improved response process to crop simulation models. It deliberately omits yield response in Chapter 2 and the identification of mismatches in drought patterns between observation and model might be a starting point but is nowhere near an improvement of any type (Chapter 3). It leaves the implementation of new specific processes to future studies.

Some aspects are universal in crop modelling, e.g. simplification, and generalisation and have to be considered in some way for all models alike. Therefore, it is a reasonable assumption that working with one model as an example to resolve aspects around adverse environmental conditions can provide some general insight into some crop simulation models handling the topic, well-knowing that each model will provide its very own results. Chapter 1 showed various approaches could be found in common models to simulate the impact of adverse environmental conditions on crop development. Only a crop model comparison study can provide clarity about how DSSAT performs in relation to other models on this topic. Certainly, these comparison studies are more resource-intensive than applying a single mode, but they are an excellent method to assess different models' capabilities. They are typically finding many similarities in the response of various models suggesting that there is a decent transferability between them (Rosenzweig et al. 2013; Ruane et al. 2016; Rötter et al. 2018a). Additionally, ensemble studies show the potential to set findings on a broader foundation providing ranges for uncertainties. This is based on the realisation that means of many models predicts more accurate than one (Martre et al. 2015; Challinor et al. 2018; Wallach et al. 2018).

However, while there are some ensemble studies on the impact of adverse environmental conditions (Trnka et al. 2014), such studies must be seen as critical. The problem evolves not around means 'the showpiece' of crop simulation models, but the complex specific response to adverse environmental conditions. Specific crop growth processes and stress reactions have a much higher weight when simulating extremes in crop production (Martre et al. 2015).

Conclusion and outlook

This thesis provides some insight into the challenges that the impact of adverse environmental conditions on critical development stages brings to the agricultural production of the North German Plain. Besides giving some general overview, it analyses the complex issue using two very different approaches: One approach is a top-down approach that examines the abundance of adverse environmental conditions during specific development stages showing implications for the future. The other is a bottom-up approach that identifies patterns of drought impact for agricultural production systems describing the recent state. It is evident that adverse environmental conditions, especially during critical production stages, can impact the agricultural pursuit negatively and jeopardise the usually reliable crop production on high levels found in the North German Plain. It is quite conciliatory that at least the hurdles for the terminal impact of adverse environmental conditions usually are quite high. However, the significant impact on the quality and quantity of yield takes place much earlier under less unfavourable conditions.

Indeed, these impacts are of most concern, in a world where challenging boundary conditions exert high pressure on agricultural production, e.g. by the necessity to guarantee stable nutrition for an ever-growing world population or by environmental shifts through climate change. The well-established production systems of the North German Plain are no exception to this.

Therefore, it is necessary to develop feasible mitigation strategies for the problem. Many adaptations and technologies are imaginable, e.g. breeding new resilient cultivars, nanoparticle soil additives improving soil properties, or autonomous robots caring for individual crops.

The first step of finding a strategy is to assess and to quantify the problem. This requires systematic research on the complex issue of adverse environmental conditions and critical development stages. The approaches used in this thesis can provide some focus that will help to navigate the complex problem of adverse environmental conditions and critical development stages. They can help to inspire the development of new methods like improved crop simulation models that can assess this specific problem adequately.

If the right focus and novel methods are provided, the innovative and industrious agricultural sector has undoubtedly the resources to develop the right mitigation strategies. These, in turn, will help secure reliable agricultural production in the North German Plain and world-wide.

References

Abrahamsen P (2015) Daisy Program Reference Manual. Manual 1–581.

Abrahamsen P, Hansen S (2000) Daisy: an open soil-crop-atmosphere system model. Environ Model Softw 15:313–330. doi: 10.1016/S1364-8152(00)00003-7

Ahmadi M, Bahrani M (2009a) Yield and yield components of rapeseed as influenced by water stress at different growth stages and nitrogen levels. Am J Agric … 5:755–761.

Ahmadi M, Bahrani MJ (2009b) Yield and Yield Components of Rapeseed as Influenced by Water Stress at Different Growth Stages and Nitrogen Levels. 5:755–761.

Angadi S, Cutforth H (2000) Response of three *Brassica* species to high temperature stress during reproductive growth. Can J Plant Sci 693–702.

Asseng S (2014) Uncertainties of climate change impacts in agriculture. Procedia Environ Sci 29:304. doi: 10.1016/j.proenv.2015.07.276

Asseng S, Keating B., Fillery IR., Gregory P., Bowden J., Turner N., Palta J., Abrecht D. (1998) Performance of the APSIM-wheat model in Western Australia. F Crop Res 57:163–179. doi: 10.1016/S0378-4290(97)00117-2

Asseng S, Foster I, Turner NC (2011) The impact of temperature variability on wheat yields. Glob Chang Biol 17:997–1012. doi: 10.1111/j.1365-2486.2010.02262.x

Asseng S, Ewert F, Rosenzweig C, Jones JW, Hatfield JL, Ruane AC, Boote KJ, Thorburn PJ, Rötter RP, Cammarano D, Brisson N, Basso B, Martre P, Aggarwal PK, Angulo C, Bertuzzi P, Biernath C, Challinor AJ, Doltra J, Gayler S, Goldberg R, Grant RF, Heng L, Hooker J, Hunt LA, Ingwersen J, Izaurralde RC, Kersebaum KC, Muller C, Naresh Kumar S, Nendel C, O'Leary G, Olesen JE, Osborne TM, Palosuo T, Priesack E, Ripoche D, Semenov MA, Shcherbak I, Steduto P, Stockle C, Stratonovitch P, Streck T, Supit I, Tao F, Travasso M, Waha K, Wallach D, White JW, Williams JR, Wolf J (2013) Uncertainty in simulating wheat yields under climate change. Nat Clim Chang 3:827–832. doi: 10.1038/ncliamte1916

Barker T (2007) Climate Change 2007 : An assessment of the intergovernmental panel on climate change. Change 446:12–17. doi: 10.1256/004316502320517344

Barlow KM, Christy BP, O'Leary GJ, Riffkin PA, Nuttall JG (2015) Simulating the impact of extreme heat and frost events on wheat crop production: A review. F Crop Res 171:109–119. doi: 10.1016/j.fcr.2014.11.010

Barnabás B, Jäger K, Fehér A (2008) The effect of drought and heat stress on reproductive processes in cereals. Plant, Cell Environ 31:11–38. doi: 10.1111/j.1365-3040.2007.01727.x

Begueria S, Serrano V (2015) SPEI: Calculation of Standardised Precipitation-Evapotranspiration index. R package version 1.6. 16. doi: 10.1175/2009JCLI2909.1.http

Beguería S, Vicente-Serrano SM, Reig F, Latorre B (2014) Standardized precipitation evapotranspiration index (SPEI) revisited: Parameter fitting, evapotranspiration models, tools, datasets and drought monitoring. Int J Climatol 34:3001–3023. doi: 10.1002/joc.3887

Beveridge L, Whitfield S, Challinor A (2018) Crop modelling: towards locally relevant and climate-informed adaptation. Clim Change 147:475–489. doi: 10.1007/s10584-018-2160-z

Bindi M, Olesen JE (2011) The responses of agriculture in Europe to climate change. Reg Environ Chang 11:151–158. doi: 10.1007/s10113-010-0173-x

BirunAra A, Shekari F, Hassanpouraghdam MB, Khorshidi MB, Esfandyari E (2011) Effects of water deficit stress on yield, yield components and phenology of canola (Brassica napus L.) at different growth stages. J Food Agric Env 9:506–509.

BMEL (2015) Agrarpolitischer Bericht der Bundesregierung 2015. Berlin, Germany

BMEL (2017) Improving the use of crop models for risk assessment and climate change adaptation. Bundesministerium für Ernährung und Landwirtschaft (BMEL), Referat 531, Berlin, Germany

BMEL (2019) Agrarpolitischer Bericht der Bundesregierung 2019. Cambridge University Press, Berlin, Germany

Boogaard HL, Van Diepen CA, Rötter RP, Cabrera JMC., Van Laar HH (2014) WOFOST Control Centre 2.1 and WOFOST 7.1.7. 1–133.

Boydston RA, Seymour MD, Brown CR, Alva AK (2006) Freezing Behavior of Potato (*Solanum tuberosum*) Tubers in Soil. Am J Potato Res 83:305–315.

Brisson N, Gary C, Justes E, Roche R (2003) An overview of the crop model STICS. Eur J Agron 18:309–332.

Brown KF, Messem AB, Dunham RJ, Biscoe P V. (1987) Effect of drought on growth and water use of sugar beet. J Agric Sci 109:421–435.

Cárcova J, Otegui ME (2001) Ear temperature and pollination timing effects on maize kernel set. Crop Sci 41:1809–1815. doi: 10.2135/cropsci2001.1809

Cary JW (1975) Factors affecting cold injury of sugarbeet seedlings. Agron J 67:258–262. doi: 10.2134/agronj1975.00021962006700020022x

Castro M, Peterson CJ, Rizza MD, Dellavalle PDí, Vázquez D, IbáÑez V, Ross A (2007) Influence of Heat Stress on Wheat Grain Characteristics and Protein Molecular Weight Distribution. In: Buck HT, Nisi JE, Salomón N (eds) Wheat Production in Stressed Environments. Springer Netherlands, Dordrecht, pp 365–371

Caussinus H, Mestre O (2004) Detection and Correction of Artificial Shifts in Climate Series. Appl Stat 3:405–425.

Challinor AJ, Wheeler TR, Craufurd PQ, Slingo JM (2005) Simulation of the impact of high temperature stress on annual crop yields. Agric For Meteorol 135:180–189. doi: 10.1016/j.agrformet.2005.11.015

Challinor AJ, Wheeler TR, Craufurd PQ, Ferro CAT, Stephenson DB (2007) Adaptation of crops to climate change through genotypic responses to mean and extreme temperatures. Agric Ecosyst Environ 119:190–204. doi: 10.1016/j.agee.2006.07.009

Challinor AJ, Ewert F, Arnold S, Simelton E, Fraser E (2009) Crops and climate change: progress, trends, and challenges in simulating impacts and informing adaptation. J Exp Bot 60:2775–2789. doi: 10.1093/jxb/erp062

Challinor AJ, Müller C, Asseng S, Deva C, Niklin KJ, Wallach D, Vanuytrecht E, Whitfield S, Ramirez-Villages J, Koehler A-K (2018) Improving the use of crop models for risk assessment and climate change adaptation. Agric Syst 159:296–306. doi: https://doi.org/10.1016/j.agsy.2017.07.010

Chauhan JS, Meena ML, Saini M, Meena DR, Singh M, Meena SS, Singh KH, Meena SS, Singh KH (2009) Heat stress effects on morpho-physiological characters of Indian mustard (Brassica juncea L.). In: 16th Australian Research Assembly on Brassicas. Ballarat, Victoria,

Chmielewski F-M, Kühn W (2000) Impact of weather on yield components of winter rye over 30 years. Agric For Meteorol 102:253–261. doi: DOI: 10.1016/S0168-1923(00)00125-8

Chmielewski FM, Müller A, Bruns E (2004) Climate changes and trends in phenology of fruit trees and field crops in Germany, 1961-2000. Agric For Meteorol 121:69–78. doi: 10.1016/S0168-1923(03)00161-8

Corbeels M, Berre D, Rusinamhodzi L, Lopez-Ridaura S (2018) Can we use crop modelling for identifying climate change adaptation options? Agric For Meteorol 256–257:46–52. doi: 10.1016/J.AGRFORMET.2018.02.026

Daryanto S, Wang L, Jacinthe P-A (2017) Global synthesis of drought effects on cereal, legume, tuber and root crops production: A review. Agric Water Manag 179:18–33. doi: https://doi.org/10.1016/j.agwat.2016.04.022

de San Celedonio RP, Abeledo LG, Miralles DJ (2014) Identifying the critical period for waterlogging on yield and its components in wheat and barley. Plant Soil 378:265–277. doi: 10.1007/s11104-014-2028-6

Dejong TM, Da Silva D, Vos J, Escobar-Gutirrez AJ (2011) Using functionalstructural plant models to study, understand and integrate plant development and ecophysiology. Ann Bot 108:987–989. doi: 10.1093/aob/mcr257

Donatelli M, Russell G, Rizzoli A, Acutis M, Adam M, Athanasiadis I, Balderacchi M, Bechini L, Belhouchette H, Bellocchi G, Bergez J-E, Botta M, Braudeau E, Bregaglio S, Carlini L, Casellas E, Celette F, Ceotto E, Charron-Moirez M, Confalonieri R, Corbeels M, Criscuolo L, Cruz P, di Guardo A, Ditto D, Dupraz C, Duru M, Fiorani D, Gentile A, Ewert F, Gary C, Habyarimana E, Jouany C, Kansou K, Knapen R, Filippi G, Leffelaar P, Manici L, Martin G, Martin P, Meuter E, Mugueta N, Mulia R, van Noordwijk M, Oomen R, Rosenmund A, Rossi V, Salinari F, Serrano A, Sorce A, Vincent G, Theau J-P, Thérond O, Trevisan M, Trevisiol P, van Evert F, Wallach D, Wery J, Zerourou A (2010) A component-based framework for simulating agricultural production and externalities. In: Brouwer FM, Ittersum MK (eds) Environmental and Agricultural Modelling. Springer, pp 63–108

Dwyer LM, Boisvert JB (1990) Response to irrigation of two potato cultivars (Solatium tuberosum L . "Kennebec" and 'Superior'). Can Agric Eng 88:197–203.

Eitzinger J, Thaler S (2012) Sensitivities of crop models to extreme weather conditions during flowering period demonstrated for maize and winter wheat in Austria. J … 1–23. doi: 10.1017/S0021859612000779

Emberlin J, Adams-Groom B, Tidmarsh J (1999) A Report on the Dispersal of Maize Pollen. Worcester WR2 6 AJ, UK

Estrella N, Sparks TH, Menzel A (2007) Trends and temperature response in the phenology of crops in Germany. Glob Chang Biol 13:1737–1747. doi: 10.1111/j.1365-2486.2007.01374.x

Ewing EE (1981) Heat stress and the tuberization stimulus. Am Potato J 58:31–49. doi: 10.1007/BF02855378

Eyshi Rezaei E, Siebert S, Ewert F (2015) Impact of data resolution on heat and drought stress simulated for winter wheat in Germany. Eur J Agron 65:69–82. doi: 10.1016/j.eja.2015.02.003

Farooq M, Hussain M, Siddique KHM (2014) Drought stress in wheat during flowering and grain-filling periods. CRC Crit Rev Plant Sci 33:331–349. doi: 10.1080/07352689.2014.875291

Ferrise R (2017) Sensitivities of crop models to extreme weather conditions during flowering period demonstrated for maize and winter wheat ... doi: 10.1017/S0021859612000779

Fonseca AE, Westgate ME (2005) Relationship between desiccation and viability of maize pollen. F Crop Res 94:114–125. doi: 10.1016/j.fcr.2004.12.001

Fowler D, Limin A, Wang S, Ward R (1996) Relationship between low-temperature tolerance and vernalization response in wheat and rye. Can J Plant Sci 37–42.

Frielinghaus U, Schindler M Bei welchem Wassergehalt sind bindige Böden bearbeitbar ? 1.

Gallusci P, Dai Z, Génard M, Gauffretau A, Leblanc-Fournier N, Richard-Molard C, Vile D, Brunel-Muguet S (2017) Epigenetics for Plant Improvement: Current Knowledge and Modeling Avenues. Trends Plant Sci 22:610–623.

García GA, Serrago RA, Dreccer MF, Miralles DJ (2016) Post-anthesis warm nights reduce grain weight in field-grown wheat and barley. F Crop Res 195:50–59. doi: 10.1016/j.fcr.2016.06.002

Geerts S (2008) Deficit irrigation strategies via crop water productivity modeling: Field research of quinoa in the Bolivian Altiplano. Katholieke Universiteit Leuven

Geerts S, Raes D, Garcia M, Mendoza J, Huanca R (2008) Crop water use indicators to quantify the flexible phenology of quinoa (Chenopodium quinoa Willd.) in response to drought stress. F Crop Res 108:150–156. doi: 10.1016/j.fcr.2008.04.008

Geerts S, Raes D, Garcia M, Taboada C, Miranda R, Cusicanqui J, Mhizha T, Vacher J (2009)

Modeling the potential for closing quinoa yield gaps under varying water availability in the Bolivian Altiplano. Agric Water Manag 96:1652–1658. doi: 10.1016/j.agwat.2009.06.020

Gerstengarbe F, Werner P, Österle H, Burghoff O (2013) Winter storm- and summer thunderstorm-related loss events with regard to climate change in Germany. Theor Appl Clim 114:715–724.

Ghobadi M, Bakhshandeh M, Fathi G, Gharineh MH, Alami-Said K, Naderi A, Ghobadi ME (2006) Short and long periods of water stress during different growth stages of canola (Brassica napus L.): Effect on yield, yield components, seed oil and protein contents. J Agron 5:336–341.

Gobin A (2012) Impact of heat and drought stress on arable crop production in Belgium. Nat Hazards Earth Syst Sci 12:1911–1922. doi: 10.5194/nhess-12-1911-2012

Gömann H, Bender A, Bolte A, Dirksmeyer W, Englert H, Feil J, Frühauf C, Hauschild M, Krengel S, Lilienthal H, Löpmeier F, Müller J, Mußhoff O, Natkhin M, Offermann F, Seidel P, Schmidt M, Seintsch B, Steidl J, Strohm K, Zimmer Y (2015) Agrarrelevante Extremwetterlagen und Möglichkeiten von Risikomanagementsystemen. Braunschweig, Germany

Gutierrez Boem FH, Lavado RS, Porcelli CA (1996) Note on the effects of winter and spring waterlogging on growth, chemical composition and yield of rapeseed. F Crop Res 47:175–179. doi: 10.1016/0378-4290(96)00025-1

Gutschick VP, BassiriRad H (2003) Extreme events as shaping physiology, ecology, and evolution of plants: toward a unified definition and evaluation of their consequences. New Phytol 160:21–42. doi: 10.1046/j.1469-8137.2003.00866.x

Hagedorn R, Doblas-Reyes FJ, Palmer TN (2005) The rationale behind the success of multi-model ensembles in seasonal forecasting — I. Basic concept. Tellus A Dyn Meteorol Oceanogr 57:219–233. doi: 10.3402/tellusa.v57i3.14657

Hanel M, Rakovec O, Markonis Y, Máca P, Samaniego L, Kyselý J, Kumar R (2018) Revisiting the recent European droughts from a long-term perspective. Sci Rep 8:1–11. doi: 10.1038/s41598-018-27464-4

Hansen S, Abrahamsen P, Petersen CT, Styczen M (2012) Daisy: Model Use, Calibration, and Validation. Trans ASABE 55:1315–1333.

Harrison MT, Tardieu F, Dong Z, Messina CD, Hammer GL (2014) Characterizing drought stress and trait influence on maize yield under current and future conditions. Glob Chang Biol 20:867–78. doi: 10.1111/gcb.12381

Haverkort AJ, Van De Waart M, Bodlaender KBA (1990) The effect of early drought stress on numbers of tubers and stolons of potato in controlled and field conditions. Potato Res 33:89–96. doi: 10.1007/BF02358133

Hlaváčová M, Klem K, Rapantová B, Novotná K, Urban O, Hlavinka P, Smutná P, Horáková V, Škarpa P, Pohanková E, Wimmerová M, Orság M, Jurečka F, Trnka M (2018) Interactive effects of high temperature and drought stress during stem elongation, anthesis and early grain filling on the yield formation and photosynthesis of winter wheat. F Crop Res 221:182–195. doi: 10.1016/j.fcr.2018.02.022

Hlavinka P, Trnka M, Eitzinger J, Smutný V, Thaler S, Žalud Z, Rischbeck P, Kr J (2010) The performance of CERES-Barley and CERES-Wheat under various soil conditions and tillage practices in Central Europe bei verschiedenen Böden und unterschiedlicher Bodenbearbeitung in Mitteleuropa.

Hoffmann A, Jungk C (1995) Growth and phosphorus supply of sugar beet as affected by soil compaction and water tension. Plant Soil 176:15–25.

Hoffmann CM (2010a) Root Quality of Sugarbeet. Sugar Tech 12:276–287. doi: 10.1007/s12355-010-0040-6

Hoffmann CM (2010b) Sucrose accumulation in sugar beet under drought stress. J Agron Crop Sci 196:243–252. doi: 10.1111/j.1439-037X.2009.00415.x

Hoffmann CM, Huijbregts T, van Swaaij N, Jansen R (2009) Impact of different environments in Europe on yield and quality of sugar beet genotypes. Eur J Agron 30:17–26. doi: 10.1016/j.eja.2008.06.004

Hoffmann MP, Haakana M, Asseng S, Höhn JG, Palosuo T, Ruiz-Ramos M, Fronzek S, Ewert F, Gaiser T, Kassie BT, Paff K, Rezaei EE, Rodríguez A, Semenov M, Srivastava AK, Stratonovitch P, Tao F, Chen Y, Rötter RP (2018) How does inter-annual variability of attainable yield affect the magnitude of yield gaps for wheat and maize? An analysis at ten sites. Agric Syst 159:199–208. doi: 10.1016/j.agsy.2017.03.012

Hoogenboom G, Jones JW, Wilkens PW, Porter CH, Boote KJ, Hunt LA, Singh U, Lizaso JL, White JW, Uryasev O, Royce F, Ogoshi R, Gijsman AJ, Tsuji GY, Koo J (2012) Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.5 [CD-ROM]. University of Hawaii, Honolulu, Hawaii.

Houghton JT, Jenkins GJ, Ephraums JJ (1990) CLIMATE CHANGE - The IPCC Scientific Assessment. 414.

Hussain J, Khaliq T, Ahmad A, Akhtar J (2018) Performance of four crop model for simulations of wheat phenology, leaf growth, biomass and yield across planting dates. PLoS One 13:1–14. doi: 10.1371/journal.pone.0197546

Hussain MZ, Vanloocke A, Siebers MH, Ruiz-Vera UM, Cody Markelz RJ, Leakey ADB, Ort DR, Bernacchi CJ (2013) Future carbon dioxide concentration decreases canopy evapotranspiration and soil water depletion by field-grown maize. Glob Chang Biol 19:1572–1584. doi: 10.1111/gcb.12155

Iglesias A, Garrote L, Quiroga S, Moneo M (2012) A regional comparison of the effects of climate change on agricultural crops in Europe. Clim Change 112:29–46. doi: 10.1007/s10584-011-0338-8

IPCC (2007) Climate change 2007 : impacts, adaptation and vulnerability : Working Group II contribution to the Fourth Assessment Report of the IPCC Intergovernmental Panel on Climate Change. Work Gr II Contrib to Intergov Panel Clim Chang Fourth Assess Rep 1:976. doi: 10.2134/jeq2008.0015br

IPCC (2014) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Jackson MB, Black CR (1993) Interacting Stresses on Plants in a Changing Climate.

Jacob D, Ries H, Weber B Entwicklung von Extremwetterereignissen in Deutschland. Geesthacht, Germany

Jacobsen B (2006) Root rot diseases of sugar beet. Proc Nat Sci, Matica Srp 110:9–19.

Jones J, Hoogenboom G, Porter C, Boote K, Batchelor W, Hunt L., Wilkens P, Singh U, Gijsman A, Ritchie J (2003a) The DSSAT cropping system model. Eur J Agron 18:235–265. doi: 10.1016/S1161-0301(02)00107-7

Jones P, Thornton P (2003a) The potential impacts of climate change on maize production in Africa and Latin America in 2055. Glob Environ Chang 13:51–59. doi: 10.1016/S0959-3780(02)00090-0

Jones P, Lister D, Jaggard K, Pidgeon J (2003b) Future climate impact on the productivity of sugar beet (*Beta vulgaris* L.) in Europe. Clim Change 58:93–108.

Jones PG, Thornton PK (2003b) The potential impacts of climate change on maize production in Africa and Latin America in 2055. Glob Environ Chang 13:51–59. doi: 10.1016/S0959-3780(02)00090-0

Kahiluoto H, Kaseva J, Balek J, Olesen JE, Ruiz-Ramos M, Gobin A, Kersebaum KC, Takáč J, Ruget F, Ferrise R, Bezak P, Capellades G, Dibari C, Mäkinen H, Nendel C, Ventrella D, Rodríguez A, Bindi M, Trnka M (2019) Decline in climate resilience of european wheat. Proc Natl Acad Sci U S A 116:123–128. doi: 10.1073/pnas.1804387115

Keating BA, Carberry PS, Hammer GL, Probert ME, Robertson MJ, Holzworth D, Huth NI, Hargrea JNG (2003) An overview of APSIM, a model designed for farming systems simulation. Eur J Agron 18:267–288.

Kersebaum KC (2006) Modelling nitrogen dynamics in soil–crop systems with HERMES. Nutr Cycl Agroecosystems 77:39–52. doi: 10.1007/s10705-006-9044-8

Kersebaum KC (2011) Special Features of the HERMES Model and Additional Procedures for Parameterization, Calibration, Validation, and Applications. In: Advances in Agricultural Systems Modeling. pp 65–94

Kirda C, Kanber R, Tülücü K, Güngör H (1999) Yield Response of cotton, maize, soybean, sugar beet, sunflower and wheat to deficit irrigation. In: Kirda C, Moutonnet P, Hera C, Nielsen DR (eds) Crop Yield Response to Deficit Irrigation. Kluwer Academic, p 258

Knutti R, Sedlacek J (2013) Robustness and uncertainties in the new CMIP5 climate model projections. Nat Clim Chang 3:369–373.

Kollas C, Kersebaum KC, Nendel C, Manevski K, Müller C, Palosuo T, Armas-Herrera CM, Beaudoin N, Bindi M, Charfeddine M, Conradt T, Constantin J, Eitzinger J, Ewert F, Ferrise R, Gaiser T, Cortazar-Atauri IG de, Giglio L, Hlavinka P, Hoffmann H, Hoffmann MP, Launay M, Manderscheid R, Mary B, Mirschel W, Moriondo M, Olesen JE, Öztürk I, Pacholski A, Ripoche-Wachter D, Roggero PP, Roncossek S, Rötter RP, Ruget F, Sharif B, Trnka M, Ventrella D, Waha K, Wegehenkel M, Weigel HJ, Wu L (2015) Crop rotation modelling-A European model intercomparison. Eur J Agron 70:98–111. doi: 10.1016/j.eja.2015.06.007

Kumar PS, Singh Y, Nangare DD, Bhagat K, Kumar M, Taware PB, Kumari A, Minhas PS (2015) Influence of growth stage specific water stress on the yield, physico-chemical quality and functional characteristics of tomato grown in shallow basaltic soils. Sci Hortic (Amsterdam) 197:261–271. doi: 10.1016/j.scienta.2015.09.054

Kumudini S, Andrade FH, Boote KJ, Brown GA, Dzotsi KA, Edmeades GO, Gocken T, Goodwin M, Halter AL, Hammer GL, Hatfield JL, Jones JW, Kemanian AR, Kim SH, Kiniry J, Lizaso JI, Nendel C, Nielsen RL, Parent B, Stöckle CO, Tardieu F, Thomison PR, Timlin DJ, Vyn TJ, Wallach D, Yang HS, Tollenaar M (2014) Predicting maize phenology: Intercomparison of functions for developmental response to temperature. Agron J 106:2087–2097. doi: 10.2134/agronj14.0200

Laegdsmand M (2011) Crop simulation model. 1–9.

Lesk C, Rowhani P, Ramankutty N (2016) Influence of extreme weather disasters on global crop production. Nature 529:84–87. doi: 10.1038/nature16467

Levy D (1985) The response of potatoes to a single transient heat or drought stress imposed at different stages of tuber growth. Potato Res 28:415–424. doi: 10.1007/BF02357516

Levy D, Veilleux RE (2007) Adaptation of potato to high temperatures and salinity a review. Amer J Potato Res 84:487–506. doi: 10.1007/BF02987885

Li L, McMaster GS, Yu Q, Du J (2008) Simulating winter wheat development response to temperature: Modifying Malo's exponential sine equation. Comput Electron Agric 63:274–281. doi: 10.1016/j.compag.2008.03.006

Liu B, Asseng S, Liu L, Tang L, Cao W, Zhu Y (2016) Testing the responses of four wheat crop models to heat stress at anthesis and grain filling. Glob Chang Biol 22:1890–1903. doi: 10.1111/gcb.13212

Liu Y-H, Offler CE, Ruan Y-L (2013) Regulation of fruit and seed response to heat and drought by sugars as nutrients and signals. Front Plant Sci 4:282. doi: 10.3389/fpls.2013.00282

Lizaso JI, Ruiz-Ramos M, Rodríguez L, Gabaldon-Leal C, Oliveira JAS, Lorite IJ, Rodríguez A, Maddonni GA, Otegui ME, Rodriguez L, Gabaldon-Leal C, Oliveira JAS, Lorite IJ, Rodriguez A, Maddonni GA, Otegui ME, Rodríguez L, Gabaldon-Leal C, Oliveira JAS, Lorite IJ, Rodríguez A, Maddonni GA, Otegui ME (2017) Modeling the response of maize phenology, kernel set, and yield components to heat stress and heat shock with CSM-IXIM. F Crop Res 214:239–254. doi: https://doi.org/10.1016/j.fcr.2017.09.019

Lizaso JI, Ruiz-Ramos M, Rodriguez L, Gabaldon-Leal C (2018) Impact of high temperatures in maize: Phenology and yield components. F Crop Res 216:129–140. doi: 10.1016/j.fcr.2017.11.013

Ljungqvist FC, Krusic PJ, Sundqvist HS, Zorita E, Brattström G, Frank D (2016) Northern Hemisphere hydroclimate variability over the past twelve centuries. Nature 532:94–98. doi: 10.1038/nature17418

Lobell DB, Cassman KG, Field CB (2009) Crop Yield Gaps: Their Importance, Magnitudes, and Causes. Annu Rev Environ Resour 34:179–204. doi: 10.1146/annurev.environ.041008.093740

Lobell DB, Sibley A, Ortiz-Monasterio JI (2012) Extreme heat effects on wheat senescence in India. Nat Clim Chang 2:186–189. doi: /10.1038/ NCLIMATE1356

Lobell DB, Hammer GL, Chenu K, Zheng B, Mclean G, Chapman SC (2015) The shifting influence of drought and heat stress for crops in northeast Australia. Glob Chang Biol 21:4115–4127. doi: 10.1111/gcb.13022

MacKerron DKL, Jefferies RA (1986) The influence of early soil moisture stress on tuber numbers in potato. Potato Res 29:299–312. doi: 10.1007/BF02359959

Mäkinen H, Kaseva J, Trnka M, Balek J, Kersebaum KC, Nendel C, Gobin A, Olesen JE, Bindi M, Ferrise R, Moriondo M, Rodríguez A, Ruiz-ramos M, Taká J, Bezák P, Ventrella D, Ruget F, Capellades G, Kahiluoto H (2018) Sensitivity of European wheat to extreme weather. F Crop Res 222:209–217. doi: 10.1016/j.fcr.2017.11.008

Makowski D, Asseng S, Ewert F, Bassu S, Durand JL, Li T, Martre P, Adam M, Aggarwal PK, Angulo C, Baron C, Basso B, Bertuzzi P, Biernath C, Boogaard H, Boote KJ, Bouman B, Bregaglio S, Brisson N, Buis S, Cammarano D, Challinor AJ, Confalonieri R, Conijn JG, Corbeels M, Deryng D, De Sanctis G, Doltra J, Fumoto T, Gaydon D, Gayler S, Goldberg R, Grant RF, Grassini P, Hatfield JL, Hasegawa T, Heng L, Hoek S, Hooker J, Hunt LA, Ingwersen J, Izaurralde RC, Jongschaap REE, Jones JW, Kemanian RA, Kersebaum KC, Kim SH, Lizaso J, Marcaida M, Müller C, Nakagawa H, Naresh Kumar S, Nendel C, O'Leary GJ, Olesen JE, Oriol P, Osborne TM, Palosuo T, Pravia M V., Priesack E, Ripoche D, Rosenzweig C, Ruane AC, Ruget F, Sau F, Semenov MA, Shcherbak I, Singh B, Singh U, Soo HK, Steduto P, Stöckle C, Stratonovitch P, Streck T, Supit I, Tang L, Tao F, Teixeira EI, Thorburn P, Timlin D, Travasso M, Rötter RP, Waha K, Wallach D, White JW, Wilkens P, Williams JR, Wolf J, Yin X, Yoshida H, Zhang Z, Zhu Y (2015) A statistical analysis of three ensembles of crop model responses to temperature and CO2 concentration. Agric For Meteorol 214–215:483–493. doi: 10.1016/j.agrformet.2015.09.013

Malik AI, Islam AKMR, Colmer TD (2011) Transfer of the barrier to radial oxygen loss in roots of Hordeum marinum to wheat (Triticum aestivum): Evaluation of four H.marinum-wheat amphiploids. New Phytol 190:499–508. doi: 10.1111/j.1469-8137.2010.03519.x

Maracchi G, Sirotenko O, Bindi M (2005) Impacts of Present and Future Climate Variability on Agriculture and Forestry in the Temperate Regions. Clim Change 70:117–135. doi: 10.1007/1-4020-4166-7_6

Martre P, Wallach D, Asseng S, Ewert F, Jones JW, Rötter RP, Boote KJ, Ruane AC, Thorburn PJ, Cammarano D, Hatfield JL, Rosenzweig C, Aggarwal PK, Angulo C, Basso BJ (2015) Multimodel ensembles of wheat growth: Many models are better than one. Glob Chang Biol 21:911--925. doi: 10.1111/gcb.12768

Masearenhas JP, Crone DE (1996) Pollen and the heat shock response. Sex Plant Reprod 9:370–374.

McCown RL, Hammer GL, Hargreaves JNG, Holzworth DP, Freebairn DM (1996) APSIM: A novel software system for model development, model testing and simulation in agricultural systems research. Agric Syst 50:255–271. doi: 10.1016/0308-521X(94)00055-V

McMaster GS, Wilhelm WW, Frank AB (2005a) Developmental sequences for simulating crop phenology for water-limiting conditions. Aust J Agric Res 56:1277–1288. doi: http://dx.doi.org/10.1071/AR05068

McMaster GS, Wilhelm W, Frank AB (2005b) Developmental sequences for simulating crop phenology for water-limiting conditions. Aust J Agric Res 56:1277–1288.

McMaster GS, White JW, Hunt LA, Jamieson PD, Dhillon SS, Ortiz-Monasterio JI (2008) Simulating the influence of vernalization, photoperiod and optimum temperature on wheat developmental rates. Ann Bot 102:561–569. doi: 10.1093/aob/mcn115

Meier U (2001) Growth stages of mono-and dicotyledonous plants. BBCH Monographie. 166.

Meier U, Bleiholder H, Buhr L, Feller C, Hack H, Heß M, Lancashire P, Schnock U, Stauß R, Van den Boom T, Weber E, Zwerger P (2009) The BBCH system to coding the phenological growth stages of plants-history and publications. J für Kult 61:41–52.

Menzel (2002) Phenology: Its Importance To the Global Change Community. Clim Change 379–385. doi: 10.1023/A:1016125215496

Menzel A, Fabian P (1999) Growing season extended in Europe. Nature 397:659. doi: 10.1038/17709

Menzel A, Jakobi G, Ahas R, Scheifinger H, Estrella N (2003) Variations of the climatological growing season (1951-2000) in Germany compared with other countries. Int J Climatol 23:793–812. doi: 10.1002/joc.915

Menzel A, Sparks TH, Estrella N, Koch E, Aaasa A, Ahas R, Alm-Kübler K, Bissolli P, Braslavská O, Briede A, Chmielewski FM, Crepinsek Z, Curnel Y, Dahl Å, Defila C, Donnelly A, Filella Y, Jatczak K, Måge F, Mestre A, Nordli Ø, Peñuelas J, Pirinen P, Remišová V, Scheifinger H, Striz M, Susnik A, Van Vliet AJH, Wielgolaski FE, Zach S, Zust A (2006) European phenological response to climate change matches the warming pattern. Glob Chang Biol 12:1969–1976. doi: 10.1111/j.1365-2486.2006.01193.x

Metzger MJ, Bunce RGH, Jongman RHG, Mücher CA, Watkins JW (2005) A climatic stratification of the environment of Europe. Glob Ecol Biogeogr 14:549–563.

Mittra MK, Stickler FC (1961) Excess Water Effects on Different Crops. Trans Kansas Acad Sci 64:275–286. doi: 10.2307/3626753

Moran MS, T.R. C, Inoue Y, Vidal A (1994) Estimating crop water defficiency using the relation between surface minus air temperature and spectral vegetation index. Remote Sens Environ 49:246–263. doi: 10.1016/0034-4257(94)90020-5

Morrison MJ, Stewart DW (2000) Heat stress during flowering in summer Brassica. Crop Sci 42:797–803.

Motha RP (2011) Use of Crop Models for Drought Analysis Use of Crop Models for Drought Analysis. Lincoln, Nebraska, USA

Mutasa-Gottgens ES, Qi A, Zhang W, Schulze-Buxloh G, Jennings A, Hohmann U, Muller AE, Hedden P (2010) Bolting and flowering control in sugar beet: relationships and effects of gibberellin, the bolting gene B and vernalization. AoB Plants 2010:plq012–plq012. doi: 10.1093/aobpla/plq012

Nendel C (2012) MONICA - Das Modell für Stickstoff und Kohlenstoff in Agrarökosystemen. 54.

Nendel C, Specka X (2013) MONICA-The Modell for Nitrogen and Carbon in Agro-Ecosystems. 18.

Nendel C, Kersebaum KC, Mirschel W, Manderscheid R, Weigel H-J, Wenkel K-O (2009) Testing different CO2 response algorithms against a FACE crop rotation experiment. NJAS - Wageningen J Life Sci 57:17–25. doi: 10.1016/j.njas.2009.07.005

Nendel C, Berg M, Kersebaum K (2011) The MONICA model: Testing predictability for crop growth, soil moisture and nitrogen dynamics. Ecol Modell 222:1614–1625. doi: 10.1016/j.ecolmodel.2011.02.018

Nendel C, Wieland R, Mirschel W (2013) Simulating regional winter wheat yields using input data of different spatial resolution. F Crop Res 145:67–77. doi: 10.1016/j.fcr.2013.02.014

Ober E (2001) The search for drought tolerance in sugar beet. Br Sugar Beet Rev 69:40–43.

Ober ES, Rajabi A (2010) Abiotic stress in sugar beet. Sugar Tech 12:294–298. doi: 10.1007/s12355-010-0035-3

OECD (1997) Consensus Document on the Biology of Brassica napus L. Paris, France

OECD (1999) Consensus Document on the Biology of Triticum aestivum. Paris, France

Oehme V (2012) Effects of elevated atmospheric CO2 concentrations on insects and pathogens of spring wheat (Triticum aestivum L . cv . Triso) and oilseed rape (Brassica napus cv . Campino). Hohenheim, Stuttgart

Ojala J, Stark J, Kleinkopf G (1990) Influence of irrigation and nitrogen management on potato yield and quality. Am Potato J 67:29–43.

Olesen JE, Petersen BM, Berntsen J, Hansen S, Jamieson PD, Thomsen a. G (2002) Comparison of methods for simulating effects of nitrogen on green area index and dry matter growth in winter wheat. F Crop Res 74:131–149. doi: 10.1016/S0378-4290(01)00204-0

Olesen JE, Carter TR, Díaz-Ambrona CH, Fronzek S, Heidmann T, Hickler T, Holt T, Minguez MI, Morales P, Palutikof JP, Quemada M, Ruiz-Ramos M, Rubæk GH, Sau F, Smith B, Sykes MT (2007) Uncertainties in projected impacts of climate change on European agriculture and terrestrial ecosystems based on scenarios from regional climate models. Clim Change 81:123–143. doi: 10.1007/s10584-006-9216-1

Olesen JE, Trnka M, Kersebaum KC, Skjelvag AO, Seguin B, Peltonen-Sainio P, Rossi F, Kozyra J, Micale F (2011) Impacts and adaptation of European crop production systems to climate change. Eur J Agron 34:96–112.

Ortega RA, Santibanez OA (2007) Determination of management zones in corn (*Zea mays* L.)

based on soil fertility. Comput Electron Agric 58:49–59.

Oury V, Caldeira CF, Prodhomme D, Pichon J-P, Gibon Y, Tardieu F, Turc O (2016) Is change in ovary carbon status a cause or a consequence of maize ovary abortion in water deficit during flowering? Plant Physiol 171:997–1008. doi: 10.1104/pp.15.01130

Palosuo T, Kersebaum KC, Angulo C, Hlavinka P, Moriondo M, Olesen JE, Patil RH, Ruget F, Rumbaur C, Takáč J, Trnka M, Bindi M, Çaldağ B, Ewert F, Ferrise R, Mirschel W, Şaylan L, Šiška B, Rötter R (2011) Simulation of winter wheat yield and its variability in different climates of Europe: A comparison of eight crop growth models. Eur J Agron 35:103–114. doi: 10.1016/j.eja.2011.05.001

Pandey P, Ramegowda V, Senthil-Kumar M (2015) Shared and unique responses of plants to multiple individual stresses and stress combinations: physiological and molecular mechanisms. Front Plant Sci 6:723. doi: 10.3389/fpls.2015.00723

Pandey P, Irulappan V, Bagavathiannan M V., Senthil-Kumar M (2017) Impact of combined abiotic and biotic stresses on plant growth and avenues for crop improvement by exploiting physio-morphological traits. Front Plant Sci 8:1–15. doi: 10.3389/fpls.2017.00537

Parent B, Tardieu F (2014) Can current crop models be used in the phenotyping era for predicting the genetic variability of yield of plants subjected to drought or high temperature? J Exp Bot 65:6179–6189. doi: 10.1093/jxb/eru223

Peel MC, Finlayson BL, Mcmahon TA (2007) Updated world map of the Köppen-Geiger climate classification. Hydrolocical Earth Syst Sci 11:1633–1644.

Pendleton RA (1950) Soil Compaction and Tillage Operation Effects on Sugar Beet Root Distribution and Seed Yields 2.

Perata P, Armstrong W, Voesenek LACJ (2011) Plants and flooding stress. New Phytol 190:269–273. doi: 10.1111/j.1469-8137.2011.03702.x

Pirttioja N, Carter TR, Fronzek S, Bindi M, Hoffmann H, Palosuo T, Ruiz-Ramos M, Tao F, Trnka M, Acutis M, Asseng S, Baranowski P, Basso B, Bodin P, Buis S, Cammarano D, Deligios P, Destain M-F, Dumont B, Ewert F, Ferrise R, François L, Gaiser T, Hlavinka P, Jacquemin I, Christian K, Kersebaum, Kollas C, Krzyszczak J, Lorite IJ, Minet J, Minguez MI, Montesino M, Moriond M, Müller C, Nendel C, Öztürk I, Perego A, Rodríguez A, Ruane AC, Ruget F, Sanna M, Semenov MA, Slawinski C, Stratonovitch P, Supit I, Waha K, Wang E, Wu L, Zhao Z, Rötter. RP (2015) A crop model ensemble analysis of temperature and precipitation effects on wheat yield across a European transect using impact response surfaces. Clim Res 65:87–105. doi: 10.3354/cr01322

Pohanková E, Trnka M, Hlavinka P, Takáč J, Kersebaum K (2013) Comparison of DAISY and HERMES crop growth models for winter wheat and spring barley in Czech-Moravian Highlands. In: Al ŠB et (ed) Environmental changes and adaptation strategies. Skalica, Slovakia,

Porter J (2005) Rising temperatures are likely to reduce crop yields. Nature 436:2005.

Porter JR, Gawith M (1999) Temperatures and the growth and development of wheat: A review. Eur J Agron 10:23–36. doi: DOI: 10.1016/S1161-0301(98)00047-1

Porter JR, Semenov MA (2005) Crop responses to climatic variation. Philos Trans R Soc Lond B Biol Sci 360:2021–35. doi: 10.1098/rstb.2005.1752

Potopová V, Štěpánek P, Možný M, Türkott L, Soukup J (2015) Performance of the standardised precipitation evapotranspiration index at various lags for agricultural drought risk assessment in the Czech Republic. Agric For Meteorol 202:26–38. doi: 10.1016/j.agrformet.2014.11.022

Prasad PV V, Pisipati SR, Momčilović I, Ristic Z (2011) Independent and Combined Effects of High Temperature and Drought Stress During Grain Filling on Plant Yield and Chloroplast EF-Tu Expression in Spring Wheat. J Agron Crop Sci 197:430–441. doi: 10.1111/j.1439-037X.2011.00477.x

Prusinkiewicz P, Rolland-Lagan AG (2006) Modeling plant morphogenesis. Curr Opin Plant Biol 9:83–88. doi: 10.1016/j.pbi.2005.11.015

Pulatov B, Linderson M-L, Hall K, Jönsson AM (2015) Modeling climate change impact on potato crop phenology, and risk of frost damage and heat stress in northern Europe. Agric For Meteorol 214–215:281–292. doi: 10.1016/j.agrformet.2015.08.266

Qi A, Kenter C, Hoffmann C, Jaggard KW (2005) The Broom's Barn sugar beet growth model and its adaptation to soils with varied available water content. Eur J Agron 23:108–122. doi: 10.1016/j.eja.2004.09.007

R Development Core Team (2013) R: A Language and Environment for Statistical Computing.

Rácz I, Kovács M, Lasztity D, Veisz O, Szalai G, Páldi E (1996) Effect of short-term and long-term low temperature stress on polyamine biosynthesis in wheat genotypes with varying degrees of frost tolerance. J Plant Physiol 148:368–373. doi: 10.1016/S0176-1617(96)80267-7

Ray DK, Gerber JS, MacDonald GK, West PC (2015) Climate variation explains a third of global crop yield variability. Nat Commun 6:5989. doi: 10.1038/ncomms6989

Reynolds MP, Ewing EE (1989) Effects of high air and soil temperature stress on growth and tuberization in *Solarium tuberosum* *. Ann Bot 64:241–247.

Richter A, Adler GH, Fahark M, Eckelmann W (2007) Erläuterungen zur nutzungsdifferenzierten Bodenübersichtskarte der Bundesrepublik Deutschland BÜK 1000 N. 46.

Rizhsky L, Liang H, Shuman J, Shulaev V, Davletova S, Mittler R, Rizhsky L., Liang H., Shuman J., Shulaev V., Davletova S., R. M (2004) When defense pathways collide. The response of *Arabidopsis* to a combination of drought and heat stress. Plant Physiol 134:1683–1696. doi: 10.1104/pp.103.033431.1

Romano A, Sorgonà A, Lupini A, Araniti F, Stevanato P, Cacco G, Abenavoli MR (2012) Morpho-physiological responses of sugar beet (*Beta vulgaris* L.) genotypes to drought stress. Acta Physiol Plant. doi: 10.1007/s11738-012-1129-1

Rosenzweig C, Jones JW, Hatfield JL, Ruane a. C, Boote KJ, Thorburn P, Antle JM, Nelson GC, Porter C, Janssen S, Asseng S, Basso B, Ewert F, Wallach D, Baigorria G, Winter JM (2013) The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. Agric For Meteorol 170:166–182. doi: 10.1016/j.agrformet.2012.09.011

Rötter R, Hoffmann M, Koch M, Müller C (2018a) Progress in modelling agricultural impacts of and adaptations to climate change. Curr Opin Plant Biol 45:255–261. doi: 10.1016/J.PBI.2018.05.009

Rötter RP, Carter TR, Olesen JE, Porter JR (2011) Crop-climate models need an overhaul. Nat Clim Chang 1:175–177.

Rötter RP, Palosuo T, Kersebaum CK, Angulo C, Bindi M, Ewert F, Ferrise R, Hlavinka P, Moriondo M, Nendel C, Olesen JE, Patil RH, Takáˇ J, Trnka M (2012) Simulation of spring barley yield in different climatic zones of Northern and Central Europe : A comparison of nine crop models. F Crop Res 133:23–36. doi: 10.1016/j.fcr.2012.03.016

Rötter RP, Appiah M, Fichtler E, Kersebaum KC, Trnka M, Hoffmann M. (2018b) Linking modelling and experimentation to better capture crop impacts of agroclimatic extremes—A review. F Crop Res 221:142–156. doi: 10.1016/J.FCR.2018.02.023

Ruane AC, Hudson NI, Asseng S, Camarrano D, Ewert F, Martre P, Boote KJ, Thorburn PJ, Aggarwal PK, Angulo C, Basso B, Bertuzzi P, Biernath C, Brisson N, Challinor AJ, Doltra J, Gayler S, Goldberg R, Grant RF, Heng L, Hooker J, Hunt LA, Ingwersen J, Izaurralde RC, Kersebaum KC, Kumar SN, Müller C, Nendel C, O'Leary G, Olesen JE, Osborne TM, Palosuo T, Priesack E, Ripoche D, Rötter RP, Semenov MA, Shcherbak I, Steduto P, Stöckle CO, Stratonovitch P, Streck T, Supit I, Tao F, Travasso M, Waha K, Wallach D, White JW, Wolf J (2016) Multi-wheat-model ensemble responses to interannual climate variability. Environ Model Softw 81:86–101. doi: 10.1016/j.envsoft.2016.03.008

Russo S, Sillmann J, Fischer EM (2015) Top ten European heatwaves since 1950 and their occurrence in the coming decades. Environ Res Lett. doi: 10.1088/1748-9326/10/12/124003

Saini HS (1997) Effects of water stress on male gametophyte development in plants. Sex Plant Reprod 10:67–73.

Saini HS, Aspinall D (1982) Abnormal sporogenesis in wheat (Triticum aestivum L.) induced by short periods of high temperature. Ann Bot 49:835–846.

Saini HS, Westgate ME (1999) Reproductive development in grain crops during drought. Adv Agron 68:59–96. doi: 10.1016/S0065-2113(08)60843-3

Sánchez B, Rasmussen A, Porter JR (2014) Temperatures and the growth and development of maize and rice: a review. Glob Chang Biol 20:408–417. doi: 10.1111/gcb.12389

Schröder W, Schmidt G, Schönrock S (2014) Modelling and mapping of plant phenological stages as bio-meteorological indicators for climate change. Environ Sci Eur 26:5. doi: 10.1186/2190-4715-26-5

Semenov MA (2009) Impacts of climate change on wheat in England and Wales. JR Soc

Interface 6 no. 33:343–350.

Semenov MA, Shewry PR (2011) Modelling predicts that heat stress, not drought, will increase vulnerability of wheat in Europe. Sci Rep 1:66. doi: 10.1038/srep00066

Shrestha N, Geerts S, Raes D, Horemans S, Soentjens S, Maupas F, Clouet P (2010) Yield response of sugar beets to water stress under Western European conditions. Agric Water Manag 97:346–350. doi: 10.1016/j.agwat.2009.10.005

Siebert S, Ewert F (2012) Spatio-temporal patterns of phenological development in Germany in relation to temperature and day length. Agric For Meteorol 152:44–57. doi: 10.1016/j.agrformet.2011.08.007

Siebert S, Ewert F, Eyshi Rezaei E, Kage H, Graß R (2014) Impact of heat stress on crop yield—on the importance of considering canopy temperature. Environ Res Lett 9:044012. doi: 10.1088/1748-9326/9/4/044012

Simon M (2009) Die landwirtschaftliche bewässerung in ostdeutschland seit 1949 - Eine historische analyse vor dem hintergrund des klimawandels. PIK Rep 1–93.

Soler CMT, Sentelhas PC, Hoogenboom G (2007) Application of the CSM-CERES-Maize model for planting date evaluation and yield forecasting for maize grown off-season in a subtropical environment. Eur J Agron 27:165–177. doi: 10.1016/j.eja.2007.03.002

Spellmann H, Ahrends B, Albert M, Andert S, Barkmann T, Böcher M, Breckling B, Christen O, Dvorak J, Eggers M, Fleck S, Fohrer N, Gauly M, Gerowitt B, Gieseke D, Grocholl J, Hakes W, Hammes V, Hartje V, Haunert G, Hoffmann M, Hufnagel J, Isselstein J, Kätzel R, Kayser M, Kehr I, Knauer H, Krott M, Lambertz C, Lange A, Langer G, Leefken G, Löffler S, Meesenburg H, Meißner R, Messal H, Meyer P, Möhring B, Möller K, Nagel J, Nuske R, Oetzmann A, Ohrmann S, v. Redwitz C, Riediger J, Schmidt M, Schröder J, Schröder W, Siebert R, Spindelndreher D, Stahlmann H, Stöck L, Sutmöller J, Svoboda N, Tänzer D, Tiedemann A, Ulber B, Wegner K, Werner PC, M W, Wüstemann H, Zander P, Ziesche T (2017) Nachhaltiges Landmanagement im Norddeutschen Tiefland. Beiträge aus der Nordwestdtsch Forstl Versuchsanstalt 18:446.

Stagge J, Tallaksen L (2014) Standardized precipitation-evapotranspiration index (SPEI): Sensitivity to potential evapotranspiration model and parameters. In: International Association of Hydrological Sciences (IAHS). Montpellier, France, pp 367–373

Stankowski S, Michalska B, Smagacz J, Gibczyńska M (2015) Estimation of Wheat Straw and Rapeseed Usefulness for Wheat Fertilisation in Arable Farming. J Ecol Eng 16:101–109. doi: 10.12911/22998993/1863

Stöckle C, Donatelli M, Nelson R (2003) CropSyst, a cropping systems simulation model. Eur J Agron 18:289–307.

Stout M, Owen F (1942) Vernalization of Sugar-Beet Seed. In: American Society of Sugar Beet Technologists - Proceedings from the 3rd Biennial Meeting. Salt Lake City, Utah, USA, pp 386–395

Stratonovitch P, Semenov MA (2015) Heat tolerance around flowering in wheat identified as a key trait for increased yield potential in Europe under climate change. J Exp Bot

66:3599–3609. doi: 10.1093/jxb/erv070

Streck NA, Weiss A (2003) Improving predictions of developmental stages in winter wheat: a modified Wang and Engel model. Agric For Meteorol 115:139–150.

Strer M, Svoboda N, Herrmann A (2014) Yield 2050: Risks and opportunities for the German agriculture - A modelling approach. 1984–1992.

Strer M, Hammrich A, Gutow L, Moenickes S (2016) Model-based analysis of causes for habitat segregation in Idotea species (Crustacea, Isopoda). Mar Biol 163:68. doi: 10.1007/s00227-016-2843-9

Strer M, Svoboda N, Herrmann A (2018) Abundance of adverse environmental conditions during critical stages of crop production in Northern Germany. Environ Sci Eur 30:16. doi: 10.1186/s12302-018-0138-0

Struik P, Wiersema S (2012) Seed potato technology. Wageningen Academic Publishers., Wageningen, The Netherlands

Struik PC, Geertsema J, Custers CHMG (1989a) Effects of shoot, root and stolon temperature on the development of the potato (Solanum tuberosum L.) plant. I. Development of the haulm. Potato Res 32:133–141. doi: 10.1007/BF02358225

Struik PC, Geertsema J, Custers CHMG (1989b) Effects of shoot, root and stolon temperature on the development of the potato (Solanum tuberosum L.) plant. II. Development of stolons. Potato Res 32:143–149.

Struik PC, Geertsema J, Custers CHMG (1989c) Effects of shoot, root and stolon temperature on the development of the potato (Solanum tuberosum L.) plant. III. Development of tubers. Potato Res 32:151–158. doi: 10.1007/BF02358227

Suanda DK (2012) Cardinal Temperatures of Brassica sp . and How to Determine It. AGROTROP 2:33–39.

Supit I, Hooijer AA, van Diepen CA (1994) System description of the WOFOST 6.0 crop simulation model implemented in CGMS. Volume 1: Theory and Algorithms. 150.

Suzuki N, Rivero RM, Shulaev V, Blumwald E, Mittler R (2014) Abiotic and biotic stress combinations. New Phytol 203:32–43. doi: 10.1111/nph.12797

Svoboda N, Strer M, Hufnagel J (2015) Rainfed winter wheat cultivation in the North German Plain will be water limited under climate change until 2070. Environ Sci Eur. doi: 10.1186/s12302-015-0061-6

Tao F, Rötter RP, Palosuo T, Gregorio Hernández Díaz-Ambrona C, Mínguez MI, Semenov MA, Kersebaum KC, Nendel C, Specka X, Hoffmann H, Ewert F, Dambreville A, Martre P, Rodríguez L, Ruiz-Ramos M, Gaiser T, Höhn JG, Salo T, Ferrise R, Bindi M, Cammarano D, Schulman AH (2018) Contribution of crop model structure, parameters and climate projections to uncertainty in climate change impact assessments. Glob Chang Biol 24:1291–1307. doi: 10.1111/gcb.14019

Terry N (1970) Developmental physiology of sugar-beet. II. Effects of temperature and nitrogen supply on the growth, soluble carbohydrate content and nitrogen content of leaves and roots. J Exp Bot 21:477–496.

Thimme Gowda P, Satyareddi SA, Manjunath S (2013) Crop Growth Modeling: A Review. Res Rev J Agric Allied Sci 2:1–11.

Thorp K, Batchelor W, Paz JO, Kaleita AL, DeJonge KC (2007) Using cross-validation to evaluate CERES-Maize yield simulations within a decision support system for precision agriculture. Agric Biosyst Eng 50:1467–1479.

Travasso MI, Caldiz DO, Saluzzo J a. (1996) Yield prediction using the SUBSTOR-potato model under Argentinian conditions. Potato Res 39:305–312. doi: 10.1007/BF02360922

Trnka M, Dubrovský M, Semerádová D, Žalud Z (2004) Projections of uncertainties in climate change scenarios into expected winter wheat yields. Theor Appl Climatol 77:229–249. doi: 10.1007/s00704-004-0035-x

Trnka M, Olesen JE, Kersebaum KC, Skjelvåg a. O, Eitzinger J, Seguin B, Peltonen-Sainio P, Rötter R, Iglesias A, Orlandini S, Dubrovský M, Hlavinka P, Balek J, Eckersten H, Cloppet E, Calanca P, Gobin A, Vučetić V, Nejedlik P, Kumar S, Lalic B, Mestre A, Rossi F, Kozyra J, Alexandrov V, Semerádová D, Žalud Z (2011) Agroclimatic conditions in Europe under climate change. Glob Chang Biol 17:2298–2318. doi: 10.1111/j.1365-2486.2011.02396.x

Trnka M, Rötter RP, Ruiz-Ramos M, Kersebaum KC, Olesen JE, Žalud Z, Semenov M a. (2014) Adverse weather conditions for European wheat production will become more frequent with climate change. Nat Clim Chang 4:637–643. doi: 10.1038/NCLIMATE2242

Van Dam J, Kooman PL, Struik PC (1996) Effects of temperature and photoperiod on early growth and final number of tubers in potato (Solanum tuberosum L.). Potato Res 39:51–62. doi: 10.1007/BF02358206

van der Velde M, Tubiello FN, Vrieling A, Bouraoui F (2012) Impacts of extreme weather on wheat and maize in France: Evaluating regional crop simulations against observed data. Clim Change 113:751–765. doi: 10.1007/s10584-011-0368-2

Van Ittersum MK, Leffelaar PA, Van Keulen H, Kropff MJ, Bastiaans L, Goudriaan J (2003) On approaches and applications of the Wageningen crop models. Eur J Agron 18:201–234. doi: 10.1016/S1161-0301(02)00106-5

Van Ittersum MK, Cassman KG, Grassini P, Wolf J, Tittonell P, Hochman Z (2013) Yield gap analysis with local to global relevance-A review. F Crop Res 143:4–17. doi: 10.1016/j.fcr.2012.09.009

van Rüth P, Schönthaler K, von Andrian-Werburg S, Buth M (2019) Monitoringbericht 2019 zur Deutschen Anpassungs strategie an den Klimawandel Bericht der Interministeriellen Arbeitsgruppe Anpassungsstrategie der Bundesregierung. Dessau-Roßlau, Germany

Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index. J Clim 23:1696–1718. doi: 10.1175/2009JCLI2909.1

Vining KC (1990) Effects of weather on agricultural crops and livestock: an overview. Int J

Environ Stud 36:27–39. doi: 10.1080/00207239008710581

Vos J, Evers JB, Buck-Sorlin GH, Andrieu B, Chelle M, De Visser PHB (2010) Functional-structural plant modelling: A new versatile tool in crop science. J Exp Bot 61:2101–2115. doi: 10.1093/jxb/erp345

Vučetić V (2011) Modelling of maize production in Croatia: present and future climate. J Agric Sci 149:145–157. doi: 10.1017/S0021859610000808

Wallach D, Martre P, Liu B, Asseng S, Ewert F, Thorburn PJ, van Ittersum M, Aggarwal PK, Ahmed M, Basso B, Biernath C, Cammarano D, Challinor AJ, De Sanctis G, Dumont B, Eyshi Rezaei E, Fereres E, Fitzgerald GJ, Gao Y, Garcia-Vila M, Gayler S, Girousse C, Hoogenboom G, Horan H, Izaurralde RC, Jones CD, Kassie BT, Kersebaum KC, Klein C, Koehler AK, Maiorano A, Minoli S, Müller C, Naresh Kumar S, Nendel C, O'Leary GJ, Palosuo T, Priesack E, Ripoche D, Rötter RP, Semenov MA, Stöckle C, Stratonovitch P, Streck T, Supit I, Tao F, Wolf J, Zhang Z (2018) Multimodel ensembles improve predictions of crop–environment–management interactions. Glob Chang Biol 24:5072–5083. doi: 10.1111/gcb.14411

Walther G (2003) Plants in a warmer world. 6:169–185.

Walworth JL, Carling DE (2002) Tuber initiation and development in irrigated and non-irrigated potatoes. Am J Potato Res 79:387–395. doi: 10.1007/BF02871683

Wang E, Engel T (1998) Simulation of phenological development of wheat crops. Agric Syst 58:1–24. doi: 10.1016/S0308-521X(98)00028-6

Wang E, Martre P, Zhao Z, Ewert F, Maiorano A, Rötter RP, Kimball BA, Ottman MJ, Wall GW, White JW, Reynolds MP, Alderman PD, Aggarwal PK, Anothai J, Basso B, Biernath C, Cammarano D, Challinor AJ, De Sanctis G, Doltra J, Fereres E, Garcia-Vila M, Gayler S, Hoogenboom G, Hunt LA, Izaurralde RC, Jabloun M, Jones CD, Kersebaum KC, Koehler AK, Liu L, Müller C, Kumar SN, Nendel C, O'Leary G, Olesen JE, Palosuo T, Priesack E, Rezaei EE, Ripoche D, Ruane AC, Semenov MA, Shcherbak I, Stöckle C, Stratonovitch P, Streck T, Supit I, Tao F, Thorburn P, Waha K, Wallach D, Wang Z, Wolf J, Zhu Y, Asseng S (2017) Erratum: The uncertainty of crop yield projections is reduced by improved temperature response functions. Nat plants 3:17125. doi: 10.1038/nplants.2017.125

Wang J, Wang E, Feng L, Yin H, Yu W (2013) Phenological trends of winter wheat in response to varietal and temperature changes in the North China Plain. F Crop Res 144:135–144. doi: 10.1016/j.fcr.2012.12.020

Wechsung F (2008) Die Ertragsfähigkeit ostdeutscher Ackerflächen unter Klimawandel. Berlin

Wentz FJ, Ricciardulli L, Hilburn K, Mears C (2007) How Much More Rain Will Global Warming Bring?\n10.1126/science.1140746. Science (80-) 317:233–235. doi: 10.1126/science.1140746

Wolf J, Van Diepen CA (1995) Effects of climate change on grain maize yield potential in the european community. Clim Change 29:299–331. doi: 10.1007/BF01091866

Wollenweber B (2003) Lack of Interaction between Extreme High-Temperature Events at Vegetative and Reproductive Growth Stages in Wheat. J Agron … 150:142–150.

Wood DW, Scott RK (1974) Sowing sugar beet in autumn in England. J Agric Sci 84:97–108.

Xu (2015) The effect of waterlogging on yield and seed quality at the early flowering stage in Brassica napus L. F Crop Reserch 180:238–245. doi: https://doi.org/10.1016/j.fcr.2015.06.007

Yordanov I, Velikova V, Tsonev T (2000) Plant responses to drought, acclimation, and stress tolerance. Photosynthetica 38:171–186.

Young LW, Wilen RW, Bonham-Smith PC (2004) High temperature stress of *Brassica napus* during flowering reduces micro- and megagametophyte fertility, induces fruit abortion, and disrupts seed production. J Exp Bot 55:485–495. doi: 10.1093/jxb/erh038

Zampieri M, Weissteiner C, Grizzetti B, Toreti A, M. M van den B, Dentener F (2019) Estimating resilience of annual crop production systems: theory and limitations.

Zhao G, Siebert S, Enders A, Rezaei EE, Yan C, Ewert F (2015) Demand for multi-scale weather data for regional crop modeling. Agric For Meteorol 200:156–171. doi: 10.1016/j.agrformet.2014.09.026

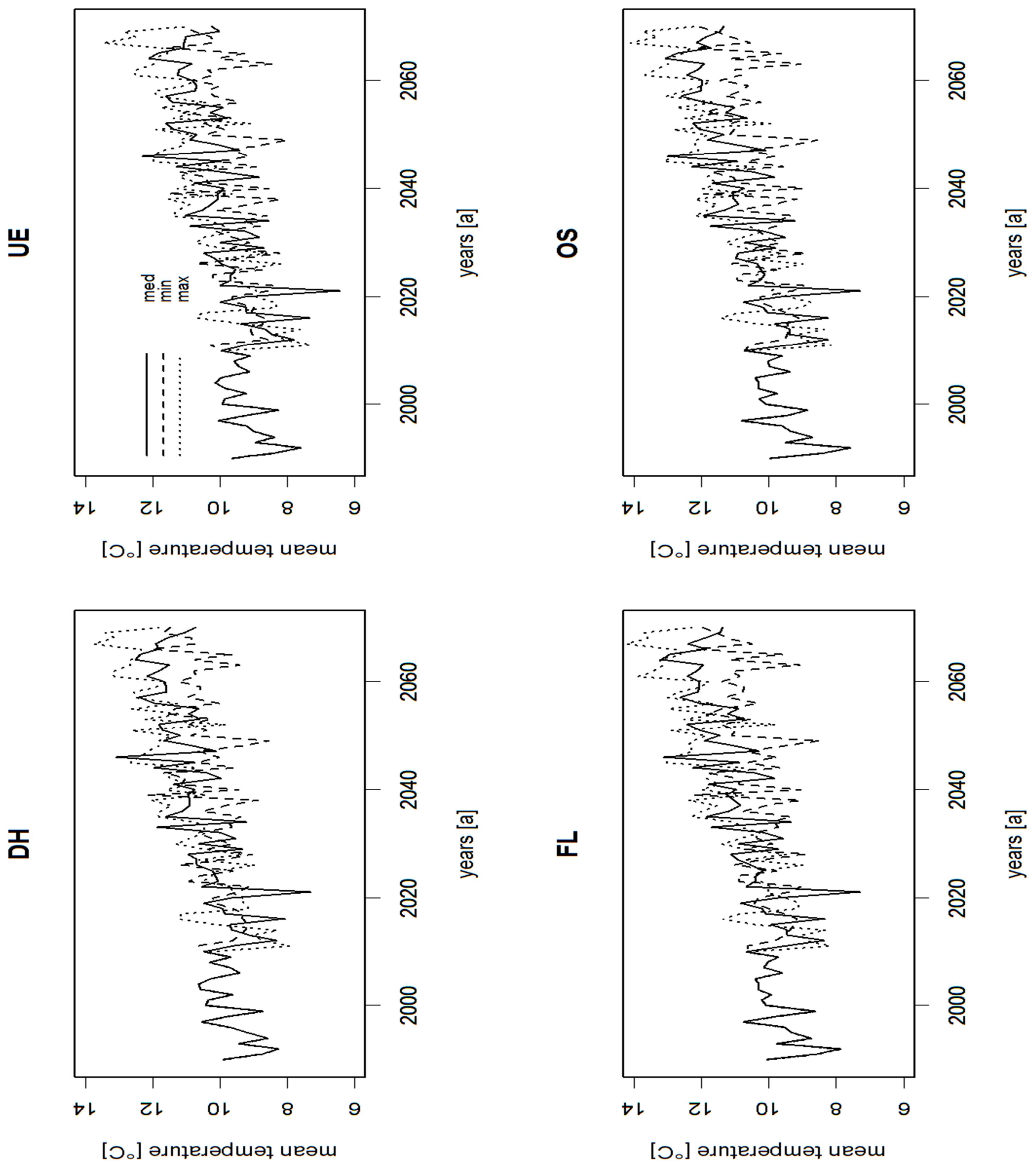
Zheng B, Chenu K, Doherty A, Chapman S (2014) The APSIM-Wheat Module (7.5 R3008).

Zhou W, Lin X (1995) Effects of Waterlogging At Different Stages of Development on the Growth and Yield of Winter Oilseed Rape (Brassica Napus L.). F Crop Res 44:103–110. doi: 10.1016/0378-4290(95)00075-5

Zirgoli MH, Kahrizi D (2015) Effects of end-season drought stress on yield and yield components of rapeseed (Brassica napus L.) in warm regions of Kermanshah Province. Biharean Biol 9:133–140.

Supplementary Material

Background



Supplementary material 1 mean temperature development in the model regions (NaLaMa-nT). Note: 1990-2010 values from the local weather stations of the Deutscher Wetterdienst (DWD, homogenised according to Caussinus and Mestre, (2004), while temperature data after 2010 is from three different climate scenarios, i.e. the max, med, and min temperature path of the climate models.

Chapter 1

Disclosure of methods

Methodology

Identification of critical crop growth stages

To identify critical crop growth stages, we conducted a keyword search using scientific databases (Web of Knowledge, Science Direct, Google Scholar). The analysis was restricted to crop species important for Central Europe, i.e. wheat (*Triticum aestivum* ssp aestivum L.), maize (*Zea mays* ssp *mays* L.), rapeseed (*Brassica napus* ssp *napus* L.), potato (*Solanum tuberosum* ssp *vulgaris* L.), and sugar beet (*Beta vulgaris* ssp *vulgaris* L.). Review and research articles were considered for evaluation. The search was restricted to articles investigating yield response to adverse environmental conditions during specific phenological stages. In this respect, the definition for adverse environmental conditions provided by Trnka et al. (2014) was applied. In detail, the authors considered winter frost without snow cover, late frost, waterlogging from sowing to anthesis, severely dry growing season (sowing–maturity), severe drought events between sowing and anthesis or between anthesis and maturity, heat stress at anthesis or during grain filling. Environmental conditions with a small spatial or temporal resolution, e.g. storms or hail events, were excluded from our study; although they are of importance at a local scale, they have a lower impact at a regional scale (Olesen et al., 2011). Likewise, articles focusing on the effect of salinity were not considered since this is not a key factor limiting crop production in the focus area. Further, articles analysing the impact of biotic factors such as competition, pests or diseases were also excluded.

Phenological growth stages were considered as critical growth stages if they were regarded to be especially susceptible to adverse environmental conditions or to be more susceptible than other stages investigated in the same article. Multiple entries per article are possible if, for example, an article addressed several crops or compared the impact of environmental stress in different development stages. For analysis, principal growth stages were assigned according to Meier (2001). Articles were discarded from the evaluation if growth stages could not be identified appropriately.

Implementation of critical stages in crop models

The second part of the current study focuses on the implementation of critical crop growth stages in dynamic crop growth models. We evaluated the APSIM, APES, CROPSYST, DAISY, DSSAT, FASSET, HERMES, MONICA, STICS and WOFOST models (Table 3), These are all well established and validated (Rosenzweig et al. 2013) but differ with respect to origin and philosophy. The evaluation was mainly restricted to wheat growth modules, which are provided by all the above-mentioned models. Two main aspects were addressed: (i) the types of phenological growth stage scales applied in the different models were identified, i.e. the algorithms and key drivers of phenological development, and (ii) the implementation of adverse environmental conditions was analysed. That is, specific response patterns to environmental stress impacts, such as drought or heat, in specific phenological growth stages. Particular attention was paid to crop growth stages, which had been identified as critical phases by the literature analysis.

Chapter 2

Supplementary material 2 DSSAT model parameters controlling the phenological development of wheat and maize.

Name	Definition	Value
Maize		
P1	Degree days (base 8°C) from emergence to end of juvenile phase	220
P2	Photoperiod sensitivity coefficient (0 -1)	0.3
P5	Degree days (base 8°C) from silking to physiological maturity	730
G2	Potential kernel number	670
G5	Potential kernel growth rate (mg/(kernel d))	8.5
PHINT	Thermal time between the appearance of leaf tips (8Cd)	38.9
Wheat		
P1D	Photoperiod sensitivity coefficient (% reduction/h near threshold)	50
P1V	Vernalisation sensitivity coefficient (%/d of unfulfilled vernalisation)	100
P5	Thermal time from the onset of linear fill to maturity (8Cd)	520
G1	Kernel number per unit stem + spike weight at anthesis (#/g)	40
G2	Potential kernel growth rate (mg/(kernel d))	40
G3	Tiller death coefficient. Standard stem + spike weight when elongation ceases (g)	2.1
PHINT	Thermal time between the appearance of leaf tips (8Cd)	95

Supplementary material 3 Generic medium silty clay properties chosen as soil for calibration (θ_s – saturated soil water content).

depth	clay	silt	θ_s
[cm]	[-]	[-]	[-]
5	0.23	0.39	0.46
15	0.23	0.39	0.46
30	0.23	0.39	0.46
45	0.25	0.41	0.46
60	0.25	0.41	0.46
90	0.31	0.45	0.46
120	0.21	0.34	0.46
150	0.26	0.37	0.46

Supplementary material 4 Soil type used for validation and phenological modelling at DH, and UE model regions; derived from BUEK 1000n [26] (θs – saturated soil water content; θ_a available water content; k_s- saturated permeability; CEC- cation exchange capacity).

depth	horizon	clay	silt	θ_s	θ_a	k_s	CEC
[cm]		[ ]	[ ]	[ ]	[ ]	[m/s]	[cmol/kg]
30	Ap	0.22	0.49	0.59	36	0.38	10
40	Al	0.11	0.28	0.50	32	0.39	5
80	Bv	0.11	0.28	0.50	24	0.2	5
100	Bv	0.07	0.26	0.48	24	0.39	3
200	C	0.15	0.30	0.48	0.24	0.25	8

Supplementary material 5 soil type used for validation and phenological modelling at FL, and OS model region; derived from BUEK 1000n [26] (θ_s – saturated soil water content; θ_a available water content; k_s- saturated permeability; CEC- cation exchange capacity).

depth	horizon	clay	silt	θ_s	θ_a	k_s	CEC
[cm]		[ ]	[ ]	[ ]	[ ]	[m/s]	[cmol/kg]
30	Ap	0.12	0.26	0.48	24	2.55	4
40	Al	0.07	0.15	0.41	25	1.8	2
50	Al	0.07	0.15	0.41	24	1.8	2
60	Bt	0.11	0.23	0.43	18	1.32	2
80	Bv	0.07	0.15	0.41	18	1.8	8
200	C	0.15	0.28	0.43	18	0.26	7

Supplementary material 6 maize phenological trends identified for the baseline (BASE 1981- 2010) and the 3 projections (MAX, MED, MIN) of the projection period (2021-2050) for region DH.

BBCH		BASE				MIN				MED				MAX			
		Estimates [doy] [doy/y]	R^2 / df []	p-value []		Estimates [doy] [doy/y]	R^2 / df []	p-value []		Estimates [doy] [doy/y]	R^2 / df []	p-value []		Estimates [doy] [doy/y]	R^2 / df []	p-value []	
1	Intercept	124 ± 1	0.41	5.7E-39	***	121 ± 3	0.45	2.7E-27	***	119 ± 4	0.01	1.7E-23	***	115 ± 4	0.00	3.9E-22	***
	Slope	-0.27 ± 0.06	28	1.4E-04	***	-0.74 ± 0.16	28	5.1E-05	***	-0.08 ± 0.21	28	7.0E-01		0.05 ± 0.23	28	8.4E-01	
11	Intercept	136 ± 2	0.39	1.9E-35	***	131 ± 3	0.37	1.4E-28	***	130 ± 4	0.01	3.7E-25	***	128 ± 3	0.00	3.7E-25	***
	Slope	-0.38 ± 0.09	28	2.3E-04	***	-0.61 ± 0.15	28	3.8E-04	***	-0.08 ± 0.20	28	7.0E-01		-0.03 ± 0.20	28	8.6E-01	
31	Intercept	163 ± 2	0.07	1.9E-33	***	160 ± 2	0.46	1.4E-33	***	160 ± 3	0.03	1.1E-28	***	157 ± 3	0.00	9.2E-29	***
	Slope	-0.18 ± 0.13	28	1.7E-01		-0.60 ± 0.12	28	3.5E-05	***	-0.17 ± 0.18	28	3.6E-01		-0.06 ± 0.18	28	7.4E-01	
61	Intercept	210 ± 2	0.20	1.6E-36	***	207 ± 2	0.51	3.0E-35	***	206 ± 3	0.07	1.5E-31	***	201 ± 3	0.00	7.0E-32	***
	Slope	-0.33 ± 0.13	28	1.4E-02	*	-0.75 ± 0.14	28	8.9E-06	***	-0.26 ± 0.19	28	1.7E-01		-0.07 ± 0.18	28	7.1E-01	
70	Intercept	223 ± 2	0.20	1.6E-36	***	221 ± 3	0.53	2.8E-35	***	218 ± 3	0.08	2.6E-32	***	213 ± 3	0.00	7.3E-32	***
	Slope	-0.36 ± 0.13	28	1.3E-02	*	-0.82 ± 0.15	28	5.9E-06	***	-0.28 ± 0.19	28	1.4E-01		-0.01 ± 0.19	28	9.5E-01	
99	Intercept	288 ± 6	0.17	3.4E-28	***	280 ± 5	0.54	3.3E-31	***	272 ± 5	0.17	1.6E-29	***	263 ± 6	0.00	1.3E-26	***

Supplementary material 7 maize phenological trends identified for the baseline (BASE 1981- 2010) and the 3 projections (MAX, MED, MIN) of the scenario period (2021-2050) for model region Uelzen (UE).

		BASE						MIN						MED						MAX					
BBCH		Estimates [doy] [doy/y]			R^2/df []	p-value []		Estimates [doy] [doy/y]			R^2/df []	p-value []		Estimates [doy] [doy/y]			R^2/df []	p-value []		Estimates [doy] [doy/y]			R^2/df []	p-value []	
1	Intercept	124	±	1	0.20	1.7E-36	***	124	±	3	0.49	8.9E-28	***	122	±	4	0.03	3.7E-23	***	119	±	4	0.00	4.0E-24	***
	Slope	-0.20	±	0.07	28	1.4E-02	*	-0.79	±	0.15	28	1.9E-05	***	-0.21	±	0.22	28	3.6E-01		-0.04	±	0.20	28	8.5E-01	
11	Intercept	136	±	2	0.21	6.7E-35	***	134	±	3	0.34	3.3E-28	***	135	±	4	0.05	1.4E-24	***	130	±	3	0.00	1.1E-26	***
	Slope	-0.26	±	0.09	28	1.1E-02	*	-0.61	±	0.16	28	7.3E-04	***	-0.26	±	0.22	28	2.5E-01		-0.05	±	0.18	28	7.8E-01	
31	Intercept	166	±	2	0.07	4.4E-34	***	163	±	2	0.51	4.1E-34	***	165	±	4	0.08	1.9E-27	***	161	±	3	0.01	1.0E-29	***
	Slope	-0.17	±	0.12	28	1.7E-01		-0.64	±	0.12	28	1.1E-05	***	-0.34	±	0.21	28	1.2E-01		-0.08	±	0.17	28	6.3E-01	
61	Intercept	214	±	2	0.14	5.4E-36	***	210	±	2	0.57	1.0E-36	***	212	±	4	0.09	1.7E-30	***	207	±	3	0.03	2.8E-32	***
	Slope	-0.29	±	0.13	28	4.1E-02	*	-0.75	±	0.12	28	1.6E-06	***	-0.36	±	0.21	28	9.9E-02	.	-0.17	±	0.18	28	3.6E-01	
70	Intercept	227	±	3	0.15	2.5E-35	***	223	±	2	0.58	7.5E-37	***	225	±	4	0.11	3.6E-31	***	219	±	3	0.00	9.8E-32	***
	Slope	-0.33	±	0.15	28	3.7E-02	*	-0.81	±	0.13	28	1.0E-06	***	-0.39	±	0.21	28	7.3E-02	.	-0.07	±	0.20	28	7.2E-01	
99	Intercept	298	±	7	0.12	9.1E-28	***	288	±	5	0.53	5.4E-30	***	287	±	6	0.20	6.5E-28	***	278	±	8	0.00	1.6E-24	***
	Slope	-0.73	±	0.37	28	5.7E-02	.	-1.67	±	0.30	28	5.1E-06	***	-0.92	±	0.35	28	1.4E-02	*	0.00	±	0.45	28	1.0E+00	

Supplementary material 8 Maize phenological trends identified for the baseline (BASE 1981- 2010) and the 3 projections (MAX, MED, MIN) of the scenario period (2021-2050) for model region Fläming (FL).

		BASE						MIN						MED						MAX					
BBCH		Estimates [doy] [doy/y]			R^2/df []	p-value []		Estimates [doy] [doy/y]			R^2/df []	p-value []		Estimates [doy] [doy/y]			R^2/df []	p-value []		Estimates [doy] [doy/y]			R^2/df []	p-value []	
1	Intercept	126	±	1	0.51	1.2E-35	***	117	±	2	0.52	4.7E-30	***	116	±	3	0.08	1.2E-24	***	117	±	4	0.03	3.1E-23	***
	Slope	-0.44	±	0.08	28	1.0E-05	***	-0.66	±	0.12	28	6.1E-06	***	-0.29	±	0.19	28	1.3E-01		-0.21	±	0.21	28	3.3E-01	
11	Intercept	136	±	2	0.30	4.7E-33	***	127	±	2	0.43	5.9E-30	***	126	±	3	0.04	4.3E-27	***	130	±	3	0.10	1.9E-26	***
	Slope	-0.37	±	0.11	28	1.9E-03	**	-0.61	±	0.13	28	7.8E-05	***	-0.18	±	0.16	28	2.8E-01		-0.31	±	0.18	28	9.2E-02	.
31	Intercept	161	±	3	0.06	6.9E-32	***	154	±	2	0.41	4.7E-33	***	155	±	3	0.08	1.3E-29	***	155	±	3	0.04	6.0E-29	***
	Slope	-0.18	±	0.14	28	2.1E-01		-0.55	±	0.12	28	1.3E-04	***	-0.26	±	0.16	28	1.3E-01		-0.19	±	0.17	28	3.0E-01	
61	Intercept	206	±	3	0.15	7.0E-35	***	197	±	2	0.51	7.3E-37	***	197	±	3	0.07	5.1E-32	***	197	±	3	0.02	1.6E-30	***
	Slope	-0.32	±	0.14	28	3.2E-02	*	-0.62	±	0.12	28	1.1E-05	***	-0.24	±	0.17	28	1.7E-01		-0.14	±	0.19	28	4.8E-01	
70	Intercept	219	±	3	0.17	6.2E-35	***	209	±	2	0.53	5.6E-37	***	210	±	3	0.09	8.6E-33	***	208	±	4	0.01	9.2E-31	***
	Slope	-0.35	±	0.15	28	2.6E-02	*	-0.68	±	0.12	28	4.8E-06	***	-0.28	±	0.17	28	1.1E-01		-0.11	±	0.20	28	6.0E-01	
99	Intercept	276	±	5	0.19	2.4E-29	***	253	±	3	0.59	5.8E-37	***	258	±	5	0.17	5.3E-30	***	253	±	5	0.00	2.9E-28	***
	Slope	-0.77	±	0.30	28	1.6E-02	*	-0.94	±	0.15	28	6.5E-07	***	-0.64	±	0.27	28	2.3E-02	*	-0.05	±	0.30	28	8.7E-01	

Supplementary material 9 Maize phenological trends identified for the baseline (BASE 1981- 2010) and the 3 projections (MAX, MED, MIN) of the scenario period (2021-2050) for model region Oder-Spree (OS).

		BASE				MIN				MED				MAX			
BBCH		Estimates [doy] [doy/y]	R^2/df []	p-value []		Estimates [doy] [doy/y]	R^2 / df []	p-value []		Estimates [doy] [doy/y]	R^2 / df []	p-value []		Estimates [doy] [doy/y]	R^2 / df []	P-value []	
1	Intercept	124 ± 2	0,11	1.1E-31	***	121 ± 2	0.62	2.4E-30	***	121 ± 4	0.12	2.7E-23	***	115 ± 4	0.01	2.0E-23	***
	Slope	-0.21 ± 0.11	28	6.9E-02	.	-0.81 ± 0.12	28	2.7E-07	***	-0.43 ± 0.22	28	5.8E-02	.	-0.11 ± 0.21	28	6.1E-01	
11	Intercept	136 ± 2	0.26	2.3E-33	***	130 ± 2	0.53	7.6E-31	***	133 ± 4	0.11	3.6E-24	***	127 ± 3	0.03	7.5E-28	***
	Slope	-0.33 ± 0.11	28	4.2E-03	**	-0.70 ± 0.13	28	5.3E-06	***	-0.41 ± 0.22	28	7.6E-02	.	-0.15 ± 0.16	28	3.6E-01	
31	Intercept	162 ± 2	0.04	1.7E-32	***	158 ± 2	0.56	1.4E-34	***	160 ± 4	0.14	6.3E-27	***	156 ± 3	0.05	6.6E-31	***
	Slope	-0.16 ± 0.14	28	2.6E-01		-0.66 ± 0.11	28	2.0E-06	***	-0.45 ± 0.21	28	4.4E-02	*	-0.18 ± 0.15	28	2.5E-01	
61	Intercept	206 ± 3	0.07	1.2E-33	***	199 ± 2	0.61	4.5E-38	***	201 ± 4	0.12	4.0E-30	***	198 ± 3	0.06	9.2E-34	***
	Slope	-0.23 ± 0.16	28	1.5E-01		-0.70 ± 0.11	28	3.1E-07	***	-0.39 ± 0.21	28	6.6E-02	.	-0.20 ± 0.15	28	1.9E-01	
70	Intercept	219 ± 3	0.11	1.2E-34	***	211 ± 2	0.59	1.4E-37	***	213 ± 4	0.14	4.2E-31	***	210 ± 3	0.06	4.4E-34	***
	Slope	-0.29 ± 0.15	28	6.7E-02	.	-0.74 ± 0.12	28	6.1E-07	***	-0.43 ± 0.20	28	4.0E-02	*	-0.20 ± 0.15	28	2.1E-01	
99	Intercept	277 ± 7	0.09	9.7E-27	***	257 ± 2	0.73	5.7E-39	***	263 ± 5	0.22	2.5E-29	***	254 ± 5	0.01	4.4E-30	***
	Slope	-0.64 ± 0.37	28	1.0E-01		-1.09 ± 0.13	28	2.3E-09	***	-0.81 ± 0.29	28	8.5E-03	**	-0.13 ± 0.26	28	6.2E-01	

Supplementary material 10 Wheat phenological trends identified for the baseline (BASE 1981- 2010) and the 3 projections (MAX, MED, MIN) of the projection period (2021-2050) for model DH.

BBCH		BASE				MIN				MED				MAX			
		Estimate [doy] [doy/y]	R^2 / df []	p-value []		Estimate [doy] [doy/y]	R^2 / df []	p-value []		Estimate [doy] [doy/y]	R^2 / df []	p-value []		Estimate [doy] [doy/y]	R^2 / df []	p-value []	
31	Intercept	122 ± 40	0.21	4.7E-03	**	120 ± 26	0.38	8.1E-05	***	118 ± 2	0.05	2.6E-30	***	117 ± 2	0.01	3.7E-29	***
	Slope	-0.90 ± 0.33	27	1.2E-02	*	-0.92 ± 0.23	27	3.8E-04	***	-0.14 ± 0.11	27	2.4E-01		-0.08 ± 0.13	27	5.3E-01	
51	Intercept	86 ± 40	0.10	4.1E-02	*	161 ± 31	0.45	2.1E-05	***	152 ± 2	0.05	2.8E-31	***	151 ± 2	0.01	4.2E-31	***
	Slope	-0.47 ± 0.26	27	8.8E-02	.	-1.00 ± 0.21	27	7.4E-05	***	-0.17 ± 0.14	27	2.2E-01		-0.06 ± 0.14	27	6.5E-01	
61	Intercept	100 ± 39	0.15	1.6E-02	*	187 ± 36	0.45	2.1E-05	***	170 ± 2	0.09	1.0E-32	***	167 ± 2	0.01	3.8E-32	***
	Slope	-0.50 ± 0.23	27	3.7E-02	*	-1.05 ± 0.22	27	6.3E-05	***	-0.22 ± 0.13	27	1.1E-01		-0.07 ± 0.14	27	6.3E-01	
74	Intercept	118 ± 43	0.18	1.0E-02	*	203 ± 35	0.52	3.0E-06	***	191 ± 2	0.08	1.9E-33	***	189 ± 2	0.01	4.0E-33	***
	Slope	-0.54 ± 0.23	27	2.3E-02	*	-1.02 ± 0.19	27	9.5E-06	***	-0.21 ± 0.14	27	1.5E-01		-0.07 ± 0.14	27	6.5E-01	
99	Intercept	222 ± 2	0.22	3.0E-35	***	203 ± 33	0.54	1.8E-06	***	217 ± 3	0.08	1.5E-34	***	214 ± 3	0.00	1.5E-33	***
	Slope	-0.39 ± 0.14	27	1.0E-02	*	-0.88 ± 0.16	27	5.9E-06	***	-0.23 ± 0.15	27	1.3E-01		0.03 ± 0.16	27	8.3E-01	

Supplementary material 11 Wheat phenological trends identified for the baseline (BASE 1981- 2010) and the 3 projections (MAX, MED, MIN) of the scenario period (2021-2050) for model region Uelzen (UE).

BBCH		BASE				MAX				MED				Min			
		Estimate	R^2/df	p-value		Estimate	R^2/df	p-value		Estimate	R^2 / df	p-value		Estimate	R^2 / df	P-value	
		[doy]				[doy]				[doy]				[doy]			
		[doy/y]	[]	[]		[doy/y]	[]	[]		[doy/y]	[]	[]		[doy/y]	[]	[]	
31	Intercept	125 ± 2	0.26	8.8E-34	***	124 ± 27	0.37	1.1E-04	***	120 ± 2	0.03	3.6E-30	***	120 ± 2	0.03	1.8E-29	***
	Slope	-0.28 ± 0.09	27	4.8E-03	**	-0.95 ± 0.24	27	4.7E-04	***	-0.11 ± 0.12	27	3.6E-01		-0.12 ± 0.13	27	3.4E-01	
51	Intercept	160 ± 2	0.19	2.5E-34	***	162 ± 31	0.46	1.5E-05	***	155 ± 2	0.05	1.2E-30	***	154 ± 2	0.01	1.1E-30	***
	Slope	-0.27 ± 0.11	27	1.9E-02	*	-1.00 ± 0.21	27	5.4E-05	***	-0.17 ± 0.15	27	2.4E-01		-0.09 ± 0.14	27	5.3E-01	
61	Intercept	179 ± 2	0.22	1.2E-34	***	182 ± 34	0.48	1.1E-05	***	173 ± 2	0.07	5.9E-32	***	172 ± 2	0.03	2.8E-32	***
	Slope	-0.33 ± 0.12	27	1.0E-02	*	-1.01 ± 0.20	27	3.4E-05	***	-0.21 ± 0.14	27	1.6E-01		-0.13 ± 0.14	27	3.8E-01	
74	Intercept	195 ± 2	0.25	3.3E-36	***	205 ± 34	0.53	2.3E-06	***	194 ± 3	0.05	3.4E-33	***	193 ± 3	0.02	9.8E-33	***
	Slope	-0.34 ± 0.11	27	5.3E-03	**	-1.05 ± 0.19	27	7.2E-06	***	-0.18 ± 0.15	27	2.2E-01		-0.10 ± 0.15	27	5.0E-01	
99	Intercept	233 ± 2	0.30	2.7E-37	***	211 ± 34	0.55	1.5E-06	***	221 ± 3	0.06	1.8E-34	***	219 ± 3	0.00	1.0E-33	***
	Slope	-0.42 ± 0.12	27	2.1E-03	**	-0.91 ± 0.16	27	4.6E-06	***	-0.20 ± 0.15	27	2.0E-01		-0.02 ± 0.16	27	9.0E-01	

Supplementary material 12 Wheat phenological trends identified for the baseline (BASE 1981- 2010) and the 3 projections (MAX, MED, MIN) of the scenario period (2021-2050) for model region Fläming (FL).

BBCH		BASE				MAX				MED				Min			
		Estimate	R^2 / df	p-value		Estimate	R^2 / df	p-value		Estimate	R^2 / df	p-value		Estimate	R^2 / df	P-value	
		[doy] [doy/y]	[]	[]		[doy] [doy/y]	[]	[]		[doy] [doy/y]	[]	[]		[doy] [doy/y]	[]	[]	
31	Intercept	129 ± 2	0.28	4.8E-34	***	123 ± 2	0.42	1.1E-32	***	124 ± 2	0.07	8.3E-31	***	123 ± 2	0.02	1.8E-30	***
	Slope	-0.29 ± 0.09	27	3.1E-03	**	-0.43 ± 0.10	27	1.6E-04	***	-0.16 ± 0.11	27	1.7E-01		-0.09 ± 0.12	27	4.4E-01	
51	Intercept	156 ± 2	0.10	2.2E-32	***	150 ± 2	0.47	3.1E-35	***	151 ± 2	0.07	1.5E-31	***	150 ± 2	0.02	2.0E-31	***
	Slope	-0.22 ± 0.13	27	8.8E-02	.	-0.47 ± 0.10	27	3.6E-05	***	-0.19 ± 0.13	27	1.6E-01		-0.10 ± 0.13	27	4.6E-01	
61	Intercept	174 ± 2	0.15	1.0E-32	***	167 ± 2	0.49	2.4E-36	***	168 ± 2	0.09	3.1E-32	***	166 ± 2	0.01	1.0E-32	***
	Slope	-0.30 ± 0.14	27	3.7E-02	*	-0.49 ± 0.10	27	2.4E-05	***	-0.22 ± 0.14	27	1.2E-01		-0.08 ± 0.13	27	5.6E-01	
74	Intercept	195 ± 2	0.18	3.6E-34	***	187 ± 1	0.60	2.8E-39	***	188 ± 2	0.08	3.1E-33	***	187 ± 2	0.02	1.3E-33	***
	Slope	-0.33 ± 0.14	27	2.3E-02	*	-0.54 ± 0.08	27	6.9E-07	***	-0.22 ± 0.14	27	1.4E-01		-0.11 ± 0.14	27	4.3E-01	
99	Intercept	222 ± 2	0.22	3.0E-35	***	213 ± 2	0.61	1.1E-39	***	214 ± 2	0.11	1.3E-34	***	211 ± 2	0.00	1.3E-34	***
	Slope	-0.39 ± 0.14	27	1.0E-02	*	-0.60 ± 0.09	27	5.7E-07	***	-0.26 ± 0.14	27	8.2E-02	.	-0.01 ± 0.14	27	9.6E-01	

Supplementary material 13 Wheat phenological trends identified for the baseline (BASE 1981- 2010) and the 3 projections (MAX, MED, MIN) of the scenario period (2021-2050) for model region Oder-Spree (OS).

BBCH		BASE				MAX				MED				Min			
		Estimate [doy] [doy/y]	R^2/n []	p-value []		Estimate [doy] [doy/y]	R^2 / n []	p-value []		Estimate [doy] [doy/y]	R^2 / n []	p-value []		Estimate [doy] [doy/y]	R^2/n []	p-value []	
31	Intercept	123 ± 1	0.21	6.0E-34	***	136 ± 23	0.50	3.2E-06	***	123 ± 2	0.07	4.6E-31	***	118 ± 2	0.01	1.1E-29	***
	Slope	-0.24 ± 0.09	27	1.1E-02	*	-1.08 ± 0.21	27	1.8E-05	***	-0.16 ± 0.11	27	1.7E-01		-0.05 ± 0.12	27	6.7E-01	
51	Intercept	156 ± 2	0.09	8.3E-33	***	174 ± 28	0.54	1.5E-06	***	152 ± 2	0.09	2.3E-31	***	150 ± 2	0.03	7.3E-32	***
	Slope	-0.20 ± 0.12	27	1.1E-01		-1.10 ± 0.20	27	6.1E-06	***	-0.22 ± 0.13	27	1.1E-01		-0.11 ± 0.13	27	4.1E-01	
61	Intercept	174 ± 2	0.18	7.1E-34	***	189 ± 31	0.53	2.1E-06	***	168 ± 2	0.09	4.6E-32	***	166 ± 2	0.01	2.9E-33	***
	Slope	-0.31 ± 0.12	27	2.0E-02	*	-1.09 ± 0.20	27	7.3E-06	***	-0.23 ± 0.14	27	1.2E-01		-0.08 ± 0.12	27	5.5E-01	
74	Intercept	195 ± 2	0.22	6.0E-35	***	231 ± 30	0.66	2.5E-08	***	188 ± 2	0.08	3.5E-33	***	187 ± 2	0.03	1.0E-33	***
	Slope	-0.35 ± 0.13	27	1.1E-02	*	-1.21 ± 0.17	27	8.6E-08	***	-0.22 ± 0.14	27	1.3E-01		-0.12 ± 0.14	27	3.6E-01	
99	Intercept	223 ± 2	0.26	1.1E-35	***	243 ± 31	0.67	2.2E-08	***	214 ± 2	0.10	7.0E-35	***	212 ± 2	0.00	1.2E-34	***
	Slope	-0.42 ± 0.14	27	4.3E-03	**	-1.11 ± 0.15	27	7.0E-08	***	-0.24 ± 0.14	27	9.4E-02	.	-0.04 ± 0.14	27	7.7E-01	

Chapter 3

Disclosure of methods

Material and Methods

Method

Annual correlation patterns derived between yield time series and climate time series provide a classification for environmental impact on agricultural production systems. We follow closely the approach presented by Potopová et al. (2015) to establish such annual correlation patterns between standardised yield residual series (SYRS) to describe yield variability, and the standardised precipitation evaporation index to describe drought (SPEI). Latter is a measure for water balance anomalies in monthly to annual resolution. The method allows for comparison between various crops, production systems, years and sites. The high grade of standardisation allows high comparability. This standardisation includes de-trending of yield and environmental time series to omit the impact of long-term shifts and developments (Potopová et al. 2015).

Region

Lower Saxony has a highly productive agriculturally dominated landscape, providing a significant fraction of German crop production. A temperate oceanic climate dominates the region (Cfb, classification Köppen (Metzger et al. 2005; Peel et al. 2007)). We selected Diepholz (centrally located) as a representative site for this region (Metzger et al. 2005). It is characterised by mostly fertile soils, mainly cultivated by maize, winter barley, summer barley, rye, potato, sugar beet, oats, and rapeseed (Richter et al. 2007). Except for regional specialised production systems, e.g. vegetables and some local soil properties, drought was generally not regarded as an imminent risk for the local agricultural production systems until, recently. Therefore, local agricultural production relies heavily on rain-fed systems.

Data preparation

Standardised yield residual series (SYRS) are prepared from observed yield data. Supplementary material 15 to Supplementary material 23 give a general overview of the available yield time series. The focus of data preparation was on de-trending the time series. In regards to this goal, standard functions can quantify yield trends for specific crops (Table 14). The adjusted coefficient of determination and Akaike information criterion (AIC) selected the crop-specific de-trending functions. The resulting residuals acquired from the de-trending process are standardised (Interpretation guidance: Table 15 b).

The focus here was to provide a de-trended time series for each crop. Arguably, functions applied here, do not meet requirements to describe physiological crop responses, e.g. growth limits.

Additionally, the calculation of the standardised precipitation evapotranspiration index (SPEI) uses a time series of *monthly* mean temperature and *monthly* precipitation sums (1946-2015). The Thornthwaite approach derives evapotranspiration needed for the calculation of the SPEI (Begueria and Serrano 2015). This study aggregates lags for SPEI of one, two, and three months. A linear model was sufficient to de-trend temperature and precipitation time series. Table 15 comprises interpretation guidance for SPEI and SYRS.

Inventory

Spearman's rho correlation coefficient determines the strength of the association between SYRS and SPEI. These correlation coefficients are calculated for each combination of month and crop respectively production system, i.e. maize, winter barley, summer barley, rye, potato, sugar beet, oats, and rapeseed. Additionally, using different time lags provides insight on longer-term impact (one month, two months, three months).

Model study

A modelling study provides simulated yield time series for maize and wheat. A comparison between observed and modelled patterns identifies the potential of the model to reproduce annual correlation patterns at the site. The analysis was restricted to maize and wheat, being important production crops and representing summer and winter cropping in Lower Saxony.

The model was set up in DSSAT as follows: we used p*henological data* sets to establish typical production schemes from sowing to maturity. Input climate data were daily weather time series in the period 1981 to 2010. Soil type was set typical for the study area as a medium silty loam accordingly to the German soil survey (Richter et al. 2007, Supplementary material 24). Model parameters are estimated by the minimisation of root mean square error (RMSE) between simulated and observed phenology and yield data (Figure 15, Figure 16).

Crop simulation models can provide sophisticated methods to determine water balance (Jones et al. 2003a; Hoogenboom et al. 2012). Nevertheless, we choose to derive evapotranspiration after Thornthwaite for better comparability with the observation procedure (Vicente-Serrano et al. 2010; Begueria and Serrano 2015). The parametrisation of crop models for maize and wheat in the period 1981-2010 was successful based on the available data (Figure 15, Figure 16). A subset of observed annual correlation patterns provides a reference for comparison that matches the model period (1981-2010 instead of 1948-2015).

Data

The present study utilises comprehensive agro and agro-climatic data compiled from the Federal Statistical Office of Germany, State Statistic Bureaus and the German Weather Service (DWD).

Yield data comprise yields of different crops from agro-data sets published by statistical bureaus in Germany 1948 to 2015. These include yields of various production crops in Lower Saxony. Supplementary material 15 to Supplementary material 23 illustrates a general overview of the available yield time series.

The climate data used falls into the following three categories.

First, climate data utilised for the calculation of SPEI are available from the German weather service DWD. It comprises in *monthly resolution* temperatures, and precipitation means respectively sums for the years 1948 to 2015.

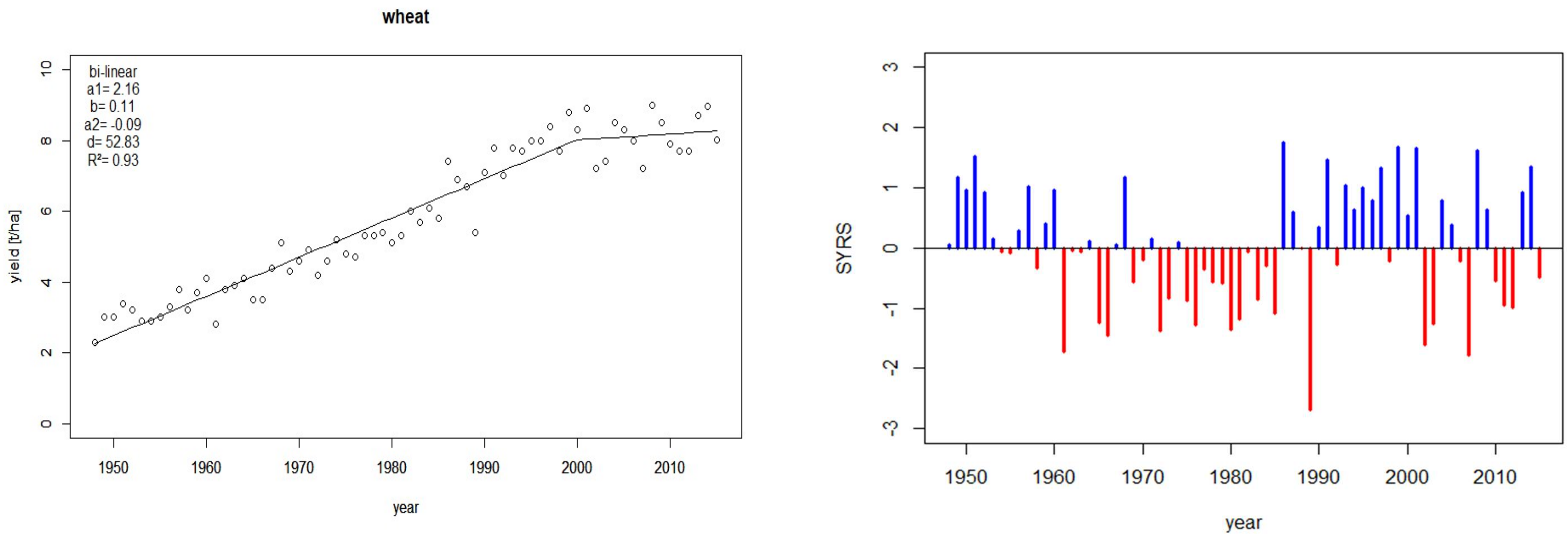
Second, climate data to model yield time series of maize and wheat in a *daily resolution* is available for the time frame 1981 to 2010. Data comprise weather data of the weather station in Diepholz operated by DWD. Data include daily mean, max and min temperatures, as well as daily precipitation, wind speeds and solar radiation.

Third, data on phenology comprises dates for numerous phenological stages of wheat and maize for the period 1981-2010 obtained from the German weather service.

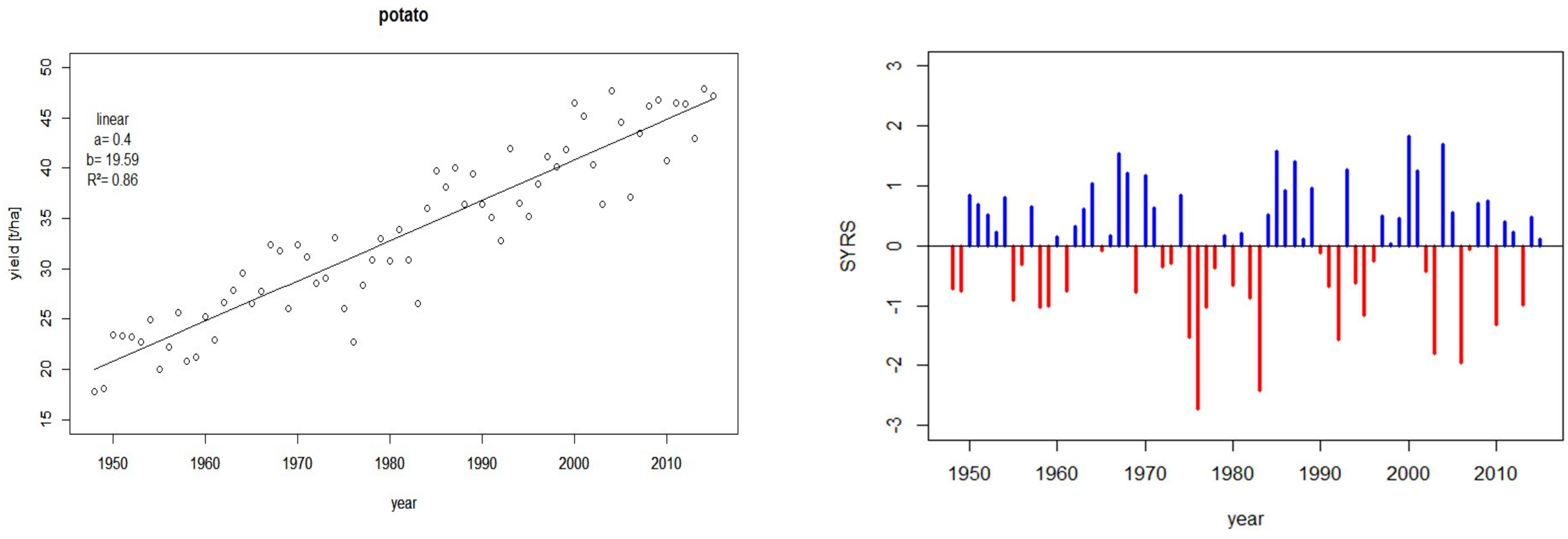
Tables and figures

Supplementary material 14 DSSAT model parameters for the development of maize and wheat.

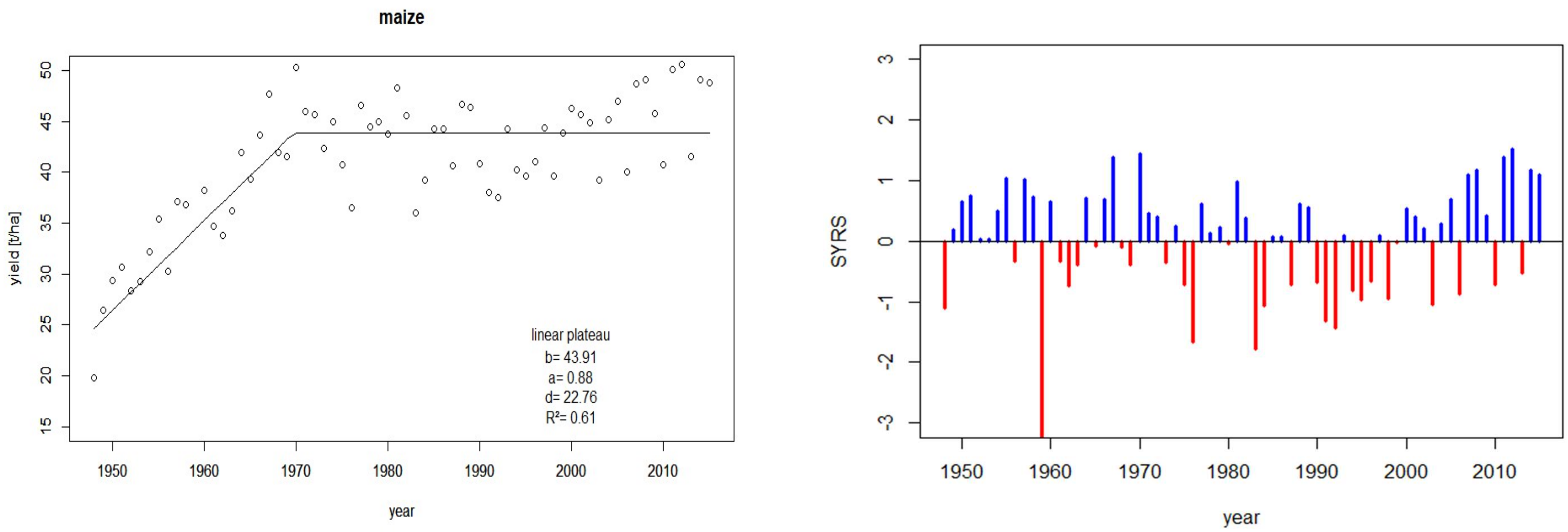
Name	Definition	Value
Maize		
P1	Degree days (base 8°C) from emergence to end of the juvenile phase	220
P2	Photoperiod sensitivity coefficient (0 -1)	0.363
P5	Degree days (base 8°C) from silking to physiological maturity	745.0
G2	Potential kernel number	267.5
G5	Potential kernel growth rate (mg/(kernel d))	17.56
PHINT	Thermal time between the appearance of leaf tips (8Cd)	38.90
Wheat		
P1D	Photoperiod sensitivity coefficient (% reduction/h near-threshold)	48.57
P1V	Vernalisation sensitivity coefficient (%/d of unfulfilled vernalisation)	50
P5	Thermal time from the onset of linear fill to maturity (8Cd)	715.4
G1	Kernel number per unit stem + spike weight at anthesis (#/g)	50.00
G2	Potential kernel growth rate (mg/(kernel d))	75.22
G3	Tiller death coefficient. Standard stem + spike weight when elongation ceases (g)	2.1
PHINT	Thermal time between the appearance of leaf tips (8Cd)	95



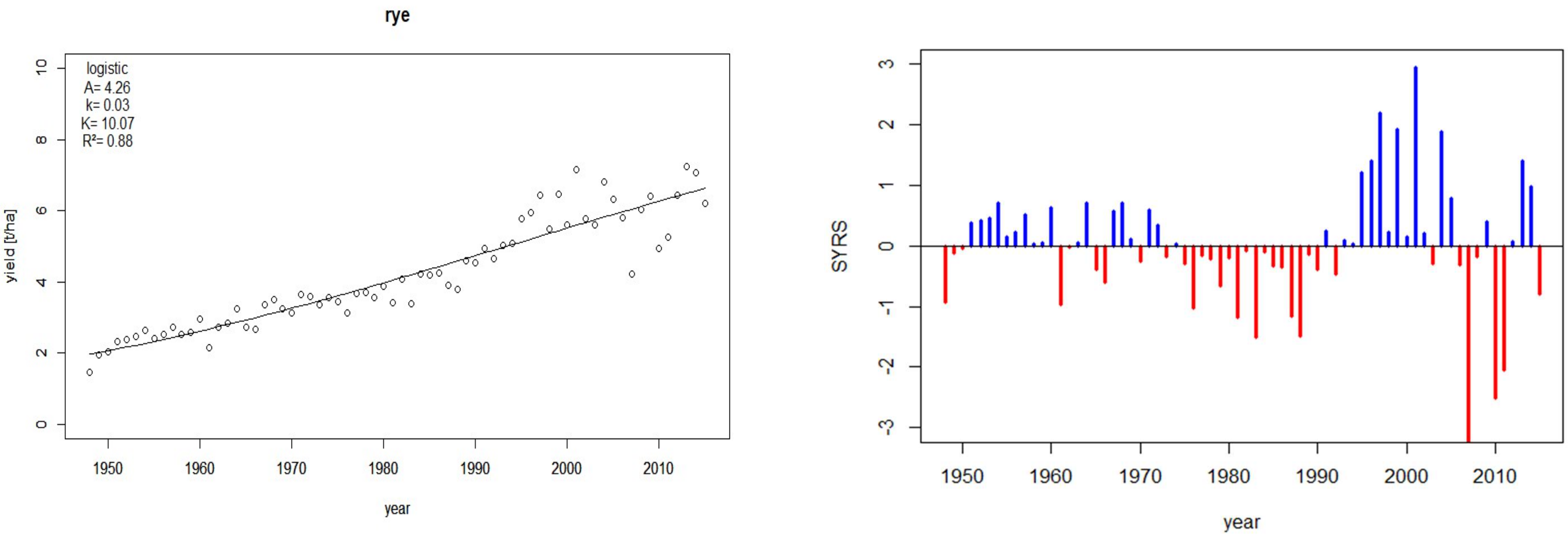
Supplementary material 15 yield time series of wheat, including best-fit trend function and resulting standardised yield residuals time series (SYRS) for Lower Saxony, Germany (functions according to Table 14).



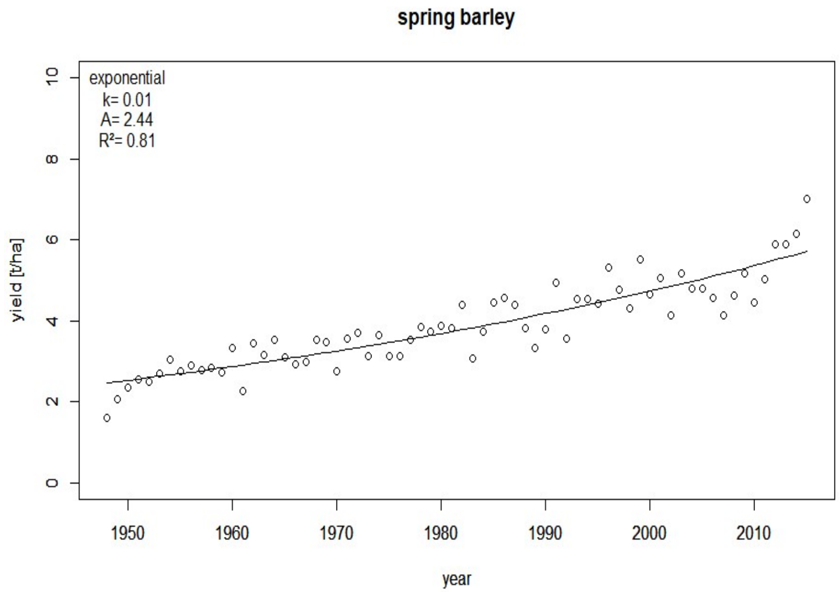
Supplementary material 16 yield time series of potato, including best-fit trend function and resulting standardised yield residuals time series (SYRS) for Lower Saxony, Germany (functions according to Table 14).

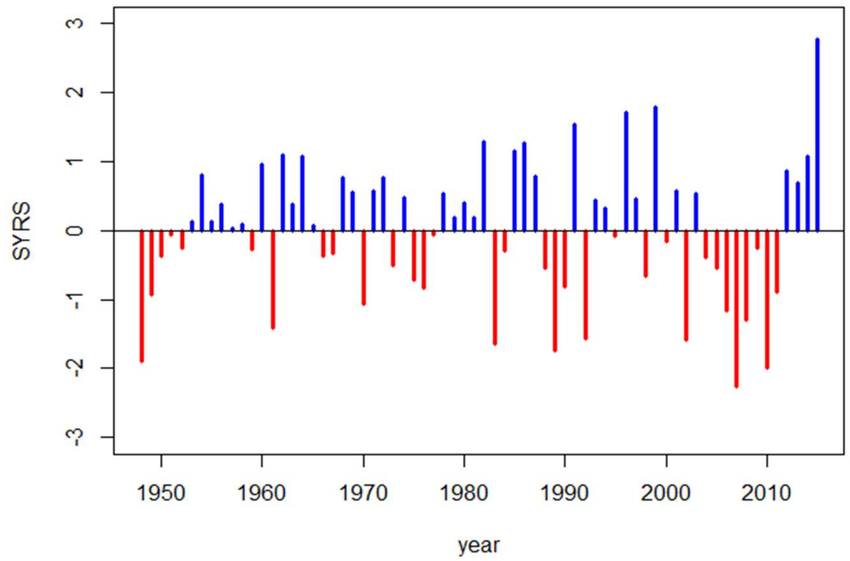


Supplementary material 17 yield time series of maize, including best-fit trend function and resulting standardised yield residuals time series (SYRS) for Lower Saxony, Germany (functions according to Table 14).

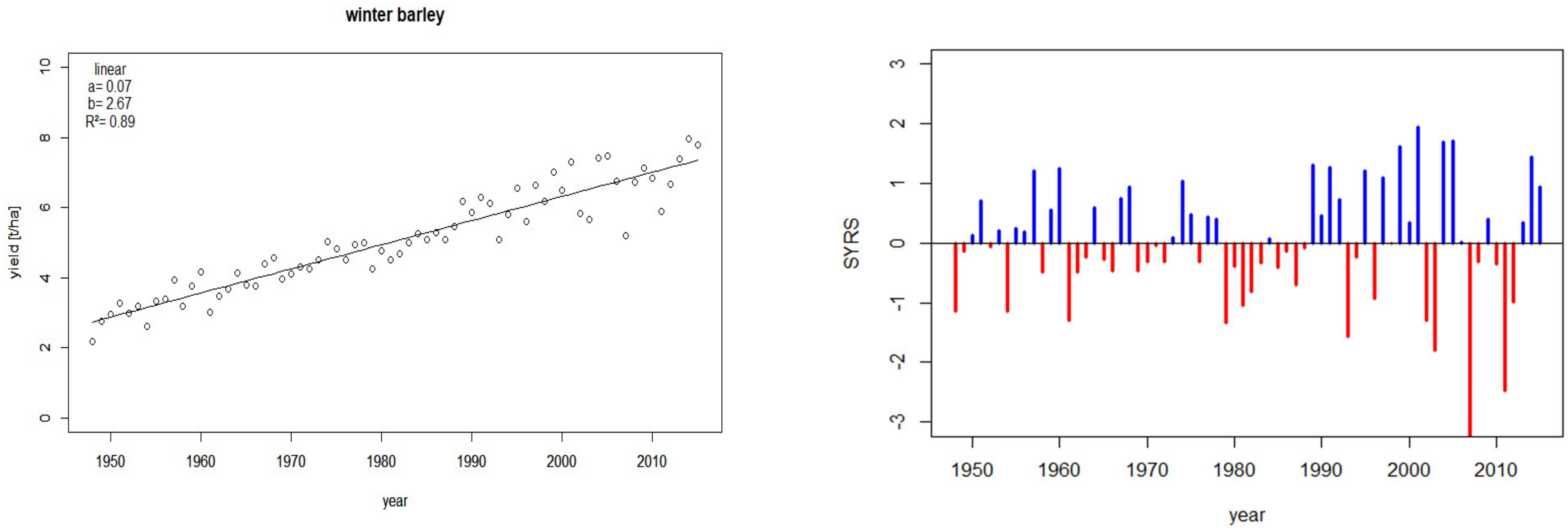


Supplementary material 18 yield time series of rye, including best-fit trend function and resulting standardised yield residuals time series (SYRS) for Lower Saxony, Germany (functions according to Table 14).

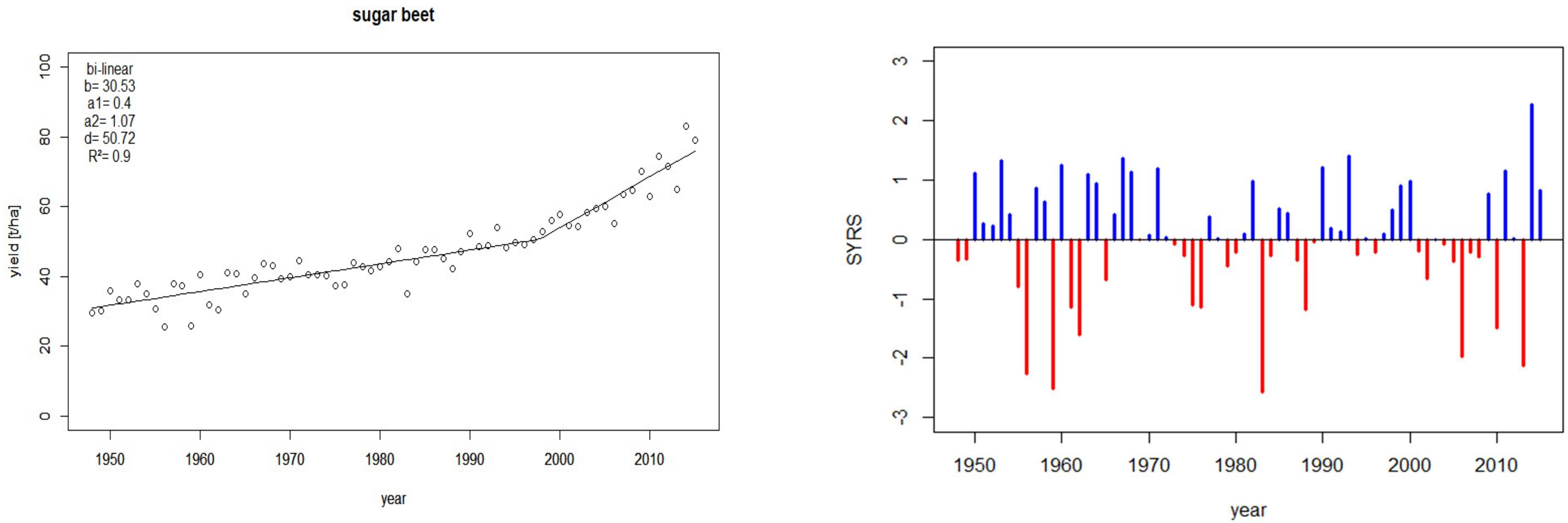




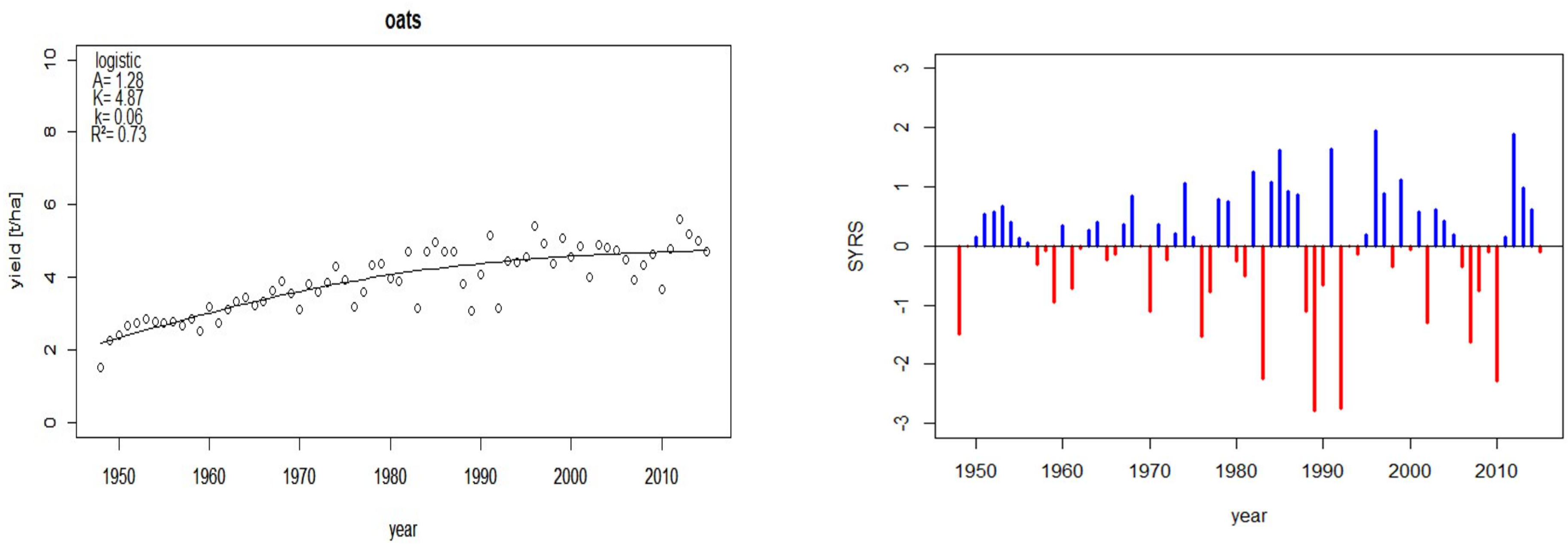
Supplementary material 19 yield time series of spring barley, including best-fit trend function and resulting standardised yield residuals time series (SYRS) for Lower Saxony, Germany (functions according to Table 14)



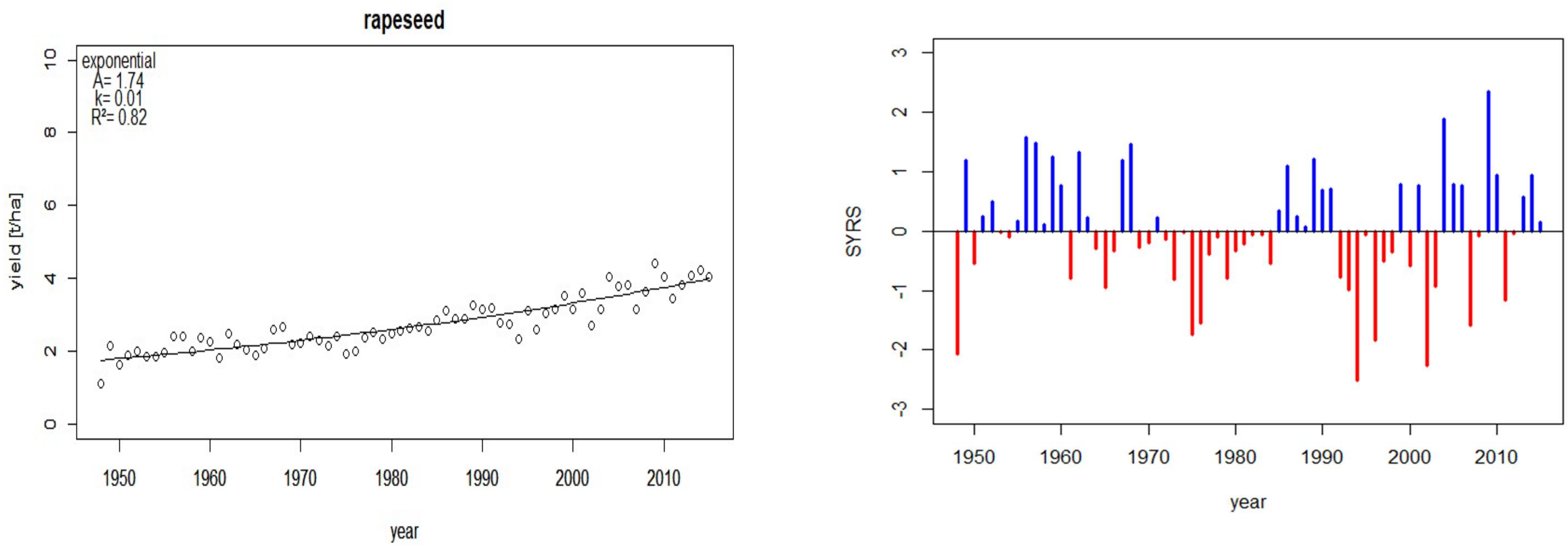
Supplementary material 20 yield time series of winter barley, including best-fit trend function and resulting standardised yield residuals time series (SYRS) for Lower Saxony, Germany (functions according to Table 14).



Supplementary material 21 yield time series of sugarbeet, including best-fit trend function and resulting standardised yield residuals time series for Lower Saxony, Germany (functions according to Table 14).



Supplementary material 22 yield time series of oats, including best-fit trend function and resulting standardised yield residuals time series for Lower Saxony, Germany (functions according to Table 14).



Supplementary material 23 yield time series of rapeseed, including best-fit trend function and resulting standardised yield residuals time series for Lower Saxony, Germany (functions according to Table 14).

Supplementary material 24 properties chosen as soil for calibration issues (θ_s – saturated soil water content, generic medium silty clay).

depth	clay	silt	θ_s
[cm]	[-]	[-]	[-]
5	0.23	0.39	0.46
15	0.23	0.39	0.46
30	0.23	0.39	0.46
45	0.25	0.41	0.46
60	0.25	0.41	0.46
90	0.31	0.45	0.46
120	0.21	0.34	0.46
150	0.26	0.37	0.46

Supplementary material 25 soil type used for validation and phenological modelling at DH; derived from BUEK 1000n [26] (θ_s – saturated soil water content; θ_a available water content; k_s- saturated permeability; CEC- cation exchange capacity).

depth	horizon	clay	silt	θ_s	θ_a	k_s	CEC
[cm]		[ ]	[ ]	[ ]	[]	[m/s]	[cmol/kg]
30	Ap	0.22	0.49	0.59	36	0.38	10
40	Al	0.11	0.28	0.50	32	0.39	5
80	Bv	0.11	0.28	0.50	24	0.2	5
100	Bv	0.07	0.26	0.48	24	0.39	3
200	C	0.15	0.30	0.48	024	0.25	8

Declarations

Maximilian Oliver Strer

Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt, dass ich die vorgelegte Dissertation mit dem Titel „Between heat death and drought stress, the impact of adverse environmental conditions on critical development stages of agricultural production in the North German Plain“ selbständig und ohne unerlaubte Hilfe angefertigt habe und dass ich die Arbeit noch keinem anderen Fachbereich bzw. noch keiner anderen Fakultät vorgelegt habe.

Kiel, den 27.03.2020

Maximilian Strer

Eidesstattliche Erklärung

Hiermit erkläre ich, dass die Dissertation nach den Regeln guter wissenschaftlicher Praxis (Standard wissenschaftlichen Arbeitens nach den Empfehlungen der DFG) abgefasst wurde.

Kiel, den 27.03.2020

Maximilian Strer

Eidesstattliche Erklärung

Hiermit erkläre ich, dass gegen mich kein strafrechtliches Ermittlungsverfahren schwebt.

Kiel, den 27.03.2020

Maximilian Strer

C A U	Christian-Albrechts-Universität zu Kiel	Agrar- und Ernährungswissenschaftliche Fakultät

Declaration of co-authorship

If a dissertation is based on already published or submitted co-authored articles, a declaration from each of the authors regarding the part of the work done by the doctoral candidate must be enclosed when submitting the dissertation.

1. Doctoral candidate
Name: Maximilian Oliver Strer

2. This co-author declaration applies to the following article:
Evaluation of crops and crop models for critical growth stages of major crops in temperate climate conditions – A Review

The extent of the doctoral candidat's contribution to the article is assessed on the following scale:

A. Has contributed to the work (0-33%)
B. Has made a substantial contribution (34-66%)
C. Did the majority of the work independently (67-100%)

3. Declaration on the individual phases of the scientific work (A,B,C)	Extent
Concept: Formulation of the basic scientific problem based on theoretical questions which require clarification, including a summery of the general questions which, it is assumed, will be answerable via analyses or concrete experiments/investigations	b
Planning: Planning of experiments/analyses and formulation of investigative methodology, including choice of method and independent methodological development, in such a way that the scientific questions asked can be expected to be answered	c
Execution: Involvement in the analysis or the concrete experiments/investgation	c
Manuscript preparation: Presentation, interpretation and discussion of the results obtained in article form	b

4. Signature of all co-authors		
Date	**Name**	**Signature**
20.3.20	Antje Herrmann	A. Herrmann
23.3.2020	Nikolai Svoboda	N. Svoboda

5. Signature of doctoral candidate		
Date	**Name**	**Signature**
27.03.2020	Maximilian Oliver Strer	Maximilian Strer

C | A | U Christian-Albrechts-Universität zu Kiel | Agrar- und Ernährungswissenschaftliche Fakultät

Declaration of co-authorship

If a dissertation is based on already published or submitted co-authored articles, a declaration from each of the authors regarding the part of the work done by the doctoral candidate must be enclosed when submitting the dissertation.

1. Doctoral candidate
Name: Maximilian Oliver Strer

2. This co-author declaration applies to the following article:
Abundance of adverse environmental conditions during critical stages of crop production in Northern Germany

The extent of the doctoral candidat's contribution to the article is assessed on the following scale:

A. Has contributed to the work (0-33%)
B. Has made a substantial contribution (34-66%)
C. Did the majority of the work independently (67-100%)

3. Declaration on the individual phases of the scientific work (A,B,C)	Extent
Concept: Formulation of the basic scientific problem based on theoretical questions which require clarification, including a summary of the general questions which, it is assumed, will be answerable via analyses or concrete experiments/investigations	B
Planning: Planning of experiments/analyses and formulation of investigative methodology, including choice of method and independent methodological development, in such a way that the scientific questions asked can be expected to be answered	C
Execution: Involvement in the analysis or the concrete experiments/investgation	C
Manuscript preparation: Presentation, interpretation and discussion of the results obtained in article form	C

4. Signature of all co-authors		
Date	**Name**	**Signature**
12.3.2020	Antje Herrmann	A. Herrmann
16.3.2020	Nikolai Svoboda	N. Svoboda

5. Signature of doctoral candidate		
Date	**Name**	**Signature**
27.03.2020	Maximilian Oliver Strer	Maximilian Strer

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1. Doctoral candidate
Name: Maximilian Oliver Strer

2. This co-author declaration applies to the following article:
Drought pattern shape yield variability: An assessment for crop production in Lower Saxony, Germany.

The extent of the doctoral candidat's contribution to the article is assessed on the following scale:

A. Has contributed to the work (0-33%)
B. Has made a substantial contribution (34-66%)
C. Did the majority of the work independently (67-100%)

3. Declaration on the individual phases of the scientific work (A,B,C)	Extent
Concept: Formulation of the basic scientific problem based on theoretical questions which require clarification, including a summery of the general questions which, it is assumed, will be answerable via analyses or concrete experiments/investigations	c
Planning: Planning of experiments/analyses and formulation of investigative methodology, including choice of method and independent methodological development, in such a way that the scientific questions asked can be expected to be answered	c
Execution: Involvement in the analysis or the concrete experiments/investgation	c
Manuscript preparation: Presentation, interpretation and discussion of the results obtained in article form	c

4. Signature of all co-authors		
Date	**Name**	**Signature**
20.3.20	Antje Herrmann	[signature]
	Nikolai Svoboda	[signature]

5. Signature of doctoral candidate		
Date	**Name**	**Signature**
27.03.2020	Maximilian Oliver Strer	[signature]