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Effects of heat and drought stress on cereal crops across spatial scales

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ABSTRACT

The production of cereal crops is increasingly influenced by heat and drought stress. Despite the typical small-scale sub-regional variability of these stresses, impacts on yields are also of concern at larger regional to global scales. Crop growth models are the most widely used tools for simulating the effects of heat and drought stress on crop yield. However, the development and application of crop models to simulate heat and drought is still a challenging issue, particularly their application at larger spatial scales. Previous research showed that there is a lack of information regarding the:

1. Response of cereal crops to heat stress,
2. Interactions between phenology and heat stress under climate change,
3. Improvement of crop models for reproducing heat stress effects on crop yield,
4. Upscaling of heat and drought stress effects with crop models,
5. Effects of climate and management interactions on crop yield in semi-arid environments.

Five detailed studies were arranged to improve the understanding on the aforementioned gaps of knowledge:

1. A review study was set up to understand how crop growth processes responded to short episodes of high temperature. In addition, the possible ways for improvement of the heat stress simulation algorithms in crop models were investigated at a field scale. The reproductive phase of development in cereals was found to be the most sensitive phase to heat stress. Crop models aiming to model heat stress effects on crops under field conditions should consider the modelling of canopy temperature. This may also provide a mechanistic basis to link heat and drought stress in crop models. Generally, these two stresses occur simultaneously.

2. In a nationwide study, the interactions between the advancements of phenology and heat stress on winter wheat (*Triticum aestivum* L.) due to global warming, were evaluated between 1951-2009 across Germany. The increase in temperature (~1.8°C) shifted crop phenology to cooler parts of the growing season (~14 days) and compensated for the effect of global warming on heat stress intensity in the period 1976-2009. The intensity of heat stress on winter wheat could have increased by up to 59% without any advancement in phenology.

3. A large-scale simulation study was conducted to investigate the effects of input (climate and soil) and output data aggregation on simulated heat and drought stress for winter wheat over the

period of 1980-2011 across Germany. Aggregation levels were compared in several steps from 1 km × 1 km to 100 km × 100 km. Simulations were performed with SIMPLACE<LINTUL2-CC-HEAT>. Aggregation of weather and soil data showed a slight impact on the mean and median of simulated heat and drought stress at the national scale. No remarkable differences in simulated mean yields of winter wheat were evident for the different resolutions ranging from 1 km × 1 km to 100 km × 100 km across Germany. However, high resolution input data was essential to reproduce spatial variability of heat and drought stress for the more heterogeneous regions.

4. Two regional studies were arranged to evaluate the interactions between management and climate on crop production under climate change conditions. A crop model (DSSAT v4.5) was employed to assess the interactions between fertilization management of pearl millet (*Pennisetum americanum* L.), crop substitution [pearl millet instead of maize (*Zea mays* L)], and climate in semi-arid environments of Iran and the Republic of Niger, respectively. The pearl millet biomass production showed a strong response to different fertilization management in Niger. The highest dry matter production of pearl millet was obtained in combination with crop residues and mineral fertilizer treatment. The dry matter production of pearl millet was reduced by 11% to 62% under different climate change scenarios and future time periods (2011-2030 and 2080-2099). Results of this study showed that higher soil fertility could compensate for the negative effects of high temperature on biomass production. This was a result of the strong positive relationship between biomass production and the sum of precipitation under high soil fertility.

Crop substitution as an adaptation strategy (new hybrids of pearl millet instead of maize) enhanced fodder production and water use efficiency in present and potential future climatic conditions in northeast Iran. However, the fodder production of both crops was reduced due to shortening of the period from floral initiation to the end of leaf growth under various climate change conditions. Benefits of crop substitution may decline under climate change resulting in higher temperature sensitivity of the new hybrids of pearl millet.

Several conclusions were drawn from this study: It is necessary to consider canopy temperature instead of air temperature in crop models and use data from experiments under field conditions to improve and properly calibrate crop models for heat and drought stress responses. Crop models must also consider that effects of heat and drought stress on crops differ with phenological phases and can be compensated for by responses of other processes. An increase in the intensity of heat stress around anthesis can, for instance, be fully compensated for by the advancement in phenology in winter cereals under climate change. It is not necessary to use high resolution weather and soil input data for simulating the effects of heat and drought stress on crop yield at a national scale; but, high resolution input data are necessary to reproduce spatial patterns of heat and drought. Finally, implementation of management practices in cropping systems may change the response of crops to climate change. For this reason, management practices should be considered as an adaptation strategy.

ZUSAMMENFASSUNG

Die Erträge im Getreideanbau werden zunehmend durch Hitze- und Trockenstress beeinflusst. Trotz der räumlichen Heterogenität dieser Einflußfaktoren sind die Auswirkungen auf den Ertrag auch auf regionaler und globaler Skala von Bedeutung. Pflanzenwachstumsmodelle werden häufig genutzt, um die Effekte von Hitze- und Trockenstress auf den Ertrag zu simulieren. Entwicklung und Anwendung solcher Simulationsmodelle stellen eine Herausforderung dar, insbesondere bei Anwendung auf größeren räumlichen Skalen. Die bisherige Forschung dazu hat gezeigt, dass es Informationsdefizite insbesondere gibt:

1. zur Reaktion von Getreidepflanzen auf Hitzestress,
2. zu den Wechselbeziehungen zwischen Phänologie und Hitzestress bei sich verändernden Klimabedingungen,
3. zur Verbesserung von Pflanzenwachstumsmodellen im Hinblick auf die Simulation von Hitzestresseffekten auf den Ertrag,
4. zur Hochskalierung von Hitze- und Trockenstresseffekten mithilfe von Wachstumsmodellen,
5. zu Wechselwirkungen zwischen Klima und Management auf den Ertrag im semi-ariden Regionen.

Fünf detaillierte Studien wurden durchgeführt, um die oben genannten Wissensdefizite zu verringern:

1. Ein Übersichtsartikel wurde erstellt um den gegenwärtigen Kenntnisstand zu Auswirkungen von Hitzestress auf Pflanzenwachstumsprozesse zusammenzufassen und diesbezügliche Algorithen in gegenwärtig hauptsächlich auf Feldskala angewendeten Simulationsmodellen zu verbessern. Es wurde herausgefunden, dass bei Getreidepflanzen Hitzestress die größten Auswirkungen auf den Ertrag in der generativen Entwicklungsphase bewirkt. Die Modellierung von Hitzestresseffekten unter Feldbedingungen sollte auf gemessenen oder simulierten Bestandestemperaturen basieren. Dies bietet auch die Möglichkeit Hitze- und Trockenstress in Wachstumsmodellen zu verknüpfen, was sinnvoll ist, da beide Stressfaktoren häufig gleichzeitig auftreten.
2. In einer deutschlandweiten Studie für den Zeitraum 1951-2009 wurden Wechselbeziehungen zwischen phänologischer Entwicklung und Hitzestress bei Winterweizen (*Triticum aestivum* L.) unter sich ändernden Klimabedingungen untersucht. Die Temperaturzunahme im untersuchten Zeitraum von ca. 1,8 °C verschob die phänologischen Stadien zum früheren und damit kühleren

Teil der Wachstumsperiode (etwa 14 Tage für den Beginn des Ährenschiebens). Dadurch wurden die Effekte der globalen Erwärmung auf die Hitzestressintensität in der Periode 1976-2009 weitgehend kompensiert. Ohne die Verfrühung im Eintreten der phänologischen Stadien hätte die Intensität des Hitzestresses von Winterweizen um 59% zugenommen.

3. Eine deutschlandweite Simulationsstudie wurde durchgeführt, um die Effekte der Aggregierung von Modelleingabedaten (Klima und Boden) und Modellergebnissen auf simulierten Hitze- und Trockenstress bei Winterweizen für die Periode 1980-2011 zu untersuchen. Die Effekte wurden für verschiedene Aggregierungsstufen in Schritten von 1 km x 1 km bis zu 100 km x 100 km verglichen. Simulationen wurden mit dem Pflanzenwachstumsmodell SIMPLACE<LINTUL2-CC-HEAT> durchgeführt. Die Aggregierung von Wetter- und Bodendaten führte zu geringen Einflüssen auf den Mittelwert und den Median des simulierten Hitze- und Trockenstresses auf nationaler Ebene. Ebenso zeigten sich keine nennenswerten Unterschiede in den simulierten mittleren Erträgen von Winterweizen zwischen den verschiedenen Auflösungen. Allerdings wurde gezeigt dass hochaufgelöste Eingangsdaten essentiell sind, um die räumliche Variabilität von Hitze- und Trockenstress in Regionen mit heterogenen Klima- und Bodenbedingungen zu reproduzieren.

4. Zwei Regionalstudien wurden erstellt um die Wechselbeziehungen zwischen Management und Klima auf die Getreideproduktion unter dem Einfluß des Klimawandels zu untersuchen. Die kombinierten Effekte von Nährstoffmanagement und Klima auf den Ertrag von Perlhirse (*Pennisetum americanum* L.), sowie der Wechsel der angebauten Feldfrucht (Perlhirse statt Mais (*Zea mays* L.)) wurden im semi-ariden Klima des Irans und der Republik Niger mithilfe des Wachstumsmodells DSSAT 4.5 untersucht. Die Biomasseproduktion von Perlhirse im Niger zeigte eine starke Reaktion auf unterschiedliches Nährstoffmanagement. Die höchste Trockenmasseproduktion von Perlhirse wurde bei der Kombination von auf dem Feld belassenen Ernterückständen und Mineraldüngeranwendung erzielt. In Abhängigkeit der genutzten Klimaänderungsszenarien und untersuchten Zeiträume (2011-2030 oder 2080-2099) reduzierte sich die Trockenmasseproduktion um 11% bis 62%, hauptsächlich durch höhere Temperaturen. Die Ergebnisse dieser Studie zeigen aber, dass höhere Bodenfruchtbarkeit die durch höhere Temperaturen hervorgerufenen negativen Effekte auf den Biomasseertrag kompensieren könnte. Der Wechsel von gegenwärtig angebautem Mais zu neuen Perlhirsehybriden steigerte Futterproduktion und Wassernutzungseffizienz unter derzeitigen und zukünftigen

Klimabedingungen im Nordosten Irans. Allerdings wurde der Futterertrag durch die Erwärmung als Folge des Klimawandels reduziert, da sich der Zeitraum von Blütenbildung bis zum Ende des Blattwachstums verkürzt. Die Vorteile des Feldfruchtwechsels könnten sich unter Einwirkung des Klimawandels verringern, da die untersuchten Perlhirsehybriden eine höhere Temperatursensitivität als der gegenwärtig angebaute Mais zeigten.

Verschiedene Schlussfolgerungen werden aus dieser Dissertation abgeleitet. In Pflanzenwachstumsmodellen sollte die Bestandestemperatur statt der Lufttemperatur verwendet werden. Desweiteren sollten Daten aus Feldversuchen genutzt werden, um Modelle zu verbessern und besser bezüglich der Effekte von Hitze- und Trockenstress zu kalibrieren. In der Modellierung sollte berücksichtigt werden, dass sich Effekte von Hitze- und Trockenstress in den Entwicklungsphasen unterscheiden können und durch die Effekte anderer Prozesse kompensiert werden können. Ein Anstieg der Intensität des Hitzestresses während der Blütezeit kann zum Beispiel bei Winterweizen vollständig durch ein Vorrücken der Phänologie kompensiert werden. Es ist nicht nötig, hoch aufgelöste Wetter- und Bodendaten zur Simulation des Einflusses von Hitze- und Trockenstress auf den landesweiten Ertrag zu nutzen. Allerdings ist eine hohe Auflösung vonnöten, um räumliche Muster von Hitze und Trockenheit abzubilden. Massnahmen der Bestandesführung können die Reaktion von Feldfrüchten auf den Klimawandel beeinflussen und sollten daher zur Adaptation in Betracht gezogen werden.

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Chapter 1

General introduction

1.1. Impact of heat and drought stress on cereal production

1.1.1. Relevance of studying heat and drought stress

Cereal crops with an annual production of about 2780 Mt (FAO, 2013) are a key source of carbohydrates in human diet (Balkovič et al., 2014). Wheat (713 Mt yr^{-1}), maize (1016 Mt yr^{-1}) and millet (29 Mt yr^{-1}) are important sources of food (FAO, 2013). Therefore, stability and/or increase in the production of cereals have played a pivotal role in global food security (Godfray et al., 2010). The future global food demand will further increase over the next decades due to population growth, economic development and urbanization (Godfray et al., 2010). Global agricultural production may need to double in order to meet this growing demand by 2050 (Ray et al., 2013). Maize and wheat production must increase by approximately 67% and 38%, respectively by 2050 to meet these growth demands (Ray et al., 2013).

However, many challenges arise with the increasing demand for cereal production and even more so under conditions of climate change. Climate models projected not only an increase in mean temperature and a large variability of precipitation, but also forecasted more frequent heat waves and extreme droughts in the future (Fischer and Schär, 2010; Schär et al., 2004). The mean temperature during the growing season at the end of the 21st century will be higher than the most extreme seasonal temperature observed for the period 1900 to 2006 (Battisti and Naylor, 2009). The rise in frequency and magnitude of heat and drought events are considered as the most critical yield reduction factors under climate change conditions (Ciais et al., 2005; Rosenzweig et al., 2001). This may have a significant effect on food security and may increase the risk of hunger from 5 to 170 million people by 2080, depending on socio-economic scenarios (Schmidhuber and Tubiello, 2007). Future climate change scenarios projected that the risk of crop damage may mostly increase within areas at high latitudes (40 and 60 °N) (Teixeira et al., 2013), and the global wheat production may reduce (10%) by 2080s (Parry et al., 2004). Another global study showed that the attainable wheat yield may reduce between 15% to 45% under different climate change scenarios (Fischer et al., 2005).

1.1.2. Mechanisms of heat and drought stress on crop yield

1.1.2.1. Heat stress

The rise in seasonal mean temperature showed a strong negative impact on crop yield mainly by a reduction in the length of the growing season (Liu et al., 2010). However, heat stress mainly refers to short periods of extreme heat events that may result in a substantial negative impact on crop yield (Lobell et al., 2013). High temperatures influence photosynthesis (Allakhverdiev et al., 2008), respiration (Allakhverdiev et al., 2008), transpiration (Crawford et al., 2012), development rate (Tahir and Nakata, 2005), reproductive development (Tashiro and Wardlaw, 1989) and root growth (Kaspar and Bland, 1992).

Crops are more sensitive to heat stress during the reproductive growth phase compared to the vegetative phase (Prasad et al., 2008). The occurrence of heat stress during the anthesis stage could significantly reduce the number of grains, and consequently grain yield (Ferris et al., 1998; Wheeler et al., 1996; Wheeler et al., 2000). Heat stress after anthesis may predominantly affect grain weight due to the acceleration of leaf senescence during the grain-filling period (Al-Khatib and Paulsen, 1990; Barnabás et al., 2008; Porter and Semenov, 2005). There is also high variability in the sensitivity to heat stress between cereal species and across cultivars. The critical temperature threshold for heat stress at anthesis is around 27 ºC to 31 ºC for C3 cereals such as wheat (Mitchell et al., 1993; Porter and Gawith, 1999) and 32 ºC to 38 ºC for C4 crops such as maize (Cicchino et al., 2010a; Cicchino et al., 2010b; Rattalino Edreira et al., 2011). The differences in the responses of cultivars to heat stress may be explained by other mechanisms such as higher leaf chlorophyll content in flag leaf (Balla et al., 2009), stability of protein synthesis (Farooq et al., 2011) and remobilization of nitrogen to flag leaf (Tahir and Nakata, 2005).

1.1.2.2. Drought stress

Global warming may lead to increased crop evapotranspiration as well as increased water demand. This, in turn, will result in a higher variability of precipitation events under climate change, and increase the frequency of extreme droughts (Richter and Semenov, 2005). Agricultural drought is defined as a period with low soil water content due to low precipitation or high evaporation resulting in a decline of plant growth and yield (Dai, 2011). Crops are more sensitive to drought during the reproductive growth phase (Barnabás et al., 2008; Garrity and O'Toole, 1994; Saini and Westgate, 1999). The occurrence of drought stress around anthesis reduces the floret set for grains. The reduction in the floret set occurs due to a decline in the water content within the shoot and an increase in Abscisic Acid, leading to less grain being produced (Foulkes et al., 2007; Rajala et al., 2009; Westgate et al., 1996).

However, drought stress in the exponential grain filling period accelerates the leaf senescence and therefore reduces the weight of single grains (Plaut et al., 2004; Rajala et al., 2009). There is a considerable range of tolerance to drought stress across cereals and cultivars (Araus et al., 2002). Some of the tolerance mechanisms are related to stomatal conductance and photosynthetic capacity (Lawlor and Cornic, 2002), flexibility in phenology (Richards, 2006), partitioning and remobilization (Slafer et al., 2005), stay green (Rajcan and Tollenaar, 1999), rooting depth (Sharp et al., 2004) and osmotic adjustment (Serraj and Sinclair, 2002).

1.1.3. Interactions between heat and drought stress

Heat and drought often happen simultaneously under field conditions, particularly at the end of the growing season (Allen et al., 2010; Jiang and Huang, 2000; Mittler, 2006). The combined effect of heat and drought on crop yield is considerably higher than each effect individually (Craufurd and Peacock, 1993; Heyne and Brunson, 1940; Savin and Nicolas, 1996). In general, crops close their stomata to avoid water loss under drought stress but this induces increased canopy temperature when the stomata remain closed. Similarly, the leaf temperature under combined heat and drought was significantly higher under individual heat and drought stress conditions (Mittler, 2006). Therefore, soil moisture is one of the controlling factors of canopy temperature. The difference between canopy and air temperature reached up to 7 ºC in rainfed conditions and sandy soils, while for soil under irrigated conditions, this difference was between 0 to -2 ºC (Siebert et al., 2014). The combination of heat and drought during grain filling increased the water use efficiency of wheat, although the grain yield was reduced (Aprile et al., 2013). The yield reduction was mainly caused by the shortening of the grain filling period due to high temperature and it was not as affected by drought stress (Wardlaw, 2002).

1.1.4. Interactions between phenology advancement due to climate change and heat stress

High temperatures during the growing season not only decline the efficiency of growth processes such as photosynthesis, but also increase the crop development rate (Wheeler et al., 1996; Wheeler et al., 2000). Crop phenology is one of the most important bio-indicators of climate change (Tao et al., 2006) due to the importance of temperature to determine development rate (Chmielewski and Rotzer, 2002). However, long term changes in crop phenology are not only caused by temperature increase but are also influenced by management practices such as sowing and harvest date (Tao et al., 2006). The phenology of winter rye, sugar beet and maize remarkably advanced due to the rise of mean temperature from 1961 to 2000 in Germany (Chmielewski et al., 2004). Another study showed that phenology of crops advanced by 1.1 to 1.3 days per decade from 1951 to 2004 across Germany (Estrella et al., 2007). The results of climate change impact assessments proposed a considerable rise in future intensity of heat stress on crop production in Europe (Kristensen et al., 2011; Ortiz et al., 2008). Acceleration of crop phenology due to higher mean temperature may shift the anthesis stage of winter cereals to the cooler part of the growing season (Siebert and Ewert, 2012). Many studies applied statistical crop models for climate change impact assessments and concluded that heat stress intensity will increase in the future under global warming conditions. However, the effects of phenology advancement due to higher temperature are often neglected in such studies. Therefore, it is important to quantify how acceleration of phenology can affect crop heat stress intensity.

1.2. Modeling effect of heat and drought stress on cereals

1.2.1. Modeling of heat stress

Crop growth models are appropriate tools for simulating the effects of extreme events such as heat and drought on crop growth (Asseng et al., 2015; Asseng et al., 2013; Kage et al., 2004). Simulation of heat stress is though one of the less developed parts of these models, generally due to difficulties in obtaining appropriate data under field conditions (methodological issues), a lack of knowledge on the mechanisms involved and the simultaneous occurrence of heat and drought stress. Modeling of the heat effect on cereal yield focuses on physiological aspects such as grain filling duration, leaf senescence, grain growth rate, grain number reduction and grain size (Barlow et al., 2015). There are different methods for simulating the heat stress effect on cereals including empirical reduction functions on grain yield (Challinor et al., 2004), harvest index (Wollenweber et al., 2003), grain number (Keating et al., 2003), determining source-sink relationships (Lizaso et al., 2007), and high temperature response on growth processes including senescence (Asseng et al., 2011; Asseng et al., 2004). Most of the abovementioned approaches decrease the grain number if heat stress occurs around anthesis, and they also reduce grain weight if heat stress falls into the grain filing period. There is no comprehensive knowledge about response mechanisms, study methods and modeling of heat stress effects on cereal crops. A comprehensive review study can improve the understanding of the pros and cons of different modeling approaches of heat stress and allow for the development of more precise crop models.

1.2.2. Modeling of drought stress

The occurrence of drought stress in crops can be caused by high evapotranspiration, low water content in the root zone and poor root distribution (Farooq et al., 2009). Many models estimate intensity of drought stress based on the relationship between actual and potential evapotranspiration in relation to plant available water (Lipiec et al., 2013). For instance, intensity of drought stress in crop models from Wageningen, such as LINTUL, SUCROS, ORYZA and WOFOST, is estimated by computing actual and potential evapotranspiration (Van Ittersum et al., 2003). Drought stress reduces the plant growth and changes the partitioning coefficients in those models (Van Ittersum et al., 2003; Van Ittersum and Donatelli, 2003). The leaf senescence also influences the carbon partitioning in some crop models such as Sirius (Semenov et al., 2009). The potential biomass accumulation and transpiration rate is reduced by ratio between water uptake and transpiration in CERES models (Eitzinger et al., 2003).

1.2.3. Upscaling impact of heat and drought stress on crop yield

Crop growth models are widely applied to evaluate the impacts of climate change and climate variability on crop yield at a subnational, national and global scale (Ewert et al., in press; Asseng et al., 2013; Olesen et al., 2011). However, most of the crop growth models applied at large scales have been established and tested at the field scale (Hansen and Jones, 2000; Van Bussel et al., 2011a). On the other hand, one of the main restrictions for large scale studies is the limitation in available input data such as weather and soil variables and management activities. Therefore, large scale climate impact assessments mainly use gridded weather or climate and soil data interpolated between climate stations or soil observations (Harris et al., 2014). Additionally, large scale climate data often represent monthly means while crop models normally require daily inputs. Stochastic weather generators are generally used for disaggregation of daily data from monthly means (Bannayan and Rezaei, 2014; Semenov et al., 2013). However, weather generators have some limitations such as general underestimation of inter-annual variance of climate variables (Chen et al., 2011; Kim et al., 2012). It is also difficult to represent the heterogeneity in soil characteristics observed at field scale in large scale studies. Input and output data aggregation are commonly used for large scale assessments (Ewert et al., 2011). In general, aggregation or averaging of input variables from high to low resolutions, decrease the variability of climate and soil variables (Diffenbaugh et al., 2005). However, little is known which data resolution is required to reproduce the mean of heat and drought stress over the large scale and which data resolution is required to reproduce spatial patterns of stressors and crop yield.

1.3. Adaptation to heat and drought under climate change

Adaptation is a key concept of climate change risk management (Smit and Wandel, 2006). The Intergovernmental Panel on Climate Change (IPCC) defines adaptation as an adjustment in natural or human systems in response to actual or expected climatic stimuli and their effects (Orlove, 2005). Adaptation approaches for cropping systems under climate change are classified into short term and long term adjustments (Olesen and Bindi, 2002). Many different short term adaptation approaches suggest the reduction of the negative impact of climate change on cropping systems by changing the sowing date, cropping patterns, and introducing heat-drought resistant cultivars as well as new crops (Byjesh et al., 2010; Gibbons and Ramsden, 2008; Seo and Mendelsohn, 2008; Trnka et al., 2004). The growing areas of cereals have changed considerably during the last decade at both the national and global scale (FAO, 2013). This means that the preference of cultivation for different crops have changed over decades. The increment in temperature and drought may force the farmers to cultivate the crops or cultivars which are more adapted to extreme events. Therefore, it is important to evaluate potential effects of crop change under climate change conditions. The relationship between climatic variables and fertilization management and their combined effects on crop yield under climate change has received little attention so far. The potential change in precipitation during the growing season of cereals as a result of climate change, may influence nitrogen and phosphorus dynamics including uptake by plants and leaching in the future (Olesen et al., 2011). High temperature could also affect the nitrogen accumulation in wheat plants (Tahir and Nakata, 2005).

In most of the climate change impact assessments it was assumed that current management practices such as fertilization and cultivar choice will be static under future climatic conditions.

This may lead to an over or under estimation of heat and drought stress effects under varying climate change conditions. Recent studies suggest a considerable change in characteristics of modern varieties in comparison to old varieties (Fang et al., 2011; Sadras and Lawson, 2013), sowing date and fertilization management over the time (Fan et al., 2011). Previous studies often predicted remarkable yield losses under climate change conditions caused by temperature rise and decline in precipitation, especially for semi-arid environments (Seo and Mendelsohn, 2008) but ignored changes in management. Therefore, it is essential to understand possible interactions between crop management and climate change to develop effective adaptation strategies to climate change.

1.4. Objectives and research questions

The general objective of this thesis was to improve the understanding of the response of cereal crops to heat and drought stress at different scales. First, the possible avenues for improvement of heat stress algorithms in crop models were explored at field scale. Then, the interactions between phenology advancement and the increase in heat stress under climate change were evaluated at national extent for Germany. Next, the effects of data aggregation on simulated heat and drought stress were assessed for different spatial resolutions. Finally, the interactions between management and climate were evaluated under present and the future climate change conditions.

The related research questions mainly addressed in this thesis (Figure 1.1) are:

Question 1 (Q1): How can crop models be improved to better simulate heat stress effects on cereals yield at the process level and the field scale?

Question 2 (Q2): How does phenology advancement under climate change affect the accession of heat stress?

Question 3 (Q3): Does spatial data aggregation cause any systematic bias in simulated heat and drought effects on yield?

Question 4 (Q4): Do changes in management practices influence the crop response to climate change?

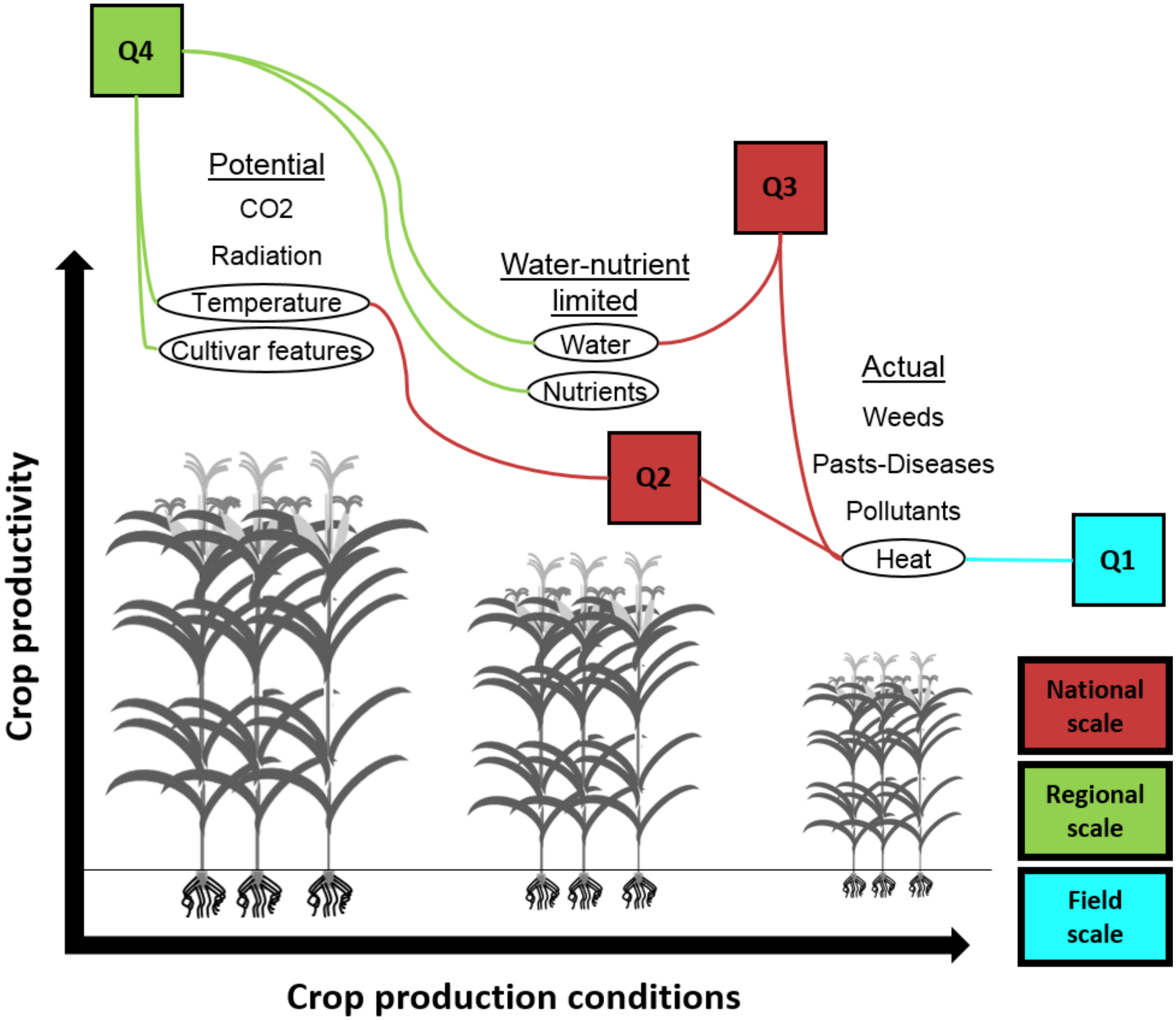

Figure 1.1. Schematic overview of research questions related to different crop production conditions (Van de Ven et al., 2003) and spatial scales.

1.5. Study setting and outline of thesis

Different research methods including a review study, modeling experiments and statistical analysis of time series data were applied to address the above research questions. A brief overview on the type of studies and methods in this thesis is presented in Table 1.1. The thesis is composed of seven chapters of which two comprise the overall introduction (Chapter 1) and discussion (Chapter 7). Chapters 2 to 6 contain the main results of the study. To answer the first question (Q1), a literature review was undertaken. This review summarizes current knowledge on the response of cereal's growth processes to heat stress and suggests approaches to simulate heat stress effects on cereal yield at a field scale (Chapter 2).

The second question (Q2) was addressed by an analysis of the long-term trend of phenology, mean temperature and heat stress around anthesis for winter wheat for the period 1951-2009 at the national scale of Germany (Chapter 3).

A simulation study of heat and drought stress on winter wheat using different climate and soil data resolutions was designed to answer the third question (Q3). The climate and soil data were aggregated to five resolutions (10 km × 10 km, 25 km × 25 km, 50 km × 50 km and 100 km × 100 km) from 1 km × 1 km resolution. The uncertainties introduced by data aggregation to the model results are systematically assessed (Chapter 4).

The last question (Q4) was answered by evaluating the interactions between the management strategies (crop substitution and fertilization management) and climate to inform about adaptation options to climate change. In Chapter 5, the effects of climate variability and change on the suitability of different fertilization managements in Niger are evaluated. Chapter 6 investigates whether the cultivation of pearl millet instead of maize will compensate for the negative impact of climate change and can be considered a feasible adaptation strategy in the semi-arid region of North-east Iran. Lastly, Chapter 7 summarizes the main achievements of the current thesis from which conclusions for future research directions are derived.

Table 1.1. Overview on the types of studies and methods used to answer the main research questions of the thesis.

Topic of the study	Methodology
Chapter 2 - Processes and modeling of heat stress in cereals	**Review study** • Review of impact of heat stress on different growth processes of cereals • Review of all approaches to simulate effect of heat stress on cereals
Chapter 3 - Interactions between phenology and heat stress under climate change	**Statistical analysis of time series** • Study period: 1951-2009 • Scale: National (Germany) • Statistics: Piecewise regression • Study crop: Winter wheat
Chapter 4, 5 and 6 - Upscaling of heat and drought effects on crop production - Interactions between soil fertilization and climate - Crop substitution as an adaptation strategy to climate change	**Modeling studies** • Crop model: SIMPLACE, Scale: National, Crop: Winter wheat • Crop model: DSSAT 4.5, Scale: Regional, Crop: Pearl millet • Crop model: DSSAT 4.5, Scale: Regional, Crop: Pearl millet and Maize

Chapter 2

Heat stress in cereals: Mechanisms and modeling

Based on:

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Abstract

Increased climate variability and higher mean temperatures are expected across many world regions, both of which will contribute to more frequent extreme high temperatures events. Empirical evidence increasingly shows that short episodes of high temperature experienced around flowering can have large negative impacts on cereal grain yields, a phenomenon increasingly referred to as heat stress. Crop models are currently the best tools available to investigate how crops will grow under future climatic conditions, though the need to include heat stress effects has been recognized only relatively recently. We reviewed literature on both how key crop physiological processes and the observed yields under production conditions are impacted by high temperatures occurring particularly in the flowering and grain filling phases for wheat, maize and rice. This state of the art in crop response to heat stress was then contrasted with generic approaches to simulate the impacts of high temperatures in crop growth models. We found that the observed impacts of heat stress on crop yield are the end result of the integration of many processes, not all of which will be affected by a "high temperature" regime. This complexity confirms an important role for crop models in systematizing the effects of high temperatures on many processes under a range of environments and realizations of crop phenology. Four generic approaches to simulate high temperature impacts on yield were identified: (1) empirical reduction of final yield, (2) empirical reduction in daily increment in harvest index, (3) empirical reduction in grain number, and (4) semi-deterministic models of sink and source limitation. Consideration of canopy temperature is suggested as a promising approach to concurrently account for heat and drought stress, which are likely to occur simultaneously. Improving crop models' response to high temperature impacts on cereal yields will require experimental data representative of field production and should be designed to connect what is already know about physiological responses and observed yield impacts.

2.1. Introduction

Increased climate variability and higher mean temperatures are expected across many world regions (Weisheimer and Palmer, 2005; Tebaldi et al., 2006; Battisti and Naylor, 2009; Field et al., 2012) and are likely to cause large negative impacts on crop productivity (Porter and Semenov, 2005). Empirical evidence increasingly shows that short episodes of high temperature can have large negative impacts on crop yields (Reidsma et al., 2009; Schlenker and Roberts, 2009; Lobell et al., 2013). At a global scale, wheat yields have been negatively impacted by rising temperatures, as detected by Lobell and Field (2007) between 1961 and 2002. The negative trend of decreasing wheat yields with more frequent high temperature extremes during sensitive reproductive stages is apparent across many regions, as found by Gourdji et al. (2013) for recent decades (1980-2011) across Central and South Asia and South America. Wheat yields in Mexico show a significant negative response to higher night-time temperatures (Lobell et al., 2005). Likewise for maize, an analysis of the past 50-years of historical yields in France revealed that since approximately 2000, daily maximum temperatures explain as much yield variability as precipitation (Hawkins et al., 2012), with the cumulative number of days with a maximum temperature over 32°C associated with yield reductions. Lobell et al. (2011) determined maize kernel set was reduced by 1% per degree day (and 1.7% per degree day under drought stressed conditions) when daily temperatures were above a threshold 30°C in Sub-Saharan Africa. A national panel analysis of county level maize yields in the United States detected negative impacts on maize yields when daily temperatures were above 29°C (Schlenker and Roberts, 2009). Evidence in rice suggests that this crop is also sensitive to increasing nighttime temperatures, expected to increase with climate change (Tebaldi et al., 2006). In an analysis of historical station data across China for the period 1981- 2000, rice yields declined with higher nighttime temperatures, decreasing at a rate of 4.6% per 1°C increase in minimum temperature (Tao et al., 2006). The decline in an indica rice varietals' yield over a 25-year period in the Philippines was associated with an increase in minimum nighttime temperature but not correlated with the concurrent but smaller increase in daily maximum temperature (Peng et al., 2004). As the majority of cereal production, particularly rice and maize, now occurs at mean temperatures above the optimal (Hatfield et al., 2011) increases in global mean temperature would augment yield reductions (Lobell and Gourdji, 2012).

The term heat stress is increasingly used to describe these negative impacts of high temperature on plant growth, though a definitive definition has yet to emerge in the literature and remains elusive. Heat stress has been used to refer to brief episodes of high temperature lying outside of the range typically experienced (Porter and Gawith, 1999; Luo, 2011; Moriondo et al., 2011). Porter and Semenov (2005) and Wheeler et al. (2000) emphasize that negative yield impacts are greatest when high temperatures are experienced during the reproductive phases centered on flowering. Some authors define a high temperature event as heat stress if it results in large, irreversible yield reductions (Wahid et al., 2007). Attribution of yield losses is frequently explained by a reduction in the number of viable seeds produced (Wheeler et al., 2000; Moriondo et al., 2011) or accelerated leaf senescence that reduces yields by shortening the duration of grain filling (Al-Khatib and Paulsen, 1984; Asseng et al., 2011; Lobell et al., 2012). Finally, other authors have defined heat stress as the departure from the regular linear yield response to rising temperatures that occurs when a threshold is surpassed, apparent in the analysis of large panel datasets (Schlenker and Roberts, 2009; Lobell et al., 2011).

The lack of convergence in definitions may simply reflect the need to illustrate specific aspects or levels of detail in different cases. However, it likely also reflects the limitations of our understanding of the mechanisms of high temperature impacts on yield in field crops. Such impacts are the end result of the integration of many processes that operate at the organelle and lower levels all with differing sensitivities to temperature (Sage and Kubien, 2007) and their interactions with other temperature sensitive processes such as transpiration, assimilation and partitioning (Ferrise et al., 2011). These processes are generally studied in isolation (Wahid et al., 2007; Barnabás et al., 2008) and are difficult to abstract to conditions typical in the field. Secondly, the relatively few field scale experimental trials on heat stress have imposed high temperature at different periods, for differing durations and levels, under varying environmental conditions and using different varieties (Lobell et al., 2012), sometimes leading to what seem to be conflicting conclusions. Further, while at the field and larger scales, heat stress is frequently understood to represent a non-linear temperature response, many of the underlying individual mechanisms may not be deviating from their linear response (e.g. the acceleration of crop development with elevated temperatures that results in shorter duration of grain filling). For the remainder of this paper, we use the term very broadly to mean yield reductions resulting from high temperature whose mechanism and impacts are hypothesized to vary with crop, region and the scale considered.

This complexity suggests an important role for crop models to systematize the effects of many processes under a range of environments. However, despite the evidence of the role of high temperatures in reducing grain number (Porter and Gawith, 1999; Wheeler et al., 2000), a key determinant of final yield in cereals (Cirilo and Andrade, 1994; Otegui, 1995; Ferris et al., 1998; Fischer et al., 1998; Hayashi et al., 2012), crop model simulation efforts to date have focused largely on how high temperature accelerates leaf senescence in wheat (Asseng et al., 2011; Lobell et al., 2012) or changes atmospheric water demand and soil water supply in maize (Lobell et al.,

2013) and not the direct impacts on grain number (Carberry et al., 1989; Moriondo et al., 2011). While these studies demonstrate that the impacts of high temperature on water use and accelerated senescence dominate as explanations for yield loss in some regions (Asseng et al., 2011), it is not clear if such modelling approaches are appropriate across regions and scales, and perhaps do not adequately reflect the state of the art in understanding crop response to high temperatures (Ferrise et al., 2011; Rötter et al., 2011; White et al., 2011; Eitzinger et al., 2012).

The aim of this review is to compile the state of the art on plant, canopy and regional scale cereal yield formation in response to high temperature stress to serve as a basis for crop models' improvements. We focus on wheat, maize and rice, as globally, these represent the three most important cereal crops. In section 2, the influence of temperature, across optimal and higher values, on key physiological processes affecting crop growth and development is reviewed. Section 3 presents the impacts of high temperatures in the flowering and grain filling phases (in the following referred to as "heat stress") observed for the main yield determinants across crops. Efforts made to link this knowledge to an underlying physiological process response. Finally, broad approaches to modelling heat stress are reviewed and related to the main mechanisms of heat stress. We conclude with a statement of the research needs to enable better simulation of heat stress impacts in real production settings.

2.2. Crop growth and development processes' response to temperature

Temperature plays a role in nearly all aspects of crop growth and development (Ferrise et al., 2011), such as photosynthesis (Sage et al., 2011), respiration (Atkin and Tjoelker, 2003), transpiration (Crawford et al., 2012), dry matter partitioning (Zhao et al., 2013), plant development (Wolkovich et al., 2012) and root growth (Kaspar and Bland, 1992). The optimal conditions for growth processes of plants usually occur within a range of temperatures (Criddle et al., 1997), with higher or lower temperatures decreasing growth and development rates (Porter and Gawith, 1999; Rötter and van de Geijn, 1999; Thomashow, 1999; Ciais et al., 2005; Sánchez et al., 2013). For many processes the decline in rates above optimal can initially be relatively gradual and fully reversible (Sage and Kubien, 2007), and in isolation not capable of describing the large non-linear response to increasing temperature observed in the field (Porter and Gawith, 1999; Sánchez et al., 2013). Nonetheless, as many of these processes influence final yield determination, we review them here as a basis for understanding how to adequately represent heat stress on crop yield formation. We begin by offering a generic description of the temperature response of key processes for temperatures near their optimal range, and then for temperatures beyond this range. We recognize our method of dividing the response is somewhat artificial, not necessarily corresponding to temperatures constituting heat stress in the field. In Section 3, our emphasis is on summarizing the integrated impacts of heat stress on crop yield components, largely based on observations from agronomic trials that exposed plants to episodes of high temperature under field conditions.

2.2.1. Photosynthesis and respiration

The photosynthetic response to temperature is significantly related to crops' photosynthetic pathway (C3 or C4) (Pessarakli, 2005), though as a whole, photosynthesis rates increase linearly from a base temperature to a lower optimum and sharply decline with increasing the temperature from an upper optimum (Sage and Kubien, 2007). Generally, most cold adapted C3 plants in high latitudes which are grown from winter to mid spring are photosynthetically active between 0°C to 30°C (Larcher, 2003), whereas the temperature range for photosynthesis of warm season and/or summer season C4 plants is between 7°C to 40°C (Sage and Kubien, 2007), with optimal values for both pathways between these extremes. In C3 species, at light saturation and current CO2 levels, leaf level photosynthetic response to temperature is determined by the availability of inorganic phosphates to photophosphorylation at low temperatures and whereas it is controlled by Rubisco availability to fix atmospheric carbon in the optimal range of temperatures for photosynthesis (Sage and Kubien, 2007). In C4 plants which are adapted to warmer environments, Rubisco availability limits photosynthesis at cool temperatures, whereas at warmer temperatures in the thermal optimal range, it is not clear which process limit photosynthesis (Crafts-Brandner and Law, 2000; Sage and Kubien, 2007). Net assimilation of plant material is determined by the balance between photosynthetic gains and respiration losses (Amthor, 1984), associated with both growth and maintenance processes (Tjoelker et al., 1999). Temperature impacts on respiration are driven by changes in enzyme activity (Brooks and Farquhar, 1985) which result in logistically increasing rates from 0°C to 40°C which level off at higher temperatures. The Q10 temperature coefficient of respiration declines linearly from 3 to 1 with increasing the temperature (Atkin and Tjoelker, 2003).

Photosynthetic rates decline increasingly steeply as temperatures increase past the optimal range (Sharkey, 2005; Sage and Kubien, 2007; Barnabás et al., 2008). The decline is associated with reduced light harvesting in photosystem II (PSII) that results from cyclic electron flow (Heckathorn et al., 1998; Sharkey and Schrader, 2006), thylakoid membrane instability and limitations in ribulose-1,5-bisphosphate carboxylase/oxygenase (Rubisco) (Crafts-Brandner and Salvucci, 2002). PSII is the most heat sensitive protein complex of photosynthesis (Havaux, 1992), with high temperatures directly deactivating the oxygen evolving complex (Nash et al., 1985), and even low levels of heat stress leading to the photoinhibition of PSII (Murata et al., 2007). On the other hand, some scientists find little or no damage to PSII due to moderate heat stress (Sharkey, 2005). Heat stress reduces the rate of PSII repair by stimulation of reactive oxygen species (ROS) production across the thylakoid membrane (Takahashi and Murata, 2005), which is itself influenced by high temperatures (Bukhov et al., 1999). The thylakoid membrane stability under high temperature stress, located between 32°C to 45°C, is largely determined by the stability of membrane’s fatty acids double bonds (Raison et al., 1982). Increasing ROS generation under heat stress conditions leads to a decline in the fatty acids double bonds (lipid peroxidation) and increased denaturation of thylakoid membrane proteins, thereby increasing membrane electron leakage (Xu et al., 2006). Rubisco activity, the most important photosynthetic enzyme, is decreased by heat stress (Crafts-Brandner and Law, 2000). The decline in Rubisco activity derived to gradually decrease in light-saturated CO2-exchange rate (CER) from 33 °C to 45 °C (Law and Crafts-Brandner, 1999).

Maintenance respiration (turnover of protein complexes) increases under heat stress with the result of reducing assimilates available for plant growth (Peng et al., 2004). Temperature increases from 18°C to 33°C consequently increased the rate of maintenance respiration of maize by more than 80% (De Vries, 1975). Respiration rate measurements could be a suitable indicator for simulation of crop stress under elevated temperatures, as respiration rates increase much more than photosynthesis rates initially decrease (Criddle et al., 1997). The change in key respiration enzymes’ Q10 temperature coefficient is the main cause of high temperature effects on respiration (Ryan, 1991), with enzyme degradation rates significantly increasing under high temperature conditions (Parsell and Lindquist, 1993).

2.2.2. Transpiration

Transpiration is a mechanism of heat avoidance and serves as the primary mediator of energy dissipation (Zhao et al., 2013). The rate of transpiration is determined by the vapour pressure deficit (VPD) between the inside of leaves and the surrounding air, as well as the intensity of incident radiation (Seversike et al., 2012), with leaf and air temperatures, wind speed and relative humidity comprising the main environmental factors modulating transpiration rates (Gates, 1968). Generally, the rate of transpiration increases with increasing of canopy temperatures (Zhao et al., 2013) due to its effects on both vaporization and VPD. For example, cumulative transpiration at 28°C was 50% higher than cumulative transpiration at 22 ºC under well watered conditions (Crawford et al., 2012). In non-limiting conditions, transpiration rates determine the rate of soil water extraction and the timing of subsequent water stress (Lobell et al., 2013).

Crop transpiration is the most active and common method of cooling crop tissues, with plant cooling requirements increasing with temperature (Seginer, 1994). Under non-water limiting conditions, increased transpiration with high temperature, may lead to significant sensible heat transfer and relative cooling of leaves, creating a negative feedback on increasing transpiration rates. Such phenomon is a partial explanation of observations that transpiration rates of plants increases nonlinearly as stomatal resistance is reduced with increasing temperature (Downes, 1970; Ku et al., 1977; Montero et al., 2001). Stomatal conductance of sunflower (Helianthus annuus L.), soybean (Glycine max L.), barley (Hordeum vulgare L.) and broadbean (Vicia faba L.) gradually increased with increasing growth chamber temperatures from 15 °C to 35 °C (Bunce, 2000). Also, the transpiration rates of maize fluctuated between 0.36-0.54 mm h-1 under a temperatures regime of 40/35 °C (daytime/nighttime), which is relatively greater than the range of transpiration rates (0.25-0.36 mm h-1) under a temperature regime of 25/20 °C in growth chambers (Ben-Asher et al., 2008). However, transpiration increases caused by high temperatures will be modulated as a function of wind speed and crop water status (Drake and Salisbury, 1972). Higher wind speed (Gates, 1968) and well watered conditions (Machado and Paulsen, 2001) are positively correlated with transpiration increases as temperatures increase. On the other hand, pre-acclimation to heat stress has an influence on transpiration rates, and was found to limit the increase in transpiration under various intensities of heat stress in wheat (Wang et al., 2011).

2.2.3. Development rate

Temperatures are largely responsible for controlling the rate of plant development, in some cases together with photoperiod and internal plant signals (Nord and Lynch, 2009). Additionally, temperature is well established as a signal in vernalisation processes to induce of flowering in winter cereals (Morison and Morecroft, 2008). Together with photoperiod, temperature largely determines the duration of sowing to flowering, and continues to affect the rate of crop development to maturity (Roberts and Summerfield, 1987). Increasing the temperature to optimal thresholds accelerates biochemical reactions and consequently development rates, declining the growing season lengths (Cleland et al., 2007). Shorter developmental phases for field crops could have relatively negative effects on the formation of yield components (Chmielewski et al., 2004). Siebert and Ewert (2012) found growing season lengths of oats in Germany declined by about 2 weeks between 1959 and 2009 resulting with an earlier occurrence of phenological stages due to by higher temperature.

As high temperatures accelerate crop development, the duration of crop growth phases decreases, producing negative effects on final grain weight and yield in field crops, though not representing a non-linear response to temperatures (Porter and Gawith, 1999; Chmielewski et al., 2004; Sánchez et al., 2013). High temperatures during reproductive phases result in a significant acceleration of leaf senescence (Harding et al., 1990) related to higher oxidative damage induction under high temperatures (Djanaguiraman et al., 2010). Acceleration of flag leaf senescence, thought to be driven by the degradation of thylakoid components (Harding et al., 1990) and the carbon exchange rate per unit area, is closely associated with final grain weight under heat stress (Blum, 1986). Remobilized stem non-structural carbohydrate (NSC) and nitrogen reserves in wheat play a vital role during the grain filling period when photosynthesis is suppressed due to high temperatures (Fokar et al., 1998; Tahir and Nakata, 2005). The rate of chlorophyll loss from the flag leaf is positively correlated with nitrogen and NSC remobilization efficiencies under heat stress suggesting a relationship between leaf senescence and remobilization efficiency (Tahir and Nakata, 2005).

2.2.4. Reproductive development

The number of grains and grain weight is significantly affected by temperature change (Tashiro and Wardlaw, 1990b). Grain number per ear increases with increasing maximum air temperatures from 16°C to 28°C though is severely impacted by further increases (Ferris et al., 1998). Tashiro and Wardlaw (1990a) report that the highest grain numbers in wheat are obtained at mean temperature regime of 21/16 °C. Increasing temperature to crop-specific thresholds (10°C to 21°C for wheat) increase the grain filling rate by increasing rates of cell division in the endosperm tissue (Wardlaw, 1970) and enhancing metabolic rates (Barnabás et al., 2008). Dry matter partitioning, which is the outcome of the flow of photosynthetic assimilates from source organs to the sink organs (Marcelis, 1994, 1996) increases between 10°C to 30°C in winter cereals (Farrar, 1988).

The severe decline in growth, grain yield and harvest index reported for many cereals with high temperature events are related to both the changes in source activity reported above, but also to sink limitations resulting from the sensitivity of flowering, pollen sterility, ovaries formation, fertilization and grain abortion to high temperatures (Porter and Gawith, 1999; Wollenweber et al., 2003; Wahid et al., 2007; Barnabás et al., 2008). Extremely high temperatures influence meiosis, growth of the ovaries during pre-anthesis period, production and transfer of pollen during anthesis, all leading to the decline of grain number (Saini and Aspinall, 1982). Some work (Mascarenhas and Crone, 1996) suggests that pollen does not produce heat shock proteins, which generally confer protection against heat stress. A direct relationship between grain set and grain ethylene levels in wheat has been identified (Hays et al., 2007). Effects of heat stress during grain filling period also highly influenced quantity and quality final grain yield (Tahir and Nakata, 2005; Perrotta, 1998). Increasing mean temperatures from 25°C to 31°C enhanced the grain filling rate although, final grain yield declined by shortening of grain filling period (Dias and Lidon, 2009).

In pepper plants, heat stress lead to a decline in sucrose concentrations in flowers/ fruits (Aloni et al., 1991), though sucrose is known to prevent ovary abortion under conditions of water stress in cereals (Boyer and Westgate, 2004). Research investigating maize response to water stress suggests irreversible yield losses due to failure to flower or grain abortion are related to either the temporary inhibition of photosynthesis or sucrose transport (Westgate and Boyer, 1986; Boyer and Westgate, 2004). Transport of dry matter is also affected by high temperatures (Taiz and Zeiger, 2010), with Wolf et al. (1990) finding that in potato 73% of total dry matter was allocated to sink organs (tubers) at 12°C to 27°C, whereas temperatures of 23°C to 32°C reduced the partitioning to tubers to 45%. The inhibitory impact of high temperature conditions (29°C to 31°C) on source strength of potato was significantly higher in comparison to sink strength due to higher stability of sucrose-metabolizing enzymes of sink organs to heat stress (Lafta and Lorenzen, 1995).

2.2.5. Root growth

Soil temperature influences both the development rate and growth patterns of roots (Kaspar and Bland, 1992). While cell growth elongation increases with increasing soil temperature up to 30°C (Burström, 1956; Kaspar and Bland, 1992), Burström (1956) determined that total wheat root length decreased as temperature was increased beyond 20°C and attributed this to an accelerated root development rate, which controls cell size, resulting in shorter cells. Further, root growth elongation is effected by many other stresses (Pregitzer and King, 2005), including shoot temperatures, which can impair cell growth, with the result of much decreased cell sizes and root lengths under stress (Kaspar and Bland, 1992). Root growth is likely more sensitive to high root temperatures than high shoot temperatures (Wilhelm et al., 1999).

2.3. Observed crop specific impacts of heat stress on crop growth

Section 2 described the response of many individual processes to temperature, both in and above their optimal range. In this section, we attempt to describe the impact of heat stress, occurring particularly around flowering and grain filling, on crop yield components. It is likely that the observed impacts represent the integrated response of crops to the various processes described above – some of which will be operating in their optimal range, and other above it. As such, this section attempts to answer what happens to crop yields under heat stress, while the previous section summarizes the basis for understanding why.

2.3.1. Impacts on wheat

High temperatures in wheat are associated with reductions in grain yield, number (Stone and Nicolas, 1995; Ferris et al., 1998; Semenov, 2009) and quality (Spiertz et al., 2006), with the period centered on anthesis constituting the most sensitive in wheat (Ferris et al., 1998; Porter and Gawith, 1999; Porter and Semenov, 2005; Farooq et al., 2011; Luo, 2011). The observed sensitivity of wheat yields to high temperatures has been attributed to accelerated development (Blum et al., 2001), reduced photosynthesis (Salvucci and Crafts-Brandner, 2004) and the direct impacts on reproductive processes (Farooq et al., 2011). A summary of the temperature response of these key processes, as well as their impacts on final yield and yield components is shown in Figure 2.1 (a) and (b), respectively.

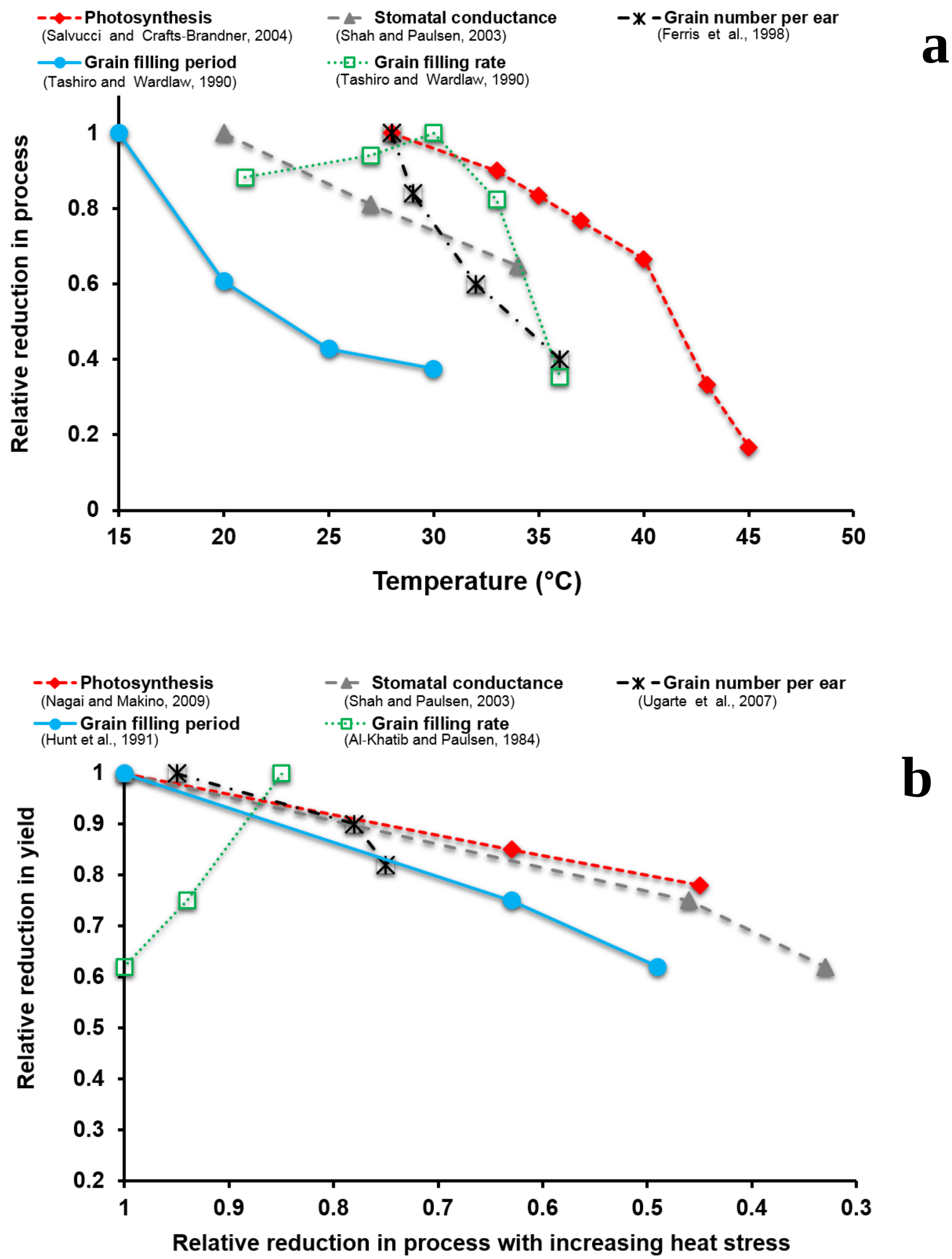


Figure 2.1. Key physiological processes in wheat and yield components' response to (a) high temperature and (b) how changes in each due to heat stress impact final yield.

Much experimental evidence supports the relationship between high temperatures around flowering and reduced grain numbers, with significant negative impacts on grain yield (Ferris et al., 1998; Barnabás et al., 2008). A threshold temperature of 31°C for wheat is generally accepted as an upper limit of temperatures near flowering without reductions in grain number (Porter and Gawith, 1999), with the sensitivity dependent on the development stage (Dias and Lidon, 2009; Wang et al., 2011), genotype (Dias et al., 2011) and water status of the crop (Atkinson and Urwin, 2012). The timing of high temperatures events (> 30°C) leading to reduced grain numbers has been reported by Fischer (1985) and Ortiz-Monasterio (1994) at approximately 20 days before and 10 days after anthesis, with the period immediately around anthesis (5 days before to 2 days after) particularly sensitive (Wheeler et al., 1996). The cause of the reduction of grain number with high temperatures near anthesis is largely attributed to effects on pollen fertility (Ferris et al., 1998; Calderini et al., 1999), or sterile grains, which Mitchell et al. (1993) report increased significantly with temperatures between 27 and 31°C during the mid-anthesis period. In addition to the direct negative impacts of heat stress on pollen fertility and grain abortion, acceleration of crop development rates with higher temperatures speeds the onset of double ridge appearance and anthesis, resulting in fewer spikelets per spike and grains per spikelet (McMaster, 1997).

Final grain weight in wheat is determined by the product of the duration and rate of grain filling (Barnabás et al., 2008). Grain filling in wheat is governed by the level of current assimilate production via photosynthesis in leaves and stems (Blum et al., 1994), re-mobilization of the stored carbohydrates and nitrogen containing compounds within these organs and their subsequent transport to the ear and grains (Plaut et al., 2004). As such, grain weight in wheat is extremely sensitive to heat stress due to reductions in photosynthesis at high temperatures during grain filling. For example, the response of 75 wheat cultivars in Australia to short episodes of high temperatures above 35°C (during grain filling) ranged from a 23% to 37% decline in individual grain weight (Stone and Nicolas, 1994). Temperatures above 34°C lead to reduced final grain weights via shortening the duration of grain filling, decreasing photosynthetic rates (Blum, 1986) and directly preventing starch biosynthesis in the endosperm cells (Jenner, 1994). While there can be an increase in the rate of grain dry matter accumulation under high temperatures, in most cases it is not sufficient to compensate for the decrease in duration of grain filling (Stone and Nicolas, 1995; Blum, 1998; Dias and Lidon, 2009). Increasing the temperature by 5ºC above 20ºC reduces the grain filling period of wheat by 12 days (Yin et al., 2009). However, the relative susceptibility of these two components of grain filling dynamics is dependent on genotype, with Hays et al. (2007) reporting grain weight declines at 38°C during early grain development as 13% higher across heat susceptible cultivars than heat tolerant cultivars of wheat with optimum temperature ranges for grain filling periods reported as between 16°C and 21°C (Ciaffi et al., 1996).

At a whole plant level, grain filling is closely associated with senescence (Barnabás et al., 2008). Al-Khatib and Paulsen (1984) concluded that the major impact of heat stress (35/25°C) during the grain development period of wheat was related to acceleration of senescence due to evanescence of photosynthesis. Wheat leaf senescence rates greatly increase under high temperature (35°C) conditions (Harding et al., 1990). The number of senesced wheat leaves per tiller during post-heading period increased from two to ten when air temperatures were raised from 21°C to 28°C in Texas, USA (Tewolde et al., 2006) following a linear relationship between grain yield and senesced wheat leaves per tiller (Tewolde et al., 2006). Larger daily temperature differences (34°C compared to 22°C) accelerated the senescence of flag leaves in wheat under heat stress conditions, compared to delayed senescence under optimum temperature treatments of 26°C/14°C and 24°C/16°C (Zhao et al., 2007).

2.3.2. Impact on maize

Unlike wheat, in which heat stress impacts on both grain number and filling are reported, evidence for the mechanisms of heat stress impacts on maize have focused largely on grain number, with yield determination in this crop largely associated with grain number (Otegui and Bonhomme, 1998) and this yield component has been demonstrated to be extremely sensitive to high temperatures in the period centered on flowering (Cicchino et al., 2010b; Rattalino Edreira and Otegui, 2013). The reduction in grain number is attributed to reduced assimilation supply arising from reductions in photosynthesis and increases in respiration (Barnabás et al., 2008), as well as to the direct negative impacts of high temperature on reproductive processes (Rattalino Edreira and Otegui, 2013). A summary of the temperature response of these key processes, as well as their impacts on final yield and yield components is shown in Figure 2.2 (a) and (b), respectively.

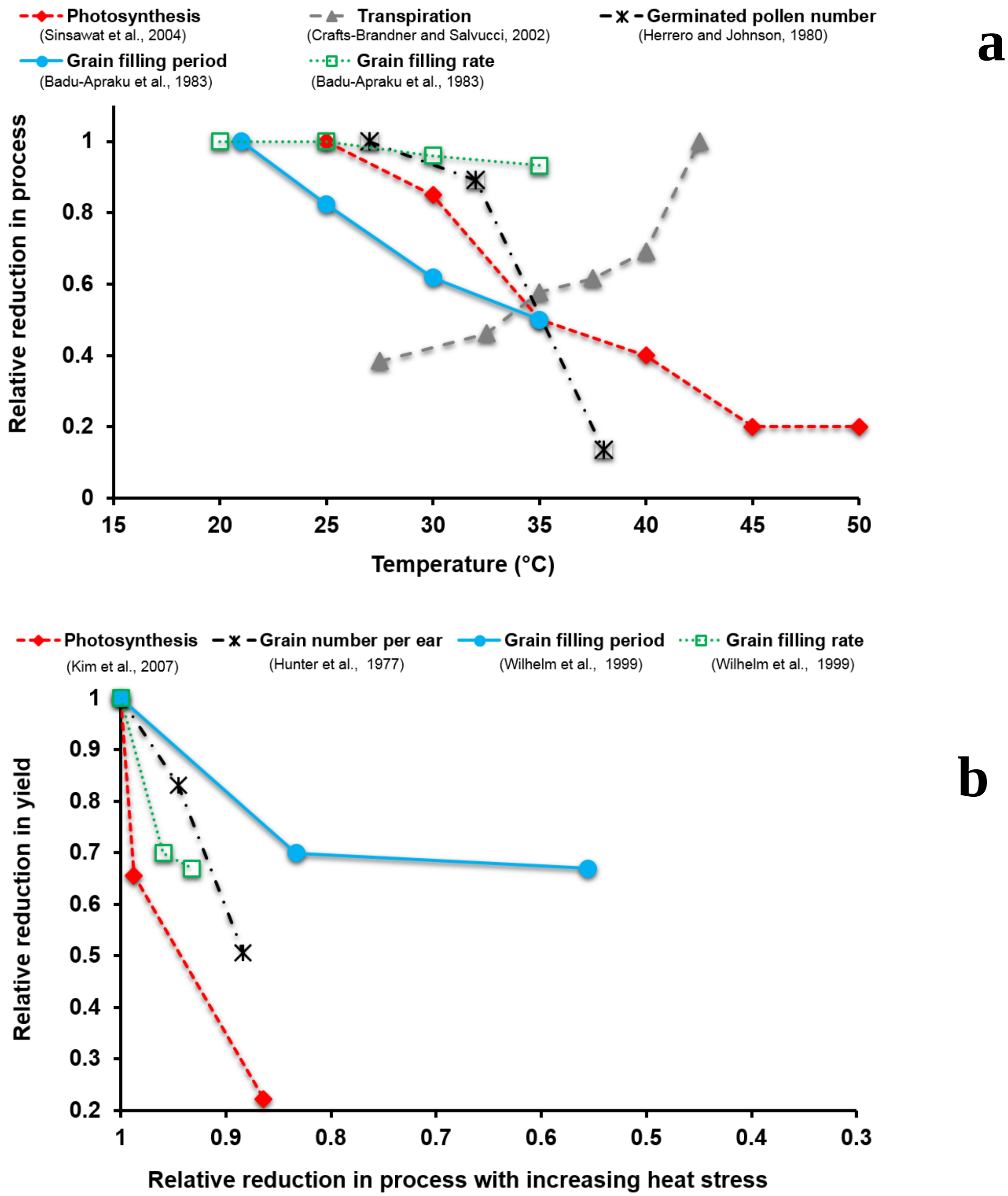


Figure 2.2. Key physiological processes in maize and yield components' response to (a) high temperature and (b) how changes in each due to heat stress impact final yield.

High temperatures at tasseling can delay both tasseling and silking, but whether this results in an increased or shortened interval between the two remains unclear. Rattalino Edreira et al. (2011) observed decreased anthesis-silking intervals (33-40°C) and Cicchino et al. (2010b) reported lengthened or unchanged intervals when maize was subjected to heat stress (30-36°C) at flowering. When harvested from field grown plants and subjected to high temperatures in controlled chambers, pollen viability increased for exposures of up to 24 hours at 32°C, whereas it was negatively impacted across a range of genotypes with exposure to 38°C (Herrero and Johnson, 1981). Rattalino Edreira et al. (2011) observed floret number, number of exposed silks and final kernel number were all negatively impacted by high temperatures at flowering. In a field experiment with a temperate variety, Cicchino et al. (2010a) determined the critical temperature at flowering in two years as 35.5 ± 1.25°C and 32.2 ± 1.11°C, while in vitro fertilization studies found the number of pollinated spikelets was reduced when exposed to temperatures above 35°C (Dupuis and Dumas, 1990).

While extreme high temperatures (38°C) can reduce pollen viability (Herrero and Johnson, 1981; Porter and Semenov, 2005), reduced kernel number is observed at lower temperatures and in the absence of negative effects on pollen availability and viability (Otegui et al., 1995). Variations in maize kernel number correlate with plant growth rate in the period around flowering (Andrade et al., 1999; Vega et al., 2001) with the critical period for kernel number determination corresponding to the period of active ear growth, determined to be 250 degree days before and 100 degree days after silking (Otegui and Bonhomme, 1998). Direct heating of kernels above 35°C lead to reduced kernel number (Jones et al., 1984), whereas heating to 30°C enhanced kernel production on the heated side and increased kernel abortion on the non-heated side, suggesting assimilate distribution was influenced by the optimal metabolic activity on the heated side of the ear (Cárcova and Otegui, 2001).

Recent work has demonstrated reduced biomass assimilation and kernel abortion are likely the two primary causes of reduced kernel number with heat stress at flowering in maize. Rattalino Edreira et al. (2011) attributed the final reduction in grain number to kernel abortion and not the failure of silks to emerge (Cárcova and Otegui, 2001) or pollen viability, as they supplied fresh pollen daily. When heat stress (30 to 36°C) was applied at silking, RUE was reduced resulting in reduced plant and ear growth rates which explained lower kernel number and final yield (Cicchino et al., 2010b; Rattalino Edreira and Otegui, 2013). These temperatures at flowering or silking did not affect biomass partitioning to the ear during silking. The only effects of heat stress on partitioning occurred during flowering when high temperatures also occurred at flowering. This response was transient with the removal of heat stress resulting in almost all assimilate being partitioned to the ear (Cicchino et al., 2010b). Contrary to drought stress, the results of Rattalino Edreira and Otegui (2013) do not support that high temperatures (30 to 38°C) at flowering reduces partitioning to the ears which explains varietal differences in kernel number (Echarte and Tollenaar, 2006). Rather sink limited cases which can arise with lowered assimilation rates during kernel formation and/or kernel abortion, both which cause reduced kernel numbers, can result in lower harvest indexes observed with heat stress (Cicchino et al., 2010b). Collectively these results demonstrate the importance of the source-sink ratio in determining the impacts of high temperatures near flowering on grain yield. While both kernel number and biomass assimilation are reduced, the recovery of RUE and biomass production when heat stress is removed may lead to reduced HI if the reduced kernel numbers results in limited sink availability.

Significant varietal differences to heat stress appear to exist in maize. Tropical genotypes exhibited lower levels of kernel abortion than temperate hybrids (Rattalino Edreira and Otegui, 2013), at 33 to 40°C during the pre-anthesis to silking stages, while all varieties exhibited the same reduction in growth rates. However, tropical and tropical-temperature cross hybrids were observed to have smaller reductions in RUE and yield losses than temperate hybrids (Rattalino Edreira and Otegui, 2012), suggesting they can withstand higher temperatures at flowering than temperate varieties. Varietal differences decreased or disappeared for heat stress (33.5/25°C) applied during grain filling for extended periods (Wilhelm et al., 1999).

2.3.3. Impacts on rice

In high yielding conditions, high rice yield is associated with sink capacity as determined by the combination of high spikelet density (Hayashi et al., 2012) and grain weight, with the relative importance of either characteristic dependent on variety (Fukushima et al., 2011). Higher yield levels in indica varietals are associated with source activity such as higher growth rates and more rapid translocation of non-structural carbohydrates to grains, both during early ripening (Yoshinaga et al., 2013). The effect of high temperatures on rice yield formation appear to be related to changes in flowering dynamics, reduced seed set and lowered grain weight, with rice exhibiting sensitivity to both elevated day and night time temperatures (Mohammed and Tarpley, 2009). A summary of the temperature response of these key processes, as well as their impacts on final yield and yield components is shown in Figure 2.3 (a) and (b), respectively.

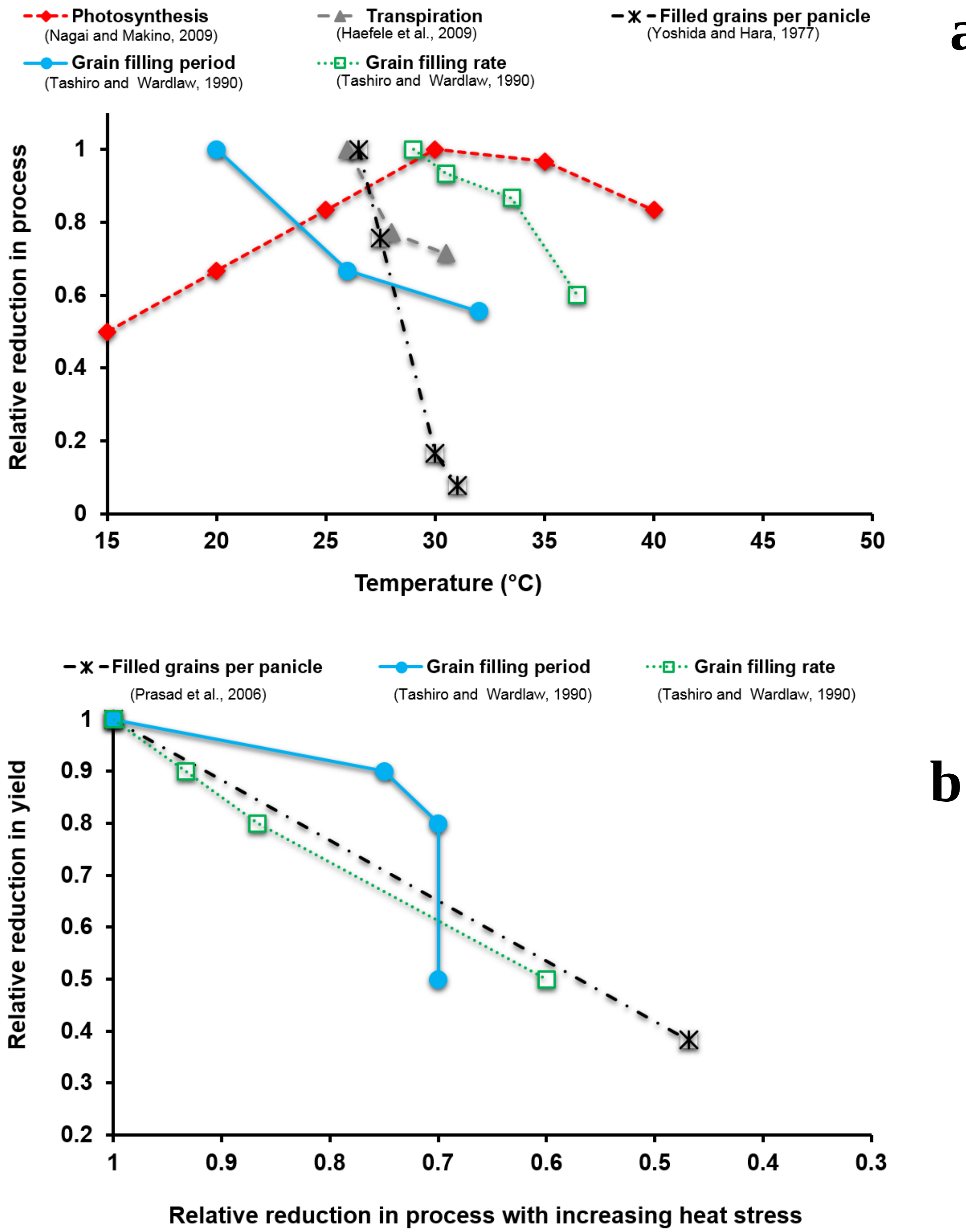


Figure 2.3. Key physiological processes in rice and yield components' response to (a) high temperature and (b) how changes in each due to heat stress impact final yield.

Changes in flowering dynamics with daytime heat stress include a general shortening of anthesis period and associated earlier arrival of peak flowering (Tao et al., 2008). Likewise, elevated nighttime temperatures from 27°C to 32°C in a greenhouse study resulted in panicle emergence occurring 2 days earlier (Mohammed and Tarpley, 2009). Tao et al. (2008) report that the heat tolerant variety evaluated responded to high daytime temperatures (40 to 42°C) by dispersing the timing of flower opening throughout the day, whereas high nighttime temperatures did not induce this response (Shi et al., 2013). High daytime temperatures of up to 36° in a greenhouse and chamber experiments caused flowering earlier in the day (by approximately 45 minutes) for both indica and japonica varieties (Jagadish et al., 2007). Varieties evaluated to have the same high temperature thresholds exhibited different rates of seed sterility associated with their daily peak time for flowering (Ishimaru et al., 2010), with varieties flowering earlier in the day escaping the high temperature impacts on seed sterility by avoiding having their flowers open at the times with highest temperature (Shah et al., 2011).

Pollen grains are generally more sensitive to heat stress than stigma (Wassmann et al., 2009). Mean elevated temperatures of 5°C (average increase from 22°C to 28°C) in gradient tunnels decreased pollen production and pollen viability (Prasad et al., 2006). Pollen germination percentages were reduced by 20% with nighttime temperatures elevated from 27°C to 32°C (Mohammed and Tarpley, 2009). Matsui et al. (2001) found that the negative impacts on pollen germination of elevated daytime temperatures to 37.5°C explained reduced seed set, but at higher temperatures (40°C), seed set was reduced by a larger amount than could be explained by pollen germination. Likewise, reduced numbers of germinated pollen on stigma led to reduced seed set (Rang et al., 2011).

High daytime high temperatures of 40 to 42°C and 38°C, respectively, led to no significant reductions in the number of spikelets per panicle across eight hybrids (Tao et al., 2008), but rather increases in the number of infertile (Rang et al., 2011) and partially developed (aborted) grains (Tao et al., 2008). Significant differences across hybrids were best explained by the heat tolerant variety having a much smaller degree of grain abortion and differences in flowering dynamics (Tao et al., 2008; Rang et al., 2011). Elevated nighttime temperatures resulted in a 72% decrease in panicle fertility when increased from 27°C to 32°C (Mohammed and Tarpley, 2009). Reduced spikelet number, reduced seed set and lower grain weight were all reported when nighttime temperatures increased from 22°C to 28°C in a field experiment (Shi et al., 2013). Prasad et al.

(2006) found that reduced spikelet formation was correlated with reductions in photosynthetic rates under heat stress. However, significant cultivar differences appear to exist (Matsui et al., 2001; Prasad et al., 2006; Jagadish et al., 2007), with some heat tolerant varieties completely avoiding yield losses despite reduced spikelet number by increasing seed set (Shi et al., 2013). In the heat tolerant variety, stem content of NSC was not impacted by heat stress whereas it was in the heat sensitive variety, though translocation of NSC to spikelets from the stem was reduced with heat stress in the tolerant variety to a greater extent than in the heat sensitive variety, presumably due to either a combination of the high temperature stress and reduced sink strength (Shi et al., 2013). Jagadish et al. (2007) found spikelet numbers increased with temperatures to 36°C in an indica variety, but decreased in a japonica variety. However, while high yielding varieties have large numbers of spikelets per area, Hayashi et al. (2012) found even in high yielding conditions large proportions of unripened and unfilled grains, highlighting the critical role of spikelet numbers together with high source activity (assimilation and/or translocation) for yield formation. Finally, while the effect of high temperature beyond a varietal threshold (Yoshida et al., 1981) appears to decrease yield via reducing the number of spikelets per unit area (Peng et al., 2004) or viable seeds set (Jagadish et al., 2007; Tao et al., 2008; Rang et al., 2011), the effect of the duration of exposure to high temperature may also depend on the variety (Satake and Yoshida, 1978) as duration of temperature stress had no impact an indica variety whereas longer exposure (one compared to six hours) of temperatures of 36°C produced larger reductions in seed set in a japonica variety (Jagadish et al., 2007), and varieties tested by Rang et al. (2011).

Decrease in rice grain weight is attributed to shortening of the grain filling duration (Nguyen et al., 2014) due to accelerated senescence of the panicle, rather than leaf senescence (Morita et al., 2004; Kim et al., 2011). Kim et al. (2011) suggest that limited sink capacity reduced grain filling duration, and not leaf senescence as has been observed in wheat. The impact of high temperature on grain filling rate is somewhat unclear, as initially it is reported to increase (Tashiro and Wardlaw, 1989; Kim et al., 2011), though some work has shown it decreases with increasingly high temperature due to limited photosynthesis/translocation (Tashiro and Wardlaw, 1989).

2.3.4. Variation of impacts between regions

Growth stages relative susceptibility to heat stress likely differ between regions due to unique combinations of climate and the timing of crop development. For example, across the

Mediterranean region, cereal yields are largely limited by episodes of heat stress during grain filling reducing its duration (Maracchi et al., 2005; Olesen et al., 2011). On the other hand, across much of central Europe future climate changes are expected to produce negative impacts on wheat yields due to reductions in grain number arising from high temperature episodes around anthesis (Semenov and Shewry, 2011). Most heat stress experiments in Australia have focused on the post-anthesis period due to higher heat stress intensity during grain filling in the region (Singletary et al., 1994; Stone and Nicolas, 1995; Savin and Nicolas, 1996; Savin et al., 1997; Skylas et al., 2002; Asseng et al., 2011).

2.4. Methods to study heat stress

Understanding crop response to high temperature stress is key to improving crop models with regards to their ability to simulate crop growth at the field and larger scale in warmer and more extreme climates. It is important for crop modelers to understand the conditions under which crop response to temperature has been studied, such that they can better gauge the applicability of such knowledge as the basis of model improvement. For example, the majority of studies on the impacts of heat stress on crop growth are performed in growth chambers (Sinsawat et al., 2004; Ananda et al., 2011), temperature gradient tunnels (Wheeler et al., 1996) or temperature free-air controlled enhancement (T-FACE) (Kimball, 2005; Kimball et al., 2008) systems.

The main advantage of growth chamber experiments is the high level of control in the imposed temperature regimes compared to those conducted in temperature gradient tunnels and the field. On the other hand, disadvantages include: restricted root growth due to the small pot size (McConnaughay et al., 1993), high relative humidity during heat stress induction (Mitchell et al., 1993), elevated water demand of plants under high temperatures conditions and the elevated temperatures experienced by roots, uncommon in field situations (Wilhelm et al., 1999). Root growth restriction influences the response of plants to applied treatments such as CO2 concentration or temperature due to inhibited nutrient and water absorption (McConnaughay et al., 1993). The percentage of sterile grains of wheat was associated with high relative humidity under heat stress conditions (Mitchell et al., 1993). Crops water demands significantly increase under heat stress conditions (Polley, 2002) nevertheless, less root development in pots limited the plants available water and roots have been shown to be more sensitive to elevated temperatures than shoots in wheat (Kuroyanagi and Paulsen, 1988).

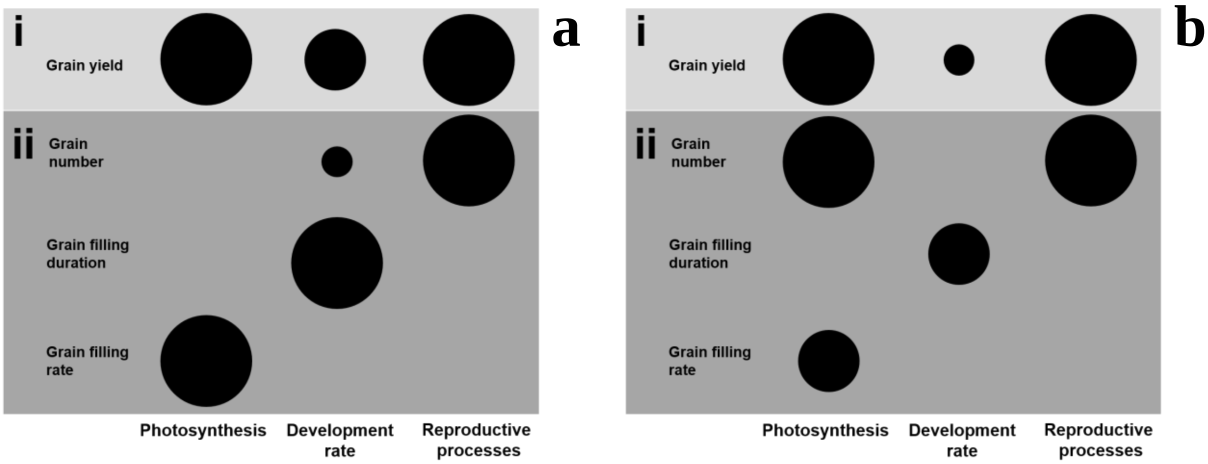
Temperature gradient tunnel experiments attempt to reproduce field conditions and overcome the rooting restriction and temperature effects of chamber studies (Pérez et al., 2005). In addition, high performance fans help to control high levels of relative humidity inside the tunnels (Martínez-Carrasco et al., 2005). Nevertheless, reduced radiation intensities due to the use of clear polyethylene in the roof and walls of the tunnels are the main limitations of this approach (Batts et al., 1996; Wheeler et al., 1996; Rattalino Edreira et al., 2011), though new tunnel systems are enclosed with very narrow polyethylene film (100 µm thickness) (Rattalino Edreira and Otegui, 2013). The reduced level of incident radiation under polyethylene cover may influence crop yield more than the applied high temperature treatments (Kittas et al., 1999).

T-FACE is the most advanced system for studying heat stress effects on crop canopies. Installed under field conditions (top of the canopy), temperatures are raised with infrared heaters (Kimball, 2005; Kimball, 2011). The main advantages of T-FACE are the low level of interference with the typical production conditions of the crop and the high degree of flexibility to accommodate crops of varying heights from tall (sorghum) (Kimball, 2005) to short cereals such as wheat (Kimball et al., 2008). Controlling the high air turbulence effects due to the temperature change under heating area is the key challenge associated with these systems (Kimball et al., 2008). However, the impact of turbulence could be significantly reduced by establishing temperature sensors to regulate heating in response to wind speeds, though this will require extensive knowledge and high energy consumption (Wall et al., 2011). All methods potentially suffer from confounding the effects of the rate and degree of temperature change, as impacts of heat stress are larger when imposed suddenly (Crafts-Brandner and Salvucci, 2002).

At the field level, multiple locations, latitudes and/or sowing dates are generally used in studies looking at temperature effects on growth and yield of crops (e.g. Midmore et al., 1982, 1984; Muchow et al., 1990; Lafitte and Edmeades, 1997). While varying elevation, latitude and sowing dates will result in readily measurable changes in air and soil temperatures these methods are usually associated with changes in the radiation regime, photoperiod or soil conditions (White and Reynolds, 2001). Slafer and Rawson (1994), in a review of wheat phenology noted that the use of sowing dates to characterize temperature sensitivity of phases prior to anthesis is problematic. Development stages just prior to flowering usually experience a narrow range of conditions (White and Reynolds, 2001). Replication within a sowing date plot is also statistically equivalent to sub-sampling (White and Reynolds, 2001).

2.5. Approaches to modelling heat stress

The preceding review of crop response to high temperatures has emphasized that across cereal crops, the most significant impacts of high temperatures on yield formation appear to be associated with reductions in grain number when heat stress occurs at flowering or reductions in grain weight when high temperatures are experienced during grain filling. A summary of the relative importance of various processes' responses to high temperature on final yield and yield formation are shown in Figure 2.4 (a). (b) and (c), respectively. Whether or not these translate into yield reductions seems to depend on cultivar sensitivity to heat stress (Rattalino Edreira et al., 2011; Shi et al., 2013), the timing of the heat stress event, the crop's relative seed set in unstressed conditions, and parallel impacts on assimilation, the existing reserve status of the crop and remobilization of NSC. In what follows, we outline some general approaches found in cropping systems' models to account for heat stress, and offer a qualitative evaluation of how each of these approaches accounts for the main processes of heat stress, and their implication. A comprehensive review of the performance of models implementing heat stress response is presented in Wang et al. (2014. unpublished results).



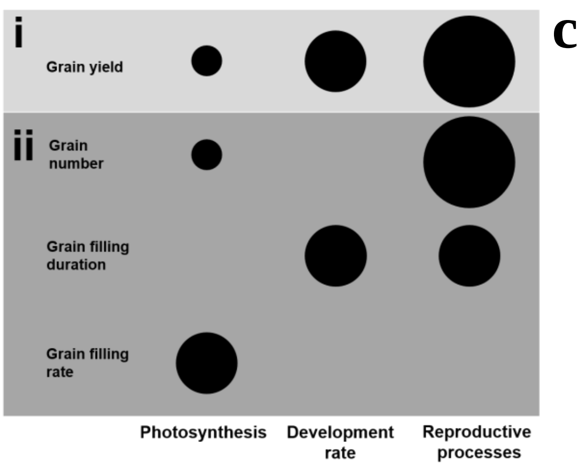


Figure 2.4. The relative impact of the main physiological processes under conditions of heat stress on cereal crop (i) yield and (ii) yield determinants (grain number, grain filling duration, and grain filling rate) are indicated by the size of circle, with large and small circles indicating relatively large and small impacts, respectively for (a) wheat, (b) maize, and (c) rice.

2.5.1. Empirical reduction functions on grain yield

The simplest approach to account for negative impacts of high temperature on yield consists of reducing final yield based on the average (or greatest) daily accumulation of temperature thermal time above a high temperature threshold during the period in which yield formation is sensitive to high temperature. At a global scale, Teixeira et al. (2013) used such an approach with the GAEZ model (Fischer, 2002) to simulate a reduction in potential production due to high temperatures for rice, maize, wheat and soybean, similar to the approach implemented by Challinor et al. (2005) with GLAM (Challinor et al., 2004) for groundnut. Within a 30-day period centered on flowering, a daily yield damage intensity factor was calculated which ranged from 0 when daytime temperatures (not maximum) were less than or equal to a crop specific critical temperature and increased linearly to a maximum value of 1 when day temperature reached a limiting upper threshold. These daily yield damage intensity factors were averaged over the 30-day sensitive period and used to scale potential production to estimate the potential yield damage due to high temperatures (Teixeira et al., 2013). The same approach is used by Rezaei et al. (2013) with the SIMPLACE modelling framework (Gaiser et al., 2013) to reduce final water limited yield. The method is attractive in its simplicity, though it cannot account for any processes (failure of flowering, grain sterility, lack of assimilate flow to flowers because of a reduction in photosynthesis, etc). It remains unclear whether or not heat stress accumulates or if it is simply the magnitude of the high temperature which results in grain sterility as shown by Jagadish et al. (2007) in rice.

2.5.2. Empirical reduction functions on daily increment in harvest index

Reducing the daily increment in harvest index in response to high temperature episodes (Porter and Gawith, 1999; Wollenweber et al., 2003) may allow for a more descriptive and dynamic approach to reducing final grain yield. In variation of this approach, the daily increment in harvest index varies throughout crop development and the impacts of high temperature on it reduced grain yield will be expressed on the day of the high temperature event. In reality, this can be due to a failure of reproductive processes, to grain abortion or to a reduction in photosynthesis inhibiting grain formation on that day. AquaCrop (Raes et al., 2009; Raes et al., 2011) implements this approach at the canopy scale, though heat stress impacts can only reduce the daily increment in harvest index by a fraction weighted according to the fraction of flowers that are opening on that particular day. The result is the maximum harvest index that can be reached is reduced. The consideration of flower dynamics is important to determine source-sink relationships (discussed in a following section), though limiting heat impacts to only the time of flower opening is likely to underestimate impacts, as research in maize and wheat demonstrate that grain yield is reduced by exposure to high temperatures before and after flowering, not only at the time of flower opening or pollination. However, the AquaCrop approach does allow for an excess of flowers, such that flower death due to heat stress may not result in a decrease in the harvest index increment. A variation of this approach is to implement a constant value of daily increment in harvest index, that is also reduced by high temperature episodes during flowering, such as is done in a modified version (Moriondo et al., 2011) of CropSyst (Stöckle et al., 2003). The use of an average increment in harvest index essentially reduces it to a reduction on final yield, though in the determination of the most limiting heat stress event to use to reduce the value of the daily increment, CropSyst weights the reduction factor by the fraction of flowers opening on that day.

2.5.3. Empirical reduction functions on grain number

An empirical reduction factor on grain number in response to high temperature allows for consideration of not only grain number reduction arising from reduced photosynthesis, failure of flowering or pollination, but also effects of changes in grain filling rate and duration. Under optimal conditions, the number of grains set in maize is directly related to photosynthetic rate (Lizaso et al., 2007), represented by either curvilinear (Andrade et al., 1993) or linear (Otegui, 1997) models in response to intercepted photosynthetic active radiation (IPAR) or curvilinear functions of shoot growth rate (Tollenaar et al., 1992; Andrade et al., 1999). Lizaso et al. (2001) found their curvilinear function of IPAR embedded in CERES-Maize (Jones et al., 1984) reproduced kernel growth best for eight varieties over 4 sites in Iowa, USA. Under stress conditions, an empirical reduction factor is used to reduce grain number to account for the failure of flowering or abortion, while RUE or photosynthesis can be directly reduced in response to high temperatures. Various APSIM v7.4 for cereals (Keating et al., 2003) simulate the direct impact of high temperatures near flowering on reducing grain number. In APSIM maize (Carberry et al., 1989) and millet, both based on derivatives of CERES-Maize (Jones and Kiniry, 1986), the direct impact of maximum daily temperatures beyond a species threshold reduces grain number, at a set rate per accumulated degree days between flag leaf and the last day of flowering. Biomass assimilation is reduced when mean temperatures exceed optimal values for photosynthesis and grain filling duration is shortened when optimal temperatures are surpassed for thermal time accumulation; each contributing to reduced kernel numbers. Different approaches in APSIM-Sorghum and a newer maize model, MaizeZ, relate largely to the calculation of the reduction factor and the timing when high temperatures reduce grain number and yield.

2.5.4. Deterministic source sink relationships

Our review has highlighted the relationships between the failure of pollination or grain abortion (reduced sink strength), and the rate of photosynthesis and carbohydrate translocation (source limited grain set), with final grain number under heat stress conditions with considerable response diversity across crops and genotypes. Likewise, the combination of grain number and further changes in photosynthesis influence the grain filling rate and grain yield. Therefore, a model approach that deterministically accounts for both sink appearance and development could potentially allow for more mechanistic representation of heat stress impacts on reproductive structures. The flowering model of Lizaso et al. (2003; 2007) evaluated with the DSSAT CERES-Maize v3.1 estimates the progression of plants reaching anthesis, pollen shed from each tassel, the progression of viable silks and the percentage of silks that will set kernels. The model does not currently consider high temperature stress effects (Lizaso et al., 2003), but could be parameterized to do so with sufficient experimental data. The approach of Nguyen et al. (2014) for simulating spikelet sterility in rice further distinguishes between the time of heading, distribution of flowering on a spikelet and flowering time of day allowing for heat stress responses to be differentiated between the two sensitive processes. However, given the significant genotypic variability of heat stress responses in maize (Schoper et al., 1987; Rattalino Edreira and Otegui, 2012) and rice (Jagadish et al., 2007; Shi et al., 2013), it is unlikely that such detailed approaches could be applicable beyond the field level (Jamieson et al., 1998).

2.5.5. High temperature response for main growth processes

The inclusion of high temperature responses for key processes such as photosynthesis, leaf area growth and senescence allow for directly accounting for some of the key causes of yield decline in cereals. In regions where hastening of crop senescence drives the shortening of grain filling duration, inclusion of a heat stress effect on senescence rate as in APSIM-N Wheat (Asseng et al., 2004) has shown satisfactory for explaining yield reduction with extreme temperatures (Asseng et al., 2011). A challenge in the combined use of reductions in photosynthesis rates (or RUE) with empirical reduction functions on grain yield or grain number is how to avoid double counting heat stress effects caused by reduced photosynthesis. For example, in maize the reduction in grain number has been attributed to both kernel abortion and reductions in RUE during yield formation (Cicchino et al., 2010b; Rattalino Edreira and Otegui, 2013). However, this double counting is likely to be of minor importance as the reduction in RUE was transitory and existed only during the time of heat stress.

2.6. Canopy temperature

Most crop models consider ambient air temperature to drive various processes and rates, including heat stress effects. For example, APSIM (Keating et al., 2003) uses daily maximum temperatures, while modified CropSyst (Moriondo et al., 2011) considers mean temperatures between 8h00 and 14h00 and SIMPLACE's heat stress module (Rezaei et al., 2013) uses a daily average weighted four times more heavily to the daily maximum than the minimum temperature. However, heat stress impacts on grain set in a crop stand are likely determined by tissue or canopy temperature (Jagadish et al., 2007; Craufurd et al., 2013; Siebert et al., 2014; van Oort et al., 2014), which can differ substantially from air temperature (Siebert et al., 2014) depending on crop transpiration rates, ambient CO_2 concentrations and soil water status (Ferrise et al., 2011). Across more than 20 irrigated cultivars of spring wheat in a very hot environment with all mean monthly maximum temperatures above 30 °C, Amani et al. (1996) found a strong negative correlation between canopy temperature depression beneath the ambient air temperature and grain yield. While the authors do not attribute this to heat stress, the results provide a compelling evidence for the consideration of canopy temperature and not air temperature when crop models do not consider mechanistic representations of stomatal conductance and photosynthesis, particularly under water limiting conditions. Likewise in wheat, Idso et al. (1977) established a strong negative relationship between canopy temperature depression (beneath air temperature), at constant vapour pressure deficit and incident radiation (Idso et al., 1981a; Idso et al., 1981b; Jackson et al., 1981), resulting from different levels of water stress.

Simulation of canopy temperature is generally difficult as it is a complex function of standard meteorological parameters in addition to canopy resistance to water flow and aerodynamic resistance to heat and vapour transfer (Monteith and Unsworth, 1990). Furthermore, canopy temperature measured with an infrared thermometer is distinct from aerodynamic temperatures at the level of the surface, particularly for sparse canopies (Stewart et al., 1994; Lhomme et al., 2000; Colaizzi et al., 2004; Matsushima, 2005; Mihailovic and Eitzinger, 2007; Boulet et al., 2012) due to variations of emissivity with time of day (Colaizzi et al., 2004) or viewing angle (Huband and Monteith, 1986). Physically robust expressions for surface and aerodynamic canopy temperatures, such as that of Mihailovic and Eitzinger (2007), require extensive parameterization for stability functions (Paulson, 1970; Monteith and Unsworth, 1990) commonly defined in terms of the Richardson number or Monin-Obuhkov length (Monteith and Unsworth, 1990) making their use for crop models applied at the field and larger scales problematic. However, in a comparison of eight methods for estimating aerodynamic resistance and associated stability functions for maize, Liu et al. (2007) found that some of the simpler, more empirical methods performed as well as more complex ones using the Monin-Obuhkov length.

A simplified expression for canopy temperature is derived from a daily canopy energy balance by equating net radiation to latent and sensible heat fluxes, assuming the soil heat flux is negligible and ignoring the stability correction factors in the aerodynamic resistance terms (Idso et al., 1981a; Jackson et al., 1981; Clawson et al., 1989). While assumptions about neutral stability conditions, employed in formulations of reference evapotranspiration from well watered cropped grass surfaces (Allen et al., 1998; Allen et al., 2005) lead to greatly simplified expressions for canopy temperature, Tc, they are likely not valid under conditions when transpiration is reduced. In addition to the error introduced by assuming neutral stability conditions, and the challenges of having good quality data common to estimating reference evapotranspiration (Allen et al., 1998) two other issues present challenges for its implementation in field and larger scale crop models. Firstly, all meteorological variables should be measured over the crop being studied (Idso et al., 1977). While this is seldom strictly observed for calculation of reference evapotranspiration (Allen et al., 1998), significant deviation is expected in wind speeds over different crops, though methods are available to translate wind speeds measured over one crop to another (Allen and Wright, 1997). Finally, specification of the canopy resistance term is expected to be very difficult in conditions where crops experience water stress or stomatal conductance is reduced. As a simplification to avoid the latter challenge, Clawson et al. (1989) estimate the canopy temperature lower and upper limits with assumptions about stomatal conductance at full and no transpiration, respectively (Idso et al., 1981a; Jackson et al., 1981; Clawson et al., 1989). Actual canopy temperature will lie between these limits, and depend on the transpiration rate. On a daily basis this could be estimated as the ratio of actual crop transpiration to potential crop transpiration, though water stress and canopy temperatures vary throughout the day, and average daily water stress is likely to underestimate heat stress effects. Further, errors introduced using erroneous estimates of aerodynamic resistance, which is a function of wind speed, would need to be evaluated, as it has a strong influence on the upper and lower temperature limits. However, in the review of Liu et al. (2007), the error associated with wind speed and assumptions related to the roughness lengths of momentum and heat were larger than those associated with method of estimating aerodynamic resistance.

Much simpler and empirical examples of representing canopy temperature exist. In a model of heat stress effects on rice sterility, van Oort et al. (2014) use an empirical expression of diurnal daily temperatures and relative humidity to estimate panicle temperature. The SIRIUS wheat simulation model (Jamieson et al., 1998) uses canopy temperature (Jamieson et al., 1995), calculated from a canopy level energy balance assuming neutral stability conditions, and no surface resistance term as latent heat flux is estimated from Penman (1948) which uses an empirical wind function (Jensen et al., 1990). Simulations of anthesis dates and final yield under different sowing dates improved when canopy temperature was used (Jamieson et al., 1995), though the impacts of heat stress were not investigated. In STICS (Brisson et al., 2003), a simple empirical formulation of canopy temperature varies with average temperature, net radiation, actual transpiration and soil evaporation fluxes, and the aerodynamic resistance, computed from Shuttleworth and Wallace (1985). Though fairly simple and making assumptions of neutral stability, the expression allows to calculate canopy temperature for conditions of variable LAI which control the contribution of soil sensible and latent energy fluxes (Shuttleworth and Wallace, 1985; Shuttleworth and Gurney, 1990).

It may be possible to avoid a direct calculation of canopy temperature, when water stress occurs frequently by directly simulating the negative effects of water stress on grain number. For example, Lobell et al. (2013) found maize grain number decrease with increasing temperature was adequately simulated with APSIM and attributed the response to increased vapour pressure deficit with higher temperatures leading to increased water stress. In APSIM-Maize, water stress reduces the grain number by reducing the grain demand for carbohydrates, in the same period as the high temperature stress factor on grain number. Such a response is consistent with that due to increased leaf temperatures resulting from reduced transpiration, as well as the delay in silking and lower rates of silk elongation that occur when maize is subjected to water deficit at flowering (Herrero and Johnson, 1981). However, such approaches do not aid in determining heat stress effects in fully transpiring crops. The interactions of high temperature and water stress contained in APSIM-Maize should likely only be implemented when the canopy temperature (air temperature in APSIM and most crop systems models) is at or close to the crop's critical temperature for high temperature stress on grain number. APSIM applies this stress factor for all air temperature and crop sensitivity combinations suggesting they are estimating the impacts water stress only, and not elevated canopy temperature effects.

2.7. Challenges and future research needs

2.7.1. For understanding heat stress

Knowledge gaps to overcome regarding the impact of heat stress on cereals near flowering, and its interaction with drought, at the plant and greater scales include: (1) the relationship between infrared canopy temperatures, aerodynamic canopy temperatures and existing knowledge on temperature thresholds determined using air temperature, typically generated in chamber studies; (2) the nature of interactions of CO_2 levels, heat and water stresses (Mittler, 2006); (3) the importance of representing within-canopy temperature gradients (i.e. tassels and ear) (Rattalino Edreira and Otegui, 2012); (4) driving mechanisms for representation of heat stress at larger scales which may include a range of soil water status and varietal responses; (5) interactions of cropping intensity (nitrogen stress, canopy architecture and plant density) with heat stress resulting from heat transfer processes in sparse canopies where sensible heat and soil heat fluxes are more prominent (Shuttleworth and Wallace, 1985; Shuttleworth and Gurney, 1990); (6) the time scale on which heat stress impacts accumulate (Jagadish et al., 2007); and (7) a more systematic comparison of heat stress responses across varieties is required to understand the basis of varietal differences in response to heat stress (Matsui et al., 2001; Prasad et al., 2006; Jagadish et al., 2007; Rattalino Edreira et al., 2011; Rattalino Edreira and Otegui, 2013).

2.7.2. For modelling heat stress

Beyond the representation of direct heat stress effects at flowering of cereals, and their interactions with other temperature (Ainsworth and Ort, 2010) and water stress effects on growth and development (Barnabás et al., 2008; Cairns et al., 2013), other distinct challenges for modelling exist such as: (1) accounting for the effects of soil water status on canopy temperature and heat stress; (2) selecting the appropriate temperature for heat stress from the gradient that exists throughout the canopy (Rattalino Edreira and Otegui, 2012) and their relation to standard air temperature measurements (Allen and Wright, 1997); (3) maintaining consistency in crop models for processes that have been developed and tuned using air temperatures but in reality are sensitive to canopy temperatures (Cicchino et al., 2010b); (4) designing appropriate responses for models of differing levels of complexity and for application at different scales, particularly to account for distinct genotypic responses (Schoper et al., 1987; Jagadish et al., 2007; Rattalino Edreira and Otegui, 2012; Shi et al., 2013). Despite these challenges, the wide variation in conditions when heat stress is studied in the field makes a strong case for the need of crop models to generalize our knowledge about heat stress (White et al., 2011), with the need to improve their various temperature responses, particularly for high temperature conditions, identified as a key finding from a large model comparisons study (Asseng et al., 2013).

A great deal of knowledge on approaches to simulating canopy temperature is found in the ecological modelling community, though to date they have not been coupled with crop models, likely due to the high parameterization demands. Efforts should be made to test methods of different levels of complexity, and to compare the level of uncertainty introduced with the parameterization of these approaches with the uncertainty of not including canopy temperature. In parallel, efforts to test model performance using canopy temperatures, either synthetic or measured, for a range of processes now calibrated with air temperatures are needed to understand how models will respond, when they have been developed, tuned and calibrated using the "wrong" temperatures.

2.8. Conclusions

This overview has highlighted the negative impacts of high temperatures, expected to become more frequent and severe with global warming, on cereal grain yields. The critical role of heat stress in reducing grain number is clear, though the mechanisms and sensitivities appear to vary between crops and within varieties. Understanding the direct impact of high temperature on grain formation is complicated due to the interactions with other temperature sensitive processes, such as development, photosynthesis, respiration and particularly transpiration, which can itself lead to heat stress via its regulating role of canopy temperatures. The complexity of these interactions suggest a crucial role for crop models in understanding future impacts, though few current models consider the direct impacts of extreme temperature on yield formation nor canopy temperatures. This is due to both limited field data suitable for testing model performance with respect to temperature as well as the complexity and level of parameterization required to simulate canopy temperatures. Canopy temperature determined by a combination of climatic, soil water, atmospheric and crop specific variables, is felt to control many heat stress responses in crops. We suggest that three broad areas must be addressed to improve our ability to simulate, and therefore anticipate, future impacts of heat stress on cereal yields. Firstly, rigorous testing of crop models is required to understand the implications of replacing air temperature with canopy temperatures across a range of processes for the impacts on yield simulation as a first step to appreciating the level of uncertainty when tuning model responses to air temperature and the implications of switching to canopy temperatures. Secondly, the environmental modelling and irrigation science research communities have generated considerable knowledge on methods of representing canopy temperatures and canopy-air temperature differences, at differing levels of complexity. However, little of this knowledge has been used to inform crop modelling. Efforts should be directed at investigating the feasibility of parameterizing and uncertainties introduced with the detailed approaches versus the nature and importance of errors introduced with simplified expressions and compared to errors associated with not accounting for the interactions of heat and drought stress. Finally and most importantly, data representative of field production conditions is needed to evaluate the need for and performance of improved models. Field experiments investigating high temperature impacts, at different CO2 concentrations, levels of water stress and production intensity, with particular emphasis on the mechanisms describing the response at the level of detail common to crop models with quantification of standard air temperature, canopy surface temperature and canopy aerodynamic temperatures will improve our understanding of processes leading to heat stress impacts on yields.

Acknowledgements

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Chapter 3

Intensity of heat stress in winter wheat – Phenology compensates for adverse effect of global warming

Based on:

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Abstract

Higher temperatures during the growing season are likely to reduce crop yields with implications for crop production and food security. The negative impact of heat stress has also been predicted to increase even further for cereals such as wheat under climate change. Previous empirical modeling studies have focused on the magnitude and frequency of extreme events during the growth period but did not consider the effect of higher temperature on crop phenology. Based on an extensive set of climate and phenology observations for Germany and period 1951–2009, interpolated to 1 × 1 km resolution and provided as supplementary data to this article (available at stacks.iop.org/ERL/10/ 024012/mmedia), we demonstrate a strong relationship between the mean temperature in spring and the day of heading (DOH) of winter wheat. We show that the cooling effect due to the 14 days earlier DOH almost fully compensates for the adverse effect of global warming on frequency and magnitude of crop heat stress. Earlier heading caused by the warmer spring period can prevent exposure to extreme heat events around anthesis, which is the most sensitive growth stage to heat stress. Consequently, the intensity of heat stress around anthesis in winter crops cultivated in Germany may not increase under climate change even if the number and duration of extreme heat waves increase. However, this does not mean that global warning would not harm crop production because of other impacts, e.g. shortening of the grain filling period. Based on the trends for the last 34 years in Germany, heat stress (stress thermal time) around anthesis would be 59% higher in year 2009 if the effect of high temperatures on accelerating wheat phenology were ignored. We conclude that climate impact assessments need to consider both the effect of high temperature on grain set at anthesis but also on crop phenology.

3.1. Introduction

Trends of increasing mean temperature and extreme heat events during the last 30 years compared to previous centuries have frequently been reported (Alexander et al., 2006; Chen et al., 2014; Hansen et al., 2006; Luterbacher et al., 2004). There is also evidence for a more pronounced increase in temperature and for more frequent summer heat waves in Europe during the last decades (Elguindi et al., 2013; Schär et al., 2004). Global assessments suggest increasing heat stress on the world's cropland due to projected future climate change (Rötzer and Chmielewski, 2001; Teixeira et al., 2013), associated negative effects on crop yields (Teixeira et al., 2013) and a higher risk of hunger by 2080 when accounting for climate change effects (Schmidhuber and Tubiello, 2007). Already in the recent past, the global impact of increasing temperature has reduced world wheat production by 4.9% between 1980 and 2008 in relation to a counterfactual without climate trends (Lobell, 2014; Lobell et al., 2011). Understanding and modeling the effects of temperature, including heat stress, on crops is still limited and prone to large uncertainties (Asseng et al., 2004; Rezaei et al., 2015; Siebert et al., 2014). Empirical evidence about long-term trends of heat stress and related effects on crops is therefore urgently required to support such understanding and to improve future yield projections.

Higher mean and/or extreme temperatures during the growing season not only reduce photosynthesis rate, grain number and weight but also accelerate crop development and leaf senescence rate (Tubiello et al., 2007; Wheeler et al., 2000). The wheat plant is mainly sensitive to heat stress around anthesis and during the grain filling period (Luo, 2011; Porter and Gawith, 1999).

Evaluation of the heat stress effect around anthesis is a particular challenge due to its specific nature, whereby effects on grain yield can already be observed as a result of short episodes of high temperature (Bakker et al., 2005). In addition, our understanding of the processes and relationships involved in heat stress effects on crops are mainly obtained under controlled environment conditions, with little understanding about their relevance under field conditions. The general assumption is that heat stress around anthesis results in fewer grains, causing the reported yield reduction (Ferris et al., 1998). The number of grains falls when the crop experiences temperatures above 31 °C immediately before anthesis (Wheeler et al., 1996). It was also found that the number of sterile grains of wheat can significantly increase when temperature during mid-anthesis is above 27 °C (Mitchell et al., 1993).

Several studies have suggested a substantial increase in the frequency and magnitude of heat stress effects on wheat production due to climate change for different parts of Europe (Gouache et al., 2012; Kristensen et al., 2011; Moore and Lobell, 2014; Ortiz et al., 2008). Some of them explicitly investigated possible adaptation strategies against increasing heat stress (Semenov et al., 2014). However, most of these studies have been conducted by using statistical models which did not consider changes in crop phenology caused by global warming. Earlier onset of phenological phases in the spring period may result in a cooling effect and compensate therefore for the effect of global warming on the intensity of extreme heat around anthesis. In contrast, most process-based crop models can reproduce changes in crop phenology due to increasing temperature (Asseng et al., 2015) but little is known on how changing phenology affects crop heat stress intensity. In this study we analyze observations to derive (i) trends in spring temperature for German cropland and period 1951–2009, (ii) related changes in the timing of the period around anthesis, (iii) trends in the intensity of heat stress around anthesis, and (iv) the effect of changes in crop phenology on the intensity of heat stress around anthesis.

3.2. Materials and methods

3.2.1. Preparation of temperature data

Daily values of minimum, mean and maximum temperature for more than 1100 weather stations and interpolated grids of monthly means of daily minimum and maximum temperature at 1 km × 1 km resolution for period 1951-2009 were derived from the WebWerdis portal of the German Meteorological Service DWD (DWD, 2013). Daily values for minimum, mean and maximum temperature $X_{grid,d}$ (°C) were computed for each 1 km × 1 km grid cell and for each day of the period 1951-2009 by using a procedure described in (Siebert and Ewert, 2012) as

$$X_{grid,d} = X_{ws,d} + X_{grid,m} - X_{ws,m} \tag{1}$$

where $X_{ws,d}$ was the daily value measured at the nearest DWD weather station (°C), $X_{grid,m}$ was the monthly mean at the grid cell according to the 1 km × 1 km grid (°C) and $X_{ws,m}$ was the monthly mean at the nearest weather station (°C). Use of this procedure ensured that the monthly mean value was equal to the value computed by the DWD for each grid cell in the 1 km × 1 km grid, while the day-to-day variation was equal to the variation reported for the nearest weather station (Siebert and Ewert, 2012). A cropland mask that is based on the Corine land cover 2006 was applied to the 1 km × 1 km daily temperature grids (Zhao et al., 2015) to mask out areas with natural vegetation, forests or grasslands (often located in mountainous regions) and to ensure that mean values calculated across the 1 km × 1 km grid cells are representative for cropland. To identify impacts of global warming on DOH we calculated, for each year, the mean temperature for the period March to May which reflects roughly the period between winter dormancy and anthesis. Hourly temperature, required for calculation of heat stress (described in section 2.3), was calculated from daily maximum and minimum temperature by applying a sine function (Goudriaan and Van Laar, 1994).

3.2.2. Preparation of phenology data

Observations of the DOH of winter wheat were collected by the phenological observation network of the German Meteorological Service and derived from the DWD WebWerdis portal (DWD, 2013) for the period 1951-2009 and filtered for potential outliers as described in . The total number of observations was 80831 after applying the filtering process. There was a gap of observations for the eastern part of Germany for the period 1961 to 1990. To fill this gap, we estimated DOH of winter wheat by using DOH observations for winter rye obtained from the same source and filtered for outliers using the same method. For each DOH observation of winter rye in eastern Germany we calculated the median of differences between DOH of winter wheat and winter rye for observations obtained in western Germany, constrained to a region varying not more than ± 0.5° in latitude and ± 50 m in altitude from the location in eastern Germany (Figure 3.1). This resulted in 14368 additional records for DOH of winter wheat in eastern Germany for the period 1961 to 1990. 5805 records obtained for the periods 1951-1959 and 1991-2009 were used for the validation of this method by comparison of estimated DOH for winter wheat with the observed DOH. We found a high accuracy with an RMSE of 1.8 days and a R^2 of 0.81 for the annual means of observed and estimated differences between heading days of winter wheat and winter rye (Figure 3.1), but less agreement for specific observations with an RMSE of 8.3 days. The final data base for DOH of winter wheat contained 95199 records from 5465 locations but the number of observations differed considerably across years and locations with most observations for year 1958 (2100) and the lowest number of observations in year 2007 (336). There was no observation site with complete data coverage for the period 1951 to 2009.

To obtain a homogenous data coverage for the whole period, the records for DOH were interpolated for each year to a 1 km × 1 km grid by using inverse distance weighting (IDW) as interpolation method. To account for the effects of altitude and latitude on DOH we performed, for each year separately, a multivariate regression of altitude and latitude on DOH (step 1 in Figure 3.2). The regression equations were then used to correct all observations to mean sea level and 50.81°N, the mean latitude of all observations (step 2 in Figure 3.2). Then, the corrected observations were interpolated to 1 km × 1 km resolution and added to another 1 km × 1 km grid that contained, for each grid cell, the difference in DOH caused by the altitude and latitude calculated based on the regression equation for the specific year (step 3 in Figure 3.2).

3.2.3. Analysis of heat stress around anthesis of winter wheat

Stress thermal time around anthesis of winter wheat STT_{27} (°C min) was calculated as indicactor for heat stress by accumulating hourly temperatures T_h (°C) higher than the critical threshold T_{crit} (°C) for a three weeks period starting one week before anthesis:

$$STT = \sum 60\, Max(T_h - T_{crit}; 0) \quad (2)$$

The critical temperature threshold for heat stress around anthesis is about 31 °C (Porter and Gawith, 1999) but for this study we used a threshold of 27 °C to account for differences between measurements of air temperature at 2 m height (used for this study) and canopy temperature indicated for rainfed wheat in Germany (Siebert et al., 2014). A sensitive period of three weeks was selected to account for the local variability of heading dates due to different crop management, mainly sowing dates.

3.2.4. Trend analysis

Visual inspection of time series of mean temperatures in period March to May and mean DOH calculated across all grid cells indicated a break point in the temperature and DOH trends with very little trend in the first period but strong trends in the second period. Therefore, segmented, piecewise linear regression of DOH and temperature on year was performed . For both variables, a breakpoint was determined for year 1976. Therefore, we distinguished in all subsequent analyzes the periods 1951-1975 and 1976-2009 and determined, at grid cell level and for the mean across all grid cells, linear trends for mean temperature, DOH and STT_{27} for both periods. The segmented, piecewise linear regression was also performed for determination of breakpoint of mean number of days with daily maximum temperature > 27 °C over Germany. The breakpoint of mean number of days with daily maximum temperature > 27 °C was determined for year 1987.

To determine the specific impact of changes in crop phenology on heat stress, the time series for DOH and the period 1976-2009 was de-trended for each 1 km × 1 km grid cell as:

$$DOH_{detrended,grid} = DOH_{observed,grid} + (year - 1975) \times trend \quad (3)$$

where $DOH_{detrended,grid}$ was the de-trended day of heading (day of the year), $DOH_{observed,grid}$ was the observed day of heading (day of the year), *year* the actual year and *trend* the trend in DOH for period 1976-2009 determined by linear regression of DOH on year. Heat stress STT_{27} was then recomputed with the de-trended DOH and compared to STT_{27} calculated with observed DOH.

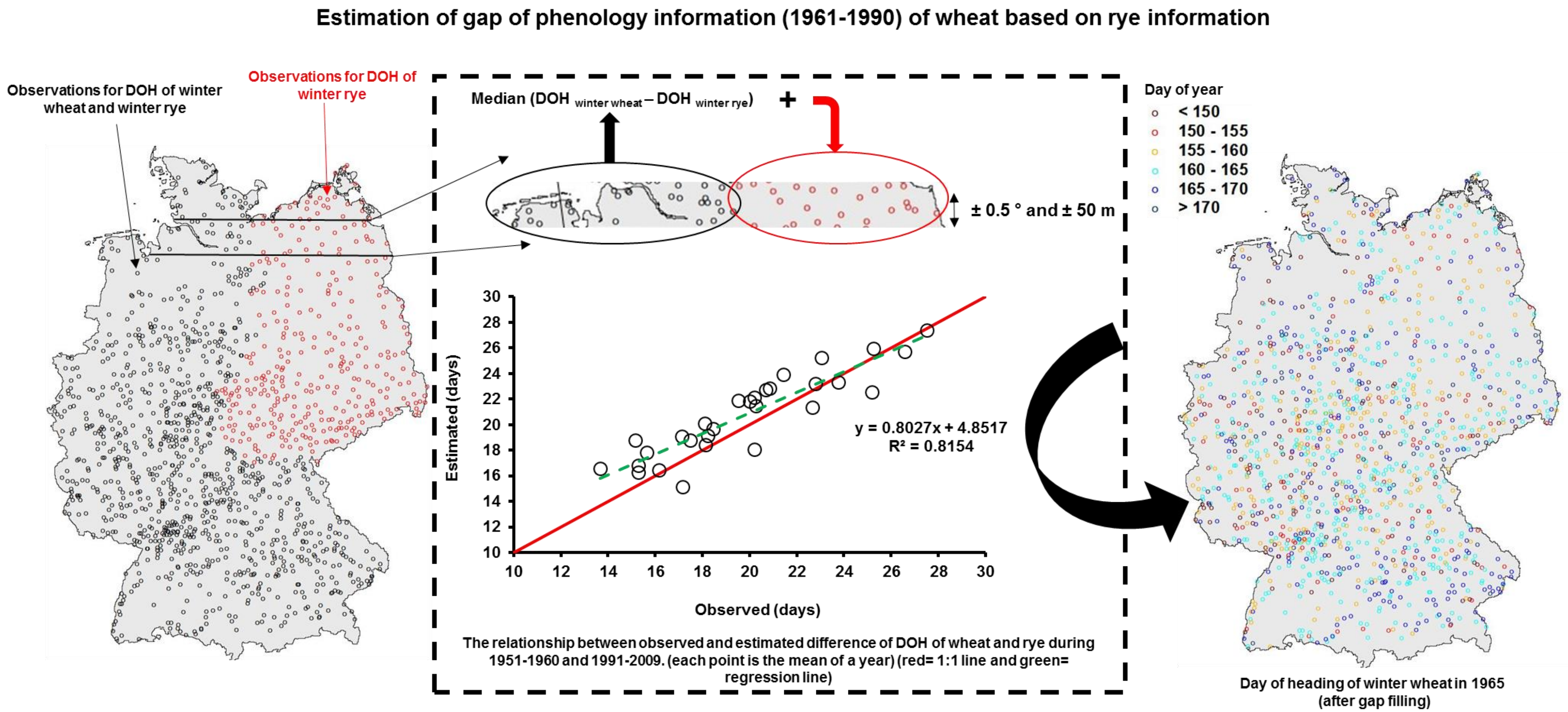

Figure 3.1. The workflow of the generation of 'day of heading' data of winter wheat to fill the data gap for East Germany and period 1961–1990. It schematically describes the data processing based on the difference in observed phenology of winter wheat and winter rye in West Germany. It also shows the 1:1 plot between estimated and observed difference between day of heading of winter wheat and winter rye during the 29 years for which the dataset was complete.

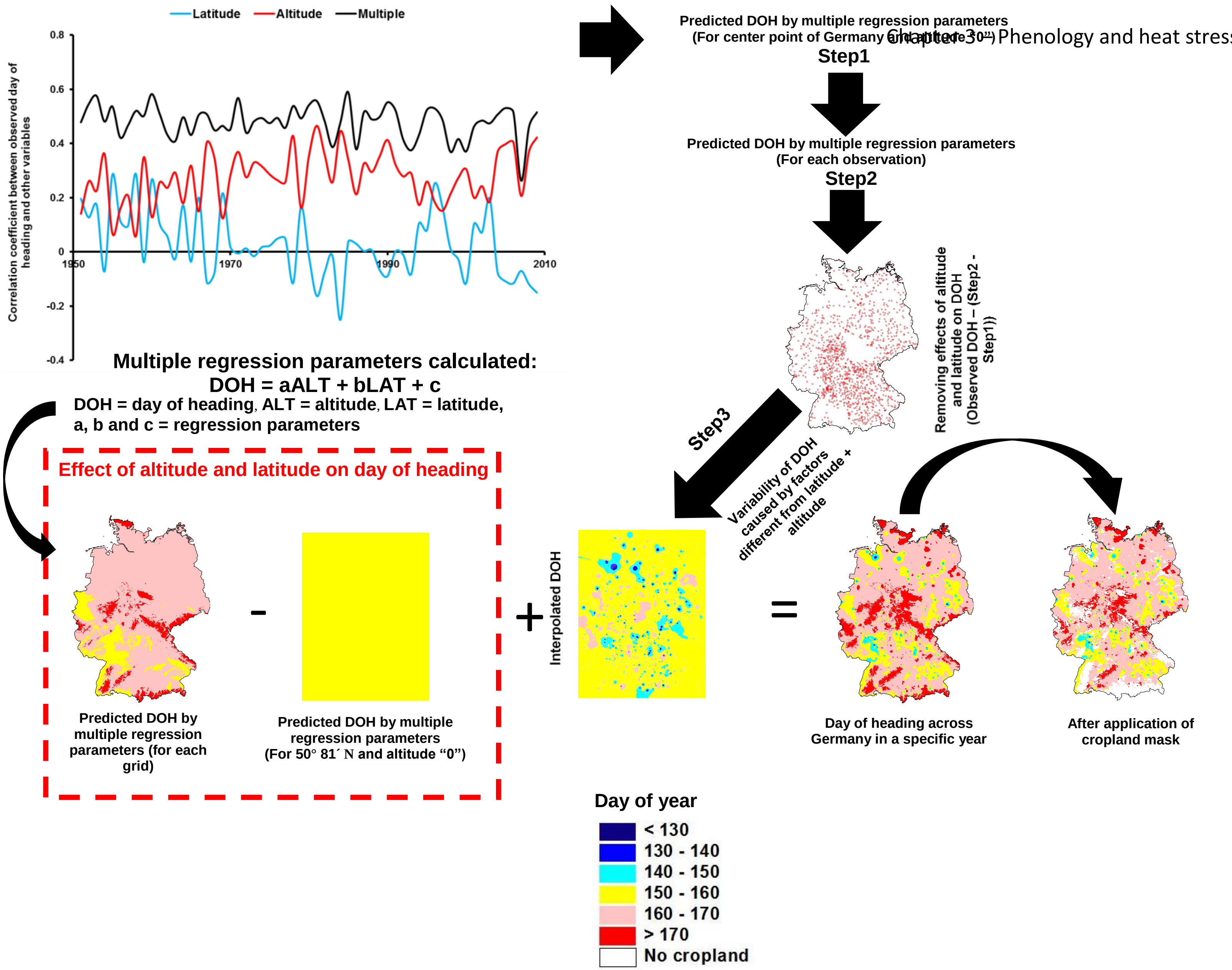

Figure 3.2. The stepwise workflow of the interpolation of day of heading with considering to latitude and altitude in 1 km × 1 km resolution across Germany.

3.3. Results

There was a remarkable increase in mean temperature from March to May in the period 1976-2009 as compared to the period 1951-1975 across the whole country (Figure 3.3a). Areas of high-temperature (>8.9 °C) extended from the former hot spots in the Rhine valley to all the lowlands in Central and Southern Germany (Figure 3.3a). Mean temperature (March to May) calculated across all grid cells had a slight negative trend (Trend = -0.005 °C per year, R^2 = 0.001) from 1951 to 1975 and a strong positive trend (Trend = 0.060 °C per year, R^2 = 0.31) from 1976 to 2009 (Figure 3.3a). The negative trends for mean temperature in period 1951 to 1975 were only detected in the southern part of the country while for period 1976 to 2009 an increasing trend (0.04 to > 0.07 °C per year) was found in all grid cells of the country (Figure 3.3a). The mean number of days with daily maximum temperature > 27 °C calculated across Germany increased by 0.01 days per year from 1951 to 1987 but by 0.05 days per year in period 1988-2009 (SI Figure 3.1).

For most regions in Germany, DOH was mainly in mid to end of June during in period 1951 to 1975 but advanced to late May to mid of June for the period 1976 to 2009 (Figure 3.3b). There was a minor change in DOH from 1951 to 1975 (Trend = 0.08 days per year, R^2 = 0.02). In contrast, a strong advancement in DOH (Trend = -0.44 days per year, R^2 = 0.51) was observed from 1976 to 2009 (Figure 3.3b). The trend in DOH showed a clear difference between the northern and southern part of Germany during the first period (1950-1975). However, the trend to earlier DOH was almost the same in the country for the period 1976-2009 (-0.4 to < -0.6 days per year) (Figure 3.3b). A high interannual variability of DOH was observed across Germany but at the same time years with very early DOH became much more frequent, particularly in the last two decades (SI Video 2). There was no notable difference in heat stress between two periods except for the southern part of Germany where an increasing trend in STT_{27} was detected for period 1976 to 2009 (Figure 3.3c). Therefore, hotspots of heat stress with mean STT_{27} larger than 2100 °C minute extended from the southern part of East Germany to river valleys in Southern Germany (Figure 3.3c). There was no obvious trend in STT from 1951 to 1975 (Trend = -0.004 °C minute, > 27 °C, R^2 = 0.001) but a slight increasing trend from 1976 to 2009 (Trend = 29.45 °C minute per year, R^2 = 0.044) (Figure 3.3c). In any case, the strong increasing trend of mean temperature from March to May (Figure 3.3a) did not translate into strong increases of heat stress in the period around anthesis (Figure 3.3c).

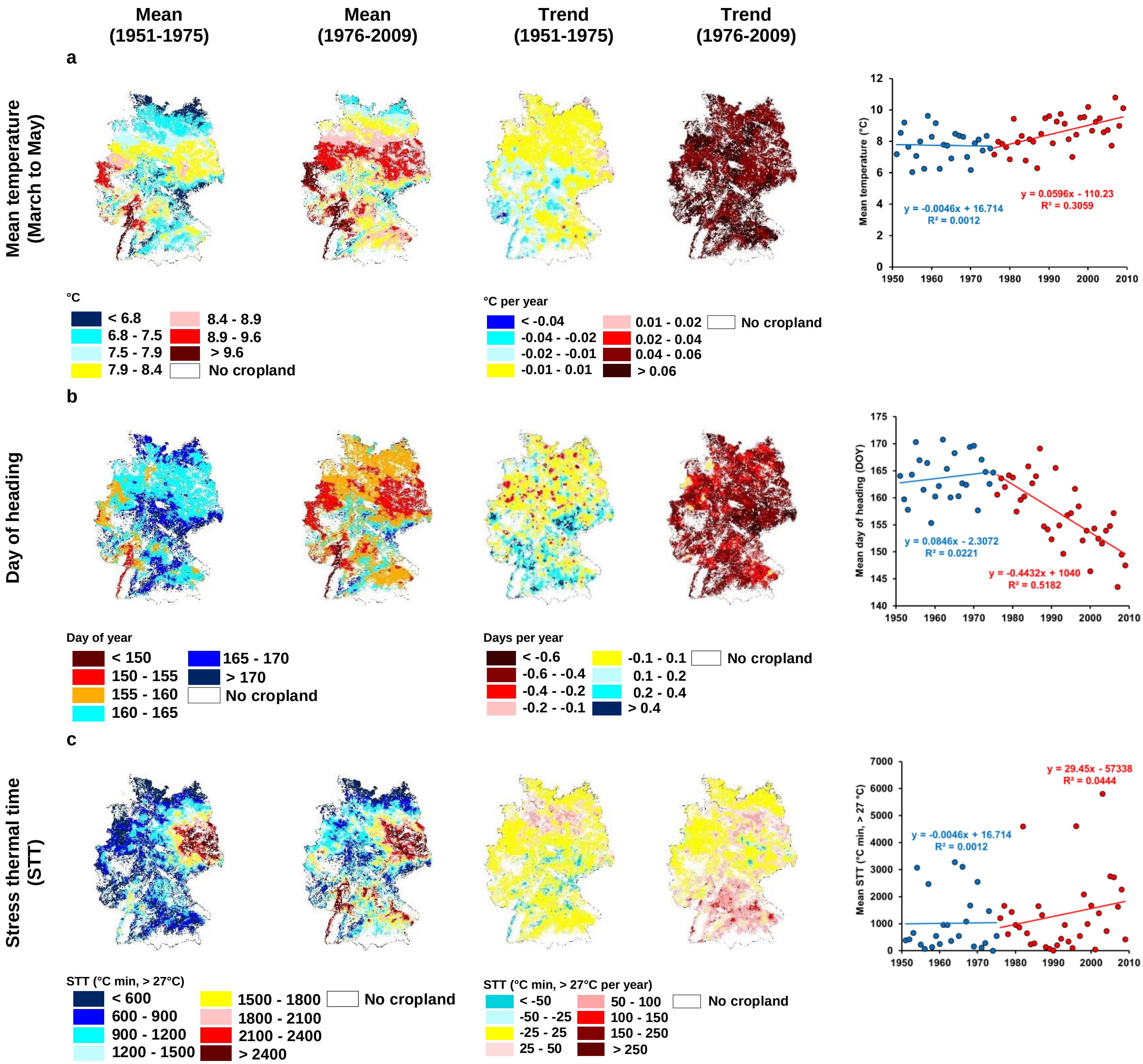

Figure 3.3. Spatial pattern of mean and trend for periods 1951-1975 and 1976-2009 in 1 km × 1 km resolution and the mean temperature for period March to May (a), mean day of heading (b) and mean stress thermal time (STT) (c) across Germany.

We also analysed the trend of mean temperature (March to May), DOH and STT_{27} for heat prone areas with a mean STT_{27} of more than 2000 °C minutes in period 1951 to 2009 and came to similar results (SI Figure 3.3). Mean temperature and DOH varied between 6.3 °C to 11.8 °C and mid-May to end of the June, respectively across Germany (SI Figure 3.3). The trend to earlier DOH in period 1976 to 2009 was quite similar (-0.47 days per year) in heat prone areas (SI Figure 3.3) as compared to the whole country (-0.44 days per year) (Figure 3.3b). Furthermore, trend of mean temperature (0.056 °C per year) and STT (29.12 °C minute, > 27 °C) showed almost no difference between head prone areas and the whole country (Figure 3.4a, Figure 3.3a and 3c).

Calculating STT_{27} for period 1976-2009 with de-trended DOH resulted in more heat stress, in particular for the latest 15 years. Consequently, there was a strong positive trend (39.507 °C minutes) in the difference between heat stress calculated with de-trended DOH and heat stress calculated with observed DOH (Figure 3.4a). Positive difference in the trend of heat stress calculated with de-trended DOH to heat stress calculated with observed DOH were found for almost all grid cells in Germany. Some exceptions in the data along the coastline or at the country boundary maybe artifacts of the interpolation procedure, which did not consider data outside of Germany.

The results suggest that the trend to ealier DOH observed for period 1976-2009 (Figure 3.3b) and the corresponding shift of the period around anthesis towards the cooler spring season, compensated almost completely for the warming trend (Figure 3.3b) so that heat stress around anthesis increased only slightly (Figure 3.3c).

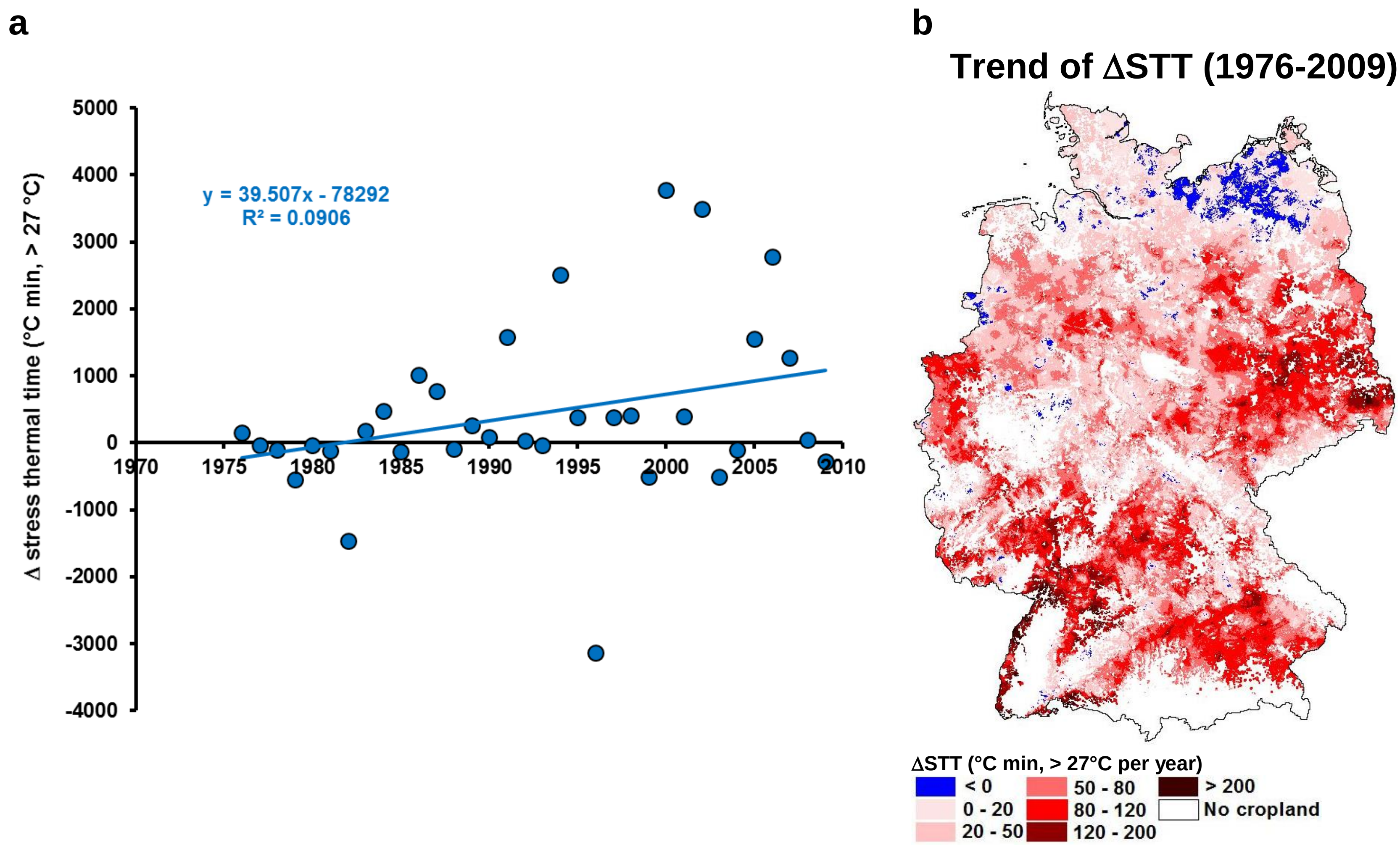

Figure 3.4. Effect of advanced day of heading on stress thermal time (ΔSTT = de-trended stress thermal time - observed stress thermal time) (a) and spatial pattern of ΔSTT's trend (trend of de-trended stress thermal time - trend of observed stress thermal time) (b) during 1976-2009 in Germany.

3.4. Discussion

Our findings that DOH of winter wheat advanced in recent decades in parallel with an increase in the air temperature in spring is in good agreement with results from previous studies. For example, significant changes in plant phenology have been detected in response to temperature increase across 19 European countries (Menzel et al., 2006). The length of the growing period and the period from emergence to heading of oats (*Avena sativa* L.) for the period 1959-2009 across Germany fell by 14 or 8 days, respectively (Siebert and Ewert, 2012).

While there is evidence for the change in crop phenology, it is more difficult to find the reasons for the changes. Many studies suggest a close link between changes in crop phenology and changes in temperature during the growing season. For example, simulation of wheat phenology under expected future climate change suggested that the crop development rate will accelerate due to effect of higher temperature, causing a two-week advancement in anthesis for 2060 compared to the present across 14 diverse sites across Europe (Trnka et al., 2014). The advancement of DOH in winter wheat found in this study may therefore be explained by the 2 °C increase in mean temperature (March-May) at the same period over Germany (figure. 3.3(a)). We found a strong relationship between temperature rise and advancement of phenology (SI figure 3.4(a)), in line with other studies.

The slope of the increment in mean temperature against DOH showed a relatively homogenous pattern across Germany (figures 3(a) and (b)). However, changes in DOH could also be determined by changes in preceding phenological stages including day of sowing (DOS). We therefore compared the trends in the observations for DOH of winter wheat with observations for DOS and day of emergence (DOE) and based on the equations of the piecewise regressions (SI figure 3.4(b)) we estimate that DOS, DOE and DOH have advanced by 5.1, 4.2, and 13.2 days in period 1951–2009. This indicates that the major change in crop phenology happened in the phase between emergence and heading which is also supported by the increasing mean temperature in this phase (SI figure 3.4 (d)). This means that the cooling effect due to the shift of the phase towards the spring could not fully compensate for the increase in temperature due to global warming, which is similar to the results found in another study on oats (Siebert and Ewert, 2012).

Changes in crop phenology could also be caused by changes in cultivar properties. An indicator for systematic changes in the maturity type of cultivars is the change in the temperature sum above the base temperature (Tb). Temperature sum above the base temperature, set to 0 °C in the phase between emergence and heading, showed a small increasing trend (SI figure 3.4(e)) but at the same time, the mean day length in the growing period before heading declined due to the shift of the heading day into the spring season (SI figure 3.4(f)). Since the development rate of wheat declines in response to shorter day length (Chen et al., 2014), this decline in day length will offset the effect of increased temperature sum, suggesting only very little change of cultivars used in Germany with regard to their phenological properties.

The small increase in STT27 from 1976 to 2009 (figure. 3.3(c)) could also be caused by an increase in variability of temperature. STT27 responds to high temperature but not to low temperature extremes (equation (2)). Therefore, increase in variability may lead to a positive trend in STT, even when the mean temperature remains the same. In fact, we only found a very small increase in mean temperature in the period around anthesis (SI figure 5) while there was a very extreme heat stress event in year 2003 (6000 °C min, >27 °C, figure. 3.3(c)). Based on German agricultural statistics (Statistisches Bundesamt, 2013) the lowest winter wheat yield from 1994 to 2009 was observed in that year with a reduction of 20% in comparison to the year with the highest yield.

The analysis presented here was constrained to the period around anthesis, but heat stress can also reduce crop yield in the subsequent grain-filling period (Asseng et al., 2011). However, the critical temperature threshold for heat stress in the grain-filling period is higher (Porter and Gawith, 1999). Therefore we think that for German climatic conditions, heat stress around anthesis may be more relevant. However, since the grain-filling period is typically also finished before the beginning of the hottest period of the year, an advance in crop phenology would have a similar effect on heat stress during grain filling as shown in this study for the phase around anthesis. More research is however required to test this hypothesis. Similarly to this, the relationship between heat stress and crop phenology needs to be tested for other regions and crops. We expect similar effects for crops for which maturity falls in the season of increasing temperature, e.g. other winter cereals. In contrast, there is likely very little potential to escape heat stress by accelerated phenological development for spring sown crops like maize that are harvested in autumn and grow through the hottest period of the year. The effect of advanced flowering date in a cooler part of the season is not likely to be relevant for crops grown in tropical climates either, in which temperature variability throughout the year is very low.

We show in this study that the length of the period between emergence and heading has declined over the period 1976–2009 in Germany. Very likely, this has also reduced winter wheat yields because plant canopies have less time to intercept radiation which is needed to produce biomass by photosynthesis. Therefore, other studies suggested that farmers need to adapt (Menzel et al., 2006), e.g. by growing cultivars with higher thermal requirements and later maturity (Martín et al., 2014). We show in this study that such an adaptation would expose the crop to more heat, while the accelerated phenological development protected winter wheat in recent decades to a large extent from the harmful effects of heat stress. Therefore, the potential to adapt to climate change by changing sowing dates and cultivars may be more limited than previously thought (Lobell, 2014; Moore and Lobell, 2014).
Finally, our results suggest that studies attempting to analyze and project heat stress effects on crops should not only consider effects of heat on grain number and yield but also need to account for changes in the phenological development caused by higher temperature to avoid misleading conclusions. This is in particular important when the adaptation of crop production to climate change is investigated by empirical models.

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Chapter 4

Impact of data resolution on heat and drought stress simulated for winter wheat in Germany

Based on:

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Abstract

Heat and drought stress can reduce crop yields considerably which is increasingly assessed with crop models for larger areas. Applying these models originally developed for the field scale at large spatial extent typically implies the use of input data with coarse resolution. Little is known about the effect of data resolution on the simulated impact of extreme events like heat and drought on crops. Hence, in this study the effect of input and output data aggregation on simulated heat and drought stress and their impact on yield of winter wheat is systematically analyzed. The crop model SIMPLACE<LINTUL2-CC-HEAT> was applied for the period 1980-2011 across Germany at a resolution of 1 km × 1 km. Weather and soil input data and model output data were then aggregated to 10 km × 10 km, 25 km × 25 km, 50 km × 50 km and 100 km × 100 km resolution to analyse the aggregation effect on heat and drought stress and crop yield. We found that aggregation of model input and output data barely influenced the mean and median of heat and drought stress reduction factors and crop yields simulated across Germany. However, data aggregation resulted in less spatial variability of model results and a reduced severity of simulated stress events, particularly for regions with high heterogeneity in weather and soil conditions. Comparisons of simulations at coarse resolution with those at high resolution showed distinct patterns of positive and negative deviations which compensated each other so that aggregation effects for large regions were small for mean or median yields. Therefore, modelling at a resolution of 100 km × 100 km was sufficient to determine mean wheat yield as affected by heat and drought stress for Germany. Further research is required to clarify whether the results can be generalized across crop models differing in structure and detail. Attention should also be given to better understand the effect of data resolution on interactions between heat and drought impacts.

4. 1. Introduction

Climate change will likely cause an increase in the frequency and magnitude of heat and drought stress during the winter wheat (*Triticum aestivum* L.) growing season across Europe (Semenov and Shewry, 2011, Gourdji et al., 2013). A higher frequency of extreme temperature episodes would result in more than one high temperature episode during the growth period (Ortiz et al., 2008). Higher mean and/or extreme temperatures during the growing season not only reduce photosynthesis rate, grain number and weight but also accelerate crop development and leaf senescence rate (Wheeler et al., 2000; Tubiello et al., 2007; Asseng et al., 2011). Heat stress mainly influences the reproductive phase of wheat (Ferris et al., 1998; Luo, 2011). In winter wheat, the number of grains remarkably decreased when the crop experienced temperatures larger than 31 °C immediately before anthesis (Wheeler et al., 1996). Also, it was found that the number of sterile grains of wheat significantly increased when temperature during mid-anthesis was larger than 27 °C (Mitchell et al., 1993). Short episodes of temperatures larger than 35 ºC during the post-anthesis period reduced average grain weight of 75 Australian wheat cultivars by 23% (Stone and Nicolas, 1994). When mean temperature during grain filling was increased from 25 ºC to 31 ºC, final grain yield reduced by 15% through shortening of grain filling period (Dias and Lidon, 2009).

Drought is the most important limiting factor of wheat production across the world (Cattivelli et al., 2008). Effects of drought stress on wheat yield are determined by the severity and duration of the stress with a response that differs depending on the crop development stage (Rampino et al., 2006; Ji et al., 2010). Drought occurrence just before anthesis and during grain filling declined the number and weight of wheat grains, respectively (Prasad et al., 2011; Plaut et al., 2004; Dolferus et al., 2011; Rajala et al., 2009). Furthermore, drought stress influenced leaf area expansion, root growth, dry matter partitioning and photosynthesis rate (Jamieson et al., 1998).

Hot episodes during the growing season are often also dry and therefore, crops experience heat and drought stress often simultaneously (Halford, 2009). Previous research indicated that the effects of heat and drought stress on grain yield are hypo-additive, the effect of combined stress was higher than the individual effects but lower than their sum (Pradhan et al., 2012; Savin and Nicolas, 1996). Combination of drought and heat stress also resulted in higher leaf temperature and respiration than sole occurrence of heat or drought stress (Mittler, 2006).

To assess impacts of climate change and climate variability on crop yield at national or global scale, crop simulation models are increasingly used (Asseng et al., 2013; Lobell et al., 2011; Olesen et al., 2011) although, most of the crop models applied at large scales have been developed and parameterized at field scale (van Bussel et al., 2011a; Hansen and Jones, 2000). Because the density of weather stations is limited, large scale climate impact assessments are mostly forced with gridded weather or climate data interpolated between site measurements (e.g. Harris et al., 2013). Furthermore, large scale climate data often represent monthly means while crop models typically require daily values so that weather generators (e.g. Semenov et al., 2013) are used to increase the temporal resolution of the data. Alternatively, crop models are applied using measured weather data assuming that the obtained results for individual locations are representative for larger regions (Bannayan and Eyshi Rezaei, 2014). Similar to constraints in weather data, the heterogeneity in soil properties observed under field conditions is hardly reflected in large scale assessments.

Only recently, researchers started to study impacts of heat stress with crop models (Rötter et al., 2011; Asseng et al., 2013; Deryng et al., 2014; Teixeira et al., 2013). Aggregation or averaging of input variables from high to low resolutions decreases the variability of variables such as temperature (Diffenbaugh et al., 2005) but little is known about the necessity of using high resolution input data for (i) simulating large scale (regional or national) means of heat and drought stress and corresponding crop yields and (ii) for reproducing spatial variability of stress and crop yield.

The current study aims to systematically analyze the impact of data aggregation on winter wheat yields simulated across Germany between 1980-2011 with the process based crop model SIMPLACE<LINTUL2-CC-HEAT> with a specific focus on the effects of heat and drought stress.

4.2. Materials and methods

4.2.1. General workflow of analysis

The analysis of the aggregation effect on heat and drought stress and yield involved several steps. A schematic diagram (Figure 4.1) illustrates the flow of information and the different steps and types of data aggregation analysed. First, the crop model was evaluated against yield data reported by the agricultural statistics for the period 1999-2011 (section 3.1). Then we aggregated model input data (climate, soil) from 1 km × 1 km resolution to the resolutions 10 km × 10 km, 25 km × 25 km, 50 km × 50 km, and 100 km × 100 km and analysed the effects on frequency distributions and spatial patterns of climate and soil input data itself (section 3.2) and the corresponding effect of this input data aggregation on heat and drought stress (section 3.3) and crop yield (section 3.5). Finally, we aggregated the model outputs calculated with high resolution input data to the resolutions 10 km × 10 km, 25 km × 25 km, 50 km × 50 km, and 100 km × 100 km and compared the corresponding heat and drought stresses (section 3.4) and crop yields (section 3.5) with simulations based on aggregated input data. By calculating differences between heat stress, drought stress and crop yield simulated at high resolution with results at aggregated resolution we analyzed the model specific systematic bias and the loss of spatial variability due to data aggregation across regions and the whole country (sections 3.3-3.5).

4.2.2. Development of multi-resolution model input data

4.2.2.1. High resolution weather data

Daily values of minimum and maximum temperature, sunshine duration, humidity and wind speed for more than 1100 weather stations for period 1980-2011 were derived from the WebWerdis portal of the German Meteorological Service DWD (DWD, 2012a; DWD, 2012b; DWD, 2012c). In addition, the portal provided access to daily gridded precipitation at 1 km × 1 km resolution (Regnie data set) and to grids of monthly mean values of daily sunshine duration, daily minimum temperature, daily maximum temperature and daily mean temperature. These grids were developed by the DWD by interpolation of weather station data using a digital elevation model to support the interpolation (DWD, 2014). Daily values for temperature and sunshine duration $X_{grid,d}$ (°C) were computed for each 1 km × 1 km grid cell and for each day of the period 1980-2011 by using a procedure described in Zhao et al. (2015) as

$$X_{grid,d} = X_{ws,d} + X_{grid,m} - X_{ws,m} \quad (1)$$

where $X_{ws,d}$ was the daily value measured at the nearest DWD weather station, $X_{grid,m}$ was the monthly mean at the grid cell according to the 1 km × 1 km grid and $X_{ws,m}$ was the monthly mean at the nearest weather station. Use of this procedure ensured that the monthly mean value was equal to the value computed by the DWD for each grid cell in the 1 km × 1 km grid, while the day-to-day variation was equal to the variation reported for the nearest weather station (Siebert and Ewert, 2012). Daily solar radiation was then calculated from daily sunshine duration by using the Ångström–Prescott approach (Almorox and Hontoria, 2004). Extra-terrestrial radiation was calculated according to Allen et al. (1998) while the Ångström coefficients *a* and *b* were computed by comparing, on sunny and overcast days, incoming shortwave radiation derived from satellite imagery to computed extraterrestrial radiation. Daily mean incoming shortwave radiation (W m^{-2}) and daily mean fractional cloud cover (%) were derived from the Satellite Application Facility on Climate Monitoring (CMSAF, 2012a; CMSAF, 2012b) and analyzed for period 2005-2012. Daily wind speed was calculated by averaging daily mean wind speed across the weather stations of the DWD network. In total, 378 weather stations measured wind speed in period 1980-2011 but only stations with a measuring height of maximal 20 m above ground and an altitude of not more than 900 m. were considered when calculating the mean across stations, so that the number of stations considered in this study was 236. Measured wind speed was corrected to a sensor height of 2 m according to Allen et al. (1998) as

$$u_2 = u_s \frac{4.87}{\ln(67.8z - 5.42)} \quad (2)$$

where u_2 was the wind speed in 2 m height (m s^{-1}), u_s the wind speed at the sensor (m s^{-1}) and z the sensor height (m). The stations were selected because wind speed was measured there in an appropriate height and because the stations were located on or close to cropland. The calculation procedure resulted in wind speed that was similar for all grid cells in Germany but varied from day to day.

4.2.2.2. Soil properties at high resolution

Maximum rooting depth and volumetric water content at full saturation, field capacity and wilting point were derived from the Bodenübersichtskarte (BÜK) 1000 N data set developed by the Federal Institute for Geosciences and Natural Resources, BGR (BGR, 2013). The soil data set was developed in the period 2000 – 2007 by combining soil information with land use information derived from the Corine land cover classification. The BÜK 1000 N distinguishes 71 soil mapping units, each of them in 5 climatic zones and for the land uses “cropland”, “grassland and heterogeneous agricultural land” and “forest” (BGR, 2013). In addition, the BGR provided descriptions of representative soil profiles with up to 12 soil layers for each of the soil mapping units, in each climate zone and each land use type as MS-Access databases (Dr. Andreas-Alexander Maul, B4.2 Geodaten, Geologische Informationen, Stratigraphie, personal communication). To derive maximum rootable soil depth it was assumed that roots cannot grow into layers with the following properties/horizon designation suffixes:

- r (low oxygen content)
- m (massive soil material due to pedogenetic induration e.g. iron cementation)

- Cn (unweathered rock)
- d (extremely dense, high bulk density)
- C-horizons derived from parent materials marls, sandstone, moraines loams, shale, lime stone, granite, and basalt,
- C-horizons with more than 50% -Vol gravel or stones.

It was also assumed that roots cannot grow into layers below such a non-rootable layer. Furthermore maximum rooting depth for winter wheat was constrained to 1.2 m, even when the soil properties would allow for a larger rooting depth.

4.2.2.3. Emergence date at high resolution

Emergence day of winter wheat was obtained from the phenology database of the German Meteorological Service DWD provided by the WebWerdis portal (DWD, 2013). The phenology database contained 91230 observations for period 1950-2009, of which 72507 were selected after application of an outliers filtering procedure. The filtering procedure computed for each of the 89 DWD eco-regions the mean and standard deviation of the observations and filtered out all records deviating from the computed mean more than ±2 times the standard deviation (Siebert and Ewert, 2012). From these 72507 records we selected 39680 records at 3018 locations for the period 1980-2009. To reduce the effect of observations in years with uncommon phenology we selected the records for 2243 locations with at least 5 years of observations and computed for each of them the mean emergence day. The point observations were then interpolated to a grid at 1 km × 1 km resolution by using the Inverse Distance Weighted (IDW) method with a power of 2 and considering 12 neighbor points (Mabit and Bernard, 2007). Consequently, the calculated emergence day was similar for all years but varied across grid cells.

4.2.2.4. Aggregation of the input and output data to lower resolutions

Weather data, soil properties and emergence day was aggregated from 1 km × 1 km resolution to 10 km × 10 km, 25 km × 25 km, 50 km × 50 km and 100 km × 100 km resolution. First a cropland mask was applied to avoid that weather and soil properties in mountainous regions, which are mainly covered with forest or grassland, impact the crop model input data. At 1 km × 1 km resolution, grid cells were masked out and not considered in subsequent calculations when no cropland or mosaic of cropland and other land cover was contained according to the Corine land cover 2006 (EEA, 2010). Daily weather data were then aggregated to lower resolution by computing the mean of the values of the 1 km × 1 km grid cells contained in grid cells of larger extent. Soil data were aggregated by selecting the properties of the dominant soil (the soil type with the largest extent on cropland in each specific grid cell). Emergence day was computed for each grid cell as the mean of the emergence observations made in the respective grid cell. In particular at the higher resolutions it happened frequently that grid cells did not contain any phenology observation point at all. Then the mean of the emergence day of the enclosed 1 km × 1 km cropland grid cells was computed. The application of the cropland mask and the aggregation methods described before resulted in 231,601 grid cells for Germany at 1 km × 1 km resolution, 3440 grids at 10 km × 10 km resolution, 609 grids at 25 km × 25 km resolution, 171 grids at 50 km × 50 km resolution, and 51 grids at 100 km resolution by 100 km resolution. The aggregation of output data was performed by averaging high resolution model outputs such as heat and drought stress reduction factors or crop yield at coarse resolution.

4.2.2.5. Crop yield data

To evaluate the crop model, winter wheat yield at district level was derived for period 1999-2011 from the Regional database of the German Federal Statistical Office (DESTATIS, 2013). There are 404 districts in Germany but several of them (e.g. larger cities) do not contain winter wheat growing areas, reducing the number of districts with reported winter wheat yields to 345.

4.2.3. Crop model description

SIMPLACE (Scientific Impact assessment and Modeling Platform for Advanced Crop and Ecosystem management) is a modeling framework based on the concept of encapsulating the solution of a modeling problem in discrete, replaceable, and interchangeable software units called Sim-Components or sub-models (Enders et al., 2010). A specific combination of sub-models within the framework is called a model solution (Gaiser et al., 2013). The crop model LINTUL2 (van Oijen and Leffelaar, 2008) has been modified with respect to heat stress and phenology as described below and was implemented into the SIMPLACE modeling framework as solution SIMPLACE<LINTUL2-CC-HEAT>. The solution consists of sub-modules, to simulate crop phenology, potential and actual evapotranspiration, root growth, drainage and runoff, biomass production, biomass partitioning, crop drought stress and crop heat stress. All Sim-Components, except phenology and heat stress, were implemented according to the approach used in LINTUL2 (van Oijen and Leffelaar, 2008). Drought stress is determined as ratio between actual and potential transpiration and affects leaf expansion, root growth, biomass accumulation and dry matter partitioning (van Oijen and Leffelaar, 2008).

The crop phenology component of the model was modified for considering vernalization and photoperiod effects on wheat phenology. Crop development rate is relative to the daily increment of photo-vernal-thermal time (°C d) for the period between emergence and anthesis or to the daily increment of thermal time (°C d) for the period between anthesis and maturity. Photo-vernal-thermal time is calculated by correcting thermal time by factors describing the response of the cultivar to photoperiod and vernalization (Eyshi Rezaei et al., 2013).

The impact of heat stress on crop yield is simulated based on the modified GAEZ model approach (Teixeira et al., 2013). It is assumed that crops are only sensitive to heat stress during a period around anthesis (15 days before anthesis to 15 days after anthesis), here named the thermal-sensitive period. In this period a daily heat stress intensity is calculated and then averaged to derive a yield reduction factor for the thermal-sensitive period. The yield reduction factor is 0 for maximal heat stress and complete yield loss and 1 for no heat stress. Winter wheat yield is then adjusted for heat stress around anthesis by multiplying grain yield with the yield reduction factor (Eyshi Rezaei et al., 2013). In SIMPLACE<LINTUL2-CC-HEAT> heat stress occurs when daily maximum temperature exceeds a critical temperature threshold set to 27 °C and maximum impact occurs when daily maximum temperature exceeds a temperature threshold of 40 °C. The original heat stress approach (Teixeira et al., 2013) used day time temperature to compute the yield reduction. We decided to use daily maximum temperature because 11 years (2001-2011) of field observations in three winter wheat variety trials at Roda, Nossen and Christgrün (Eastern Germany) showed that use of maximum temperature instead of day temperature significantly improved the relationship between the heat stress reduction factor and relative crop yield reduction (SI Figure 4.1). The threshold of 27 °C was selected to account for differences between air temperature measured at 2 m height (used in this study as temperature input) and canopy temperature. Previous research indicated that the daily maximum of canopy temperature is often higher than the daily maximum of air temperature, in particular when crop transpiration is reduced because of too low soil moisture content (Siebert et al., 2014).

4.2.4. Crop model parameterization

Required photo-vernal-thermal time of winter wheat in Germany was obtained from reports of variety experiments conducted at three sites in the eastern part of Germany (Roda, Nossen, and Christgrün) in the period 2001-2011 (Bundessortenamt, 2013). At these sites most varieties grown in Germany have been tested. The cultivar differences for day of heading (i.e. mean cultivar specific day of heading compared to the mean across all cultivars) varied between 1.2 days at Roda in year 2009 and 3.9 days at Nossen in year 2011 while maturity (yellow ripeness) varied between 0.7 days at Christgrün in year 2005 and 4.5 days at Christgrün in year 2010. We used the mean calculated across all varieties for each site and year to parameterize the crop phenology in the model. Specific leaf area (SLA), base temperature before and after anthesis and transpiration constant (TRANCO) (Table. 4.1) were obtained from previous studies (van Bussel et al., 2011b; McMaster et al., 2008; Kristensen et al., 2009; Allen et al., 1998).

4.2.5. Crop model evaluation

To test the model performance, yields reported for the three winter wheat variety trials and 11 years (mean yield of all tested varieties) were compared with simulated yields for the same locations and years and correlation coefficient and root mean squared error (RMSE) were calculated. In addition, yields reported by the agricultural statistics at district level (mean of period 1999-2011) were compared to mean yields simulated for the same period at 50 km × 50 km resolution. We calculated the correlation coefficient between the yield of each 50 km × 50 km grid cell and the yield reported by the statistics for the district located at the center point of the 50 km × 50 km grid cell. Additionally we visually compared the spatial pattern of reported and simulated yields.

Table. 4.1. Cultivar-specific parameter values used in the model.

Parameter	Value	Unit
Photo-vernal-thermal time (PVTT)	470	°C day
Thermal time (TT)	402	°C day
Base temperature (before anthesis)	1	°C
Base temperature (after anthesis)	9	°C
Light use efficiency (LUE)	3	g^{-1} MJ^{-2}
Specific leaf area (SLA)	0.025	m^2 g^{-1}
Transpiration constant (TRANCO)	5	mm day^{-1}

4.2.6. Analysis of the effects of model input data and output data aggregation

Differences between model input data (temperature, precipitation and TAWC) at different resolution were evaluated visually and by calculating summary statistics (mean, median) and frequency distributions to describe aggregation effects on the model input data (section 3.2). Spatial patterns in model output (yield, heat stress intensity and drought stress) were compared between maps by calculating the absolute difference *AD* and the difference *D* at pixel level. Furthermore, the mean of absolute differences $\overline{AD}$ and the mean of differences $\overline{D}$ across all grid cells were calculated. Absolute difference *AD* was calculated as

$$AD = abs(a - b) \tag{3}$$

and difference *D* as

$$D = a - b \tag{4}$$

where *a* was the value in a certain grid cell of map *a* and *b* was the value of the spatially corresponding certain grid cell of map *b*. *AD* is always positive so that the mean across all pixels $\overline{AD}$ represents an indicator for the agreement of maps at grid cell level. In contrast, *D* may become positive or negative so that deviations at pixel level can average out when the mean across all pixels $\overline{D}$ is computed. $\overline{D}$ is therefore an indicator for systematic differences or bias between maps. We first applied the crop model by using input data at 1 km × 1 km resolution and then with aggregated input data (Figure 4.1). The calculated model output from aggregated resolutions was disaggregated to 1 km × 1 km resolution and compared to the output achieved with the high resolution input data (Figure 4.1, section 3.3). Then model output calculated with high resolution input data (1 km × 1 km) was aggregated (output aggregation) and compared to model output calculated with aggregated input data (Figure 1, sections 3.4 and 3.5). Difference D and absolute difference AD at grid cell level were used to describe local differences between the compared maps while mean difference $\overline{D}$ and mean absolute difference $\overline{AD}$ calculated across the whole country were used to quantify the large scale effect of data aggregation at national level with $\overline{D}$

as indicator of systematic large scale bias and $\overline{AD}$ as indicator of large scale heterogeneity of differences. The comparisons were performed for year 2003, in which extreme heat and drought stress was reported for many regions in Germany, and additionally for long-term mean values of the period 1980-2011 (results shown as SI).

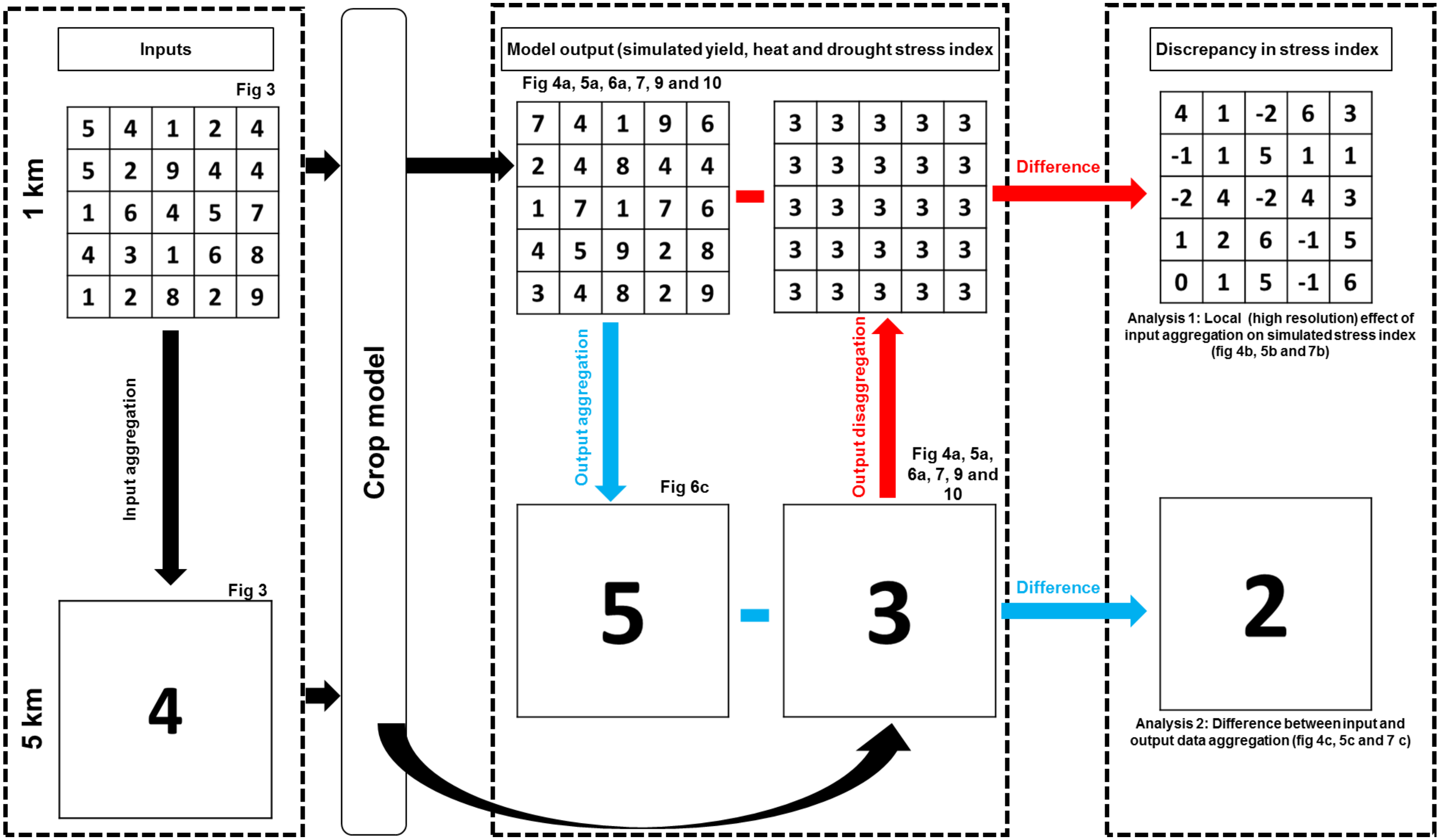

Figure 4.1. Processing steps of model input data and model output data to systematically analyze the effects of data aggregation on simulated heat and drought and corresponding crop yield. Note: A grid cell size of 5km is only used for indication of workflow of study and not used in present analysis. The analysis was repeated for each data aggregation level (10 km × 10 km, 25 km × 25 km, 50 km × 50 km and 100 km × 100 km) separately.

4.3. Results

4.3.1. Crop model evaluation

Yields simulated with the crop model were compared to yields measured at the three variety trails in Saxony and with district level crop yields reported by the agricultural statistics to test the capability of the model to reproduce temporal and spatial variability of crop yield at different scales. We found a highly significant correlation ($R = 0.79^{**}$) between yields observed for 11 years at the three variety trial sites and yields simulated by the crop model for the same years and locations (SI Figure 4.2). However, simulated yields were lower than observed yields, which is surprising because the model does not account for yield reducing factors like pests and diseases or frost damage. A reason could be that the size of the single test plots was small in the variety trials so that, because of boundary effects (Ewert et al., 2002), the growing conditions may not be representative for field conditions. The comparison of yields simulated at 50 km × 50 km resolution to yield reported at district level showed that the model well reproduced the pattern of low yields in eastern Germany and Central Germany and high yields in north-western Germany and southern Germany (Figure 4.2a). Yields in the southern part of western Germany and along the coastline in northern Germany were however underestimated by the model. There was a significant ($R = 0.49^{*}$) correlation between simulated and observed yields with very similar mean yield across districts or grid cells (Figure 4.2b). The temporal variability of the observed yield (annual mean of district level yields 1999-2011) was also well reproduced by the crop model (annual mean of yields simulated at 50 km × 50 km resolution) at national scale ($R = 0.56^{*}$, Figure 4.2b).

4.3.2. Effect of data aggregation on weather and soil input variables

The mean and median of annual mean of daily maximum temperature, annual sum of precipitation and total available water capacity in 1 m soil were not considerably influenced by aggregation of input data from 1 km × 1 km to 100 km × 100 km and even the frequency distributions of weather and soil variables were quite similar for the different aggregation levels (Figure 4.3a). The extremes in temperature, precipitation and soil water storage capacity, clearly visible at 1 km × 1 km resolution, disappeared when data were aggregated to 100 km × 100 km resolution so that the value range narrowed (Figure 4.3b – Figure 4.3d) but the 5th and 95th percentiles were again quite similar (Figure 4.3a). On the other hand, the spatial extent of areas with low annual precipitation sum in north-eastern Germany declined with increasing aggregation (Figure 4.3c).

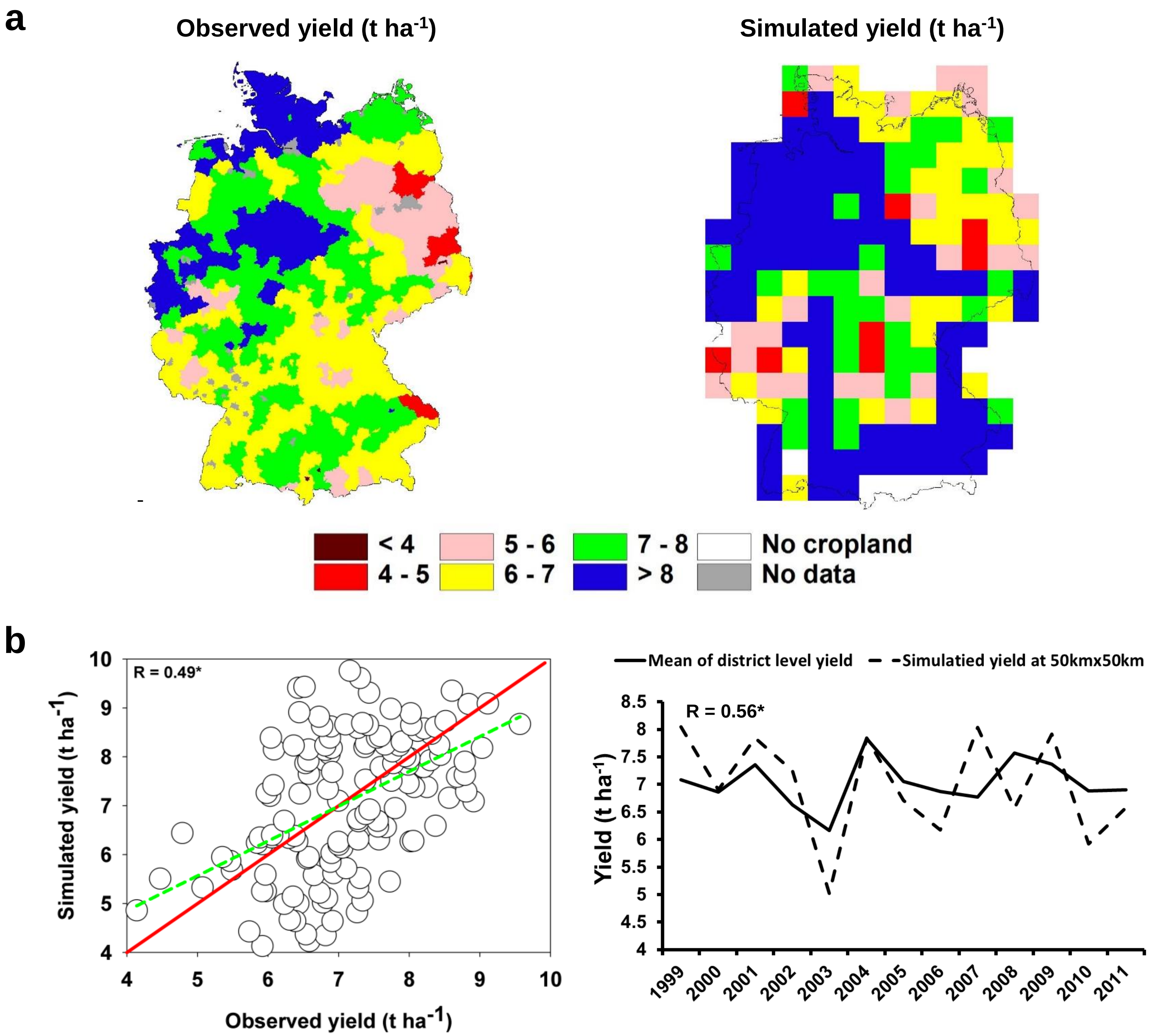

Figure 4.2. Mean winter wheat yield observed at district level and simulated at 50 km × 50 km resolution for period 1999-2011 (a) and 1:1 plot and inter-annual variability of simulated and observed yield (b) (red line: 1:1 line and green line: regression line).

4.3.3. Effect of input data aggregation on simulated heat and drought stress

Heat stress caused a mean winter wheat yield reduction of up to 5% across Germany in the period 1980-2011 (SI Figure 4.3), while the simulated yield reduction was up to 20% in the extreme year 2003 (Figure 4.4a). The mean absolute difference ($\overline{AD}$) between the heat stress reduction factors across Germany at 1 km × 1 km resolution and heat stress calculated with aggregated temperature data gradually increased with the aggregation level indicating an increasing loss of heterogeneity due to aggregation. For the year 2003, $\overline{AD}$ between 1 km resolution and 10 km resolution was 0.005 but 0.013 when comparing 1 km resolution with 100 km resolution (Figure 4.4b). Mean difference $\overline{D}$ changed from -0.001 when comparing 1 km input data resolution and 10 km resolution to -0.003 when comparing 1 km resolution with 100 km resolution (Figure 4.4b). However, $\overline{D}$ was much lower than $\overline{AD}$ indicating that positive and negative differences compensated for each other to a large extent at national level.

The simulated effect of drought stress on winter wheat yields was larger than the simulated heat stress effect (Figures 4 and 5). Simulated mean yield reduction by drought stress in period 1980-2011 was up to 50% for selected grid cells in eastern and southern Germany (SI Figure 4.4) with extremes of up to 80% in the extreme dry and hot year 2003 (Figure 4.5a). The comparison of the spatial pattern of the drought stress reduction factor between 1 km × 1 km resolution and drought stress computed with aggregated input data showed that, similar as for heat stress, mean absolute difference $\overline{AD}$ gradually increased with the aggregation of input data to lower resolutions (Figure 4.5b). Mean difference $\overline{D}$ increased with aggregation as well (Figure 4.5b) but the difference $\overline{D}$ was in all comparisons less than 10% of the absolute difference $\overline{AD}$ because positive and negative differences at the grid cell level compensated for each other when calculating the mean at national extent.

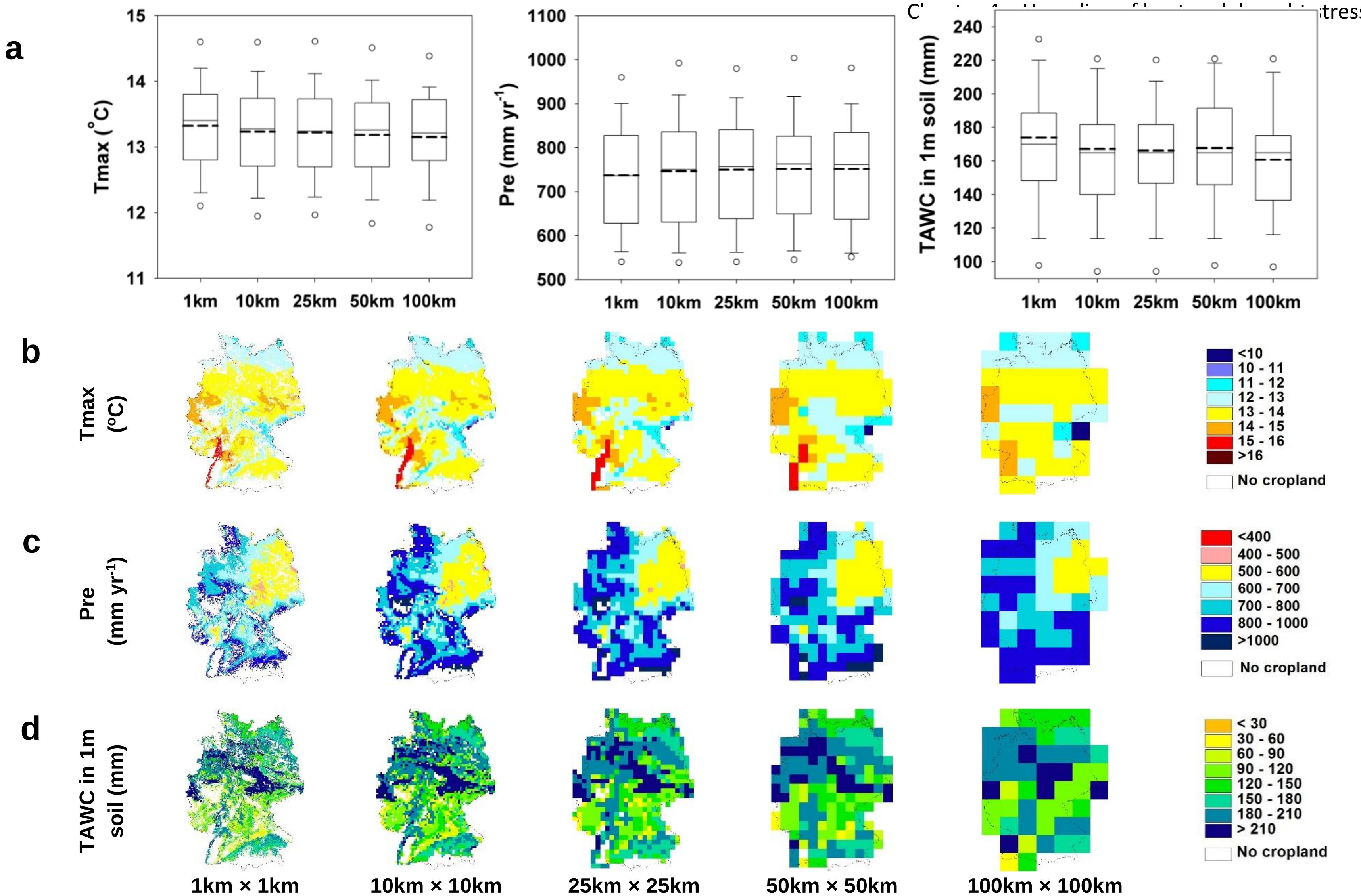

Figure 4.3. Effects of data aggregation on frequency distribution (a) and spatial pattern of mean daily maximum temperature (Tmax) (b), mean annual sum of precipitation (Pre) (c) for period 1980-2011, and total available water capacity (TAWC) in 1 meter soil across Germany (d). (Dashed line: mean, solid line: median; upper point and lower point show 5th and 95th percentiles, respectively).

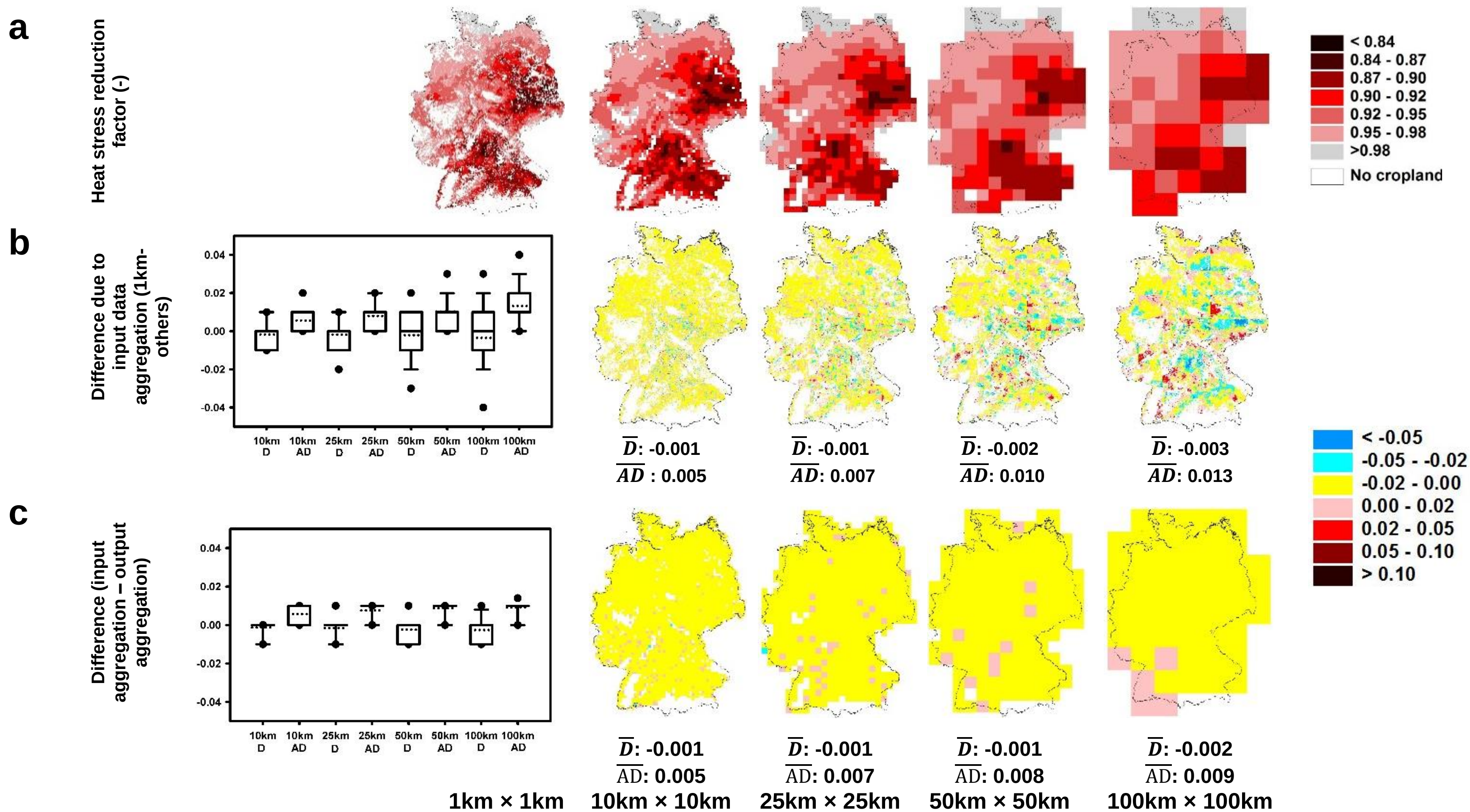

Figure 4.4. Effect of data aggregation on simulated heat stress for (a) heat stress reduction factor simulated at different spatial resolutions for the extreme year 2003, (b) difference between the heat stress reduction factor simulated with input data of different resolutions, and (c) difference between heat stress reduction factors simulated with aggregated input data and with aggregated high resolution output data. (Dashed line: mean, solid line: median; upper point and lower point show 5th and 95th percentiles, respectively). Please notice: a heat stress reduction factor of 1 means no effect of heat on crop yield.

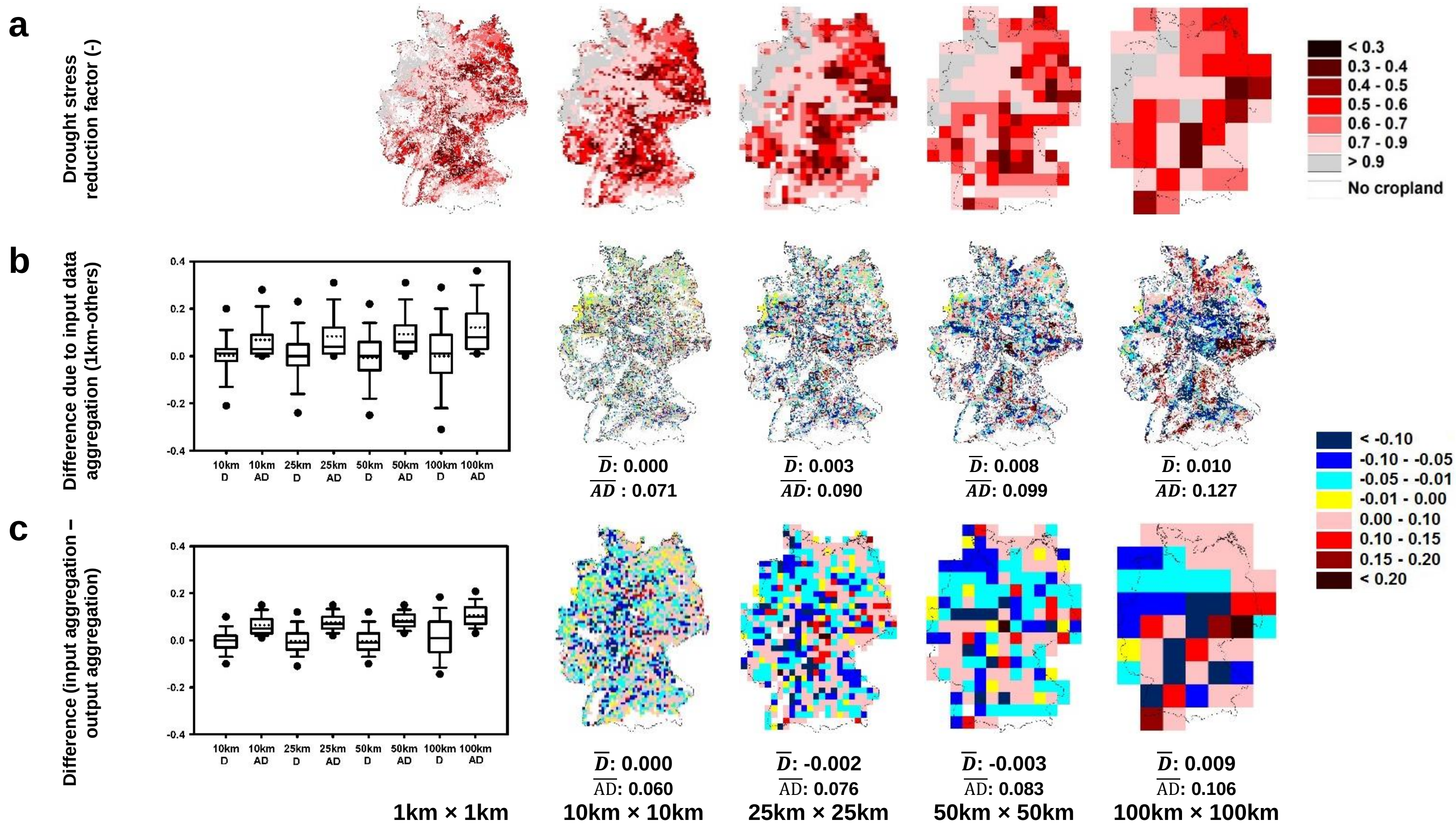

Figure 4.5. Effect of data aggregation on simulated drought stress for (a) drought stress reduction factor simulated at different spatial resolutions for the extreme year 2003, (b) difference between the drought stress reduction factor simulated with input data of different resolutions (b), and (c) difference between drought stress reduction factors simulated with aggregated input data and with aggregated high resolution output data. (Dashed line: mean, solid line: median; upper point and lower point show 5th and 95th percentiles, respectively). Please notice: a drought stress reduction factor of 1 means no effect of drought on crop yield.

4.3.4. Effect of model output aggregation on heat and drought stress

The mean absolute difference $\overline{AD}$ between heat stress reduction factors calculated with aggregated model input data (temperature) and aggregated high resolution model output showed an increase from 0.005 at 10 km × 10 km resolution to 0.009 at 100 km × 100 km resolution, while the mean difference $\overline{D}$ was much lower with values between -0.001 and - 0.002 (Figure 4.4c). Frequency distributions of *AD* and *D* for the comparisons of input- and output aggregation were quite similar across resolutions (Figure 4.4c).

The mean absolute difference $\overline{AD}$ between drought stress reduction factors calculated with aggregated model input data and aggregated high resolution model output increased from 0.060 at 10 km × 10 km resolution to 0.106 at 100 km × 100 km resolution (Figure 4.5c). Mean difference $\overline{D}$ was very small for the resolutions 10 km × 10 km to 50 km × 50 km (-0.001 - -0.003) and increased to 0.009 at 100 km × 100 km resolution (Figure 4.5c). The highest positive difference *D* was obtained for the major drought prone areas in East and South Germany while *D* was negative in the more humid northwestern part of the country (compare Figures 5a and 5c), indicating that input data aggregation results in an overestimate of drought stress in drought prone regions and an underestimate in more humid regions. Maxima and range in the frequency distributions of absolute differences *AD* and differences *D* gradually increased with increasing aggregation level from 10 km × 10 km to 100 km × 100 km resolution (Figure 4.5c).

4.3.5. Effects of model input and output aggregation on crop yield

Aggregation of model input data had only a small impact on mean (7.33 t ha^{-1} to 7.46 t ha^{-1}) and median (7.45 t ha^{-1} to 7.60 t ha^{-1}) of crop yields simulated across Germany (Figure 4.6a). In addition, standard deviation of yields simulated in different aggregation levels was quite similar (Figure 4.6a). However, aggregating input data considerably reduced the range between minimum and maximum of simulated yield (9.4 t ha^{-1} at 1 km × 1 km resolution but 5.0 t ha^{-1} at 100 km × 100 km resolution, Figure 4.6a). The agreement between mean of winter wheat yield calculated across Germany simulated with input data at different resolutions was also very high for specific years (Figure 4.6b). Mean yields across Germany in the period 1980-2011 varied between 4.9 t ha^{-1} and 9.3 t ha^{-1} (Figure 4.6b) and aggregation of input data caused only small differences (R^2 of 0.97 between time series of national mean yields simulated with input data at 1 km resolution compared to time series simulated with input data at 100 km resolution).

Aggregation of output data (wheat yields) resulted in mean and median yields quite similar to yields simulated with aggregated input data with small differences across aggregation levels (7.30 t ha^{-1} to 7.40 t ha^{-1} for mean yield and 7.32 t ha^{-1} to 7.45 t ha^{-1} for the median, Figure 4.6c). The range of simulated yields considerably decreased from 9.4 t ha^{-1} to 4.0 t ha^{-1} by output data aggregation from 1 km × 1 km to 100 km × 100 km, but, in contrast to yields computed with aggregated input data, standard deviation decreased by output data aggregation as well (Figure 4.6c).

Input data aggregation resulted in a remarkable decline of heterogeneity in simulated crop yields in particular for regions with low crop yields with an $\overline{AD}$ of 1.157 t ha^{-1} between yields simulated at 1 km × 1 km and 100 km × 100 km (Figures 7a, 7b). Mean difference $\overline{D}$ was negative for all aggregation levels (-0.079 t ha^{-1} for input data aggregation to 100 km × 100 km) which shows that input data aggregation caused a small but systematic overestimate of mean crop yield simulated across Germany (Figure 4.7b). We also found distinct spatial patterns of differences in yields simulated with aggregated input data to yields calculated by aggregating high resolution yield output data, in particular for the resolution 100 km × 100 km (Figure 4.7c). Mean absolute difference $\overline{AD}$ between yields simulated with aggregated input data and aggregated yield output was 0.506 t ha^{-1} at 10 km × 10 km resolution and increased to 0.783 t ha^{-1} at 100 km × 100 km resolution (Figure 4.7c). The difference between the 25th and 75th percentiles of absolute difference *AD* (input - output aggregation) of yields simulated across Germany was between 0.7 t ha^{-1} and 1.1 t ha^{-1} for resolutions lower than 100 km × 100 km but increased to 1.4 t ha^{-1} for the most aggregated data at 100 km × 100 km resolution (Figure 4.7c). Highest positive or negative differences between input and output data aggregation were obtained for the regions with the lowest yields, in particular in the eastern and central parts of the country (Figures 7a, 7c). In contrast, mean difference between input data aggregation and output data aggregation was negligible at national scale (Figure 4.7c). The range of difference *D* between input and output aggregation was remarkably higher at 100 km × 100 km resolution as compared to the other aggregation levels (Figure 4.7c). High positive and negative differences, in particular in the centre and south-eastern part of Germany, compensated at national extent for each other.

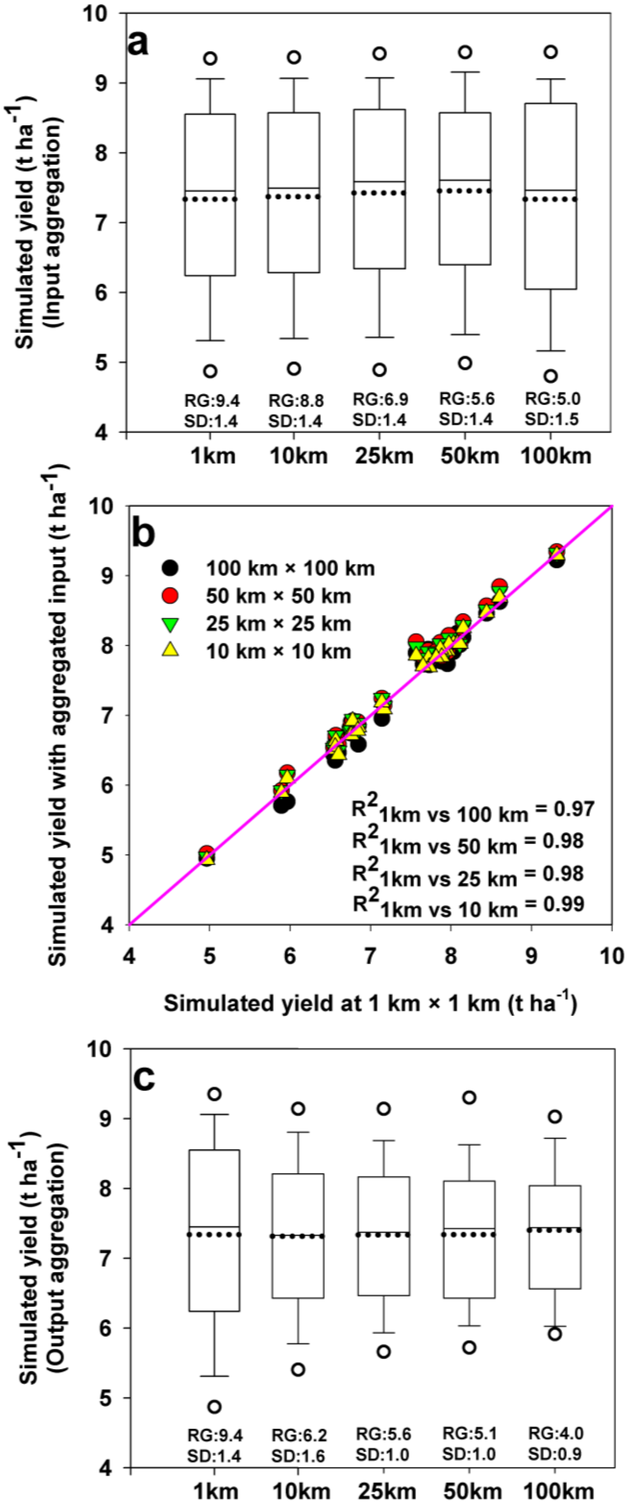

Figure 4.6. Boxplots of mean crop yields in period 1980-2011 simulated with input data at different resolution (a), annual mean of crop yields simulated across Germany with aggregated input data plotted against the corresponding yields at 1 km × 1 km resolution (b), boxplots of mean crop yields in period 1980-2011 at 1 km × 1 km resolution and aggregated to other resolutions (c). (Dashed line: mean, solid line: median; RG: range of data; SD: standard deviation of data; upper point and lower point show 5th and 95th percentiles, respectively).

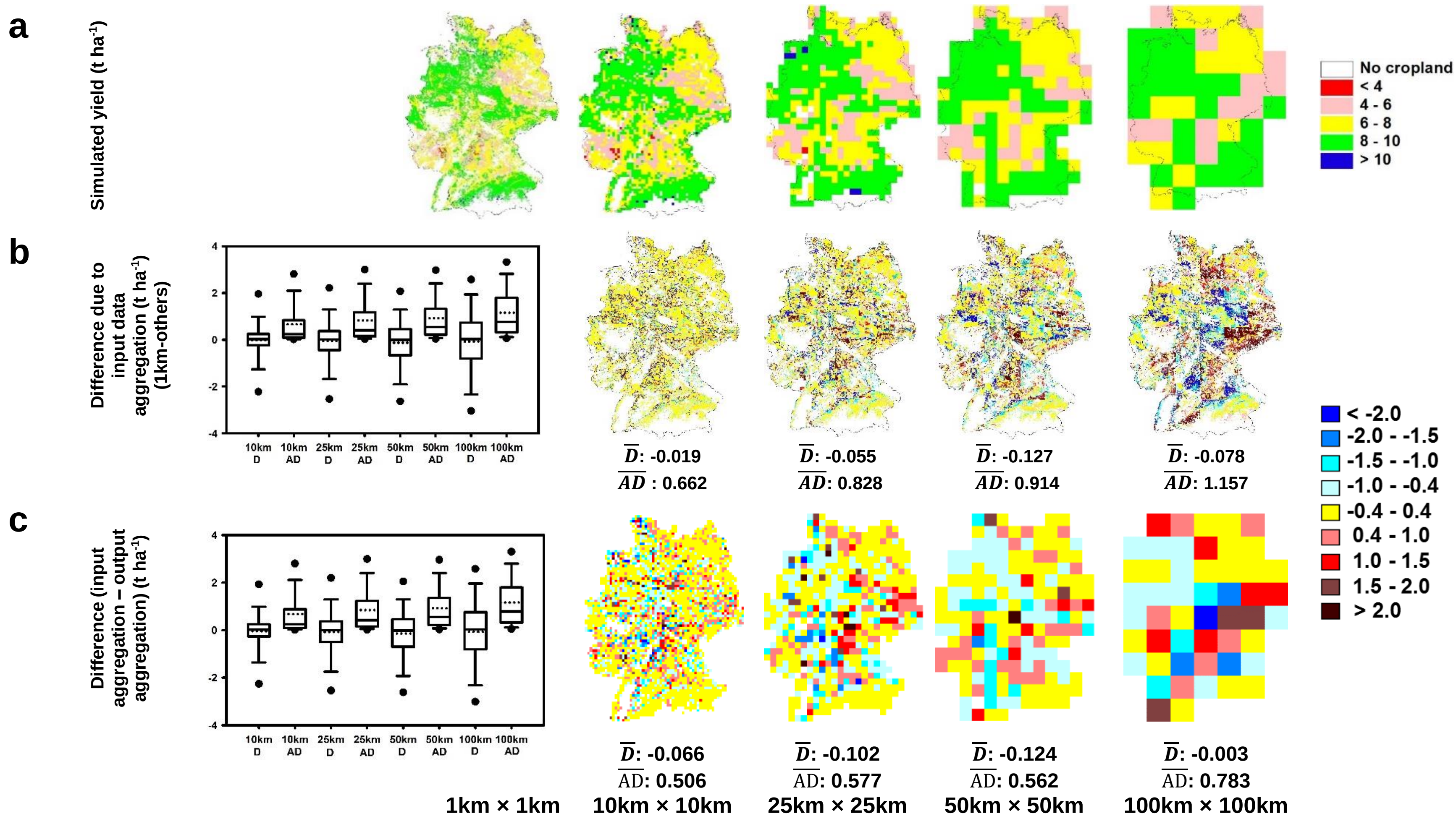

Figure 4.7. Yields of winter wheat simulated at different spatial resolutions for the period 1980-2011 (a), difference between crop yield simulated with input data of different resolutions (b), and difference (c) between crop yields simulated with aggregated input data and with aggregated high resolution output data. (Dashed line: mean, solid line: median; upper point and lower point show 5th and 95th percentiles, respectively).

4.4. Discussion

4.4.1. Data aggregation effects for different impact variables

The loss of spatial detail in simulated heat stress, drought stress and crop yields caused by data aggregation (sections 3.3-3.5) is determined by the decline of heterogeneity of the model input variables due to aggregation (section 3.2) and by the model structure, in particular by interactions among input variables and nonlinearities in the response of model output to variation in model input variables (Ewert et al., 2011). To further disentangle effects of data aggregation and model structure we compared the mean absolute differences $\overline{\Delta}$ in heat stress, drought stress and crop yield simulated across Germany caused by input data aggregation and by aggregation of model output (Figure 4.8). Output aggregation reduces the spatial heterogeneity by replacing high resolution model outputs with the mean calculated across the aggregated pixels. Model results calculated with aggregated input data are additionally impacted by the model structure so that differences between the effects of output aggregation and input aggregation indicate nonlinear responses of the model output to changing model input.

We found very little differences in the effects of input data and output data aggregation for heat stress with a $\overline{\Delta}$ increasing from 0.005 for aggregation to the resolution 10 km × 10 km to 0.013 for aggregation to the resolution 100 km × 100 km (Figure 4.8a). In contrast, the effect of input aggregation on drought stress was larger than the effect of output aggregation, in particular for the aggregation to the resolution of 100 km × 100 km with a $\overline{\Delta}$ of 0.127 for input aggregation and 0.104 for output aggregation (Figure 4.8b). The response of simulated crop yields to aggregation of input and output data (Figure 4.8c) were similar to the effects described for drought (Figure 4.8b) because effects of drought on crop yield were stronger than effects of heat (section 3.3). Consequently, aggregation of data to 100 km × 100 km resulted in a $\overline{\Delta}$ of 1.157 t ha^{-1} for input data aggregation but only 0.955 t ha^{-1} for output data aggregation while $\overline{\Delta}$ calculated for aggregation to 50 km × 50 km was still quite similar for input and output aggregation (Figure 4.8c). The results obtained in this study for data aggregation effects on drought and crop yield are in agreement with a previous study on wheat phenology in Germany which found little effect of aggregation of phenological observations to 50 km resolution but a larger effect when data were aggregated to 100 km resolution (Van Bussel et al., 2011b). However, these impacts on spatial patterns indicated in this study by the response of the absolute differences between model results at 1 km × 1 km resolution and 100 km × 100 km resolution did not translate in systematic differences in heat stress, drought stress or crop yield across the whole of Germany (see difference $\overline{D}$ in Figures 4, 5, 7) indicating that positive and negative regional deviations leveled out.

4.4.2. Data aggregation effects on crop yield

One major finding of this study is that aggregation of model input data or aggregation of crop yields simulated with high resolution input data (output aggregation) had little effect on mean and median of crop yield simulated across Germany. Data aggregation reduced the range between simulated maximum and minimum yields but had little effect on the 5th and 95th percentiles of simulated crop yields. Furthermore, aggregation of model input data caused only small differences in the inter-annual variability of mean crop yield across Germany (Figure 4.6). We found that spatial patterns in crop yields were moderately changed by input data aggregation or aggregation of model output (Figure 4.7) but we did not find systematic changes towards higher or lower crop yields so that the effect on the mean crop yield across Germany was small (Figure 4.7).

These results are surprising and suggest that crop modelling at high spatial resolution is not necessarily required for assessing mean crop yield and its change for a country like Germany. However, the findings in this study were obtained by using one crop model only and are thus prone to uncertainty (further discussed in section 4.4.3). To get more confidence in the obtained aggregation effects we repeated the analysis using winter wheat yields observed for period 1999-2011 (Figures 4.9a, 4.9c, 4.9d) and the extreme dry and hot year 2003 (Figures. 4.9b, 4.9e, 4.9f) at three spatial scales, district, federal state and at country level (DESTATIS, 2013). We first calculated crop yields at federal state level as the mean of crop yields reported for the districts belonging to the respective federal state and then the yield at country level as mean of the yields at district level (Figures .49a, 4.9b). This procedure is similar to a model output aggregation.

We found that mean and median of the yields computed that way for federal states and the national scale were very similar to the mean and median of crop yields reported at district level (compare DIS, ST_A and C_A in Figures. 4.9c, 4.9e). Even the effect on the 5th and 95th percentiles of crop yields by aggregation from district to state level was relatively small. These results confirm our major findings which seem even valid for further aggregation to the very coarse resolution of a federal state. Next we computed mean and median yield and the frequency distribution by using the yields directly obtained at federal state level and at national level from the agricultural statistics

(Figures. 4.9d, 4.9f). The difference to the procedure before is that yields provided by the Federal Statistics Office are area weighted, meaning that the winter wheat growing area in specific districts is considered when calculating the mean yield at federal state level or at national scale from the district level data. We found that mean and median of crop yield increased with aggregation to federal states and to national extent (compare DIS, ST_R and C_R in Figures. 4.9c, 4.9e). This suggests that changes in mean and median of crop yields reported at district, federal state or national level were less affected by data aggregation itself but by the fact that winter wheat growing areas were larger in districts with high yields than in districts with low yields.

To test whether aggregation effects on observed yields can be reproduced with yields simulated by the crop model with aggregated input data, we aggregated model input data to federal state level or national level and tested the effect on simulated yields. We found that simulated mean winter wheat yields for period 1980-2011 increased from 7.3 t ha^{-1} at 1 km × 1 km resolution to 7.6 t ha^{-1} when the yield was computed with input data aggregated to federal state level and 8.3 t ha^{-1} when the yield was computed with input data aggregated to country level (Figure 4.10). However, mean and median of crop yields computed with aggregated data was strongly impacted by the method used to aggregate the soil data. When rooting depth, volumetric water content at full saturation, at field capacity and at wilting point were not determined according to the dominant soil but averaged across 1 km × 1 km grid cells, simulated mean winter wheat yield declined to 7.1 t ha^{-1} at federal state level and to 6.7 t ha^{-1} at national level, respectively (Figure 4.10).

It is remarkable, that national mean crop yields simulated for period 1980-2011 with input data for weather, soil and emergence date averaged across all 1 km × 1 km grid cells differed only by -0.6 t ha^{-1} (8%) from the mean yield, simulated with input data at 1 km × 1 km resolution. This result confirms findings of a previous studies showing that aggregation of climate data from 10 km × 10 km to 100 km × 100 km (Angulo et al., 2013; Zhao et al., 2015) or aggregation of soil data (Angulo et al., 2014) had little impact on the mean crop yield calculated across large regions.

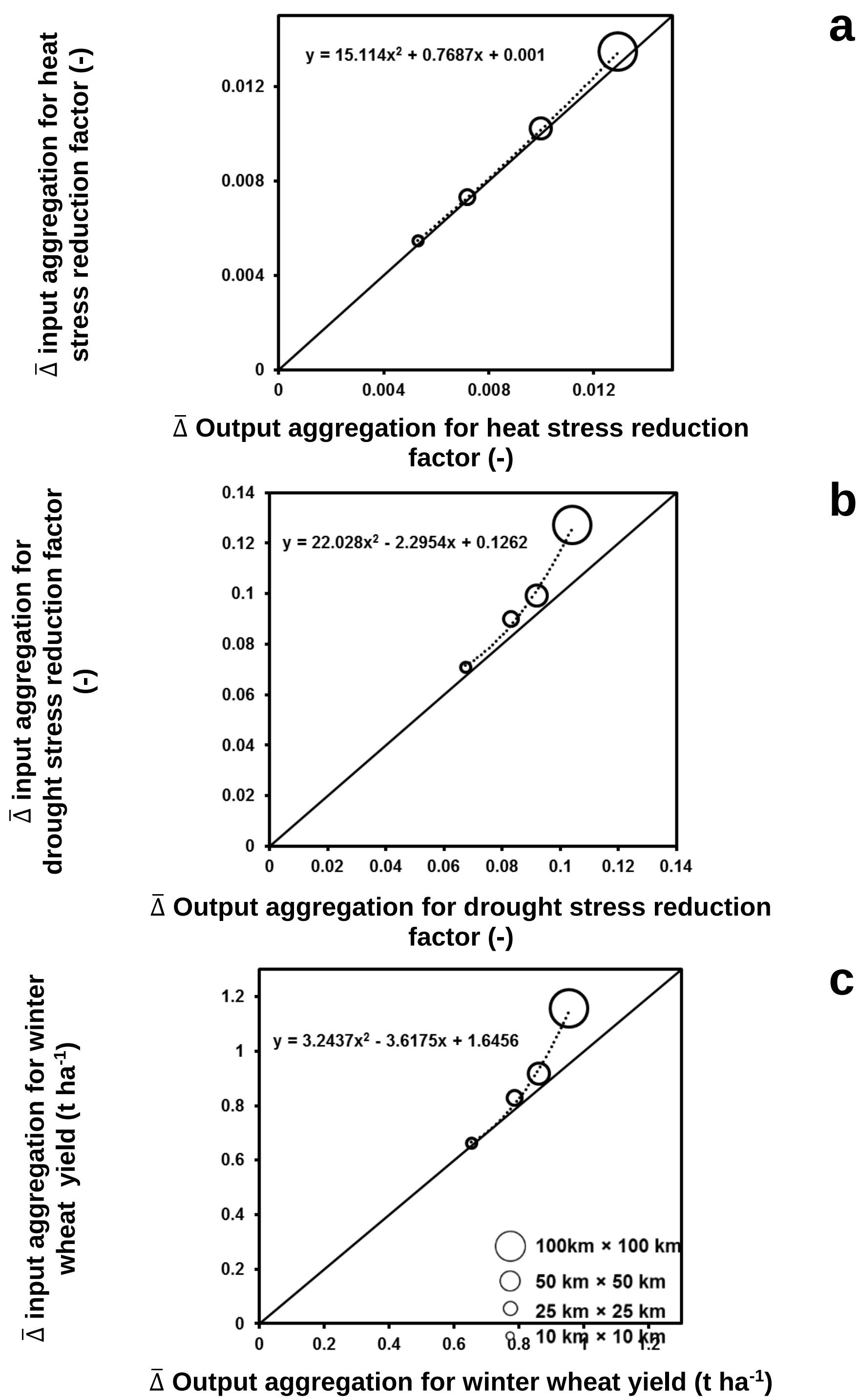

Figure 4.8. Relationship between mean absolute differences of aggregated model results to high resolution model results ($\bar{\Delta}$) caused by input data aggregation and output data aggregation for the model outputs of (a) heat stress reduction factor, (b) drought stress reduction factor and (c) winter wheat yield (t ha-1). (Dotted line is regression line and solid line is 1:1 line).

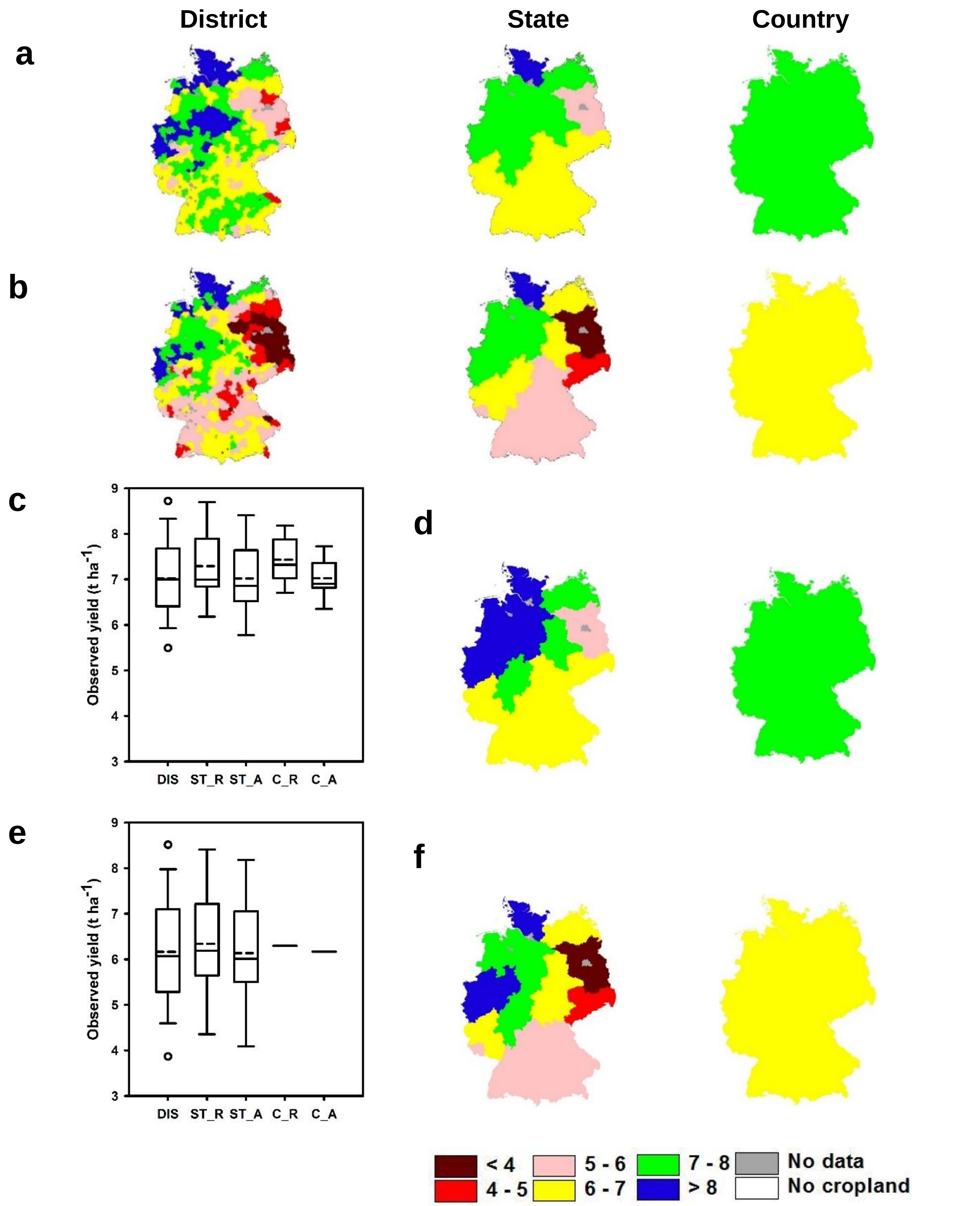

Figure 4.9. Mean yield observed for period 1999-2011 (a and d) or year 2003 (b and f) at district, state and country level, yields at state or country level were calculated as mean of the yields at district level (a and b) or taken directly as reported by agricultural statistics at state and country

level (d and f). Boxplots of mean yields observed in period 1999-2011 (c) or year 2003 (e) at district level (DIS), reported yield at state level (ST_R), yield at state level calculated as mean of the yields at district level (ST_A), reported yield at country level (C_R) and yield at country level were calculated as mean of the yields at district level (C_A) (Dashed line: mean, solid line: median; upper point and lower point show 5th and 95th percentiles, respectively).

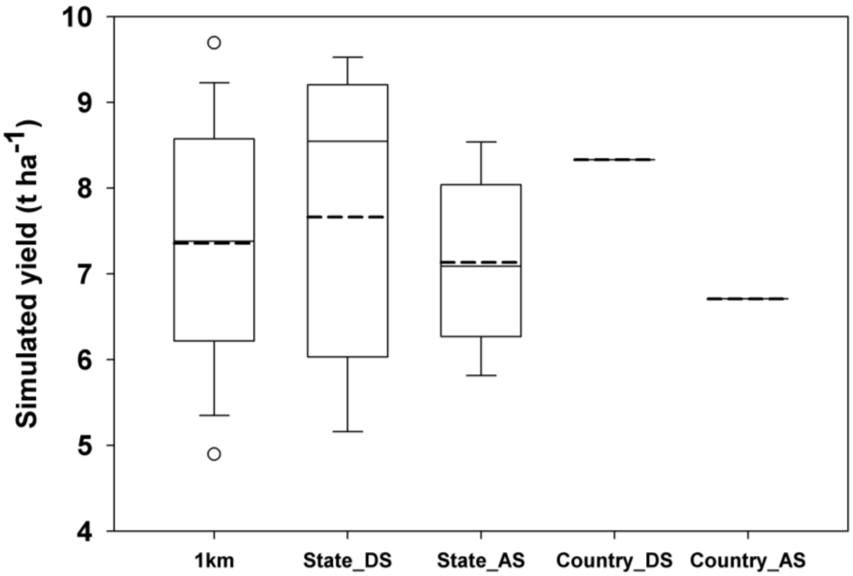

Figure 4.10. Boxplots of the yields simulated at 1 km × 1 km resolution (1 km), or with weather and soil data aggregated to state and country level with different soil aggregation methods. (DS: soil aggregation based on dominant soil, AS: soil aggregation based on averaging soil characteristics. (Dashed line: mean, solid line: median; upper point and lower point show 5th and 95th percentiles, respectively).

4.4.3. Data aggregation effects on simulated heat and drought stress

The main effect of input data aggregation was the loss of spatial detail in simulated heat- and drought stress factors because many grid cells at high resolution are represented by just one value in low resolution. However, we did not find a systematic difference in the magnitude of yield reduction due to heat or drought stress at national level because differences in mean and median of heat- and drought yield reduction factors across Germany were small (Figures 4, 5, S3, S4). This seems to be surprising because the impact of weather and soil variables on heat and drought stress and thus crop yield is typically considered to be nonlinear (Lobell et al., 2011; Lobell et al., 2012). The equations used in SIMPLACE<LINTUL2-CC-HEAT> should in fact also cause a non-linear response of the simulated crop yields to changes in daily maximum temperature, precipitation or soil water storage capacity because of the use of thresholds for critical temperatures (heat stress) or the nonlinear response of potential and actual transpiration to weather input (see model description in section 2.2). An analysis of the impacts of total soil water storage capacity in the effective root zone, mean annual precipitation sum or mean daily maximum temperature on simulated winter wheat yields showed however that the model response can well be approximated by segmented piecewise linear regression equations with breakpoints at 228 mm for the soil water storage capacity, 885 mm yr^{-1} for annual precipitation sum and 20.7 °C for mean daily maximum temperature in June (Figure 4.11). Water storage capacities and precipitation sums below these breakpoints or mean daily maximum temperatures above the breakpoint caused an almost linear decline in crop yield. It can therefore be expected, for example, that the mean crop yield in two grid cells with a soil water storage capacity of 150 mm should be similar to the mean yield of two pixels with a storage capacity of 100 mm and 200 mm, when all other input variables were similar. This may explain why intra-pixel heterogeneity (positive and negative deviations of local input variable values caused by input data aggregation) had little impact on the mean yield simulated for a large region like Germany. Our findings are in line with previous research on the impact of data resolution on crop yield (Angulo et al., 2013, 2014; Zhao et al., 2015). Similarly Olesen et al. (2000) showed, that the effect of climate change on winter wheat production at country level (Denmark) can be simulated without spatially detailed climate information while van Bussel et al (2011b) showed that spatial aggregation of climate data up to 50 km × 50 km did not negatively affect simulated crop phenology of winter wheat in Germany. Nevertheless we found that local deviations of crop yields simulated with input data of different resolution can be large so that it depends on the research question and purpose whether high resolution crop model input data are required or not. Our simulation results also showed that simulated yield is more sensitive to the variability in soil characteristics than to variability in precipitation or daily maximum temperature observed across Germany (Figure 4.11). However, this finding should not be generalized for other countries because aridity and the variability in precipitation maybe different from the conditions observed for Germany. We extent previous research by focussing in this study on the effects of data aggregation on extreme events like heat and drought. Heat and drought stress reduction factors showed a different response to input data aggregation. While effects of input data aggregation on simulated heat stress reduction factor was small (Figure 4.4b), a considerable difference was observed between drought stress reduction factor calculated with high resolution and low resolution input data, in particular for drought prone areas (Figure 4.5). We also showed that the magnitude and even the sign of the input data aggregation effect on drought stress and related yield reduction depends on the method used to aggregate soil information (average soil properties versus properties of the dominant soil, Figure 4.10). This highlights the importance of selecting appropriate aggregation methods when generating input data for models applied at coarse resolution.

While the impacts of input data aggregation on summary statistics like the mean or median heat stress, drought stress and corresponding crop yield calculated across Germany were small, we detected strong positive and negative effects of data aggregation at the local scale (Figures 4b, 5b, 7). This is in agreement with previous research showing a high correlation between spatial heterogeneity (topography) and intra-pixel difference of yield simulated across Germany (Zhao et al., 2015). Therefore a high resolution of model input data was required in regions of heterogenious topography to capture this spatial detail in crop yields (Zhao et al., 2015). Based on our findings we suggest that not only topography but also soil heterogeneity needs to be considered when defining an appropriate resolution for the application of the crop model.

4.4.4. Model uncertainties and limitations of this study

A limitation of this study is certainly that results are based on the application of a single crop model. Evaluation of the effect of resolution change of weather input data (10 km × 10 km to 100 km × 100 km) on yield simulated by four crop models (LINTUL-SLIM, DSSAT-CSM, EPIC and WOFOST) showed that the variance in simulated yields caused by different models was higher than the impact of the changes in spatial resolution (Angulo et al., 2013). However, presently only few crop models are available to simulate the impact of heat stress around anthesis on crop yield at the sub-national or national scale (Rötter et al., 2011). These models use an approach similar to the one used in SIMPLACE<LINTUL2-CC-HEAT> for evaluation of heat stress effect on grain yield (Teixeira et al., 2013; Deryng et al., 2014). The situation is different for drought stress. Here the method to describe the effect of drought stress on crop yield used in SIMPLACE<LINTUL2-CC-HEAT> (ratio between actual and potential transpiration) is rather common and used also in other crop models (van Ittersum et al., 2003). Therefore, we expect that our results can also be reproduced by applying other crop models but further research is required to sustain this.

The effect of data aggregation on temporal dynamics of model output was not within the scope of our study but differences in simulated heat and drought stress were small across resolutions as compared to interannual variability (data not shown). However, we show the coefficient of variation (CV) of heat and drought stress reduction factors (1980-2011) for all resolutions at pixel level (SI Figure 4.5a). The temporal variability of drought stress was remarkably higher than the one of heat stress. Again, there was a strong similarity between spatial patterns of soil available water capacity (Figure 4.2d) and temporal variability of drought stress (SI Figure 4.5b).

Another limitation that we have to acknowledge is the way how model input data at 1 km × 1 km resolution were developed. Since it is not possible to measure the required model input data at 1 km resolution, the data were created by interpolation of station data (weather data, emergence day) or by using soil properties of the dominant soil mapped at lower spatial resolution. Heterogeneity under real field conditions may therefore be higher than the heterogeneity reflected in the 1 km × 1 km model input data used in this study, in particular for precipitation and soil properties. While this would certainly have an impact on the model results at high resolution (spatial patterns), we don't expect an impact on our main findings and conclusions with regard to the effects of model resolution and data aggregation on crop heat stress, drought stress and crop yield. The model input data used in this study vary in a range (spatially) that is expected for Germany and should therefore be well suited to study effects of data aggregation on crop model results. Furthermore we show results for long-term means always in comparison to results for year 2003 which was one of the years with most extreme heat and drought since 1500 AD in Europe (Luterbacher et al., 2004).

Crop heat stress was simulated in SIMPLACE<LINTUL2-CC-HEAT> based on heat stress intensity and a 30 day period around anthesis and daily maximum temperature measured by weather stations in 2 m height. Recent research showed however, that the temperature in the canopy can differ a lot from the temperature measured at standard weather stations and that this temperature difference is controlled by soil moisture (Siebert et al., 2014). This points to strong and complex interactions between heat and drought that were not considered in the model applied in this study. Consequently, the impact of data aggregation on interactions between heat and drought still needs to be analysed. In addition, more research is needed to reduce other uncertainties related to the simulation of magnitude and impact of heat and drought stress at sub-national scale, e.g. to reflect better the variability in phenological development, soil properties, crop management and cultivar responses.

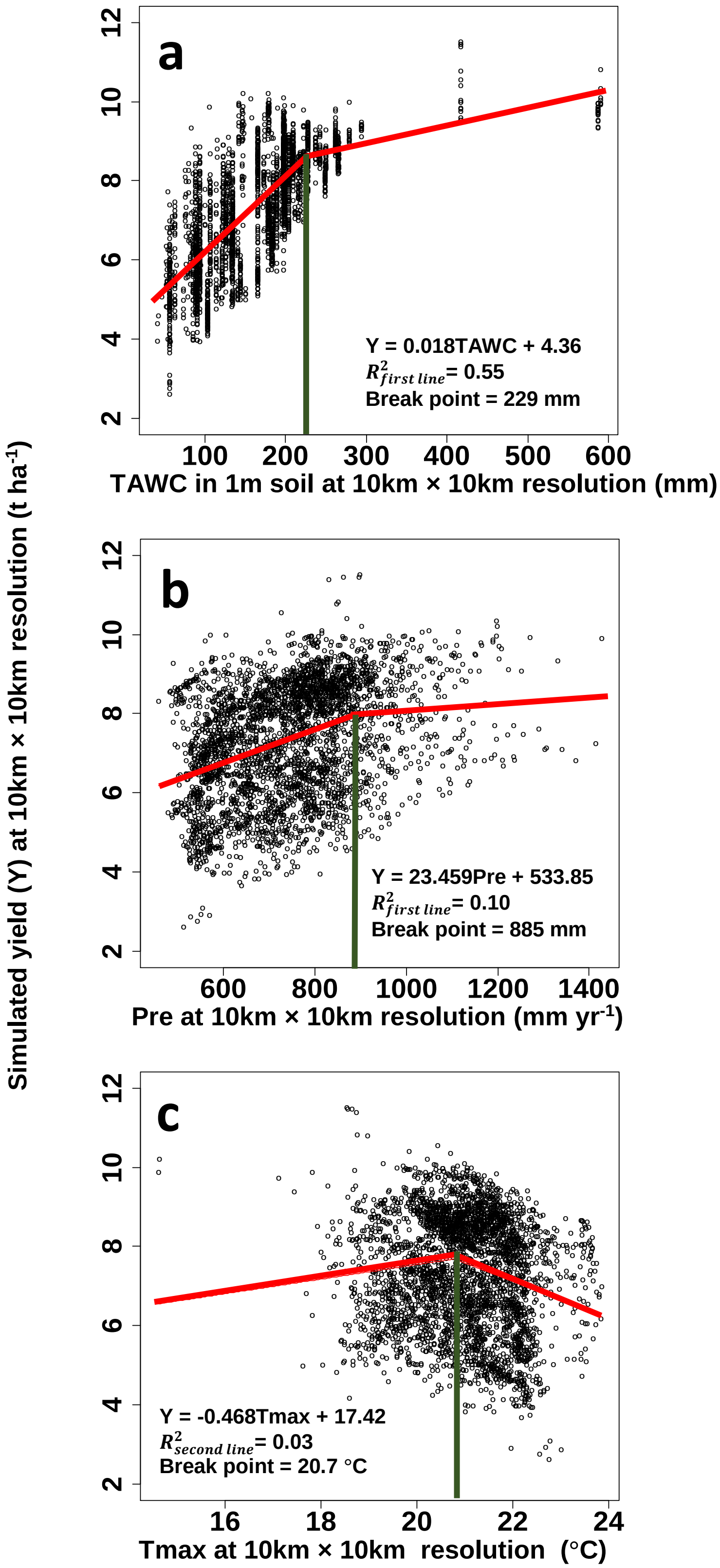

Figure 4.11. Segmented piecewise regression between crop yield simulated at 10 km × 10 km resolution and total available water capacity (TAWC) in 1 meter soil (a), mean annual

precipitation sum (Pre) (b) and mean of daily maximum temperature (Tmax) (c) at 10 km × 10 km for the period 1980-2011.

4.5. Conclusions

We conclude that high resolution crop modeling is not required to assess the effects of the extreme events of drought and heat around anthesis on mean or median yield of winter wheat calculated across Germany which may also apply to countries with similar variability in climate and soil characteristics. The use of high resolution crop modeling may however be required to gain information about the spatial variability of drought stress impacts on crop yields including its local importance (e.g. for impact analyses at farm level). Further research will be required to understand the consistency of the obtained results across crop models differing in structure and detail and for other regions and crops. The understanding of the effect of data resolution on interactions between impacts of heat and drought stress will also need further attention.

Acknowledgements

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Chapter 5

Combined impacts of climate and nutrient fertilization on yields of pearl millet in Niger

Based on:

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Abstract

Effects of climate variability and change on yields of pearl millet have frequently been evaluated but yield responses to combined changes in crop management and climate are not well understood. The objectives of this study were to determine the combined effects of nutrient fertilization management and climatic variability on yield of pearl millet in the Republic of Niger. Considered fertilization treatments refer to (i) no fertilization and the use of (ii) crop residues, (iii) mineral fertilizer and (iv) a combination of both. A crop simulation model (DSSAT 4.5) was evaluated by using data from field experiments reported in the literature and applied to estimate pearl millet yields for two historical periods and under projected climate change. Combination of crop residues and mineral fertilizer resulted in higher pearl millet yields compared to sole application of crop residues or fertilizer. Pearl millet yields showed a strong response to mean temperature under all fertilization practices except the combined treatment in which yields showed higher correlation to precipitation. The crop model reproduced reported yields well including the detected sensitivity of crop yields to mean temperature, but underestimated the response of yields to precipitation for the treatments in which crop residues were applied. The crop model simulated yield declines due to projected climate change by -11% to -62% depending on the scenario and time period. Future crop yields in the combined crop residues + fertilizer treatment were still larger than crop yields in the control treatment with baseline climate, underlining the importance of crop management for climate change adaptation. We conclude that nutrient fertilization and other crop yield limiting factors need to be considered when analyzing and assessing the impact of climate variability and change on crop yields.

5.1. Introduction

Crop production is vulnerable to climate change because meteorological variables determine resource availability (solar radiation, water) and control basic processes involved in crop growth and development (Meza and Silva, 2009). Changes in temperature and precipitation associated with continued emissions of greenhouse gases will cause changes in land suitability and crop yields (Schmidhuber and Tubiello, 2007). (Lobell and Field, 2007), for example, found a distinct negative response of global wheat, maize and barley yields to increased temperatures during the period 1981-2002. Interactions between different climate variables were simulated to decrease crop yields when humidity and precipitation decreased or when temperature increased and precipitation decreased under climate change in the central parts of the USA (Brown and Rosenberg, 1997).

The economy and food security of the rural communities in the semi-arid regions of Niger are strongly dependent on rainfed agriculture (Marteau et al., 2011). Pearl millet (*Pennisetum glaucum* [L.]) is one of the most important crops growing on more than 65% (7.5 million ha-1) of the cultivated land of Niger (Mariac et al., 2006). Different reports showed significant impacts of climate change on crop production in West Africa which is, according to the Global Hunger Index, one of the regions with the most severe hunger in the world (Von Grebmer et al., 2008). (Mohamed et al., 2002; Van Duivenbooden et al., 2002) predicted that 10% increase in average temperature may cause a 13% decrease in millet production by using an empirical method for Niger. Furthermore, (Tingem and Rivington, 2009) estimated 14% and 39% decrease in maize and sorghum yield under SRES-A2 emission scenario in Cameron. In general, 11% decrease in crop production under climate change was expected for the whole of West Africa (Roudier et al., 2011). Most climate change assessment studies did not account for differences in crop management and little is known on the interaction between climate and crop nutrition. Poor soil fertility management, high evapotranspiration demand and the low native soil fertility limit pearl millet production in Niger (Bationo et al., 1993). Changes in climate may cause larger (or smaller) losses of nitrogen through leaching and gaseous losses or changes in the demand for fertilizer, e.g. by changes in temperature and precipitation amount and pattern (Olesen and Bindi, 2002; Porter et al., 1995). (Sivakumar and Salaam, 1999) showed that the effectiveness of fertilizer application in this region depends on midseason precipitation. Average or above average midseason precipitation and high application rates of Nitrogen fertilizer resulted in highest yields of pearl millet while lower precipitation eliminated the advantage of nitrogen application. However, this study was a short term experiment (4 years) and only considered mineral fertilizer application as fertilization practice.

The main objectives of this study were therefore to investigate whether different nutrient fertilization strategies modify the sensitivity of pearl millet yields to temperature and precipitation and to which extend this affects simulations of climate change impacts on millet yield. To achieve this, an analysis of published data from different field experiments was combined with a crop model application. The widely used crop model DSSAT 4.5 was first evaluated to reproduce yield sensitivities to climate variables detected from the observations and then applied to investigate how crop yields would be affected in different fertilization treatments under observed historic and predicted future climate.

5.2. Materials and methods

5.2.1. Study area and data

5.2.1.1. Site description

This study focused on Niamey region which is located in the Sahelian bioclimatic zone, a wide semi-arid belt immediately south of the Sahara desert. It is one of the most important agricultural centers of Niger and has a population of more than 1.5 million inhabitants (Bationo and Ntare, 2000). Agriculture is the main source of income for 95% of the population and rainfed pearl millet represents the major food crop (Sivakumar, 1992). Mean monthly temperature of this region in the period 1940-2005 was highest in May (34 °C) and lowest in January (24 °C), while mean monthly precipitation sum was highest in September (178 mm) and lowest in December (0 mm). Mean annual precipitation was 555 mm and varied between 293 mm (1981) and 980 mm (1942). The soil at this region is classified as sandy siliceous with 94% sand and 3% clay content in the top soil (Bationo et al., 1998). More than 60% of pearl millet cultivated lands of Niger were classified as Arenosols soils (Graef, 1999). Furthermore, (Marteau et al., 2011) reported soil characteristics of 10 pearl millet cultivated centres (including our study location) indicating that they had similar field capacity and wilting points.

5.2.1.2. Crop yield and crop management

Data collected from three short and long term pearl millet yield experiments were obtained from the literature and used in this study for detection of climate and fertilization management interactions (long term field experiment), parameterization (short term field experiment 1) and testing (short term field experiment 2) of the crop model. The long term experiment was undertaken in the period 1983-1995 to test the impact of the application of crop residues (CR), the application of mineral fertilizer (FR), and combined crop residues and mineral fertilizer application (CR+FR). Fertilizer application rate was 15 kg P ha^{-1} yr^{-1} applied as single superphosphate and 30 kg N ha^{-1} yr^{-1} applied as calcium ammonium nitrate (Bationo et al., 1998) while the biomass (except grains) was returned to the soil each year in the treatments with residues application

(Bationo et al., 1993). Crop yields recorded in this experiment are shown in Figure 1. Data collected in short term experiment 1 and reported in (Sivakumar and Salaam, 1999) were used for crop model parameterization (genotype coefficients estimation) of the CIVT pearl millet cultivar. The field experiment was conducted in 1984 at the ICRISAT Sahelian centre, Sadore, Niger. The study evaluated water use efficiency, growth and yield responses of pearl millet fertilized with 30 kg P ha^{-1} and 45 kg N ha^{-1} or grown without fertilizer application. Short term experiment 2 was undertaken at ICRISAT Sahelian centre, Sadore, Niger in period 1986-1987 to test the impact of an early onset of precipitation (imposed with supplemental irrigation) on crop yield of the CIVT cultivar compared to a natural onset of precipitations (Sivakumar, 1990). Pearl millet yields from this experiment were obtained from (Sivakumar, 1990) and used for model testing.

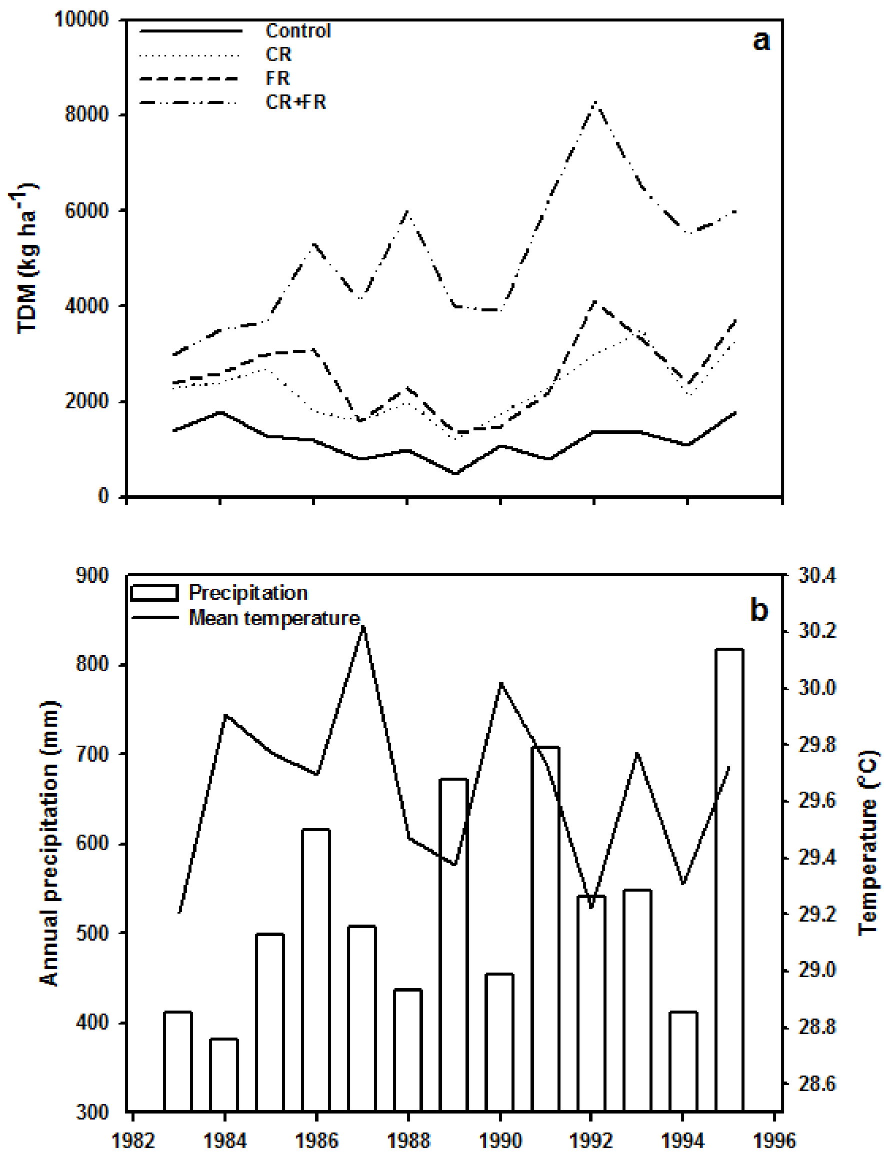


Figure 5.1. Pearl millet total dry matter yield (TDM) for the treatments without fertilizer application (Control), application of crop residue (CR), application of synthetic fertilizer (FR), and combined application of crop residue and synthetic fertilizer (CR+FR) (a), and climatic variables (b) observed in the long term experiment between 1983-1995 (yield data were obtained from Bationo et al., 1998).

5.2.1.3. Climate data

Daily time series of maximum, minimum and mean temperature (°C), precipitation sum (mm day^{-1}) and global radiation (MJ m^{-2} day^{-1}) for the period 1940-2005 were measured by an automated weather station and provided by Niger meteorological organization. Daily solar radiation was estimated by applying the Angstrom–Prescott equation (Suehrcke, 2000). Angstrom coefficients for Niamey were obtained from (Persaud et al., 1997).

5.2.2. Methods

5.2.2.1. Analysis of climate and fertilizer impact on crop production

The dependency of pearl millet yield on temperature and precipitation under different fertilization treatments was analyzed by the calculation of correlation coefficients between climatic variables (mean of daily minimum and maximum temperature, mean temperature, precipitation sum) and total dry matter production. To test possible interactions between temperature and precipitation, simple and multivariate linear regressions of temperature and precipitation sum on pearl millet yield were compared. We used multivariate regression equations of the type:

$$Y = aP + bT + c \tag{1}$$

and simple linear regression equations of the types

$$Y = aP + c \tag{2}$$

or

$$Y = bT + c \tag{3}$$

where Y was total dry matter (t yr^{-1}), P and T represented precipitation sum (mm) and mean temperature (°C) during the cropping period, and a, b, c (intercept) model coefficients. To test whether a multivariate regression describes more of the variance in crop yields than simple linear regression we compared regression coefficients adjusted for the number of variables R^2_{adj} computed as:

$$AdjustedR^2 = 1 - (1 - R^2) \times \frac{(n-1)}{(n-k-1)} \quad (4)$$

where n was the number of samples and K the number of variables used in the regression (Lobell et al., 2007).

5.2.2.2. Modelling of crop yield

To simulate pearl millet yields under current and future climate, the DSSAT (Decision Support System for Agrotechnology Transfer) version 4.5 was used. It contains modules to simulate more than 20 crops and fallow systems (Jones et al., 2003) using one soil water model and two soil C/N models (Liu et al., 2011). For this study we used CERES-Millet, embedded in the DSSAT environment, to simulate crop growth from sowing to maturity with a daily time step based on physiological processes that explain the crop's response to soil and weather. DSSAT sub-modules for CERES-Millet consider leaf area development, dry matter production, assimilate partitioning and tiller growth and development. Potential growth is dependent on photosynthetically active radiation (PAR) and its interception, whereas actual biomass production was constrained by suboptimal temperatures, soil water deficits and nutrient deficiencies (Nain et al., 2004). Genetic coefficients of the pearl millet cultivar CIVT were estimated by using the Genetic Coefficient Estimator (Gencalc) based on data obtained from short term experiment 1 (Hunt et al., 1993) Table. 5.1. Crop management (soil preparation, sowing dates, and plant protection) was specified according to reported observations at the study location and assumed to be similar in the simulations of current (long and short term experiments) and the future crop production.

Table. 5.1. Genetic coefficients of the pearl millet cultivar 'CIVT' as used in DSSAT calculated by using the Genetic Coefficient Estimator Gencalc.

Parameter	Value
P1	120
P2O	12
P2R	142
P5	590
G1	1
G4	0.6
PHINT	0.43

P1: Thermal time from seedling emergence to the end of the juvenile phase expressed in degree days above a base temperature of 1ºC for pearl millet during which the plant is not responsive to changes in photoperiod, P2O: Thermal time (degree days above a base temperature of 1ºC) from beginning of grain filling (3-4 days after flowering) to physiological maturity, P2O: Critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate. P2R: Extent to which phasic development leading to panicle initiation (expressed in degree days) is delayed for each hour increase in photoperiod above G1: Scaler for relative leaf size, G4: Scaler for partitioning of assimilates to the panicle (head) and PHINT: Phylochron interval; the interval in thermal time (degree days) between successive leaf tip appearances.

The modelling of soil water and nitrogen dynamics for low input systems and long-term studies in DSSAT v4.5 is based on the methodology used in the CENTURY soil model (Gijsman et al., 2002; Porter et al., 2010). Nitrogen uptake is calculated dependent on nitrate and ammonium concentration in the soil water, soil water content, root growth and nitrogen demand of the crop and simulated in daily steps (Liu et al., 2011). Photosynthesis rate and leaf area expansion are directly affected by nitrogen availability (Ma et al., 2006). The effect of nitrogen stress is introduced by a nitrogen stress factor (N_{stress}) calculated as:

$$N_{stress} = 1 - \frac{N_{critical} - N_{actual}}{N_{critical} - N_{min}} \quad (5)$$

where $N_{critical}$, N_{actual} and N_{min} are nitrogen concentration at maximum growth, actual nitrogen concentration of vegetation and minimum concentrations of nitrogen at which growth ceases, respectively (Godwin and Singh, 1998).

In the soil module of DSSAT crop residues enter a soil pool depending on application date, type, amount, incorporation depth, incorporation fraction, and application method. Carbon, nitrogen and phosphorus are then released by decomposition of this pool. The decomposition rate is influenced by soil temperature, soil water content, tillage, and soil texture (Porter et al., 2010). Application of crop residues results in a decline of soil bulk density, evaporation, and runoff while it increases soil water holding capacity (Gijsman et al., 2002; Porter et al., 2010) and has therefore positive impacts on crop yields beyond simple effects of additional crop nutrient supply.

5.2.2.3. Processing and analysis of climate data

Trends in historical climate data were detected by using the Mann–Kendall method (Kendall, 1948) as suggested by the World Meteorological Organization (World Meteorological Organization, 2000). In the Mann-Kendall trend test, the correlation between the rank order of the observed values and their order in time is considered (Appendix A).

To generate time series of potential future climate, monthly time series of the climate variables simulated by the four global circulation models (GCM) Institute Pierre Simon Laplace, France (IPCM4) (Semenov and Stratonovitch, 2010), United Kingdom Met Office Hadley Center (HadCM3) (Mitchell et al., 1995), Max-Planck Institute for Meteorology, Germany (MPEH5) (Brands et al., 2011) and National Centre for Atmospheric Research, USA (NCCCSM) (Jackson et al., 2011) and two emission scenarios SRES-A2 and SRES-B1 were downscaled to daily time steps using the stochastic weather generator LARS-WG (Semenov and Stratonovitch, 2010). The A2 scenario describes a more heterogeneous, market-led world, with less rapid economic growth, but more rapid population growth due to less convergence of fertility rates (Arnell, 2004). On the other hand, the B1 emission scenario describes a convergent world with lower population growth as in A1 but with rapid changes in economic structure toward a service and information economy and the introduction of clean technologies (Joos et al., 2001). Parameters of probability distributions of daily weather variables as well as correlations between them were computed from the site specific observed daily weather data (Semenov and Brooks, 1999) and applied to simulate time series for the two future periods 2011-2030 (near future) and 2080-2099 (far future).

5.2.3. Evaluation of crop and climate models

The Root Mean Squared Error (RMSE) was computed to measure the coincidence between observed and simulated variables in the climate (LARS-WG) or crop model (DSSAT) simulations. It illustrates the model's prediction error by heavily weighting high errors (Brisson et al., 2002). The model simulation accuracy increases as values of RMSE are close to 0. Relative (%) and absolute values of RMSE for evaluation climate and crop model were calculated as:

$$AbsoluteRMSE = \left[n^{-1} \sum_{i=1}^{n} (S_i - O_i)^2 \right]^{0.5} \quad (6)$$

$$rRMSE(\%) = \left[\frac{\sum_{i=1}^{n} (S_i - O_i)^2}{n} \right]^{0.5} \times \frac{100}{\bar{O}} \quad (7)$$

where *Si* and *Oi* indicated the simulated and observed data, $\bar{O}$ the mean of observed data and *n* is the number of observations. The crop model's ability to reproduce yield responses to climate signals was specifically evaluated analysing relationships between temperature and precipitation and simulated yields for different fertilization practices which were compared with the relationships obtained for observed crop yields (section 2.2.1). In addition, correlation coefficients between observed and simulated pearl millet yields were computed for the different fertilization treatments to find out whether the model can correctly detect inter-annual variability in crop yields.

5.3. Results

5.3.1. Effects of fertilization and climate on pearl millet yields

Increases of pearl millet yields due to the application of crop residues and fertilizer in the long term experiment from 1983-1995 (Bationo et al., 1998) were substantiated by our analysis showing that the effects of climatic variables on total dry matter yield changed depending on the fertilization treatment, although only small differences were observed for the effect of temperature. Total dry matter yield was negatively correlated with mean temperature during the growing period in all fertilization treatments (Figure 5.2). Correlations between crop yields and mean daily maximum temperatures or mean daily minimum temperatures were similar or weaker (data not shown). Therefore we focus in the following on the relationships to mean temperature, which showed highest negative correlation with total dry matter yield under control ($R = -0.39^{ns}$) and CR treatment ($R = -0.51^{*}$) (Figure 5.2). However, the application of crop residues increased the dependency of pearl millet total dry matter yield on precipitation. Total dry matter yield showed a negative correlation with precipitation sum during the growing period under the control treatment ($R = -0.16^{ns}$), but was positively correlated with precipitation sum in the CR ($R = 0.33^{ns}$) and CR+FR ($R = 0.61^{*}$) treatments (Figure 5.2).

Simple and multivariate regression analysis of mean temperature and precipitation on pearl millet production showed that the combination of climatic variables (multivariate linear regression) decreased the adjusted regression coefficients for all fertilization treatments compared to the simple linear regression analysis of mean temperature and precipitation (Table. 5.2). This indicates that the combined consideration of mean temperature and precipitation cannot better explain the impact of climate on the variability of pearl millet yield than a consideration of single variables.

Table. 5.2. Coefficients *a*, *b* and *c* of simple and multivariate linear regression of mean temperature and precipitation on pearl millet total dry matter production (kg ha^{-1}) observed in different fertilization management treatments during the long term experiment and correlation coefficient between simulated and observed dry matter production (R^2_{model}).

Fertilization management	Climate variable	*a*	*b*	*c*	Adj. R^2	*p*-value	R^2_{model}
	T_{mean}	-195	-	7698	0.08	0.177	
Control	Precipitation	-	-0.52	1380	-0.06	0.592	0.59
	Precipitation +T_{mean}	-0.75	-214	8595	0.05	0.302	
	T_{mean}	-262	-	11312	-0.02	0.429	
FR	Precipitation	-	0.59	2373	-0.08	0.787	0.37
	Precipitation +T_{mean}	0.32	-254	10932	-0.12	0.735	
	T_{mean}	-457	-	17480	0.20	0.069	
CR	Precipitation	-	1.9	1637	0.02	0.268	0.55
	Precipitation +T_{mean}	1.45	-420	15754	0.19	0.134	
	T_{mean}	16	-	4542	-0.09	0.979	
CR+FR	Precipitation	-	8	2281	0.32	0.024	0.25
	Precipitation +T_{mean}	8	223	-5230	0.27	0.082	

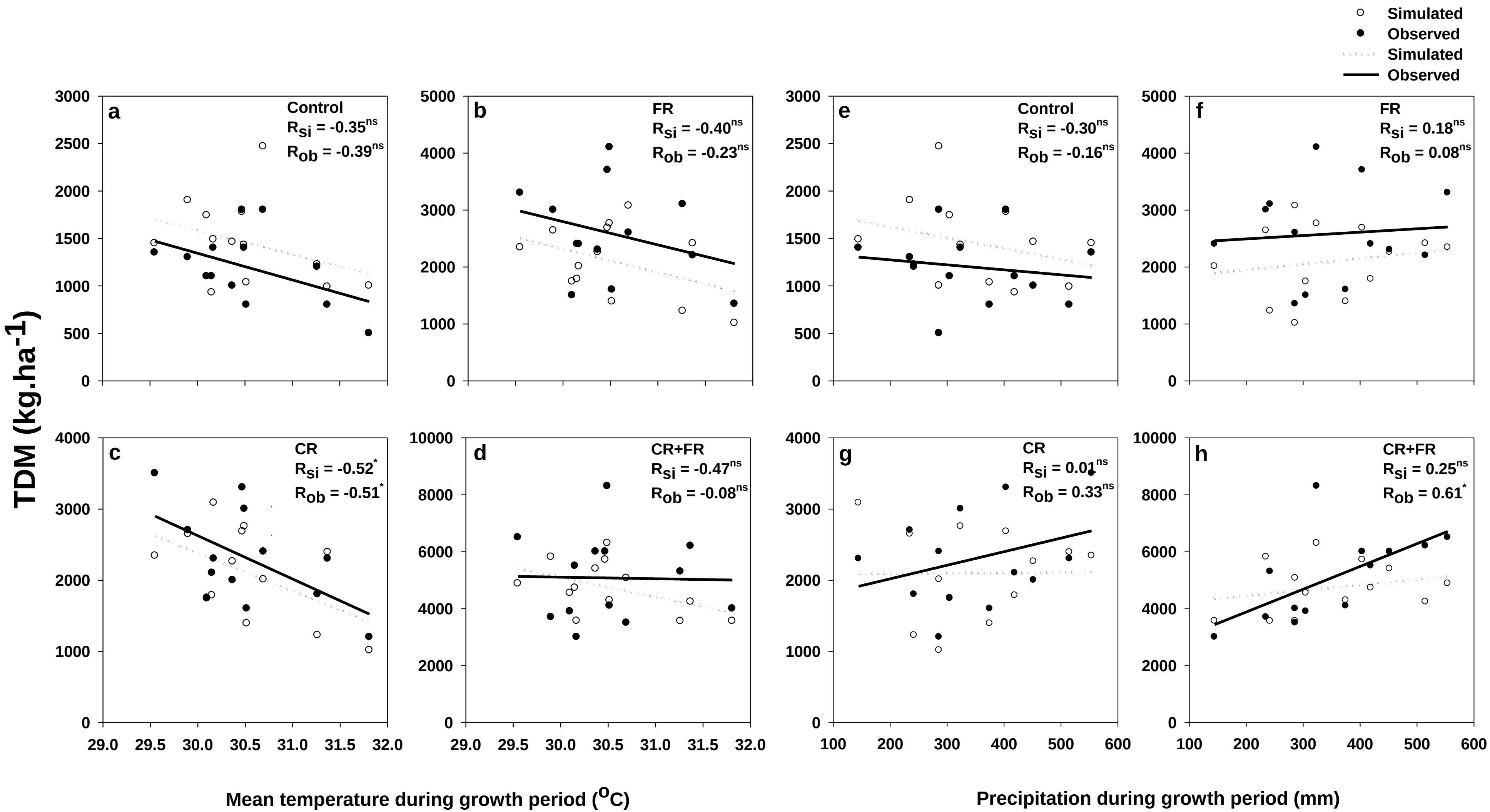


Figure 5.2. Observed and simulated relationships between total dry matter (TDM) and temperature (a, b, c, d) and precipitation (e, f, g, h) for different fertilization management treatments; without fertilization, Control (a, e) and the use of crop residue, CR (c, g), synthetic fertilizer, FR (b, f), and combination of crop residue and synthetic fertilizer, CR+FR (d, h) using data from the long term experiment between 1983-1995 (see Figure 1a). (ns, * and **: Nonsignificant and significant at 5 and 1% level of probability, respectively)

5.3.2. Evaluation of models performance

5.3.2.1. Crop model

The comparison to data of the short term experiment 1 revealed that the DSSAT model simulated grain yield (rRMSE = 11 %), leaf area index (rRMSE = 23 %), and total biomass (rRMSE = 25 %) fairly well, while total dry matter yield in the long term experiment was simulated with an rRMSE of 21% (CR), 25% (CR+FR), and 31% in the control and FR treatments, respectively (Figure 5.3). Correlation coefficients between reported and simulated dry matter yield were in the range between 0.50 (CR+FR) and 0.77 (control), indicating that the model reproduced the variability in crop yields well (Figure 5.3). Correlation coefficients between simulated pearl millet yields and mean temperature or precipitation sum in the control and FR treatments were in close agreement to the corresponding correlation coefficients calculated for observed yields. In contrast, correlation between precipitation sum and crop yield in treatments CR and CR+FR was weaker for simulated yields as compared to the coefficients from the observed yields. This indicates that the crop model reproduced very well the sensitivity of crop yields to increasing temperatures found for less fertile soil conditions (control, FR, CR) while the sensitivity of simulated crop yields to increasing precipitation under more fertile soil conditions (CR, CR+FR) was too low.

5.3.2.2. Climate model

The climate model showed a suitable performance for the baseline period (Figure 5.4). RMSE for mean monthly temperatures was 0.24 $^{\circ}$C (Figure 5.4a) while RMSE for mean of daily values of maximum (R^2 = 0.94) and minimum (R^2 = 0.97) temperature was 0.68 $^{\circ}$C, and 0.57 $^{\circ}$C respectively (Figure 5.4b and c). RMSE of monthly precipitation sum was 6.8 mm with largest deviations in September (Figure 5.4a).

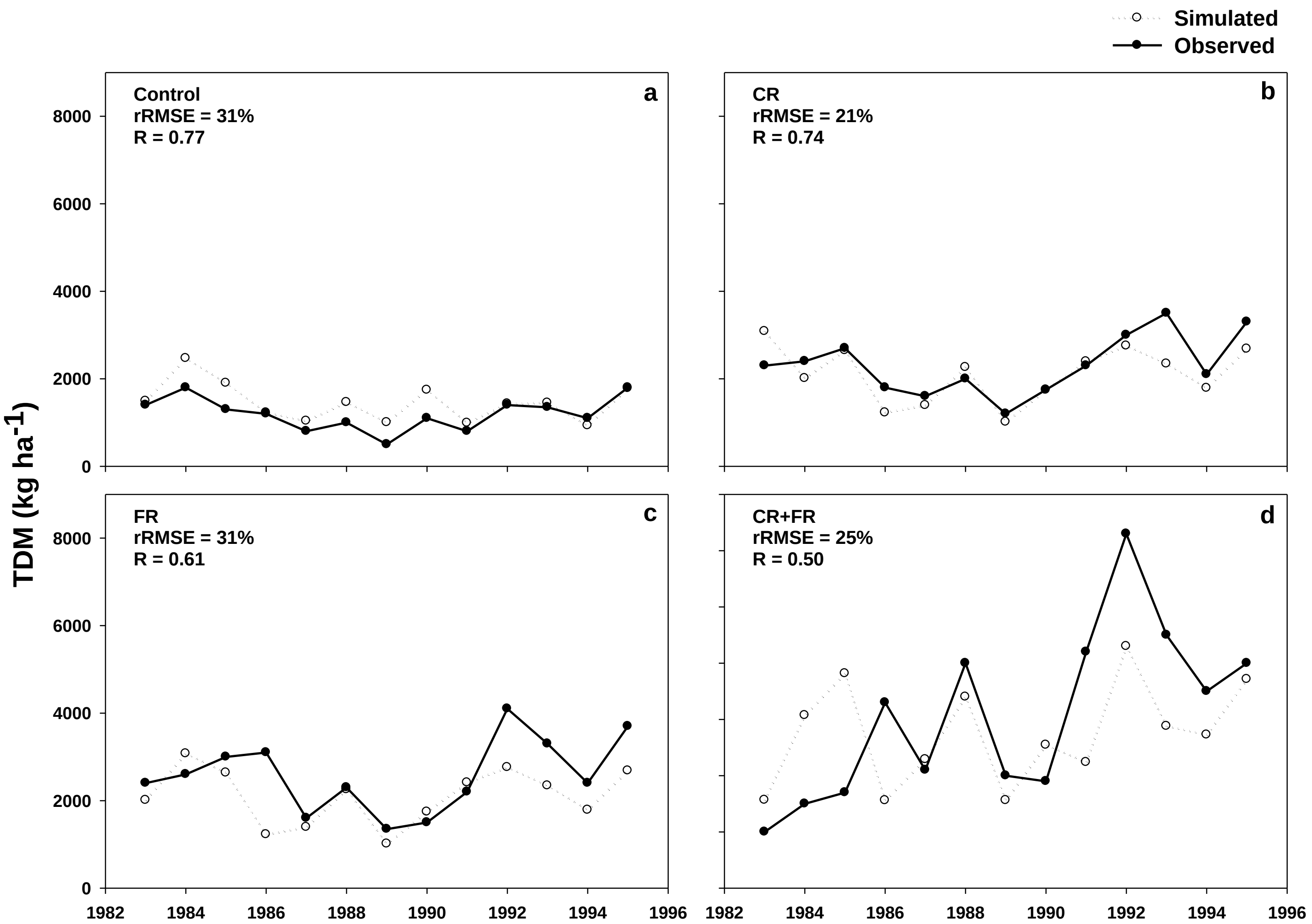


Figure 5.3. Simulated and observed pearl millet total dry matter (TDM) as affected by different fertilization treatments; without fertilization (Control, a) and the use of crop residue (CR, b), synthetic fertilizer (FR, c), and a combination of crop residue and synthetic fertilizer (CR+FR, d) in the long term field experiment between 1983-1995 (see Figure 1a).

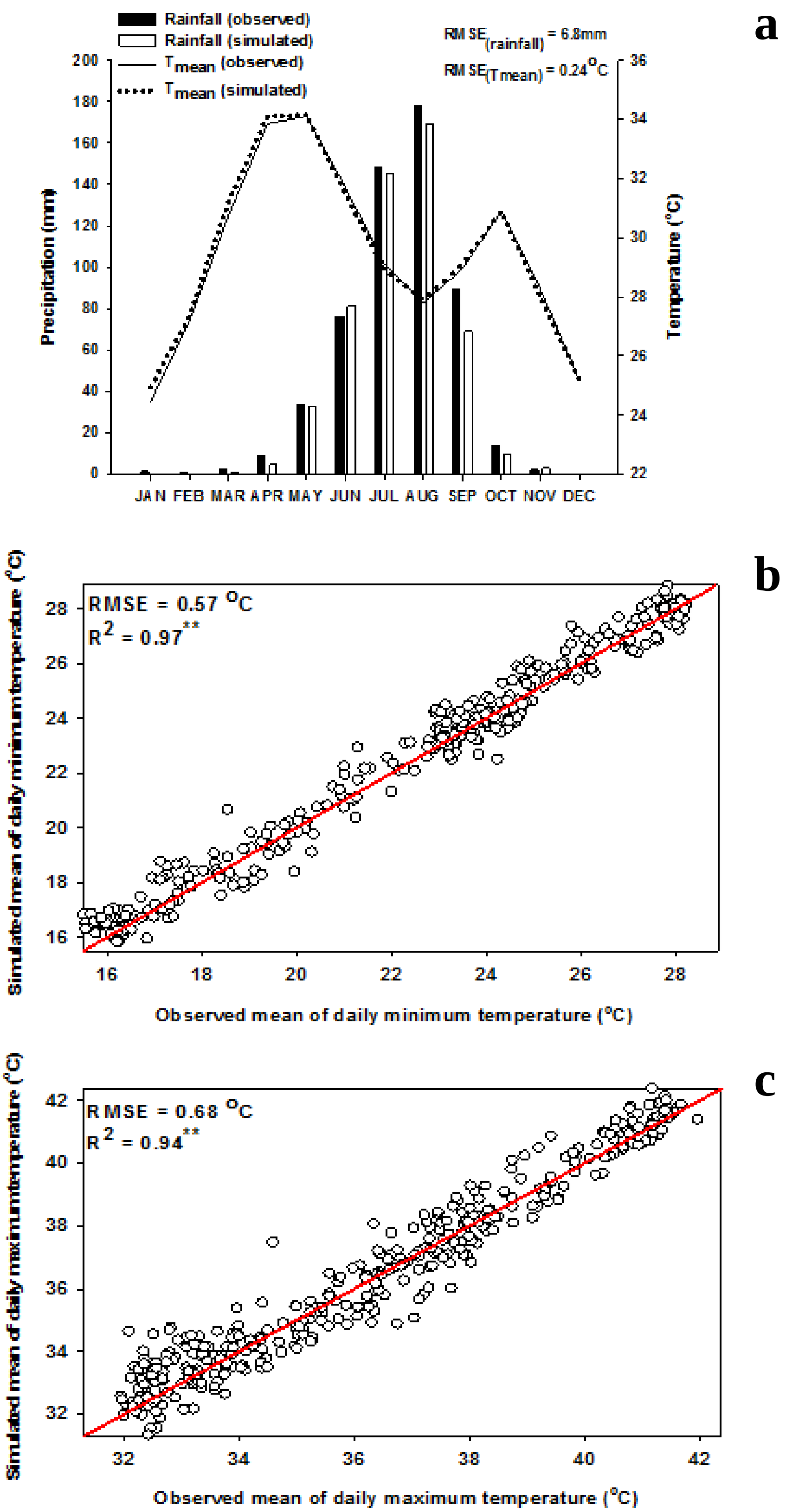


Figure 5.4. Comparison of simulated (stochastic weather generator LARS-WG) and observed mean monthly precipitation sum and mean monthly temperature (a), daily minimum temperatures (mean for each calendar day, b), and daily maximum temperatures (mean for each calendar day, c) in the baseline period 1940-2005.

5.3.3. Simulation of the impact of fertilization management on pearl millet production under historic and future climate

5.3.3.1 Trends in observed and projected climate

The results of the trend analysis indicated that mean daily minimum temperature and mean temperature increased significantly for the period 1940-2005 while annual precipitation sum declined significantly during the same period (Figure 5.5). The annual mean of daily maximum temperatures decreased but the trend was not significant (R = 0.19) (Figure 5.5).

Mean precipitation sum during the growth period was highest in the historical climate period 1940-1969 (590 mm) and declined to 442 mm during recent climate (1976-2005) conditions (Figure 5.6). The differences between scenarios and future time periods (4 to 30 mm) were much lower than differences between the applied GCMs (32 to 81 mm) (Figure 5.6).

Mean temperature during the growth period gradually increased from 28.9 °C under historic climate 1940-1969 to 33.9 °C in period 2080-2099 under emission scenario A2 (Figure 5.6). We found a large difference in projections of mean temperature during the growth period between GCMs, especially for far future (3 °C). The largest increase of mean temperature was calculated by IPCM4 and MPEH5 (Figure 5.6).

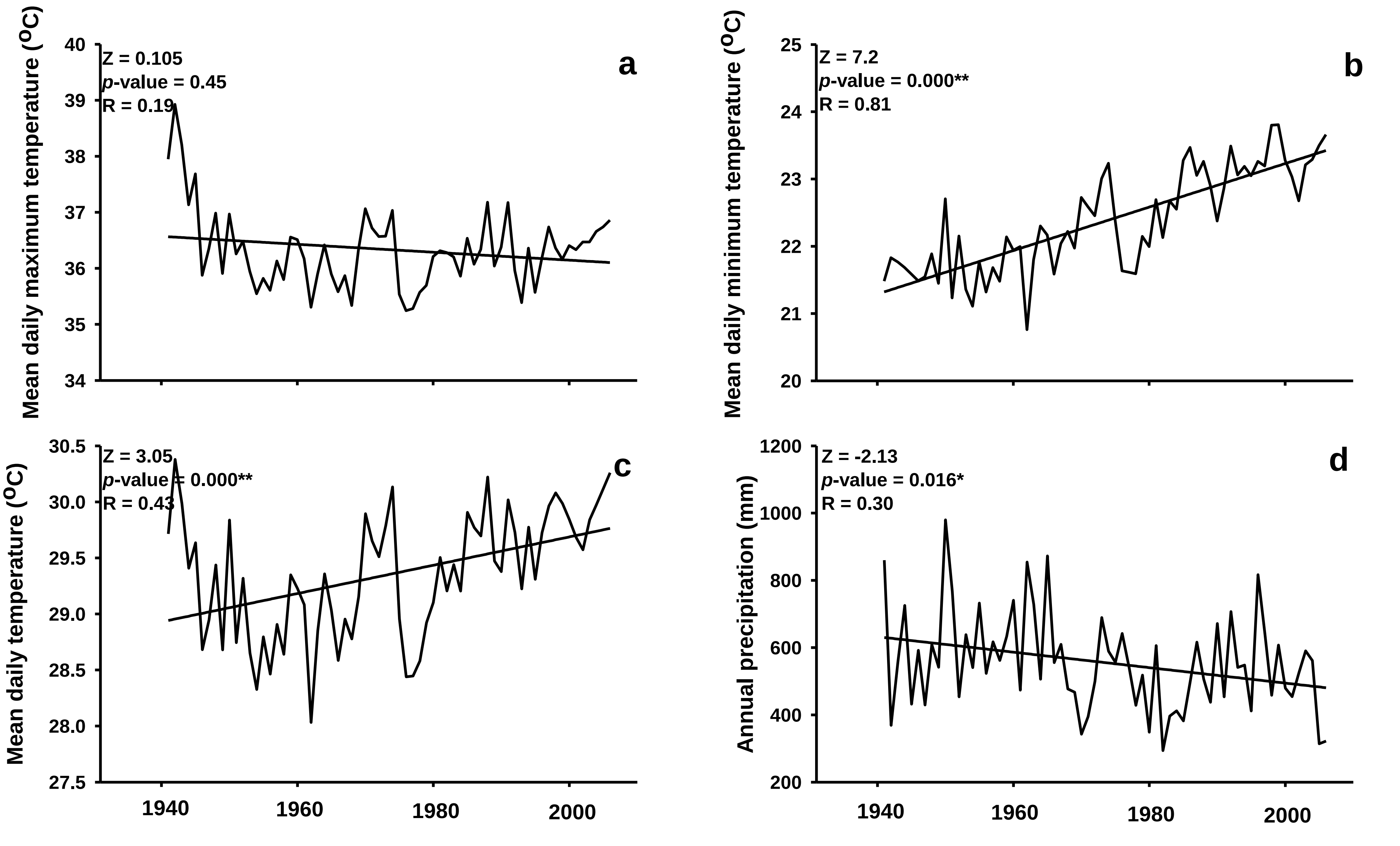


Figure 5.5. Annual mean of daily maximum (a), minimum (b) and mean temperatures (c) and mean annual precipitation sum (d) recorded by an automated weather station at Niamey (Niger Republic) during the period 1940-2005.

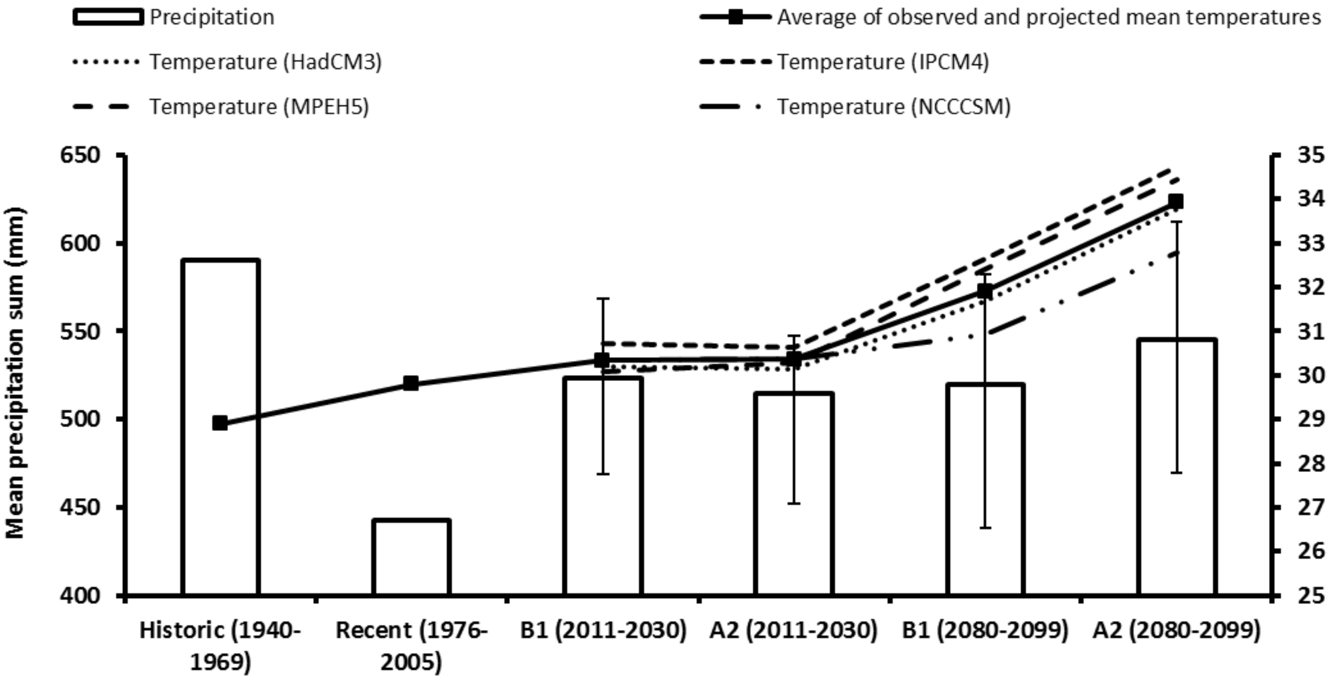


Figure 5.6. Mean temperature and precipitation sum during the pearl millet growth period projected for different time periods, scenarios, and by different general circulation models. (Error bars show the range of difference in the future precipitation projections).

5.3.3.2. Crop yields under fertilization – climate interaction

The simulation results showed a considerable impact of different fertilization practices on pearl millet total dry matter yield under different emission scenarios and time periods (Figure 5.7a). Total dry matter production was higher (13% to 28%) during recent climate in comparison to the historical period. In addition, simulated yields for period 1940-1969 were similar to the yields simulated for the period 2011-2030 (Figure 5.7a). Generally, highest pearl millet total dry matter yield was obtained for the combined application of crop residues and fertilizer (CR+FR) for all emission scenarios and time periods. However, sole application of crop residue or fertilizer significantly increased total dry matter production in all time periods and emission scenarios compared to control as well but to a smaller extent (Figure 5.7a).

Simulated future total dry matter yield was for all fertilization treatments lower than the yields of the recent period (1976-2005) (Figure 5.7a). Nevertheless, dry matter yields in the CR+FR treatment in period 2080-2099 were found to be still larger than dry matter yields in the other fertilization treatments under historic and recent climatic conditions. Dry matter yields were similar under both emission scenarios in first time period 2011-2030 [1029 kg ha^{-1} (control) to 3282 kg ha^{-1} (CR+FR)], but considerably decreased in the A2 emission scenario in second time period (2080-2099) (Figure 5.7a).

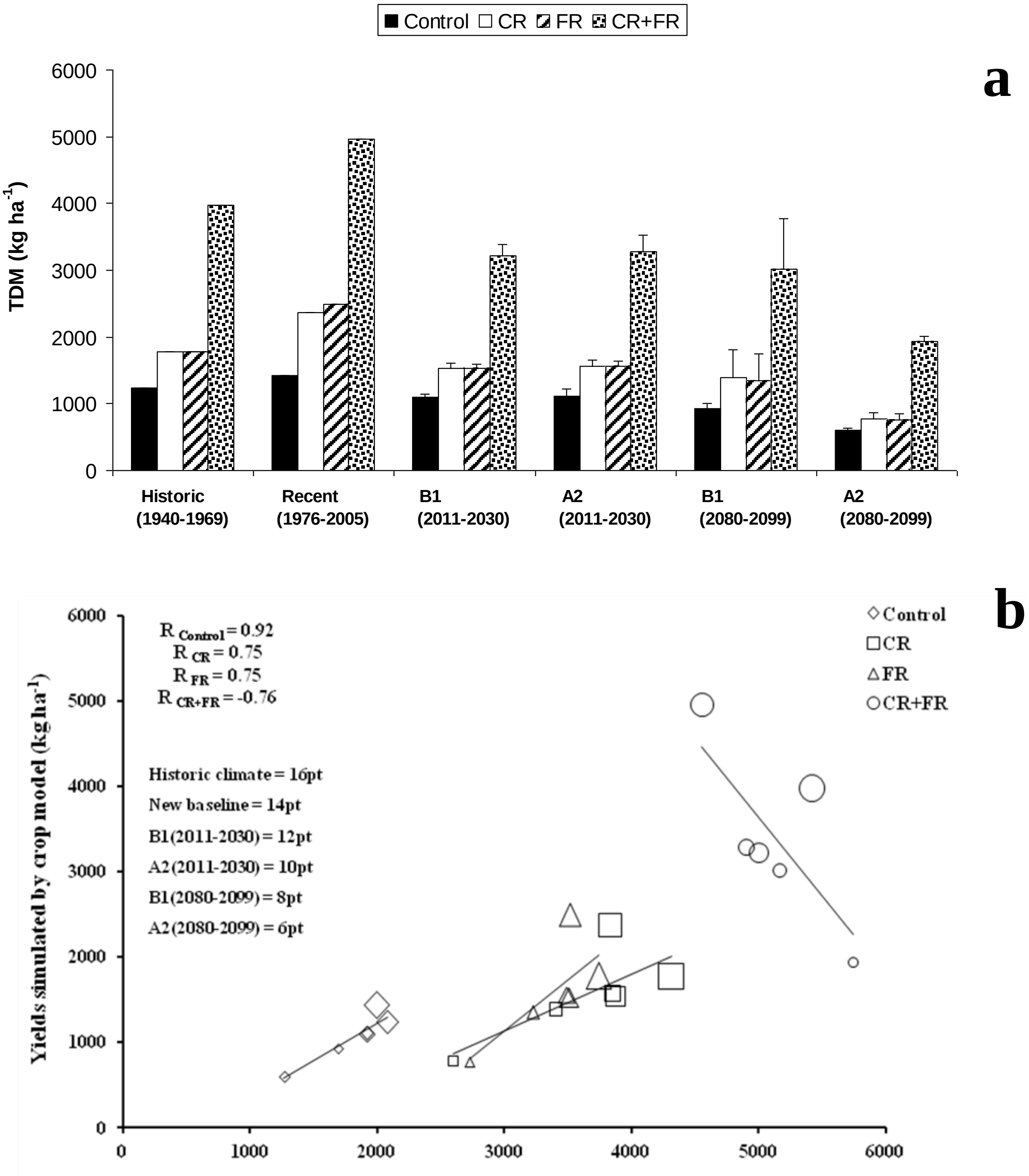


Figure 5.7. Pearl millet total dry matter production for different time periods and scenarios in response to different fertilization treatments; without fertilization (Control) und the use of crop residue (CR), synthetic fertilizer (FR), and a combination of crop residues and synthetic fertilizer (CR+FR). Error bars show the range of total dry matter yield due to the use of different GCM’s (a) and the relationship between yields simulated by the crop model and yields computed using the established regression equations (see Figure 2) for different fertilization treatments (b).

5.4. Discussion

5.4.1. Interactive effects of climate and nutrient fertilization

In this study we analysed the effect of nutrient application on the response of pearl millet to climate variability and change. The results clearly indicate that pearl millet yields strongly respond to the application of nutrients, highest and lowest crop yields were achieved when residues and fertilizer are applied in combination (CR+FR) or without any nutrient addition (Control), respectively (Figure 5.1a). However, yield variability was also determined by mean temperature and precipitation sum during the growing season and these effects showed some interaction with fertiliser treatment (Figure 5.2). The strong negative correlation between mean temperature during the growing season and observed pearl millet yields is in agreement with findings from previous research. For example, (Mohamed et al., 2002) found a linear negative relationship between annual number of days with mean minimum temperature greater than 30^{o}C and pearl millet yield. Higher temperatures generally decrease yield by increasing the plant development rate thus reducing the period available for biomass production (Chmielewski et al., 2004). There was a significant correlation in the data considered in the present study between average temperature and phenological phase duration for dry matter production of pearl millet particularly in critical phases such as grain filling for all fertilization treatments (data not shown) which is in agreement with previous research (Rezaei et al., 2013).

In contrast to the findings for the Control, FR and CR treatments, correlation between mean temperature in the growing season and pearl millet yield in the CR+FR treatment was very low (Figure 5.2) although the negative impact of higher temperature should have similar effects here as well. The high correlation of crop yields to precipitation sum in this treatment (Figure 5.2) may have masked the temperature signal as detected for the other treatments.

Annual reference evapotranspiration during the growing season calculated by using the Penman-Monteith method (Allen et al., 1998) was 411 to 467 mm for the period 1983-1995 while precipitation sum was in the range 144 mm to 554 mm. Because of the low water holding capacity of the sandy soil, the water stress factor in DSSAT 4.5 was in the range 0.03 to 0.51 (the range is between 0= no stress and 1= maximum stress) and a negative impact of drought stress on crop yields is therefore very likely for most of the years. Consequently, a significant positive correlation between precipitation sum and pearl millet yield was found for the CR and CR+FR treatments but surprisingly not for the Control and FR treatments (Figure 5.2). As indicated by previous research, a reason could be that increasing precipitation also results in increased nitrogen leaching. Heavy nitrogen leaching occurs, especially in the beginning of pearl millet growth period, when seedlings are not able to take up nutrients efficiently in the sandy soils (Esse et al., 2001). (Christianson et al., 1990) reported low nitrogen fertilizer use efficiencies with plant uptakes of 20% - 37% of the mineral fertilizer applied and (Baron et al., 2005) reported a slightly decreasing pearl millet grain yield trend in Niger when precipitation sum exceeded 500 mm. Therefore, the positive effect of less drought stress is counterbalanced by higher nutrient losses and thus poorer nutrient supply. Furthermore, long term sole application of mineral fertilizer may decrease base saturation, soil pH and increase the Al toxicity in Niger soils (Bationo et al., 1993) and continuous cultivation leads to reduction of soil organic matter. Such reduction in soil organic matter has resulted in decreased soil productivity (Bationo and Mokwunye, 1991). These studies refer to conditions similar to the common practices in pearl millet production in Niger which are without application of crop residues. In contrast, the high positive correlation between precipitation sum and pearl millet yield in CR and CR+FR treatments indicate that nutrient availability may be improved by the application of crop residues so that the positive effect of less drought stress prevailed. Application of crop residues is frequently suggested for increasing fertility of Niger soils (Bationo et al., 1998). (Bationo and Buerkert, 2001) reported that application of crop residue could increase fertilizer use efficiency and decrease soil erosion effects on soil chemical, physical and biological properties in Sahelian West Africa soils. In addition, crop residue application in sandy soils increase recycling of other nutrients such as potassium (Bationo et al., 1993), decrease the soil surface temperature by about 4 ^{o}C (Buerkert et al., 2000), improve root growth (Hafner et al., 1993), and increase water availability (Buerkert et al., 2002). Incorporation of crop residues might decline $^{15}NH_4NO_3$ losses by 39% to 45% in rotations of cereals (Thomsen and Christensen, 1998).

5.4.2. Crop model performance

The crop model showed good performance for the simulation of total dry matter production and its variability in the control, CR and FR treatments (Figure 5.2). Further analysis revealed that the main reason of the simulated yield differences between fertilization treatments was nitrogen availability. The model calculated considerable differences between the nitrogen stress factors (the range is between 0= no stress and 1= maximum stress during planting to harvest) of the different fertilization treatments (Figure 5.8a). In addition, the negative impact of high temperatures on pearl millet yield was reproduced very well by the model. However, the crop model did not completely resemble the positive effects of high precipitation on crop yields and the related shift from nutrient and heat limitation to drought limitation in the CR and CR+FR treatments (Figure 5.2). One reason could be that nitrogen leaching in CR and CR+FR treatment was overestimated by the model. In fact, nitrogen leaching simulated by the crop model in CR treatment was similar to nitrogen leaching in FR treatment while highest nitrogen leaching was computed for the CR+FR treatment (Figure 5.8b).

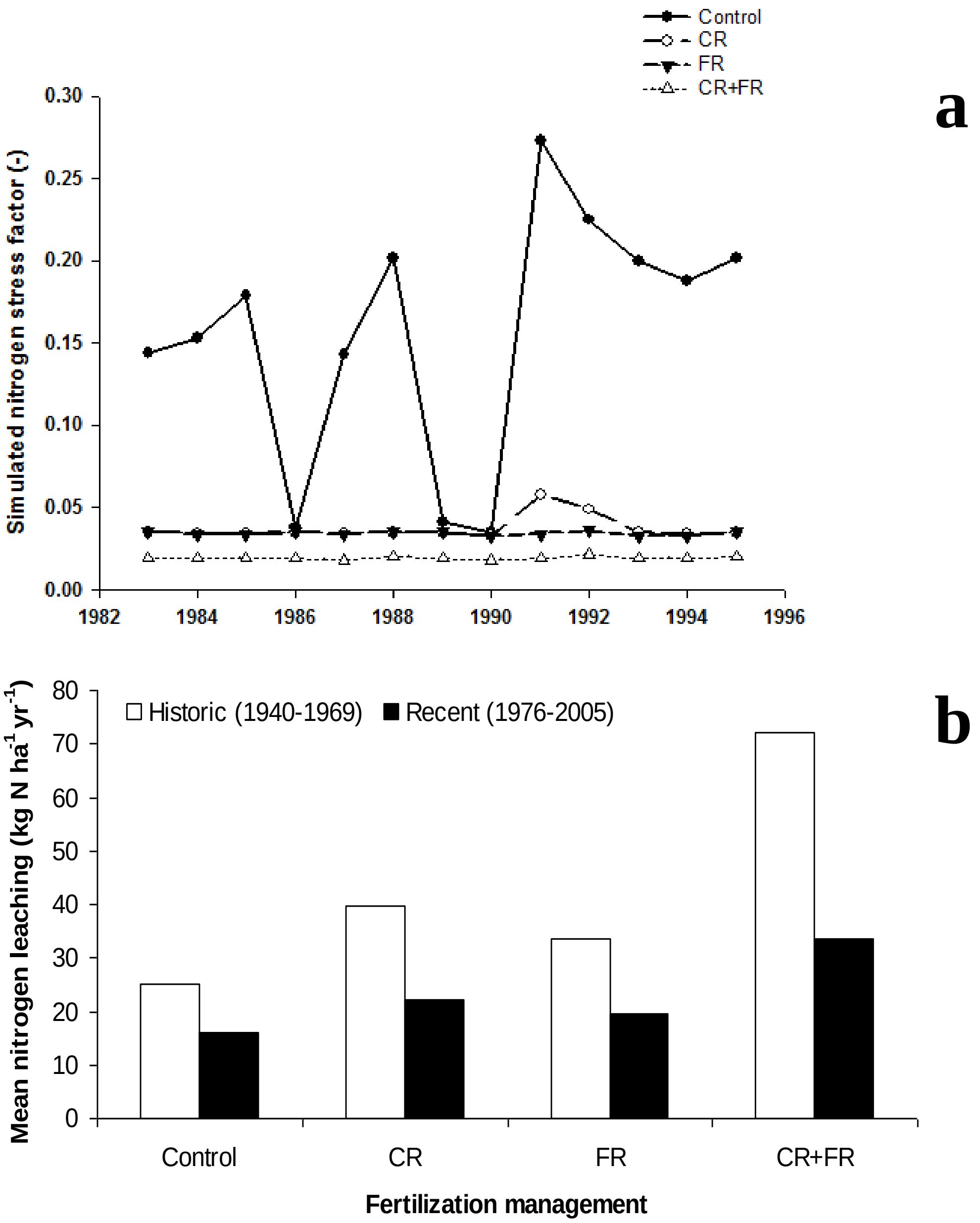


Figure 5.8. Simulated nitrogen stress factor (the range is between 0 = no stress and 1 = maximum stress) in response to different fertilization treatments; without fertilization (Control) and the use of crop residue (CR), of synthetic fertilizer (FR), and a combination of crop residue and synthetic fertilizer (CR+FR) in the long term field experiment between 1983-1995 (a) and amount of leached nitrogen (kg ha^{-1}) simulated for the historic and recent climate periods for the different fertilization treatments (b).

We found a very good agreement between total dry matter yield simulated by using the crop model and crop yields calculated by using the regression equations computed on the basis of experimental data for the Control, CR and FR treatments but a strong disagreement for the CR+FR treatment for both, current and future climate conditions (Figure 5.7b). The reasons for the disagreement for the CR+FR treatment are that the negative impact of higher temperature was not detected in the regression of temperature against observed yields while the crop model failed to reproduce the positive impact of increasing precipitation. Thus, yield projections for future time periods based on statistical regression equations can be contradictory to the yield trends predicted by crop models.

Application of multivariate regression of temperature and precipitation on crop yields did not improve the adjusted R^2 values under different fertilization management as compared to single variable regressions (Table. 5.2) although interactions between heat and drought are well described in the literature (Barnabás et al., 2008; Mittler, 2006). Furthermore, the simulations provided some explanation of the variation in crop yields which cannot be obtained from regression statistics of temperature and/or precipitation on crop yields (Table. 5.2). One possible reason for the partly unsatisfactory results of the regression models may be the use of linear regression equations. Other studies such as (Lobell et al., 2007; Urban et al., 2012) used quadratic regression equations which seemed well suited to describe crop yield response to temperature and precipitation changes. Nevertheless in our study we used linear regression equations to avoid additional variables in the regression equations because our yield time series was relatively short (13 years) and therefore not suited to derive effects of multiple variables.

5.4.3. Implications for climate change impact assessment

The historic trend of climatic variables showed that the climate at the study location has become drier and slightly warmer during the last decades. There was no considerable difference between the historic and recent periods in average mean temperature during growth period (28.9 and 29.8 ^{o}C). However, mean precipitation during growth period in period 1940-1969 (590 mm) was much higher than in period 1976-2005 (442 mm). Simulation of pearl millet yield showed higher total dry matter yields in the more recent period (Figure 5.7a). Considering the outcome of the model evaluation described before, this result should be taken with care for the CR and CR+FR treatments.

Pearl millet yield decreased significantly under climate change scenarios, especially under the A2 emission scenario and in the second time period (2080-2099). The A2 scenario is based on more than 3 ^{o}C increase in mean temperature from 2000 to 2100 (IPCC, 2001). This was mainly due to the significant correlation between average temperature and phenological phase duration with dry matter production of pearl millet particularly in critical growth stages such as grain filling period under all fertilization treatments (data not shown). Since precipitation in the climate change scenarios changed only slightly as compared to period 1976-2005, an overall decrease in pearl millet yields seems to be a reasonable result.

CO_2 concentration increase was not considered in this study, owing to the fact that C4 crops such as pearl millet already concentrate CO_2 in carboxylation site under current concentration of CO_2. Therefore elevated CO_2 concentration under climate change conditions is not expected to remarkably increase photosynthesis rate nor decline photorespiration (Ainsworth and Rogers, 2007; von Caemmerer and Furbank, 2003). On the other hand, CO_2 enrichment may affect crop yields under drought stress conditions even for C4 crops due to decreasing of stomatal conductance (Derner et al., 2003). Therefore the model may overestimate the effect of climate change on crop yield in dry years, in particular for emission scenario A2 and the far future period in which CO_2 air concentration is assumed to be highest.

In this study we analysed the combined effects of weather and fertilization on millet yields but did not investigate specifically the effects of changing climate variability. We agree that the frequency of extreme events like heat waves or strong rain can have severe impacts on nutrient availability and crop yield but believe that the uncertainty of GCM's with regard to the prediction of changes in climate variability is still too high to be considered in such an analysis. Projected changes in climate variability for West Africa are highly uncertain, in particular for precipitation (Field, 2012). For many regions in Africa GCM's even disagree considerably in projections of long-term changes in temperature and precipitation (see also Figure 6 for predictions for the study area). For example, the range of uncertainty of future climate projections across climate models was between -25% to +45% for precipitation and <+1 °C to +5 °C for mean temperature in Africa for the 2050s (Hulme et al., 2001). In AR4 of the IPCC the range of changes of precipitation projected by 14 GCMs was between -10 % to +55 % for West Africa and period 2046-2100 (IPCC, 2007).

In conclusion, we found that interactions between climate and nutrient availability need to be considered in assessments of the impact of climate change and climate variability on crop yields. Water availability may be the main limiting factor in pearl millet production whenever nutrient deficiency is reduced. The crop model showed good performance in reproducing the sensitivity of pearl millet yields to climatic variables under present low soil fertility conditions, but the sensitivity to precipitation was too low for conditions with high soil fertility. Hence, we recommend to improve the model with respect to calculation of nutrient leaching when crop residues are applied. Finally, a successful fertilization management strategy could significantly increase total dry matter production of pearl millet under current conditions and even under future climate change conditions.

Chapter 6

Adaptation of crop production to climate change by crop substitution

Based on:

Eyshi Rezaei, E., T. Gaiser, S. Siebert, F. Ewert, in press. Adaptation of crop production to climate change by crop substitution. Mitigation and Adaptation Strategies for Global Change. DOI: 10.1007/s11027-013-9528-1.

Abstract

Research on the impact of climate change on agricultural production has mainly focused on the effect of climate and its variability on individual crops, while the potential for adapting to climate change through crop substitution has received less attention. This is surprising because the proportions of individual crops in the total crop area have changed considerably over periods of time much shorter than those typically investigated in climate change studies. The flexibility of farmers to adapt to changing socioeconomic and environmental conditions by changing crop type may therefore also represent an alternative option to adapt to climate change. The objective of this case study was to investigate the potential of crop substitution as an adaptation strategy to climate change. We compared biomass yield and water use efficiency (WUE) of maize (*Zea mays* L) and pearl millet (*Pennisetum americanum* L.) grown in the semi-arid northeast of Iran for fodder production under present and potential future climatic conditions. Climate change projections for the baseline period 1970-2005 and two future time periods (2011-2030 and 2080-2099) from two emission scenarios (A2 and B1) and four general circulation models were downscaled to daily time steps using the Long Ashton Research Station-Weather Generator (LARS-WG5). Above-ground biomass was simulated for seven research sites with the Decision Support System for Agrotechnology Transfer (DSSAT 4.5) model which was calibrated and tested with independent experimental data from different field experiments in the region. The analysis of observations across all study locations showed an inverse relationship between temperature and biomass yield for both pearl millet and maize. Biomass yield was most sensitive to the duration of the phenological phase from floral initiation to end of leaf growth. For this phase we also found the highest negative correlation between mean temperature and biomass yield, which was more pronounced for pearl millet than for maize. This relationship was well reproduced by the crop model, justifying its use for the assessment. Due to the higher sensitivity of pearl millet to temperature increase, simulations suggest that the maximum benefit of crop substitution for biomass yield and WUE is to be gained for present-day conditions and would decline under future warming. The simulated increase in biomass yield due to substitution of maize by pearl millet was nevertheless larger than the yield decrease from potential climate change. Therefore, substituting maize by pearl millet should be considered as a measure for increasing fodder production in the investigated region. Differences in yields of crops that may substitute for each other because of similar use have been shown for other regions under current and potential future climatic

conditions as well, so that we suggest that our findings are of general importance for climate change research. More research is required to quantify the effects for other crop combinations, regions, and interactions with other adaptation measures.

6.1. Introduction

General circulation models (GCMs), driven by different emission scenarios, have predicted future changes in global mean temperature of between 2.0 °C and 4.5 °C in this century (Intergovernmental Panel on Climate Change (IPCC, 2001), while global temperature increase from 1850-1899 to 2001-2005 was 0.76 °C (IPCC, 2007). Temperature plays a vital role in crop growth and development and considerable deviations from optimum temperatures, especially in critical growth phases (such as leaf expansion and flowering), can considerably reduce crop yield or even result in crop failure (Asseng et al., 2013; Lobell et al., 2012; Teixeira et al., 2013).(Lobell and Field, 2007)found a distinct negative response of global wheat (*Triticum aestivum* L.), maize (*Zea mays* L) and barley (*Hordeum vulgare* L.) yields to increased temperatures during the period 1981-2002. Simulation of wheat, rice (*Oryza sativa* L.), maize and soybean (*Glycine max* L.) yields under potential future climate (2020-2080) showed a slight to moderate effect (0% to -5%) of increasing temperature on global crop production in most study scenarios (Parry et al., 2004). Reproductive growth stages of wheat, maize, rice and soybean may be exposed to higher temperatures under climate change conditions (Gourdji et al., 2013). Such effects of climate change on crop productivity call for comprehensive adaptation strategies that may even turn negative effects of climate change on agriculture into gains (Ewert, 2012). Adaptation is defined by the IPCC as an adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (Lobell et al., 2008; Reidsma et al., 2010). Adaptation approaches in crop production are classified into short-term and long-term adjustments (Olesen and Bindi, 2002). Short-term adaptation strategies include changes in sowing date, fertilization, tillage and irrigation management (Guo et al., 2010; Mall et al., 2004; Pearson et al., 2008), while long-term adjustments can be achieved by land use change and crop breeding (Jones and Thornton, 2003; Veldkamp and Lambin, 2001).

Most climate change impact studies assume that farmers make no changes in the crops grown; these studies often suggest large yield losses from climate change (Seo and Mendelsohn, 2008).

However, harvested areas of staple crops have changed remarkably during the last decade, even on a global scale. For instance, the harvested area of sugar beet and barley declined by 22% and 9%, respectively. In contrast, the growing area of maize and sunflower increased by 20% and 15% (Figure 6.1).

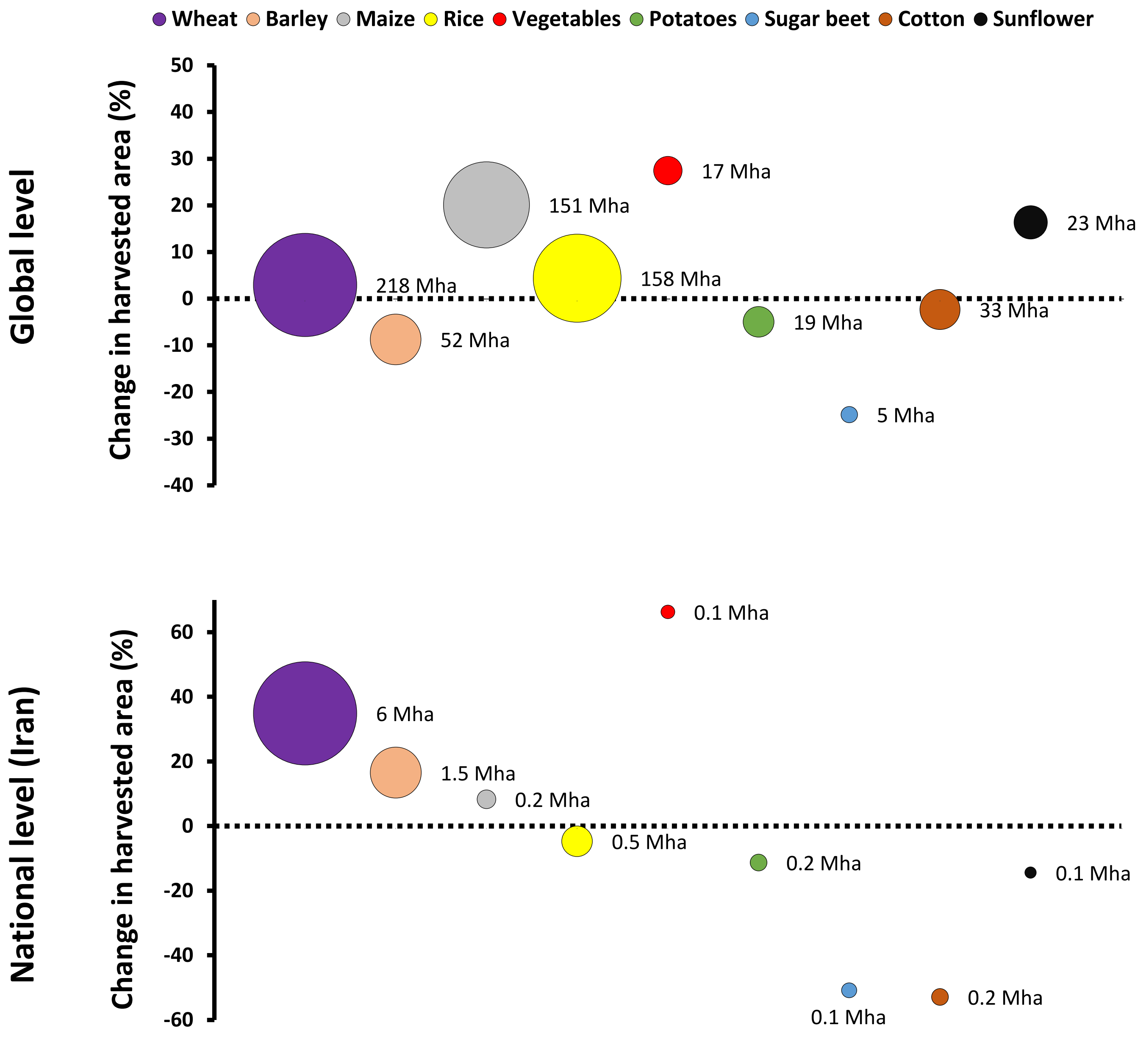


Figure 6.1. Change in harvested area (%) of specific crops at global and national level (Iran) during period 2000-2010. The bubble size shows harvested crop area in year 2010 in millions of hectares (data source: (FAO, 2013)).

(Seo and Mendelsohn, 2008) reported that choice among the seven most important crops in South America varies with climatic conditions. In another study, (Kurukulasuriya and Mendelsohn, 2007) examined whether the choice of crops is affected by climate in Africa. They found that farmers tended to choose heat-tolerant crops such as groundnut to cope with increasing temperature and drought in Africa. In some recent studies, crop productivity or crop water productivity were calculated as food calories per hectare or food calories per m^3 of crop water consumption, suggesting inherently that the crops contributing to food calorie production were exchangeable to some extent (Brauman et al., 2013; Cassidy et al., 2013).

However, little is known about the potential for crop substitution under climate change conditions. (Elsgaard et al., 2012) analyzed the effect of temperature and precipitation on crop fractions of oats (*Avena sativa* L.), wheat and maize for Europe, and assumed that the climatic factors explaining present spatial cropping patterns might also explain changes due to climate change until 2040. Based in this assumption they calculated that the proportion of oats will decline and that of maize will increase in the whole of Europe while the fraction of wheat will increase in northern Europe but decrease in southern Europe. A similar approach was used by (Ewert et al., 2005) to estimate possible changes in crop productivity.

In Iran, maize is presently one of the most important forage crops, accounting for 519,258 ha of harvested area and 11.13 million tons of production in 2011 (Ministry, 2012) but maize yields are reported to be sensitive to heat stress. Cultivation of local millet (*Pennisetum americanum* L.) varieties has a long history, but due to the introduction of new maize hybrids millet cultivation has declined, and it has become a marginal crop in this region. Recently, the introduction of high performance forage hybrids of pearl millet such as Nutrifeed has once more increased the cultivation of this crop (Aghaalikhani et al., 2008) so that it could be considered a potential substitute for maize. As with reported changes in crop proportions on a global scale, growing areas of major crops in Iran have changed quite dramatically during the last decade (Figure 6.1) and climate change impacts are expected to become a challenge for crop production in the study area. Temperature shows a significant increase during the last 60 years in the northeast of Iran (Rahimzadeh et al., 2009) while (Ragab and Prudhomme, 2002) predicted for Iran a 20-25% reduction in average rainfall and 2 to 2.75 ^{o}C increase in mean temperature for the future (2000-2050). (KOOCHEK et al., 2006), found for northeastern Iran a 21% to 41% decrease in rainfed wheat yield under future climate conditions (2025-2050) in contrast to the baseline, without considering any changes in management and adaptation strategies. In addition, simulated yields of maize would gradually decrease (by 1% to 39%) within the next 100 years compared to the baseline with normal management practices (Lashkari et al., 2012). The main objective of this paper was to explore the potential of crop substitution (pearl millet instead of maize) as a strategy for increasing fodder production and water use efficiency (WUE) under climate change conditions by comparing simulated biomass of irrigated pearl millet and irrigated maize under present and projected future climate conditions. The semi-arid region of Khorasan (northeast of Iran) was selected as study area. We tested whether the negative impact of climate change on fodder production can be compensated for or at least alleviated by growing pearl millet instead of maize. A schematic diagram illustrating data, models and workflow used in our study is shown in Figure 6.2, while a detailed description of materials and methods is provided in the next section.

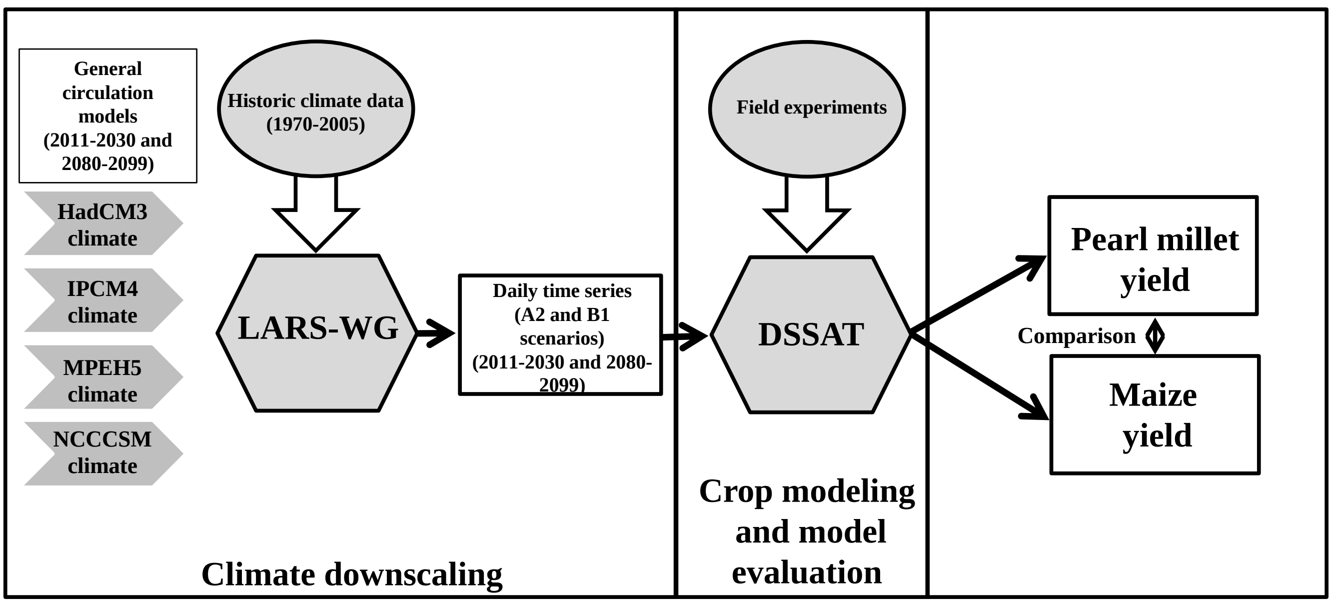


Figure 6.2. Schematic diagram of the applied climate and crop models and related flow of information.

6.2. Methods

6.2.1. Study area

Khorasan region is located in northeastern Iran and divided into three provinces (North, South and Razavi Khorasan). It covers an area of about 248,000 square kilometers and has a population of more than 8 million inhabitants. Agriculture is the main source of income for 69% of the population and is therefore the most important economic sector. The growing area of irrigated summer crops (second harvested crop during the growing season) was 62,838 ha in 2011, of which almost half (30,618 ha) was under forage maize (Ministry, 2012). Resistance of local farmers exposed to changing crop patterns and difficulties in getting access to seeds imported from other countries have until now restricted the growing area of new pearl millet hybrids like Nutrifeed, which was analyzed in this study. The research sites Mashhad, Birjand, Bojnourd, Sabzevar, Sarakhs, Gochan and Torbat-h are main agricultural centers in Khorasan, situated between 32º-37º N (Figure 6.3). The climate is continental, with a large difference between mean monthly temperature in January (3 °C) and July (27 °C). Average annual rainfall during the last 40 years was 222 mm and varied from about 169 mm in the south to 269 mm in the north (Table. 6.1). The soil type at the study locations was sandy loam, loam or clay loam with 100-140 mm available water capacity in 1 m soil depth (Table. 6.2).

Table. 6.1. Geographical coordinates and annual means of daily maximum temperature (Tmax), daily minimum temperature (Tmin), and rainfall during the period 1970-2005; common sowing date and nitrogen fertilizer application rates for pearl millet and maize cultivation at the study locations.

Location	LAT (dd)	LON (dd)	Altitude (m)	Annual rainfall (mm)	Tmax (ºC)	Tmin (ºC)	Pearl millet sowing date	Maize sowing date	Nitrogen application (kg N ha^{-1} yr^{-1})
Mashhad	36.1	59.3	999	256	21	7	June 10	May 20	300
Sabzevar	36.1	57.4	977	192	24	11	May 22	April 30	250
Sarakhs	36.3	61.1	235	189	24	10	June 10	April 30	250
Bojnourd	37.2	57.1	1091	269	20	7	July 1	June 5	300
Birjand	32.5	59.1	1491	169	24	8	May 30	May 1	250
Gochan	37.4	58.3	1287	266	19	5	July 1	June 5	300
Torbat-h	35.1	59.1	1450	244	19	7	June 10	May 20	300

Table. 6.2. Soil texture and water storage capacity at the study locations.

Location	Soil texture	Field capacity (m/m)	Permanent wilting point (m/m)
Mashhad	Clay loam	0.24	0.10
Sabzevar	Loam	0.18	0.08
Sarakhs	Clay loam	0.22	0.11
Bojnourd	Loam	0.26	0.12
Birjand	Loam	0.18	0.08
Gochan	Clay loam	0.25	0.13
Torbat-h	Sandy loam	0.20	0.09

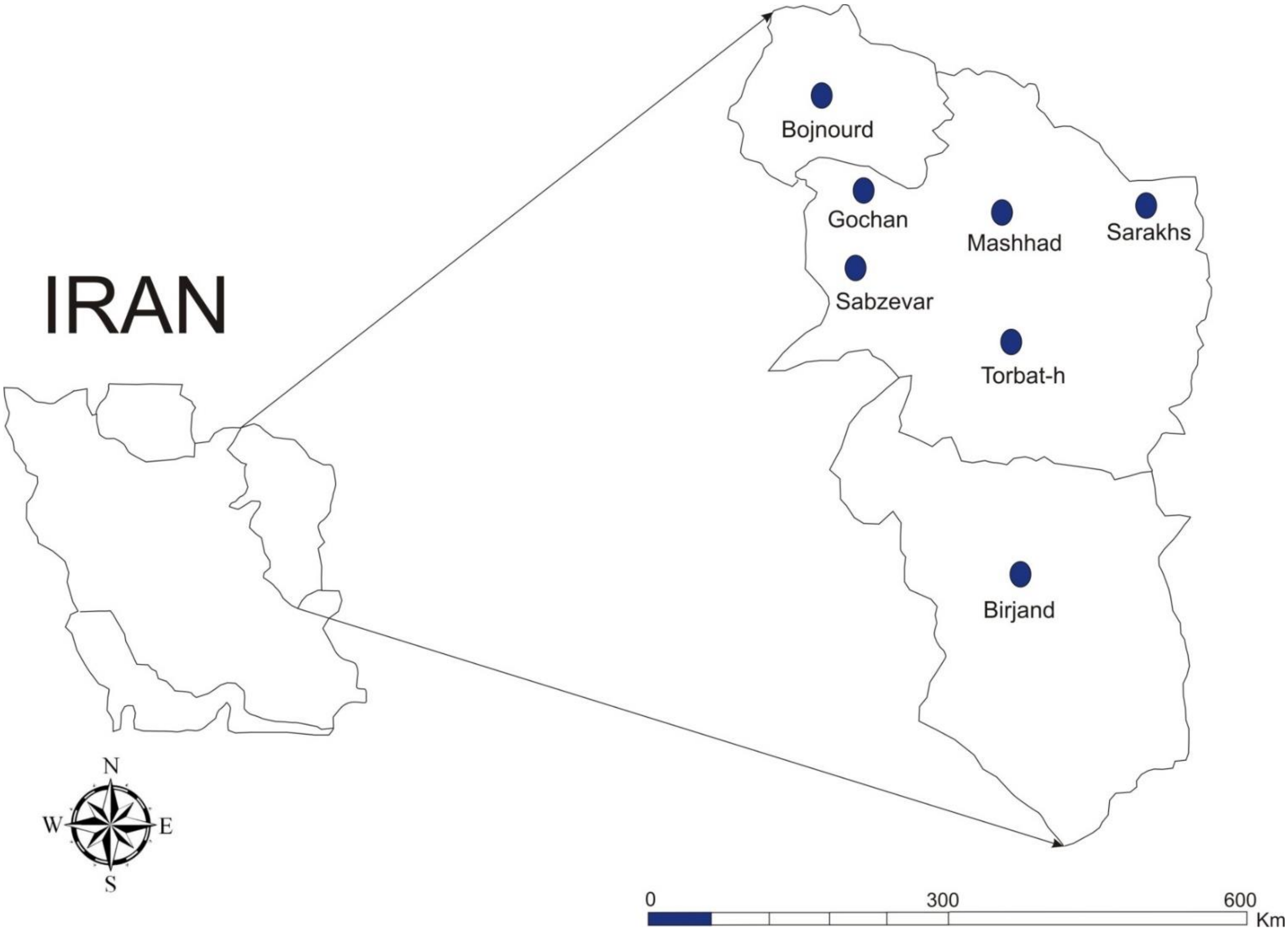


Figure 6.3. Map showing the study locations in Khorasan (northeast Iran).

6.2.2. Processing of climate data

Daily time series of maximum, mean and minimum temperature (ºC), rainfall (mm day^{-1}) and global radiation (MJ m^{-2} day^{-1}) for the period 1970-2005 were obtained from automatic weather stations located at the sites Mashhad, Birjand, Bojnourd, Sabzevar, Torbat-h, Gochan and Sarakhs and provided by Iran's meteorological organization. In some years only daily sunshine hours were available so that daily solar radiation was estimated by applying the Angstrom–Prescott equation, tested by 10 years of observed daily values (Suehrcke, 2000).

Monthly time series of the climate variables simulated by the four general circulation models (GCM) Institute Pierre Simon Laplace, France (IPCM4) (Semenov and Stratonovitch, 2010), United Kingdom Met Office Hadley Center (HadCM3) (Mitchell et al., 1995), Max-Planck Institute for Meteorology, Germany (MPEH5) (Brands et al., 2011) and National Centre for

Atmospheric Research, USA (NCCCSM) (Jackson et al., 2011) and two emission scenarios Special Report on Emissions Scenarios (SRES)-A2 and SRES-B1 were downscaled to daily time steps using the stochastic weather generator called Long Ashton Research Station-Weather Generator (LARS-WG5) (Semenov and Stratonovitch, 2010). By using various GCMs which were developed in different countries we attempt to account for model uncertainty of the GCMs. The SRES-A2 scenario is one of the most extreme scenarios, with global carbon emissions rising from about 10 Gt at present to over 25 Gt in 2100 (medium to high carbon emissions) (Prudhomme et al., 2010). This emission scenario is commonly used for 'business as usual' impact studies, projecting a 3 ^{o}C increase in global surface air temperature by 2100 (Donner et al., 2005). The SRES-B1 scenario is more optimistic (low to medium carbon emissions) describing a world with reduced use of natural resources and the use of clean and resource-efficient technologies (Levinsky et al., 2007).

LARS-WG was calibrated with 35 years' (1970-2005) observed daily weather data across study locations. The model parameters were then adjusted with the predicted changes in climatic mean and variability, derived from the GCM output (Semenov, 2009; Semenov and Brooks, 1999) to simulate daily time series for the three periods 1970-2005 (baseline), 2011-2030 (near future) and 2080-2099 (distant future). Based on this method, climate change information embedded in GCMs was employed to adjust the parameters used in LARS-WG which had previously been calibrated for the study locations by using observed daily weather data (Semenov and Barrow, 1997).

6.2.3. Crop modeling

6.2.3.1. Model description

CERES-Maize and CERES-Millet are used in this study within the frame of DSSAT (Decision Support System for Agrotechnology Transfer) version 4.5. DSSAT simulates crop phenology, biomass allocation to root, stem, leaf, and grains, and soil water and nutrient movement in daily time steps for both maize and pearl millet (Jones et al., 2003) and has been used before for simulation of crop yields in Iran (Lashkari et al., 2012). Input data used for the simulations were cultivar genetic coefficients, field characteristics, soil features, crop management details and climatic variables (Soler et al., 2008; Yang et al., 2006; Žalud and Dubrovský, 2002).

6.2.3.2. Model parameterization

We used observations for one year from field experiments for crop model parameterization (estimating genotype coefficients) for pearl millet (Nutrifeed cultivar). The field experiment was arranged in split plots in a Randomized Complete Blocks Design with 3 replications in the 2008-2009 growing season at Mashhad to investigate the effect of different irrigation water applications (800, 400, 200 and 100 mm during the growing season) on crop yield (Nabati and Mogadam, 2011). Genetic coefficients of the pearl millet cultivar were estimated by using the Genetic Coefficient Estimator (Gencalc) (Hunt et al., 1993). Maize genotype coefficients (Single Cross 704) were obtained from (Lashkari et al., 2012) (Table. 6.3).

Table. 6.3. Calculated genetic coefficients of maize cv. 'Single Cross 704' (Lashkari et al., 2012) and pearl millet cv. 'Nutrifeed' used in this study.

Pearl millet			Maize		
Parameter Name	Value	Unit	Parameter Name	Value	Unit
P1	114	°C day	P1	250	°C day
P2O	12.1	hour	P2	0.1	hour
P2R	90	°C day	P5	600	°C day
P5	160	°C day	G2	700	-
G1	2	-	G3	17	mg day^{-1}
G4	0.5	-	PHINT	30	°C day
PHINT	43	°C day	-	-	

P1: Thermal time from seedling emergence to the end of the juvenile phase expressed in degree days above a base temperature of 8°C for maize and 1ºC for pearl millet during which the plant is not responsive to changes in photoperiod, P2: Extent to which development (expressed as days) is delayed for each hour increase in photoperiod above the longest photoperiod at which development proceeds at a maximum rate (which is considered to be 12.5 h), G2: Maximum possible number of kernels per plant, G3: Kernel filling rate during the linear grain filling stage and under optimum conditions, PHINT: Phyllochron interval; the interval in thermal time (degree days) between successive leaf tip appearances, P20: Critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate. P2R: Extent to which phasic development leading to panicle initiation (expressed in degree days) is delayed for each hour increase in photoperiod above P2O, P5: Thermal time (degree days above a base temperature of 1ºC) from beginning of grain filling (3-4 days after flowering) to physiological maturity, G1: Scaler for relative leaf size, G4: Scaler for partitioning of assimilates to the panicle (head).

6.2.3.3. Model testing

Two years of field experimental data were used for crop model testing. The first pearl millet experiment was carried out in Mashhad in split plots in a Randomized Complete Blocks Design with 4 replications. Three plant densities (20, 13.3 and 10 plants m^{-2}) and three levels of nitrogen (N) application (200, 300 and 400 kg N ha^{-1} applied as urea) were arranged as main and sub-plots, respectively (Aghaalikhani et al., 2008). The second experiment for pearl millet model validation had a factorial arrangement of three millet cultivars and two sowing dates (Kamkar et al., 2005).The maize model was tested by using data from a two-year field experiment at Mashhad, in which the effect of different plant densities (3, 5, 7, 9, 11, 13 and 15 plants m^{-2}) of maize was investigated (Goldani et al., 2009). Model input data for weather, soil and treatments were set in the simulation runs according to the data from the field experiments. Crop management (e.g. soil preparation, sowing and harvesting dates (milky ripeness stage for maize and beginning of the grain-set on panicles for pearl millet), and plant protection) was specified for both crops according to reported observations of local management practices at the study locations and assumed to be similar in simulations of future crop production. Irrigation was scheduled automatically by the model (800 mm for both crops) while nitrogen fertilizer application was defined for each site based on observed local practices (Table. 6.1). Water use efficiency (WUE, kg m^{-3}) was calculated as the ratio of above-ground biomass production to crop evapotranspiration (Kar et al., 2007).

6.2.4. Evaluation of the performance of the models

The Root Mean Squared Error (RMSE) was computed to measure the agreement between measured and simulated values in the climate (LARS-WG) and crop model (DSSAT) simulations. The RMSE quantifies the model's prediction error by heavily weighting large errors (Brisson et al., 2002). The model's simulation accuracy increases as values of RMSE approach 0. Normalized (%) and absolute values (in units of O_i) of RMSE for evaluation of climate and crop model were calculated as:

$$AbsoluteRMSE = \left[n^{-1} \sum_{i=1}^{n} (P_i - O_i)^2 \right]^{0.5} \quad (1)$$

$$NormalizedRMSE(\%) = \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n} \right]^{0.5} \times \frac{100}{\overline{O}} \quad (2)$$

where Pi and Oi are the simulated and observed data, $\overline{O}$ the mean of observed data and n the number of observations.

6.2.5. Evaluation of the effect of temperature on biomass yield

The effect of temperature on biomass yields of pearl millet and maize was tested by regression of above-ground biomass yield on mean temperature during the phenological phases “emergence to end of juvenile”, “end of juvenile to floral initiation”, “floral initiation to end of leaf growth”, “end of leaf growth to beginning of grain filling”, and “grain filling”. Yield information for three study locations (Mashhad, Sabzevar and Gochan) and the period 2001 to 2005 was obtained from local farmers’ reports (Ministry, 2012) Due to lack of phenological data, development phases were simulated by the DSSAT 4.5 model. Finally the regression was repeated by using simulated crop yields to investigate whether relationships found for observed yields were reproduced by the crop growth model.

6.3. Results

6.3.1. Model evaluation

6.3.1.1. Evaluation of the climate model

The accurate prediction of climatic variables such as temperature and rainfall for the baseline period demonstrates the precision of downscaling methods in climate change assessments (Viglizzo et al., 1997). In general, LARS-WG showed a high accuracy in predicting monthly mean temperatures, especially in the baseline period at Sabzevar (RMSE = 1.4 ^{o}C) and the lowest precision at Gochan (RMSE = 2.4 ^{o}C) which had the highest rainfall record in Khorasan (Figure 4).

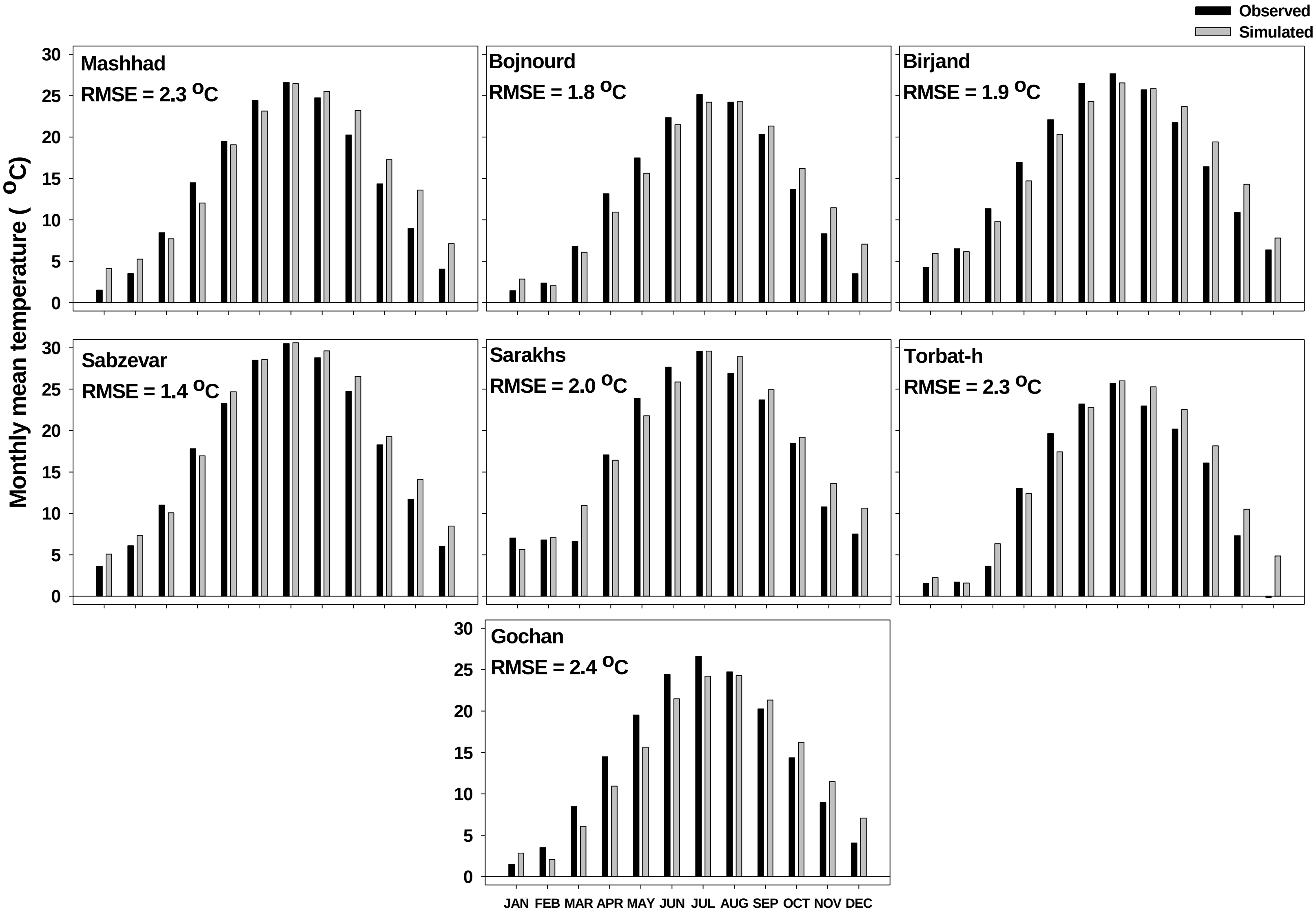


Figure 6.4. Comparison of simulated and observed average monthly mean temperature for the study locations in the baseline period 1970-2005.

6.3.1.2. Evaluation of the crop model

The results of the DSSAT model showed a satisfactory accuracy in the simulation of total biomass and leaf area for both crops. The model predicted total biomass (normalized $RMSE_{\text{pearl millet}}$ = 6% and normalized $RMSE_{\text{maize}}$ = 9%) and grain yield (normalized $RMSE_{\text{maize}}$ = 8%) with a high accuracy for both crops. Leaf area index was slightly overestimated by the model with a relative simulation error of 16% for pearl millet and 12% for maize (Table. 6.4).

Importantly, the observed inverse relationship between biomass yield and mean temperature during the period from floral initiation to the end of leaf growth was well reproduced by the model for both crops (Figure 6.5). The inverse relationship between biomass and mean temperature in this phase was stronger in pearl millet (slope of -913 and -866 kg ha^{-1} $°C^{-1}$ for observed and simulated yields, respectively) as compared to maize (slope of -461 and -489 kg ha^{-1} $°C^{-1}$ for observed and simulated yields, respectively, Figure 6.5). The good performance of the model justified its application to predict the effects of climate change on biomass yield.

Table. 6.4. Results of model testing for grain yield, total biomass and leaf area index of pearl millet and maize expressed as the normalized root mean-squared error (RMSE%).

Parameters	Pearl millet$_{\text{(RMSE\%)}}$	Maize$_{\text{(RMSE\%)}}$
Grain yield	-	8
Total biomass	6	9
Leaf area index	16	12

6.3.2. Effect of crop substitution on biomass yield and water use efficiency

6.3.2.1. Current conditions (baseline)

The results of the simulations for the baseline period 1970-2005 showed a higher crop yield of pearl millet than maize for all study locations (Figure 6.6a). The yield difference between pearl millet and maize was largest at Torbat-h (7041 kg ha^{-1}) and Gochan (6743 kg ha^{-1}) and smallest at Sabzevar (2882 kg ha^{-1}) and Sarakhs (4690 kg ha^{-1}) (Figure 6.6a). WUE of pearl millet was higher than WUE of maize at all locations except Sabzevar, the warmest location in Khorasan (Figure 6.6b). Differences in WUE between pearl millet and maize were largest in Torbat-h (0.74 kg m^{-3}) and Gochan (0.73 kg m^{-3}) which lie in the colder parts of N-E Iran (Figure 6.6b).

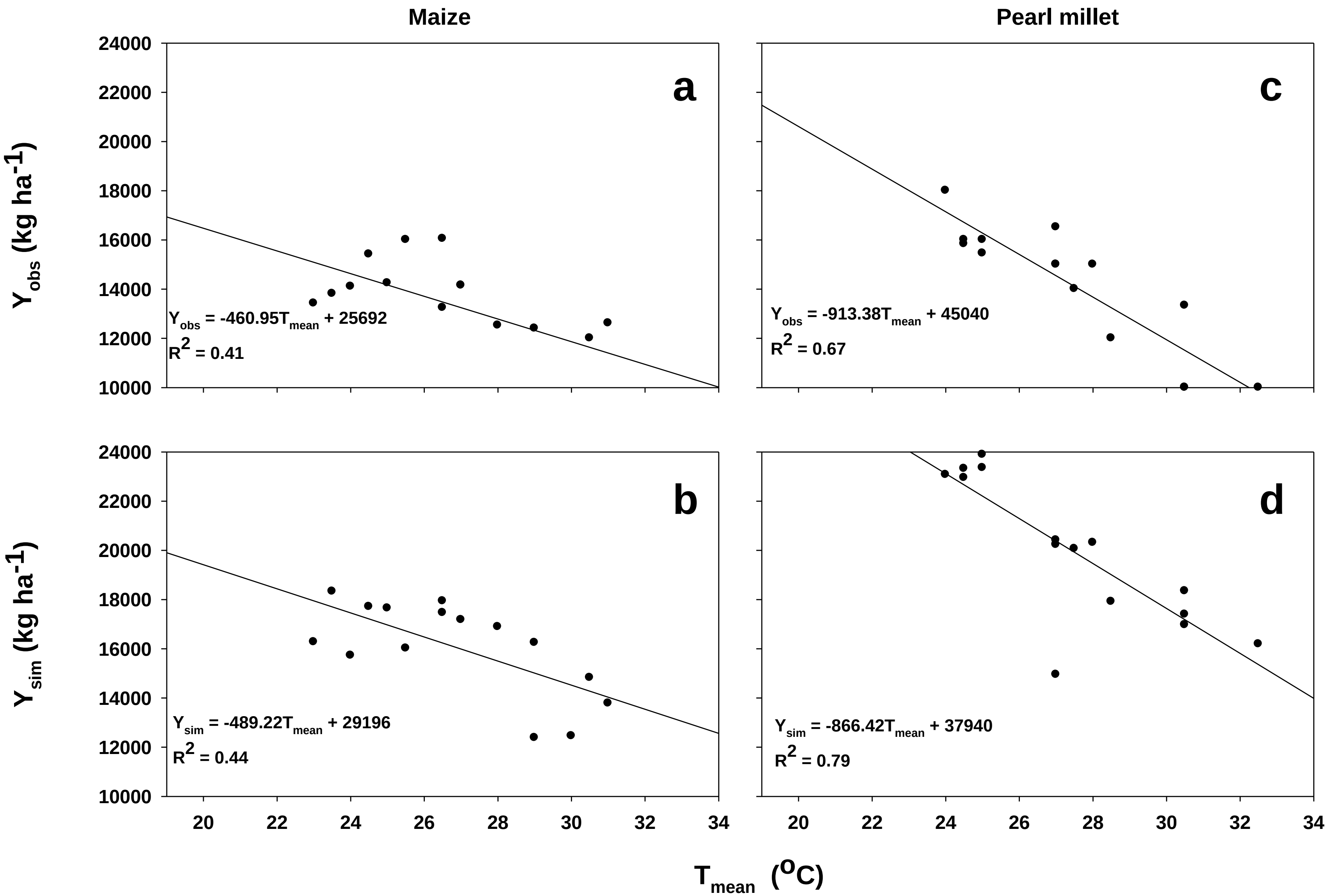


Figure 6.5. Relationship between simulated (Y_{sim}) and observed (Y_{obs}) biomass yields of maize (a and b) and pearl millet (c and d) with mean temperature during the most critical development phase (floral initiation to end of leaf growth) (T_{mean}). Data refer to three locations and five years (2001-2005). Please note: records for observed yield differ from the data used for model testing and calculation of RMSE (%) (Table. 6.4), differences between observed yield and simulated yield are likely caused by different management (e.g. fertilizer application).

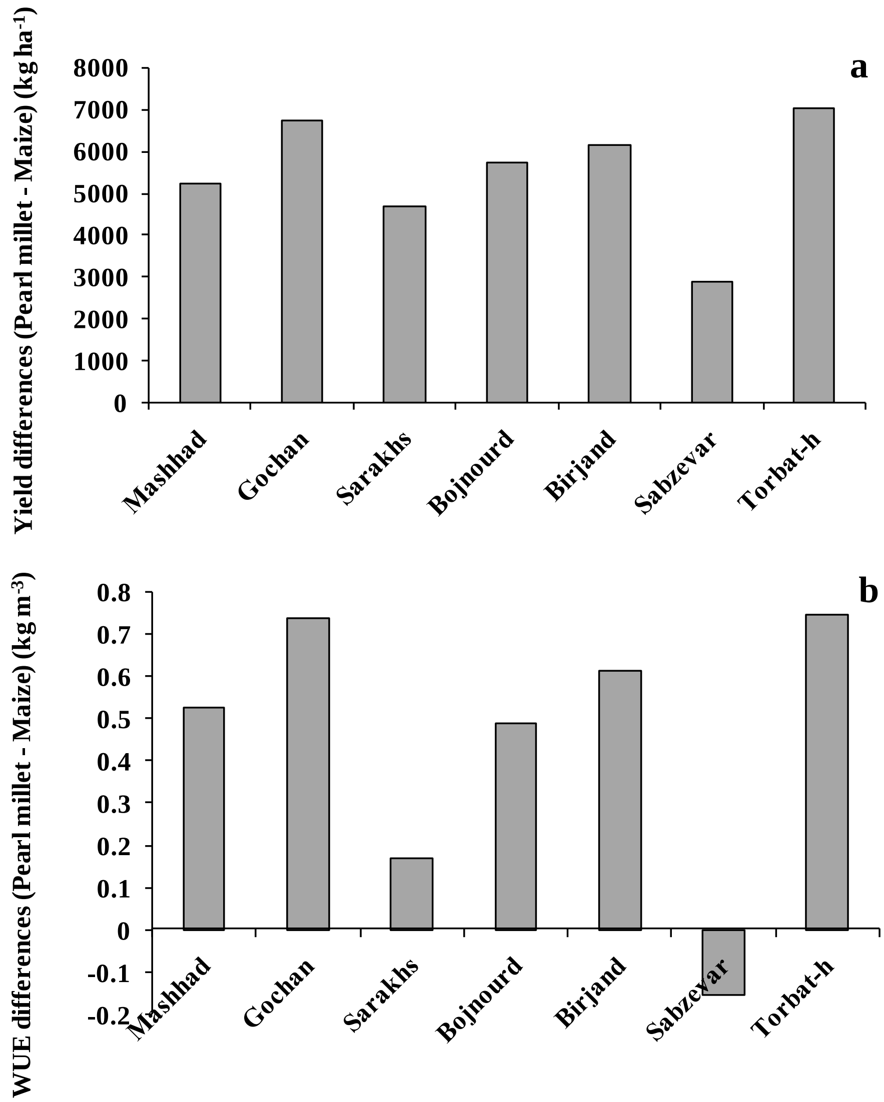


Figure 6.6. Difference between simulated biomass yield (a) and water use efficiency (WUE) (b) between pearl millet and maize under baseline conditions in different study locations.

6.3.2.2. Future climate

Simulated biomass yields under climate change remained higher for pearl millet than for maize but the difference between them narrowed. This effect of a declining difference in future biomass yields between the two crops was more pronounced in simulations assuming a large global warming (A2 scenario, period 2080-2099) and at sites characterized by cooler baseline conditions, like Torbat-h or Gochan (Figure 6.7). For example, absolute yield difference between pearl millet and maize at Torbat-h for the period 2080-2099 and the A2 scenario declined by 3669 kg ha^{-1} (average for the four climate models) while the absolute yield difference at Sabzevar for the B1 scenario declined by only 1235 kg ha^{-1}. The effect was mainly caused by the strong decline of pearl millet biomass yield under global warming (Figure 6.7).

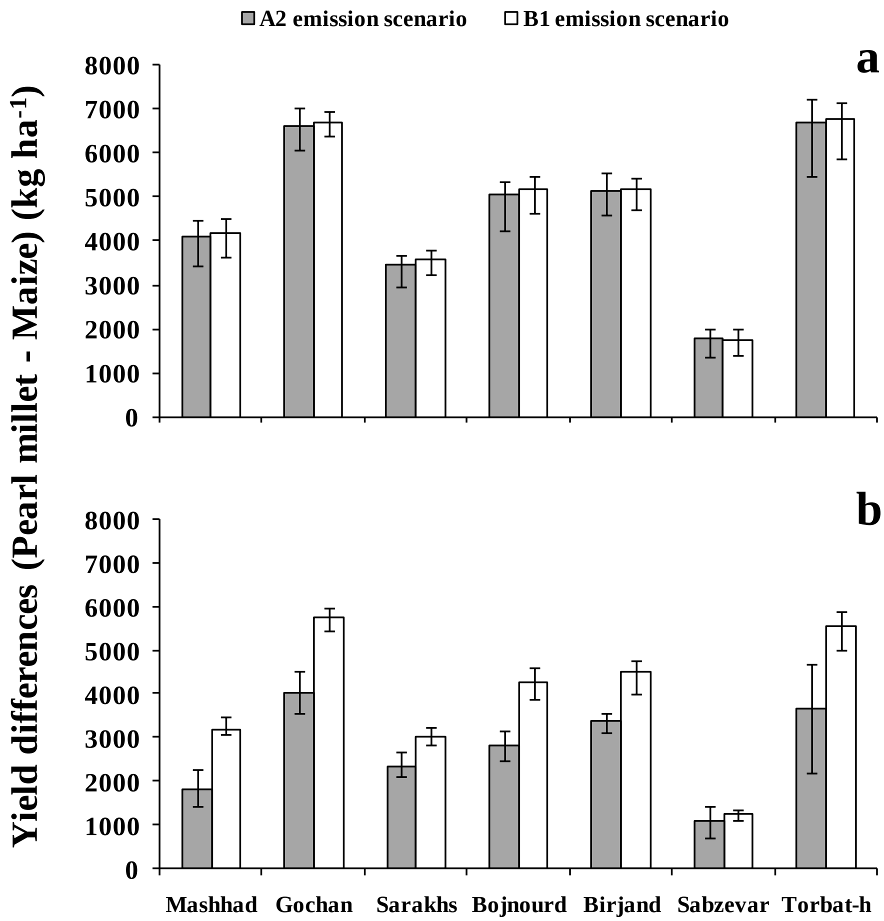


Figure 6.7. Differences in simulated biomass yield between pearl millet and maize for different study locations for the A2 and B1 emission scenarios in periods 2011-2030 (a) and 2080-2099 (b). (Error bars show range of yield difference across GCMs).

Effects of climate change on WUE were similar to those for biomass yield. Pearl millet had a higher WUE at all study locations except Sabzevar where WUE of maize was higher in the near future period under both emission scenarios (Figure 6.8). WUE at the study locations was between 5.10 and 3.26 kg m^{-3} for pearl millet and 4.77 and 3.25 kg m^{-3} for maize. The largest differences in WUE between pearl millet and maize were obtained for Gochan (0.67 to 0.72 kg m^{-3}) and Torbat-h (0.58 to 0.59 kg m^{-3}) for the near future period while the advantage of pearl millet's WUE decreased greatly for the distant future period, especially when using the SRES-A2 scenario (Figure 6.8).

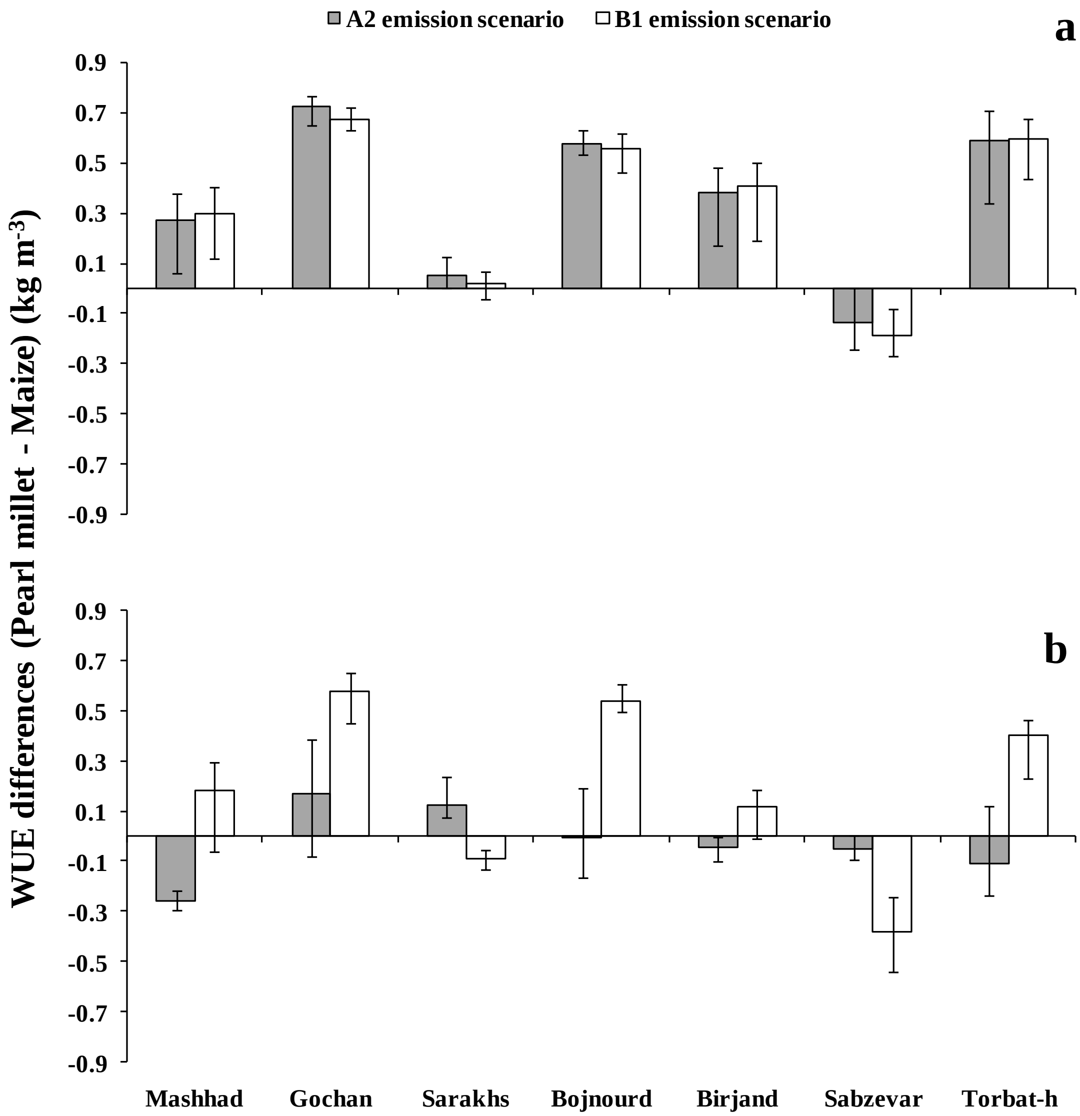


Figure 6.8. Differences in simulated water use efficiency (WUE) between pearl millet and maize for different study locations for the A2 and B1 emission scenarios in periods 2011-2030 (a) and 2080-2099 (b). (Error bars show range of water use efficiency difference across GCMs).

6.3.3. Effect of temperature on yield of pearl millet and maize

The sensitivity of pearl millet and maize biomass yields to mean temperature was largest for the development phase "floral initiation to end of leaf growth" (FI-EL, Figure 6.9). Observed and simulated biomass yields of pearl millet showed a higher sensitivity to temperature increase in the most critical development phase FI-EL than yields of maize (Figure 6.4). For millet, the length of this phase was simulated to decline sharply under global warming. The decline of the FI-EL phase duration ranged between 11.4 to 0.2 days for the SRES-A2 scenario and between 6.1 to 0.1 days for the SRES-B1 scenario, depending on the location. The shortening of the phase was less pronounced for maize except for the Sarakhs location under emission scenario SRES-A2 (Table. 6.5). The IPCM4 and NCCCSM projections showed lowest and highest changes in FI-EL phase duration respectively, across all study locations for both crops under both scenarios (Table. 6.5).

Compared to the baseline period, mean temperature during the FI-EL phase showed a moderate increase for the near future period (1.0 - 1.3^{o}C for pearl millet and 0.9 - 1.2^{o}C for maize under the SRES-A2 scenario and 1.0 - 1.3^{o}C for pearl millet and 0.5 - 1.2^{o}C for maize under the SRES-B1 scenario) and extreme increases for the distant future period (4.5 - 5.2^{o}C for pearl millet and 4.4 - 5.1^{o}C for maize under SRES-A2 scenario and 1.3 - 2.3^{o}C for pearl millet and 0.02 - 2.3^{o}C for maize under the SRES-B1 scenario) (Table. 6.6). Highest and lowest increases in average temperature during the FI-EL phase for both crops and scenarios were found for Gochan and Sarakhs locations.

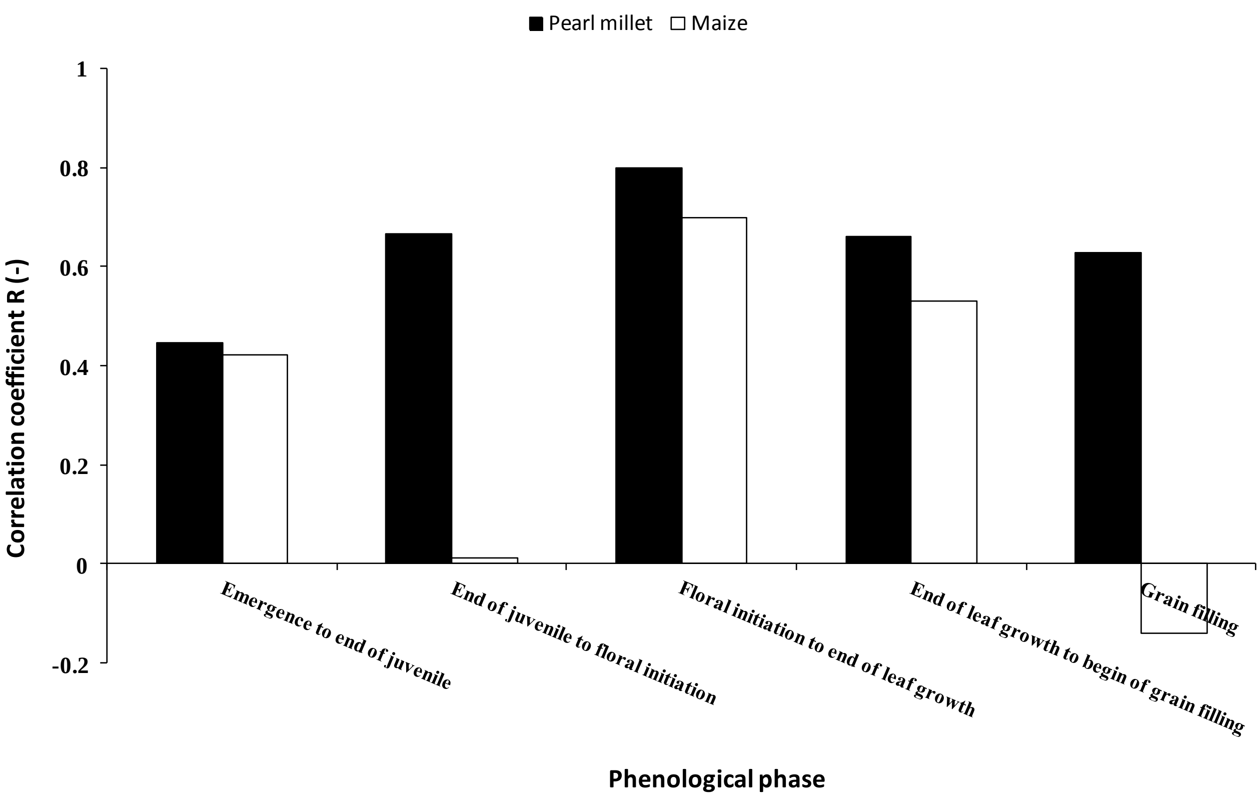


Figure 6.9. Correlation coefficient (R) between above-ground biomass yield (kg ha yr^{-1}) and length of phenological phases (days) of pearl millet and maize simulated by DSSAT 4.5 for Mashhad, Sabzevar and Gochan locations and period 2001-2005.

Table. 6.5. Changes in the duration of the most critical development phase (floral initiation to end of leaf growth) of pearl millet and maize (days) for two climate change scenarios and two future periods compared to the baseline period 1970-2005.

Location	GCM	Pearl millet A2 2011-2030	Pearl millet A2 2080-2099	Pearl millet B1 2011-2030	Pearl millet B1 2080-2099	Maize A2 2011-2030	Maize A2 2080-2099	Maize B1 2011-2030	Maize B1 2080-2099
Mashhad	HadCM3	-1.30	-5.50	-1.50	-2.65	-0.65	-4.05	-0.70	-1.15
	IPCM4	-1.25	-5.40	-1.45	-2.75	-0.65	-3.95	-0.80	-1.35
	MPEH5	-1.25	-5.60	-1.25	-3.50	-0.80	-4.30	-0.80	-3.10
	NCCCSM	-3.35	-6.35	-2.90	-2.80	-2.70	-4.75	-2.05	-1.70
	Average	**-1.79**	**-5.71**	**-1.78**	**-2.93**	**-1.20**	**-4.26**	**-1.09**	**-1.83**
Gochan	HadCM3	-2.95	-10.80	-3.50	-5.70	-0.35	-7.50	-1.45	-2.60
	IPCM4	-2.80	-10.25	-3.50	-6.15	-0.75	-7.50	-1.30	-3.15
	MPEH5	-3.05	-10.35	-2.85	-7.20	-0.65	-7.40	-0.70	-4.25
	NCCCSM	-6.45	-11.75	-5.15	-5.70	-3.60	-8.70	-2.50	-2.70
	Average	**-3.81**	**-10.79**	**-3.75**	**-6.19**	**-1.34**	**-7.65**	**-1.49**	**-3.18**
Sarakhs	HadCM3	-1.05	-3.65	-1.15	-1.60	-1.85	-11.25	0.20	2.90
	IPCM4	-1.05	-3.45	-1.10	-1.50	0.65	-8.90	-0.30	1.10
	MPEH5	-1.00	-3.35	-1.05	-1.80	-1.85	-11.10	-0.05	-3.85
	NCCCSM	-1.90	-3.95	-1.65	-1.55	-8.80	-14.55	-6.35	0.30
	Average	**-1.25**	**-3.60**	**-1.24**	**-1.61**	**-2.96**	**-11.45**	**-1.63**	**0.11**
Bojnourd	HadCM3	-2.15	-8.60	-2.55	-4.25	-1.05	-6.50	-1.30	-2.05
	IPCM4	-2.10	-7.95	-2.50	-4.75	-1.10	-5.95	-1.30	-2.65
	MPEH5	-2.25	-8.20	-2.10	-5.25	-1.20	-6.35	-0.70	-3.30
	NCCCSM	-5.35	-9.25	-3.80	-4.35	-3.55	-7.15	-2.45	-2.65
	Average	**-2.96**	**-8.50**	**-2.74**	**-4.65**	**-1.73**	**-6.49**	**-1.44**	**-2.66**
Birjand	HadCM3	-1.05	-5.05	-1.05	-2.45	-0.75	-5.35	-0.90	-2.45
	IPCM4	-0.40	-5.15	-0.90	-2.30	-0.25	-5.35	-0.60	-2.45
	MPEH5	-1.35	-5.45	-0.80	-3.60	-1.30	-5.40	-0.40	-3.40
	NCCCSM	-2.75	-5.65	-2.65	-2.50	-2.60	-5.50	-2.50	-2.50
	Average	**-1.39**	**-5.33**	**-1.35**	**-2.71**	**-1.23**	**-5.40**	**-1.10**	**-2.70**
Sabzevar	HadCM3	-0.50	-2.55	-0.75	-0.95	0.00	-1.65	-0.15	-0.20
	IPCM4	-0.50	-2.35	-0.55	-1.00	0.05	-1.50	-0.10	-0.15
	MPEH5	-0.50	-2.40	-0.50	-1.40	-0.10	-1.65	0.05	-0.80
	NCCCSM	-1.40	-2.80	-1.05	-0.85	-0.95	-2.00	-0.45	-0.10
	Average	**-0.73**	**-2.53**	**-0.71**	**-1.05**	**-0.25**	**-1.70**	**-0.16**	**-0.31**
Torbat-h	HadCM3	-1.45	-7.05	-2.10	-3.85	-1.50	-3.25	-1.50	-3.25
	IPCM4	-1.20	-6.95	-2.00	-3.75	-1.10	-6.65	-1.45	-3.45
	MPEH5	-1.90	-7.30	-1.20	-4.95	-1.40	-6.95	-1.15	-4.35
	NCCCSM	-4.20	-7.95	-3.70	-3.70	-3.70	-7.45	-3.15	-3.25
	Average	**-2.19**	**-7.31**	**-2.25**	**-4.06**	**-1.93**	**-6.08**	**-1.81**	**-3.58**

Table. 6.6. Changes in mean temperature (°C) in the most critical development phase (floral initiation to end of leaf growth) of pearl millet and maize for two climate change scenarios and two future periods compared to the baseline period 1970-2005.

Location	GCM	Pearl millet				Maize			
		A2		B1		A2		B1	
		2011-2030	2080-2099	2011-2030	2080-2099	2011-2030	2080-2099	2011-2030	2080-2099
Mashhad	HadCM3	0.80	4.55	1.00	1.95	0.70	4.55	0.90	1.93
	IPCM4	0.75	4.33	1.00	1.95	0.68	4.33	0.85	1.93
	MPEH5	0.80	4.53	0.80	2.48	0.75	4.55	0.75	2.65
	NCCCSM	2.23	5.53	1.88	1.90	2.10	5.38	1.63	1.95
	Average	**1.14**	**4.73**	**1.17**	**2.07**	**1.06**	**4.70**	**1.03**	**2.11**
Gochan	HadCM3	0.95	5.20	1.28	1.88	0.85	5.00	1.23	2.18
	IPCM4	0.95	4.63	1.23	2.00	0.85	4.75	1.15	2.30
	MPEH5	0.97	4.98	0.95	2.73	0.90	4.90	0.83	2.75
	NCCCSM	2.60	6.15	1.98	1.73	2.38	5.90	1.80	2.08
	Average	**1.37**	**5.24**	**1.36**	**2.08**	**1.24**	**5.14**	**1.25**	**2.33**
Sarakhs	HadCM3	0.85	4.63	1.00	1.88	0.50	3.83	0.05	-0.82
	IPCM4	0.68	4.40	0.93	1.78	-0.30	3.13	0.25	-0.32
	MPEH5	0.68	4.15	0.70	2.05	0.63	3.93	0.10	1.25
	NCCCSM	1.98	5.33	1.65	1.70	3.03	5.55	1.95	-0.02
	Average	**1.04**	**4.63**	**1.07**	**1.85**	**0.96**	**4.11**	**0.59**	**0.02**
Bojnourd	HadCM3	1.00	5.05	1.25	1.75	0.85	4.93	1.03	1.90
	IPCM4	1.00	4.48	1.20	1.93	0.85	4.53	1.03	2.05
	MPEH5	1.05	4.68	0.85	2.53	0.85	4.65	0.72	2.55
	NCCCSM	2.53	5.50	1.88	1.80	2.23	5.53	1.53	1.95
	Average	**1.39**	**4.93**	**1.29**	**2.00**	**1.19**	**4.91**	**1.08**	**2.11**
Birjand	HadCM3	0.78	4.75	0.95	2.18	0.68	4.75	0.80	2.10
	IPCM4	0.50	4.88	0.75	2.15	0.38	4.93	0.63	2.05
	MPEH5	1.08	5.23	0.73	3.05	0.95	5.20	0.57	3.03
	NCCCSM	2.10	5.33	2.03	2.08	1.88	5.23	1.73	2.05
	Average	**1.11**	**5.04**	**1.11**	**2.36**	**0.97**	**5.03**	**0.93**	**2.31**
Sabzevar	HadCM3	0.82	4.65	1.23	1.88	0.78	4.45	1.08	1.75
	IPCM4	0.82	4.18	1.03	1.88	0.75	3.95	0.98	1.78
	MPEH5	0.88	4.43	0.82	2.40	0.80	4.30	0.75	2.33
	NCCCSM	2.23	5.13	1.78	1.50	2.08	4.98	1.68	1.55
	Average	**1.19**	**4.59**	**1.21**	**1.91**	**1.10**	**4.42**	**1.12**	**1.85**
Torbat-h	HadCM3	0.78	4.93	1.10	2.20	0.82	4.85	1.00	2.20
	IPCM4	0.63	4.80	1.05	2.18	0.70	4.78	0.95	2.18
	MPEH5	1.00	5.15	0.60	2.90	0.93	5.05	0.70	2.93
	NCCCSM	2.33	5.85	2.05	2.13	2.25	5.68	1.83	2.13
	Average	**1.18**	**5.18**	**1.20**	**2.35**	**1.18**	**5.09**	**1.12**	**2.36**

6.4. Discussion

Based on our results, cultivation of new hybrids of pearl millet could increase fodder production under present conditions. This is in agreement with findings published by (Khalesro et al., 2011) who compared the production potential of maize (Single Cross 704), sorghum (cv. Speedfeed) and pearl millet (cv. Nutrifeed) for Iran. They found that due to a higher tiller number and higher vegetative growth rate, the highest forage yield was achieved by growing pearl millet (19.8 t ha^{-1}), followed by maize (18.5 t ha^{-1}) and sorghum (14.7 t ha^{-1}). Other studies in semiarid regions found higher water use efficiency of pearl millet (Panahi, 2004; Rostamza et al., 2011a), especially under moderate water stress (Singh and Singh, 1995). In addition, nitrogen use efficiency of pearl millet was higher than for other summer C4 fodder crops such as maize and sorghum (Rostamza et al., 2011b). Another result of this study was the clear evidence of the harmful effect of high temperatures on maize and millet yields, which were well reproduced by the crop model (Figure 6.4). Furthermore, pearl millet yield decline per unit increase in mean temperature during the FI-EL phase was considerably higher (46%) than for maize (Figure 6.4). This is in agreement with studies performed for other regions reporting that increased temperature accelerated the development rate of field crops (McMaster et al., 2008; Siebert and Ewert, 2012) and that shorter developmental periods for field crops can have adverse effects on crop yield (Asseng et al., 2011). Simulated increases in future air temperature accelerated development stages, reducing dry matter accumulation and crop production by 10-40% in two Italian locations (Tubiello et al., 2000). Moreover, (Liu et al., 2010) predicted 2-22% decrease in wheat and maize yield due to 2 to 5 ^{o}C temperature increase under future climate conditions in the Huang-Huai-Hai Plain of China. (Ong and Monteith, 1985) reported that leaf extension of pearl millet is a linear function of temperature. In addition, they showed a similar response to temperature for the determination of final tiller number and survival percentage. The relationships found in our study may therefore be of general relevance. Crop specific differences in sensitivity to temperature explain why the differences between pearl millet and maize for biomass yields and WUE should decline under future climate projections. Like (Lashkari et al., 2012), who found that maize yields would decrease by 1% to 39% under future climatic conditions, we found declining maize biomass yields for the study locations under climate change conditions (from an increase of 1% to a decrease of 11%). However, biomass yields of millet declined more (2% to 20%) than those of maize, so that the replacement of maize with pearl millet showed greater benefits for the present and near future conditions than for the distant future. However, the shortening of the FI-EL phase varied, not only depending on the crop, but also between climate change scenarios and locations. When differences in simulated yields between pearl millet and maize from all locations, scenarios and periods were plotted against average temperatures for the FI-EL phase we obtained a significant negative exponential relationship ($R^2 = 0.81^{**}$) suggesting that the crop substitution effect may decline non-linearly with increasing future temperatures (Figure 6.10).

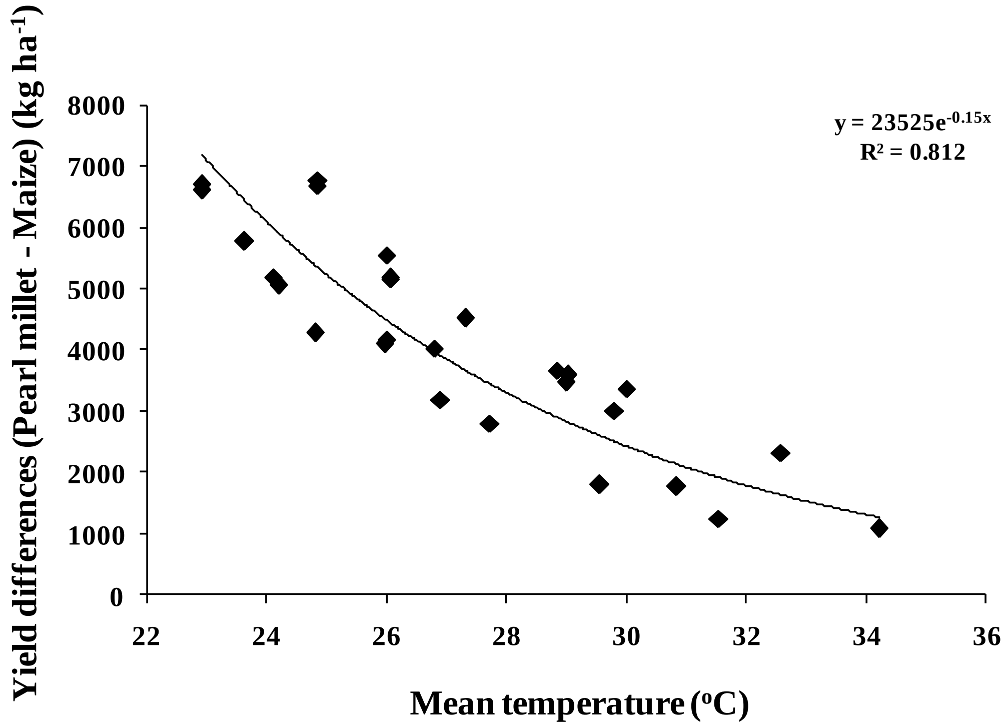


Figure 6.10. Relationship between differences in simulated yields of pearl millet and maize and mean temperature during the development phase (floral initiation to end of leaf growth) obtained from future climate projections across study locations.

The effect of crop substitution was smallest for the warmer locations Sabzevar and Sarakhs, with no discernible yield or WUE difference between the two crops. However, for the colder locations, Gochan and Torbat-h, the effect of crop substitution was considerable. There is, to our knowledge, little evidence in the literature about the possible effects of crop substitution. However, several studies investigated the effect of changing varieties within species. For instance, (Iglesias and Minguez, 1997) evaluated the performance of new maize hybrids under climate change as an adaptation strategy in Spain and reported significant changes in WUE and yield. The combination of new maize hybrids and earlier sowing date improved maize WUE by 1% to 10% in southern regions and by 10% to 60% in northern regions in Spain. Another study showed that the introduction of new maize varieties fully mitigated the adverse effects of climate change on yield at one location but only partially at the two southern locations of Greece (Kapetanaki and Rosenzweig, 1997).

We acknowledge some limitations of the present study. We compared one pearl millet to one maize cultivar although the sensitivity of crop yields to global warming also depends on the cultivars considered (Kapetanaki and Rosenzweig, 1997; Slafer and Rawson, 1995). The evaluated maize cultivar is the one mostly grown in Khorasan (Nabati and Mogadam, 2011; Tahmasebi et al., 2005). However, substitution of this cultivar by cultivars with a better performance under climate change conditions might be another adaptation strategy, which was not analyzed in this study.

Studies on the suitability of substitution of forage crops should also account for differences in the nutritive value of the crops considered. Acid detergent fiber (ADF) and crude protein (CP) content of pearl millet (Nutrifeed var.) were found to be in the range 32%-36% and 10%-19% respectively (Muir et al., 2001; Rostamza et al., 2011b), but only 23%-27% and 8.5%-9.3% for the maize cultivar SC 704 (Forouzmand et al., 2005; Moosavi, 2012). This means that maize forage was more digestible than pearl millet fodder, but it is unclear how climate change will affect forage quality in Iran.

We also did not consider the effects of other adaptation strategies, like changes in sowing dates or different irrigation management, on pearl millet and maize biomass yield. Recently, (Lashkari et al., 2012) found for example, that altering sowing dates as an adaptation practice can alleviate high temperature effects on maize yield in northeast Iran. These measures could be applied in addition to crop or cultivar substitution and result in complex interrelations. For example, we tested the effect of a four week earlier sowing date and found that the yield of pearl millet and maize at Sabzevar (the warmest research site in Khorasan) would increase. Yields of pearl millet with earlier sowing would increase more than yields of maize so that the yield difference between pearl millet and maize would further increase, e.g. from 1900 to 3300 kg ha^{-1} with the A2 emission scenario (near future period, data not shown).

Based on the results of this study, the effect of crop substitution can be evaluated from two points of view. Farmers mostly seek higher yields and therefore cultivation of pearl millet instead of maize would create a suitable opportunity for increasing fodder production under current and future conditions. On the other hand, pearl millet showed a higher sensitivity than maize to increasing temperature, so its superiority over maize may disappear in the distant future. Further research is therefore required to analyze systematically the effects of possible interactions between different adaptation strategies for different locations. In addition, we need to know about the socioeconomic effects and changes in fodder quality caused by crop substitution. Our study has pointed to an important strategy, i.e. crop substitution, which needs to be considered in such analyses.

Chapter 7

General discussion

7.1. The main findings of this thesis

Several results were obtained in the single studies presented in chapters 2 to 6 which are summarized and discussed in the following sections. In the first section of this chapter the main findings of the thesis are described in response to the research questions presented in chapter 1. In the second section, the effects of heat and drought stress on crop yield simulated at different scales (Q1, Q2 and Q3) are discussed. The interactions between climate and management is specifically addressed in the third section (Q4). New insights on the effects of high temperature and heat stress on crop yield are discussed in section 7.5. Lastly, conclusions from this work and suggestions for future research are presented in sections 7.6 and 7.7.

In the introduction of this thesis (Figure 1.1), heat stress was classified as a yield-reducing factor, which can be considered an extension of a commonly used classification scheme to distinguish between production conditions and the respective factors to determine, limit and reduce yields of crops (Van de Ven et al., 2003; Van Ittersum et al., 2013). Considering heat stress a yield-reducing was justified due to its nature to reduce grain number and grain weight as presented in chapter 2. In response to Q1, the importance of the estimation of heat effects on crops using canopy temperature instead of air temperature was highlighted. Furthermore, the need to link heat and drought stress effects to for improving crop models was stressed. In answering Q2 it was found that increments of heat stress intensity due to climate change were completely compensated for by the acceleration of phenology for winter wheat at national scale. In response to Q3, the results of the related study showed that high resolution input data is not necessary for the estimation of basic statistics such as mean or median of heat and drought stress effects on crop yields at a large spatial scale. However, it is essential to use high resolution input data for reproducing spatial patterns of heat and drought stress. In terms of interactions between management and climate (Q4), it was found that crop response to climate was influenced by fertilization management for the poor sandy soils of Niger. In addition, crop substitution can be used as an effective adaptation strategy to reduce the negative effects of high temperatures and drought under climate change in northeast of Iran.

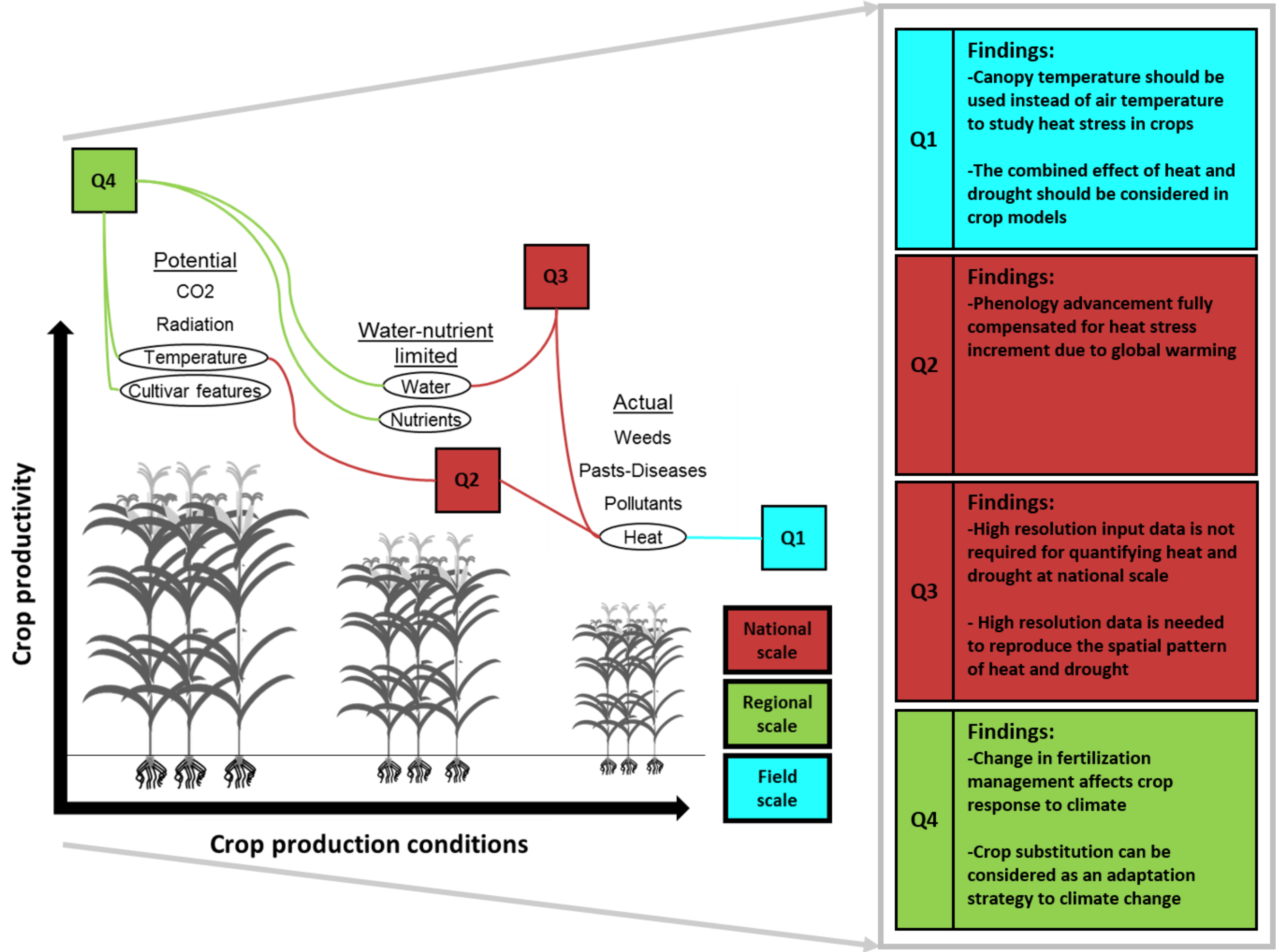


Figure 7.1. Schematic overview of main finding of this thesis in response to the posed research questions related to different crop production conditions and spatial scales.

7.2. Effect of heat and drought stress on cereal crops

7.2.1. How can modeling of heat effects in cereals at field scale be improved?

The extensive literature review (Q1), showed a considerable variability in the relative sensitivity of growth processes to heat stress. The experimental evidence also showed that the grain number is the most sensitive yield component to heat stress in cereals (Figure 6.4). Heat stress around anthesis considerably reduces grain number and consequently has a negative impact on the grain yield of cereals (Ferris et al., 1998; Rattalino Edreira and Otegui, 2013). Modeling of heat stress effects on crop yield is mainly based on simple regression equations (Eitzinger et al., 2004). Therefore, more robust process based routines are required to quantify heat effects on grain numbers in crop models. It is also fundamental to reflect the differences in the crop's response to heat stress for different phenological phases.

Advantages and disadvantages of the experimental methods to study heat stress were also reviewed. It was concluded that the experimental method used for model development and calibration may considerably influence the accuracy of the modeling experiments. Most of the studies on heat stress effects on cereals were performed in growth chambers (pot experiments) which can hardly reproduce field conditions (Sinsawat et al., 2004) for which crop models are typically applied. Plants grown in chambers have a restricted development of the root system due to the use of relatively small pots and experience a modified micro-climate in comparison with field conditions.

The temperature gradient tunnel experiment was designed to overcome root restriction issues. However, crop yield may also decline due to incident radiation from the tunnel's polyethylene cover (Kittas et al., 1999). The T-FACE system (Kimball, 2011) can best mimic field conditions under heat stress. Nonetheless, both an extensive knowledge and a high energy supply are required in order to setup and run a T-FACE experiment. Therefore, errors in observed data should be considered in the development of new modeling approaches for the simulation of heat stress effects on crop growth processes.

Most of the crop models use air temperature (measured in 2 m height) as input for the simulation of different processes such as heat stress impacts on grain yield. However, the effect of heat stress on grain yield largely depend on canopy temperature (Craufurd et al., 2013; Siebert et al., 2014). The difference between air and canopy temperature could reach up to 7 °C depending on soil water status, time of the day, and transpiration rate (Ferrise et al., 2011; Siebert et al., 2014). It also has been suggested that drought and heat stress must be linked in crop models due to the dependency of canopy temperature on soil water status and stomatal conductance. However, simulating canopy temperature is challenging mainly due to the complex functions of the energy balance for a crop canopy. Comprehensive functions are needed in order to simulate surface and aerodynamic canopy temperatures and extensive parameterization for stability functions is required (Monteith and Unsworth, 1990). A range of methods were used, ranging from complex (Mihailovic and Eitzinger, 2007) to simple, empirical (Jackson et al., 1981) approaches described in section 2.6. The implementation of these complex approaches may be appropriate for field scale studies, but not for large scale assessments. This is due to the requisite for data when calibrating the model.

However, the comparison of eight separate approaches for estimating aerodynamic resistance, and the associated stability functions for maize, showed that some of the simple approaches performed similarly well as compared to the more complex approaches (Liu et al., 2007). There was a considerable improvement when simulating anthesis date and grain yields under various sowing dates by using canopy temperatures instead of air temperatures as an input to the crop model (Brisson et al., 2003). Based on the results of this thesis, simulation of canopy temperature can be used as a promising approach to concurrently account for heat and drought stress.

7.2.2. The importance of phenology for the estimation of heat stress intensity

As discussed in the previous section, experimental evidence has shown that the period around anthesis is particularly sensitive to heat stress (Ferris et al., 1998; Luo, 2011). To tackle Q2, climate and phenology data observed across Germany for more than half a century were used to evaluate the interactions between phenology and heat stress intensity on a national scale. There was a strong relationship between the rise in mean temperature and the advancement in phenology for the spring period from 1976 to 2009 (Figure 3.3).

Some of phenology’s progress may be connected to the earlier sowing date of winter wheat (5 days over last 30 years). However, the majority of the progression in phenology of winter wheat was explained by higher temperatures during the growing period in Germany. From 1976 to 2009, the mean temperature during May to March increased by 1.8 °C throughout Germany. Such effects have also been observed elsewhere.

The average advancement in phenology of 542 plant species was 2.5 days per decade in Europe (Menzel et al., 2006). The warmer spring temperatures led to earlier flowering times of different species in Mediterranean regions, with an enhancement of 4 days per °C increase in temperature (Fitter et al., 1995).

Surprisingly, there was only a slight, increasing trend of heat stress around anthesis in the period between 1976 and 2009 throughout Germany. In addition, the mean temperature around anthesis has not changed over the last 30 years due to the advancement of phenology. The effect of phenological advancements on heat stress intensity was evaluated by comparing observed heat stress and calculated heat stress for the de-trended day of heading. The intensity of heat stress would have increased by more than 50% without advancement of phenology during this period. Hence, in response to research question Q2, the heat stress intensity around anthesis may not increase under climate change due to this advancement in phenology and earlier sowing dates for winter cereals.

Figure 7.2 shows that winter cereals may experience the same temperature under current and future climate change conditions for the stage of anthesis. However, this does not mean that yields of winter cereals will remain unchanged in the future under climate change. The acceleration of leaf senescence during the grain filling period will likely have a negative impact on grain yield (Asseng et al., 2011). In addition, the results of a simulation study (30 crop models) suggested that global wheat production may decline by 6% for each °C increase in temperature (Asseng et al., 2015). The decline in the length of the growing period, results in less time to intercept radiation, which is needed for biomass production. The cultivation of late maturing cultivars, which were suggested as an adaptation strategy, may forward the critical development stage of winter cereals to a warmer period of the season (Figure 7.2). Moreover, climate change impact assessments conducted by using statistical models generally do not account for phenology advancements and may therefore at risk to overestimate heat stress intensity.

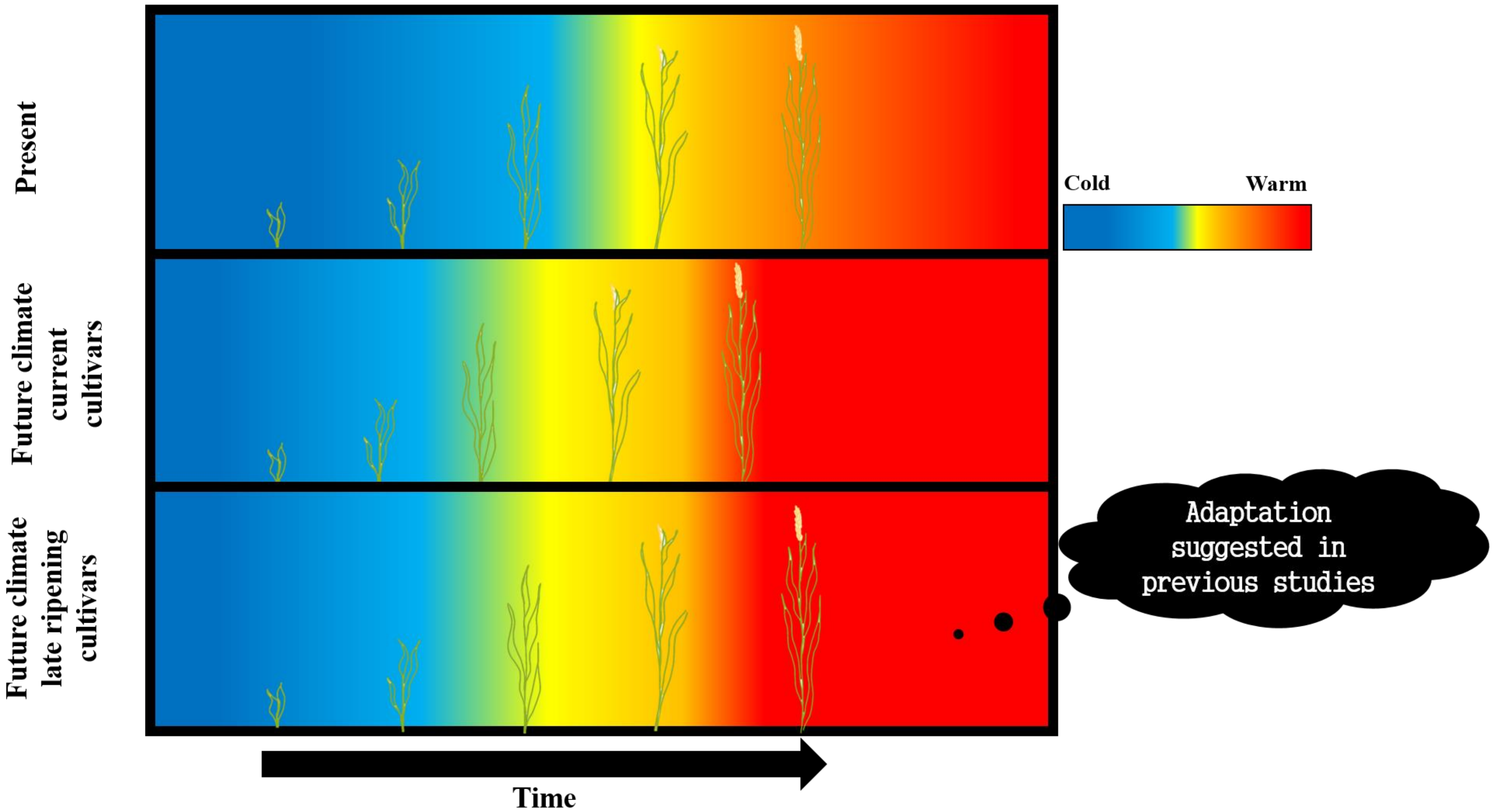


Figure 7.2. Schematic presentation of the effects of advancement in crop phenology on experienced temperatures around anthesis for current conditions, climate change + current cultivars and climate change + late ripening cultivars. Note, the last plant in each panel refers to anthesis.

7.3. Up scaling of heat and drought stress effects on crop yield at large scale

Due to the lack of high resolution input data it is often required to run large scale crop models with aggregated data. On the other hand, simulated heat and drought effects on crop yields could be influenced by data aggregation by averaging out local extremes (Baron et al., 2005; Easterling et al., 1998). Therefore, it is necessary to quantify the error, particularly the bias, on model simulations introduced by data aggregation. In response to the related research question Q3, a systematic analysis was conducted to quantify the effect of input and output data aggregation on spatial patterns and basic statistics of simulated heat and drought stress of winter wheat throughout Germany (Chapter 4).

Aggregation of input and output data from 1 km × 1 km to 100 km × 100 km was found to have a negligible impact on the basic statistics (mean and median) of simulated heat and drought in Germany. Such results suggest that high resolution input data is not required when simulating crop yields at a national level. Aggregating climate data from 10 km × 10 km to 100 km × 100 km had no considerable impact on the mean and frequency distribution of simulated yields in Finland (Angulo et al., 2013). Van Bussel et al. (2011b) found a small influence of data aggregation from 10 km × 10 km to 100 km × 100 km in Germany on simulations of crop phenology. Van Bussel et al. (2011a) also showed that spatial details of model outputs may decline by increments of the aggregation level. The spatial pattern of heat and drought were strongly affected by data aggregation. High resolution climate data are required for those regions that are characterised by heterogeneous topography to simulate realistic spatial patterns of crop yield (Zhao et al., 2015).

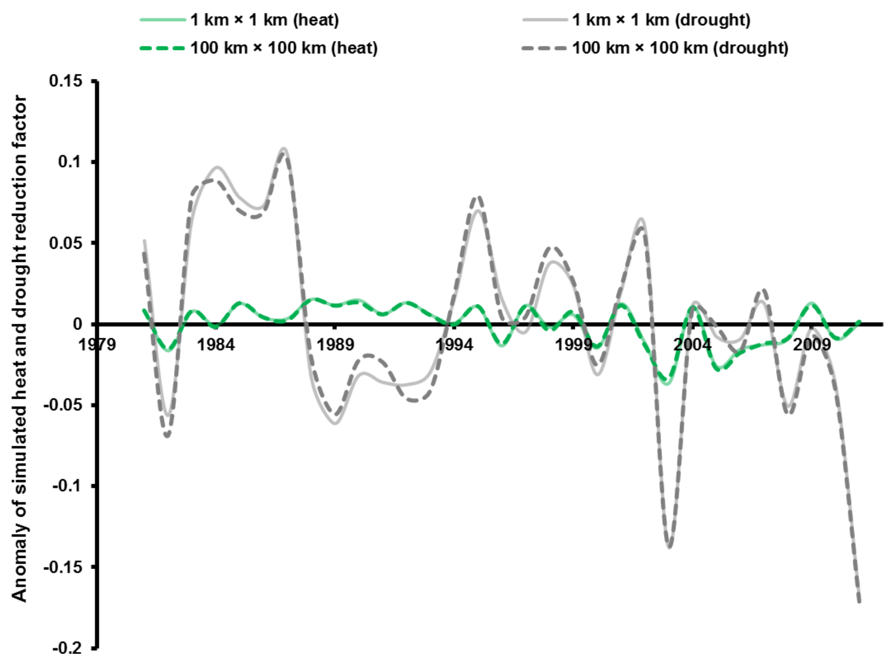
The anomaly of heat and drought stress was calculated by the subtraction of the mean of heat and drought stress factors (1980-2011) and heat and drought stress factors in a specific year over Germany (Figure 7.3). The effect of input data aggregation on the drought stress reduction factor and simulated yield was remarkably larger than that of heat stress. In addition, the variability of the drought stress anomaly was also extremely larger than the heat stress anomaly (Figure 7.3a). However, there was no considerable difference between the highest (1 km × 1 km) and lowest (100 km × 100 km) input data resolution for both stress factors in the period 1980-2011 (Figure 7.3a).

There was a strong relationship between simulated yield anomaly and the anomaly of drought stress reduction factor (R^2 = 0.54) (Figure 7.3b). This indicated that drought stress may be the dominant yield limiting factor under optimal management conditions in Germany. The annual precipitation sum and spatial pattern of precipitation are relatively high and homogenous, respectively over the most regions of Germany. Therefore, soil patterns could be the main factor impacting yields in the simulations which points to the importance of the soil aggregation data method.

The soil information was aggregated based on dominant soil characteristics. Soil data aggregation by simple averaging may result in nonsensical soil profiles which do not exist at higher resolution. The results also indicated that the aggregation method of soil data (normal aggregation and based on dominant soil) had a remarkable impact on simulated yield. Therefore, it is concluded that choosing a suitable soil aggregation method is a critical issue for the simulation of crop production at large scales, particularly if drought effects should be assessed.

The limitations and uncertainty of the results on the effects of data aggregation were acknowledged. First of all, the outcomes of the study were based on the performance of a single crop model. Angulo et al. (2013) found that the effect of the model structure is considerably higher than the effect of data aggregation on crop model results. The input data created at the highest resolution (1 km × 1 km) was another source of uncertainty in our study. The climate and soil data were generated by interpolation of point data, which may not fully reproduce the heterogeneity observed under real conditions. In addition, the simulation of heat stress effects on crop yields was derived by using air temperature (measured in 2 m height) in this study. However, it is concluded in chapter 1 that the canopy temperature could be a more suitable indicator of heat stress in crops.

a



b

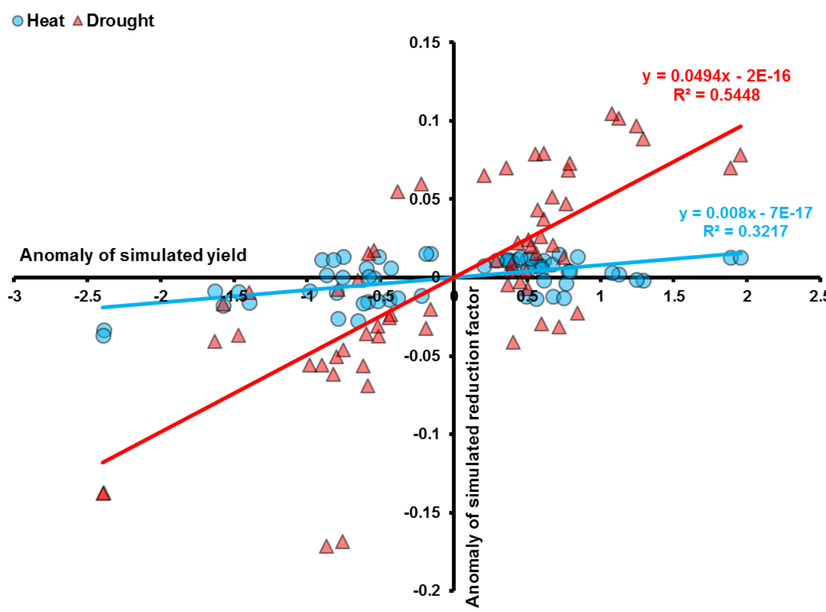


Figure 7.3. The anomaly (mean over years of stress-induced yield reduction minus stress-induced yield reduction in a specific year) of simulated heat and drought stress for highest (1 km × 1 km) and lowest (100 km × 100 km) input data resolutions for the period 1980-2011 (a) and the relationship between anomaly of simulated yield, heat and drought reduction factors for 1 km × 1 km and 100 km × 100 km resolutions (b).

7.4. Effect of climate × management interactions on cereal production

7.4.1. The interactions between fertilization management and climate

In chapter 5, interactions between fertilization practices and climate on pearl millet were evaluated using a crop model (DSSAT v4.5) applied for the Republic of Niger (Q4). In the first step, the relationship between climatic variables and biomass production was tested under different fertilization management based on a long term field experiment to evaluate the fertilization climate interaction. Then, pearl millet yield was simulated for the near future (2011-2030) and distant future (2080-2099), under various fertilization managements, including no fertilization (NF), crop residues (CR), mineral fertilization (FR) or combination of both (CR+FR). The results indicated that pearl millet yield was strongly controlled by soil nutrient levels in poor sandy soils in Niger. There was also a strong negative relationship between mean temperature during the growth period and pearl millet biomass production (Figure 5.2). Mohamed et al. 2002 found that pearl millet yield was considerably reduced by an increase in the number of days in which the minimum temperature was above 30 °C during the growth period.

However, there was no relationship between mean temperature and biomass production in the CR+FR treatment. The lack of impact of this rise in temperature could be confounded with another relationship between biomass production and the sum of annual precipitation in this treatment. The combination of crop residues and mineral fertilizers could increase fertilizer use efficiency (Bationo and Buerkert, 2001) and decrease the leaching of nitrogen (Thomsen and Christensen, 1998) in soils of West Africa. Lobell et al. (2003) found that a change in management had the highest impact on wheat yield variability compared to changes in climate and soil across Mexico. Crop response to climate change can be modified by the change in management across semi-arid agroecosystems (Paustian et al., 1995). The crop model reproduced the variability of biomass production across different fertilization practices. However, the positive relationship between total precipitation and biomass in CR and CR+FR treatments was not reproduced by the crop model. This is mainly due to the overestimation of nitrogen leaching in these treatments. The pearl millet production showed a remarkable decline under A2 scenario during the period 2080-2099 across all fertilization practices because of a 3°C increase in mean temperature (IPCC, 2007) in this scenario. As presented in Figure 5.7a the application of fertilizer may remarkably increase biomass production of pearl millet in Niger. Nonetheless, the advantages of CR+FR treatment may be reduced under climate change conditions in comparison to other fertilization managements. In general, changes in fertilization management may influence the intensity of extreme climatic conditions and can be considered as an adaptation strategy for climate change.

7.4.2. Adaptation strategies to avoid negative effects of heat and drought stress on yield

To study effect of crop substitution a crop model (DSSAT v4.5) was used to simulate the fodder production of maize (currently cultivated) and new hybrids of pearl millet (suggested as a new crop) (Chapter 6). Biomass production and water use efficiency of both crops were compared under present and future climate conditions in semi-arid regions in the northeast (NE) of Iran (Q4). Based on the findings, cultivating new hybrids of pearl millet may increase biomass production under present and potential future climate. Higher tiller numbers and an increased growth rate of new hybrids of pearl millet in contrast to current maize cultivars in NE of Iran could be reasons for higher yields in millet compared to maize (Rostamza et al., 2011a; Rostamza et al., 2011b). Based on the results, higher temperatures from floral initiation until the end of leaf growth, under climate change conditions, reduced accumulated biomass for both maize and pearl millet (Figure 6.3). The intensity of yield loss was determined by the warming in the specific climate change scenario and applied general circulation model (GCM). It was in the line with other studies which suggested a relationship between acceleration of development rate and decline in biomass accumulation in maize and wheat (Asseng et al., 2011; Liu et al., 2010).

The study also found that the effect of crop substitution was relatively low in warmer locations, in contrast to colder locations in NE Iran. The advantage of pearl millet cultivation in comparison with maize could decline with increasing temperature under climate change conditions in NE of Iran (Figure 6.9). This means that the sensitivity of biomass yields to temperature of new hybrids of pearl millet is higher than currently grown maize cultivars. The introduction of new hybrids of cereals could be considered as another adaptation strategy to help coping with climate change (Iglesias and Minguez, 1997; Kapetanaki and Rosenzweig, 1997). In summary, cultivating new hybrids of pearl millet may be a suitable option to increase fodder production in the study region. However, the advantages of crop substitution may disappear in the distant future. In general, different crops may have various responses to climate change. Therefore, a change in the cultivated crops as an adaptation strategy may be an option but needs further investigation to understand among others the sustainability of higher productivity of new crops in cropping systems under climate change.

7.5. New insights into effects of high temperature and heat stress on crop yield

The effects of temperature increase and heat stress on crop yield were evaluated separately in this thesis. Higher mean temperature during the growing period could reduce growing season length in particular the duration of the grain filling period. The results of chapter 5 and 6 confirmed that a reduction in the duration of most sensitive development phases (e.g. floral initiation to end of leaf growth in maize and pearl millet) can remarkably influence the crop yield. Higher mean temperature also caused shift of phases sensitive to heat to the cooler time of the growing season. Consequently, the intensity of heat stress which is defined as short episodes of very high temperature during the thermal sensitive stages such as anthesis (Barlow et al., 2015) may decline under global warming especially for winter cereals grown in temperate climate (Chapter 3).

It was also found that change in crop management can strongly influence crop responses to high temperature and heat stress. For instance, the negative impact of high mean temperature on biomass accumulation can be compensated by high soil fertility (Chapter 5) and by change of the cultivated crop species (Chapter 6). However, this does not mean that the response on management × climate interactions for a single crop species (Chapters 5 and 6) can be generalized for other crop species. Eyshi Rezaei et al. (under review) found that the direction and magnitude of changes in phenological development are crop specific And that management decisions can reverse the climate change signal on crop phenology (Eyshi Rezaei et al., under review).

This thesis also contributed to the improvements of methods to assess effects of heat stress on crop yield at different scales (Chapters 2 and 4). It was found that considering canopy temperature can improve crop models at small scale (Chapter 2) but model complexity and high data demand are still challenging issues for simulation of canopy temperature at larger scales and need therefore further investigation (Chapter 4). However, the close relationship between canopy temperature and soil water content (Siebert et al., 2014) can be a starting point for the development of simpler approaches (low parametrization requirement) for simulation of canopy temperature at large scales. Simulation of canopy temperature also links heat and drought stress in crop models. Upscaling of crop model results by different aggregation methods showed that the signal of heat and drought stress is not strongly modified by aggregation of input and output data from 1 km × 1 km to 100 km × 100 km (Chapter 4). Therefore, there is no need for high input data resolution and large computational effort for simulations of heat and drought stress at large scales. Nevertheless, it is necessary to test the obtained results in more heterogeneous environments to investigate the possibility of generalization of the results.

7.6. Conclusions

This thesis advanced our knowledge on important gaps in the understanding of heat and drought stress effects on cereal crops in order to improve crop models ability to assess climate change impacts. This refers specifically to interactions between heat stress and temperature effects on phenology as well as between heat stress and crop management, and the effect of spatial data aggregation on stress impacts. Important outcomes of the thesis are:

1. There is a necessity to improve the understanding of complicated interactions between different processes such as photosynthesis, transpiration, and development under heat stress conditions. In addition, crop models should not only consider canopy temperatures, instead of air temperature, but also interactions between heat and drought stress.

2. The magnitude of heat stress around anthesis may not increase due to climate change. This is largely a result of accelerated crop development rates of winter cereals under climate change.

3. It is not essential to use high resolution input data (weather and soil) for the simulation of mean crop yield at national level. Despite this, high resolution input data is required for reproducing spatial details of extreme events (heat and drought reduction factors) under heterogeneous soil conditions.

4. The relationship between climatic variables and crop production can be influenced by different fertilization management. Effective fertilization management can increase dry matter production of pearl millet under present and future climatic conditions in Niger.

5. Crop substitution can be a suitable opportunity to reduce the vulnerability of cropping systems to various negative impacts of climate change. However, additional studies are necessary in order to evaluate the combined effect of different adaptation strategies.

7.7. Outlook

The studies described in this thesis contribute to the understanding of the effects of heat and drought on crop production across spatial scales and help to design effective adaptation strategies to cope with global warming. However, some un-resolved issues and future challenges need to be acknowledged:

1. Most importantly, it is required to better understand the underlying mechanisms explaining phenotypic responses to heat stress and then develop new crop model routines for quantifying the large variability in sensitivity of cultivars to heat stress. Cultivar screening field experiments will be an important basis to achieve such advancement. We also need to develop more simple and robust approaches to estimate canopy temperatures, particularly for large scale assessments.

2. A small effect of data aggregation on basic statistics of simulated heat and drought stress of winter wheat at large spatial scale was found. Nevertheless, it is strongly recommended to conduct similar studies for summer crops and more stress prone areas. Modeling crop responses over large areas will also need to address management variability, for instance, to cover the variability of cultivars grown in a respective spatial unit which is presently often simplified to one set of crop parameters (cultivar characteristics). Probabilistic modeling approaches of input data and crop parameters in large scale assessments may be a way to account for this uncertainty.

3. It has been shown that crop responses to heat and drought stress can change depending on the management strategy. Hence, considering combined adaptation strategies such as modification of sowing date and deficit irrigation can be recommended. In more general

terms, interactions between combined adaptation strategies and climate change and their effects on crop yield will need to be better understood in the future.

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Appendixes

Appendix A for chapter 5

The Mann-Kendall test compares each value of the time-series with the others remaining, always in sequential order (Kendall, 1975). If x_1; x_2; x_2; ... ; x_n is the time series of length n, then the Mann–Kendall test statistic S is given by (Yu et al., 2002):

$$S = \sum_{i=2}^{n} \sum_{j=1}^{i-1} sign(x_i - x_j) \qquad \text{Eq. (1)}$$

Where $$\text{sgn}(x) = \begin{cases} 1\, for x > 0 \\ 0\, for x = 0 \\ -1\, for x < 0 \end{cases} \qquad \text{Eq. (2)}$$

The null hypothesis H_0 for the test is ‘‘there is no trend in the time series”. If H0 is true then S is normally distributed with

$$E(S) = 0 \qquad \text{Eq. (3)}$$

$$V(S) = \frac{n(n-1)(2n+S)}{18} \qquad \text{Eq. (4)}$$

Where *E(S)* is the mean and *V(S)* is the variance of *S*. Then the Mann–Kendall z is given by:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & if \quad S > 0 \\ 0 & if \quad S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & if \quad S < 0 \end{cases} \qquad \text{Eq. (5)}$$

A positive value of S indicates an increasing trend and vice versa. Z value gives a significance level (*SL*) of rejecting the null hypothesis (chances of rejecting null hypothesis even if there is no trend in the dataset). Confidence level (*CL*) of rejecting the null hypothesis is given by:

$$CL = 1 - SL \qquad \text{Eq. (6)}$$

Magnitude of trends has been determined using Theil–Sen approach (TSA) (Hirsch et al., 1982). The TSA slope b is given by:

$$\beta = median\left[\frac{x_j - x_i}{j - i}\right] \text{for all } i < j \qquad \text{Eq. (7)}$$

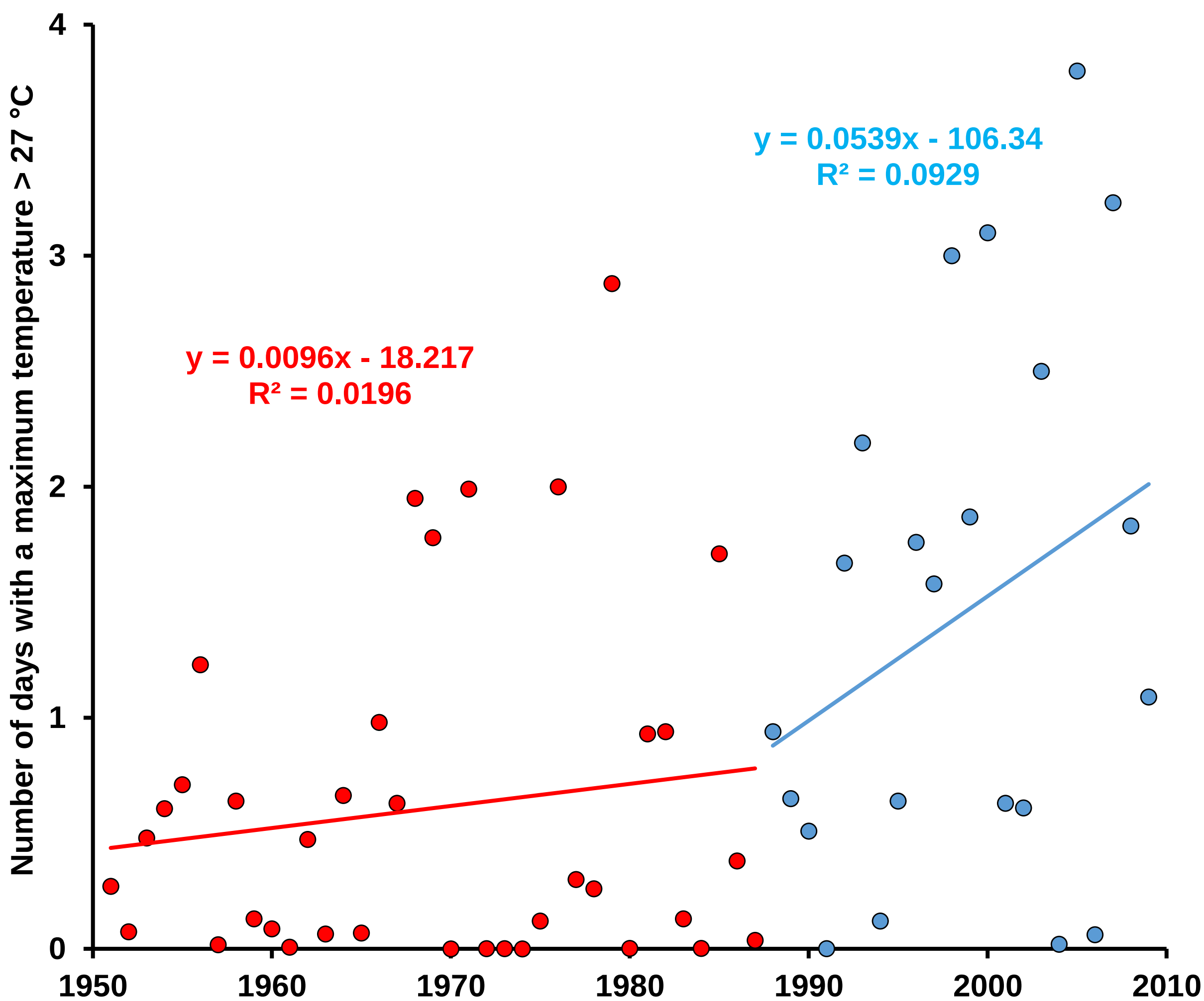
The significance levels of *p* of 0.01 and 0.05 were obtained for each analyzed time series.

Abbreviations

NSC	Non-structural carbohydrate
PSII	Photosystem II
ROS	Reactive oxygen species
CER	CO2-exchange rate
VPD	Vapour pressure deficit
T-FACE	Temperature free-air controlled enhancement
GAEZ	Global agroecological-zoning
APSIM	Agricultural Production Systems Simulator
DSSAT	Decision support system for agrotechnology transfer
RUE	Radiation use efficiency
STICS	Simulateur mulTIdisciplinaire pour les Cultures Standard
SIMPLACE	Scientific Impact assessment and Modeling Platform for Advanced Crop and Ecosystem management
DOH	Day of heading
DWD	Deutscher Wetterdienst
IDW	Inverse distance weighting
IPCC	Intergovernmental Panel on Climate Change
STT	Stress thermal time
DOS	Day of sowing
DOE	Day of emergence
u_2	Wind speed in 2 m height
u_s	Wind speed at the sensor
BÜK	Bodenübersichtskarte
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
TRANCO	Transpiration constant
LAI	Leaf area index
SLA	Specific leaf area
AD	Absolute differences
D	Differences
RMSE	Root mean squared error

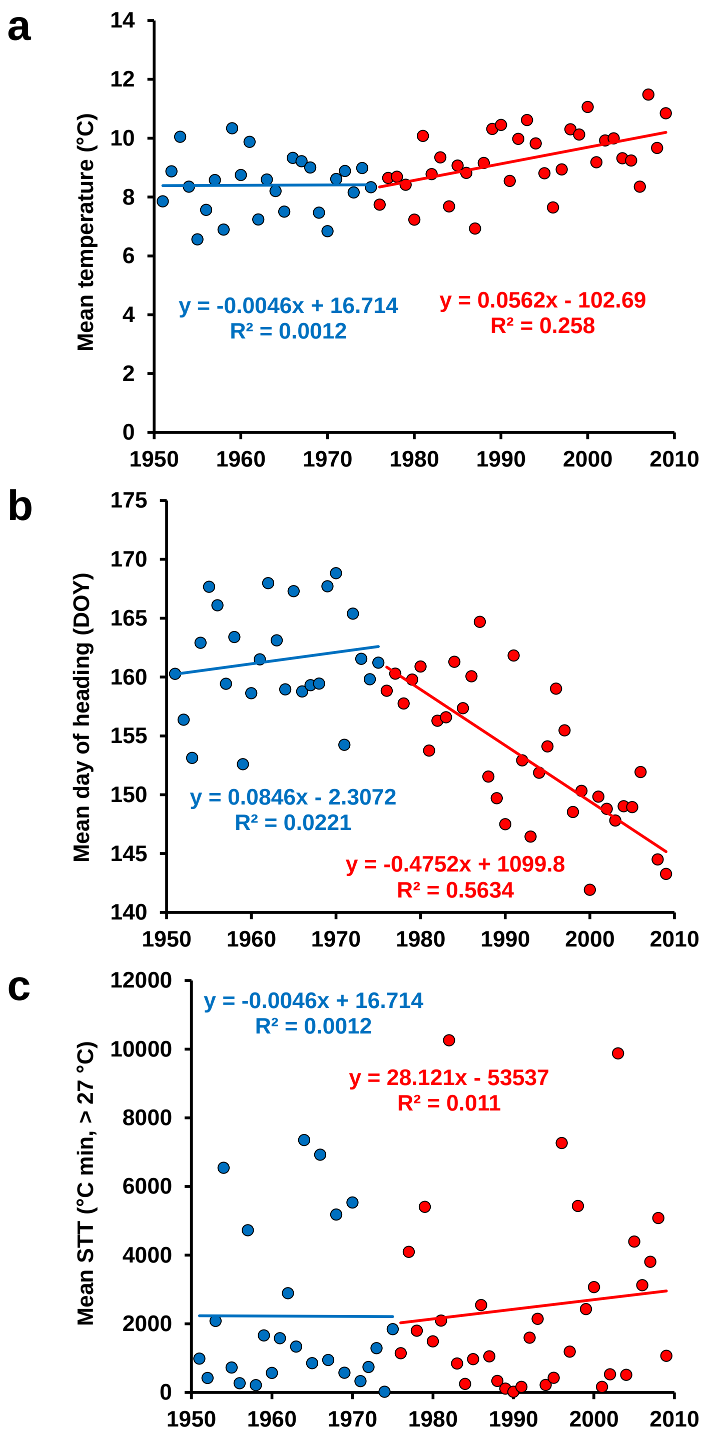
TAWC	Total available water capacity
WUE	Water use efficiency
LARS-WG5	Long Ashton Research Station-Weather Generator
GCM	General circulation model
IPCC	Intergovernmental Panel on Climate Change
FI-EL	Floral initiation to end of leaf growth
ADF	Acid detergent fiber
CP	Crude protein
CR	Crop residues
FR	Mineral fertilizer
CR+FR	Crop residues plus mineral fertilizer
N_{stress}	Nitrogen stress factor
$N_{critical}$	Nitrogen concentration at maximum growth
N_{actual}	Actual nitrogen concentration of vegetation
N_{min}	Minimum concentrations of nitrogen at which growth ceases

Supplementary materials for Chapter 3

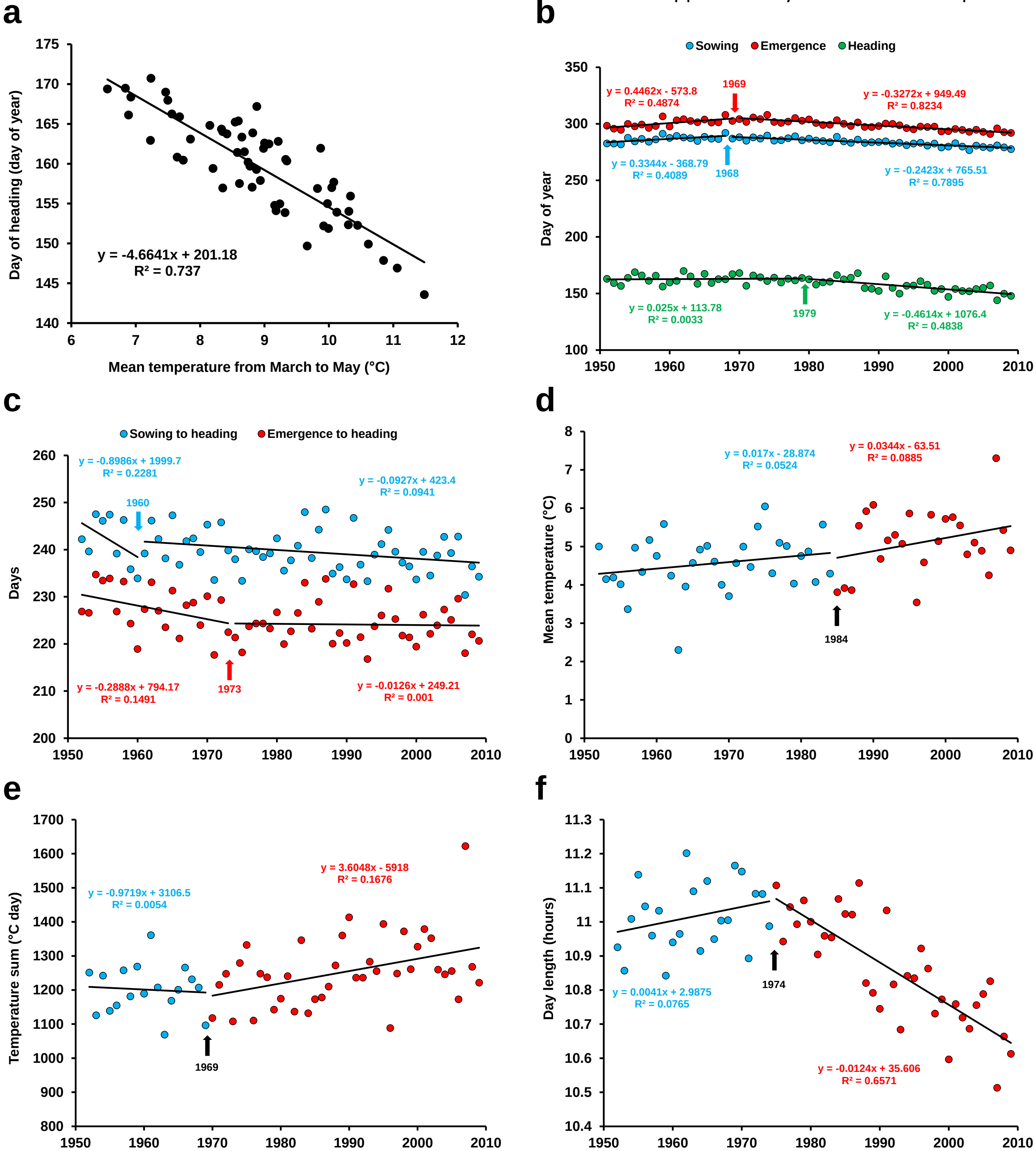


SI figure. 3.1. Number of days with maximum temperature above 27 °C in period March to May across Germany during 1951-2009.

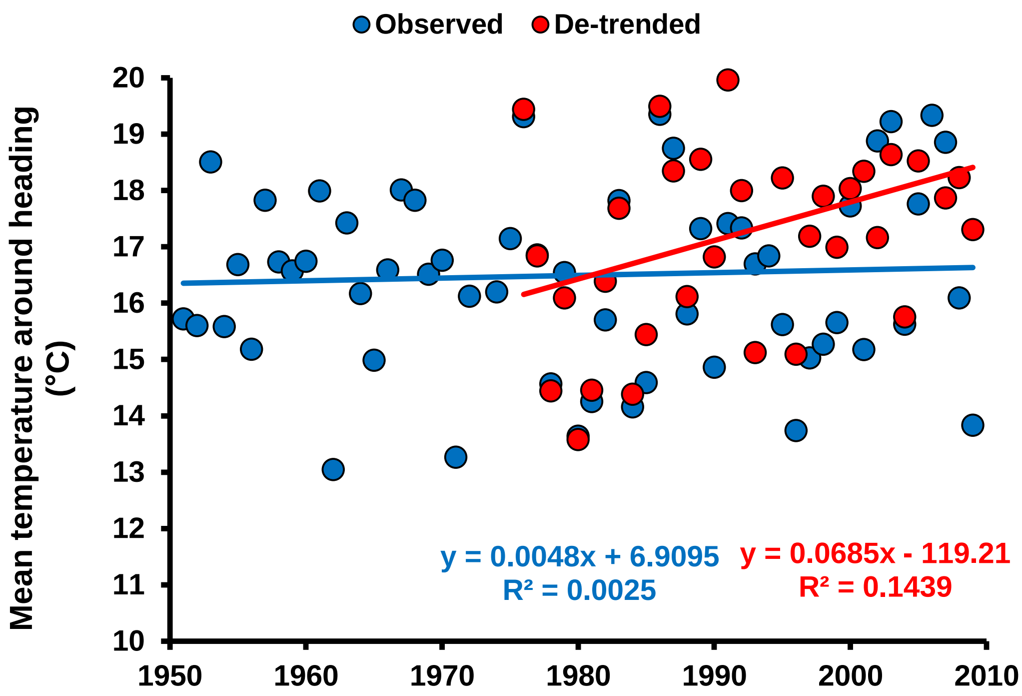
SI video2. Day of heading of winter wheat across Germany during 1951-2009.



SI figure. 3.3. Mean temperature for period March to May (a), mean day of heading (b) and mean stress thermal time (c) for the heat prone areas (in which mean stress thermal time (1951-2009) was above 2000 °C minute) in the periods 1951-1975 and 1976-2009 across Germany.

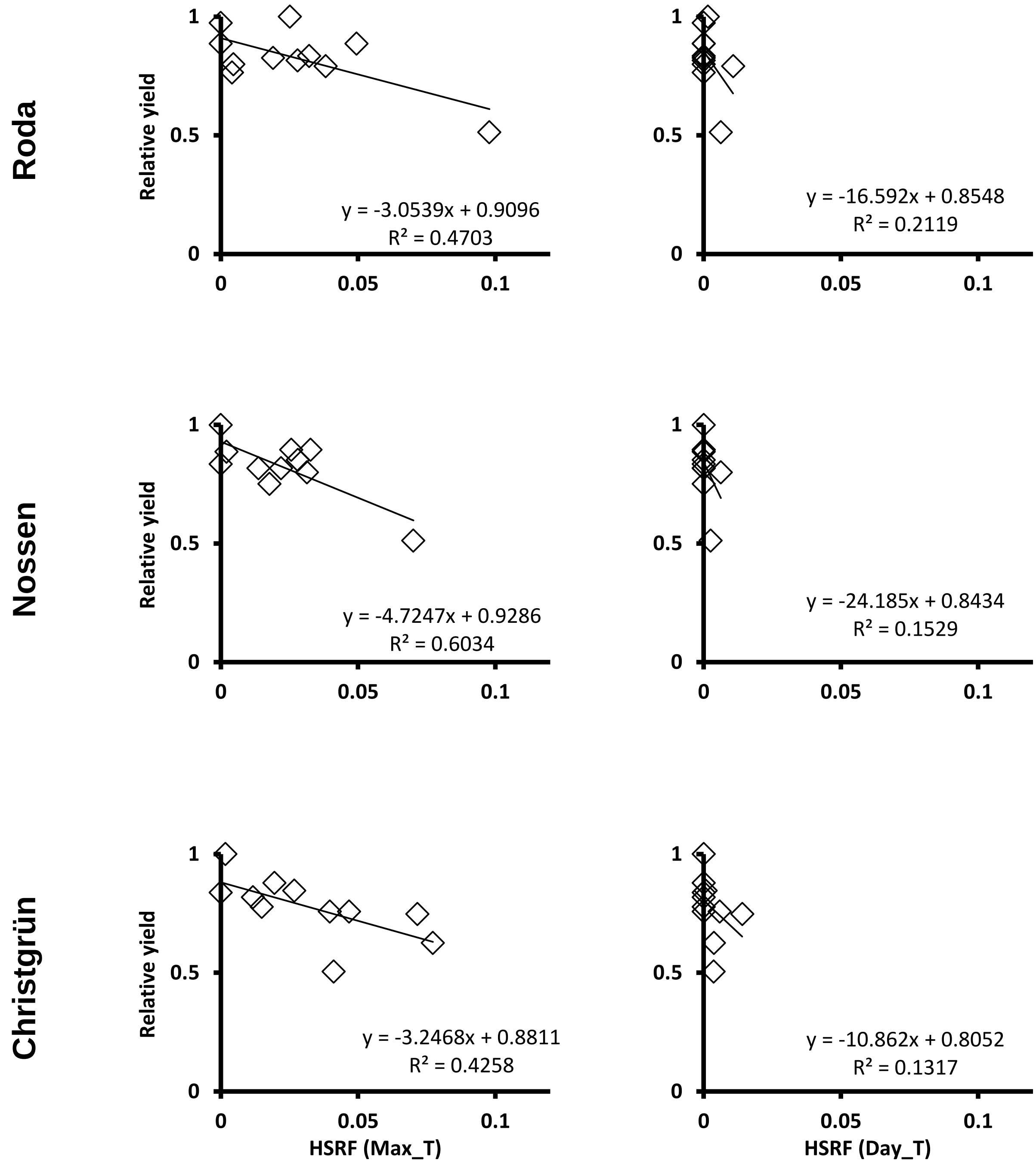


SI figure. 3.4. The relationship between observed day of heading and mean temperature from March to May (a), observed sowing, emergence and heading days (b), length of periods from sowing and emergence to heading (c), mean temperature from emergence to heading (d), temperature sum from emergence to heading (e) and daylength during growing period (f) during 1951-2009, for winter wheat across Germany. Please note: Observations in East Germany were missing from 1961 to 1990.

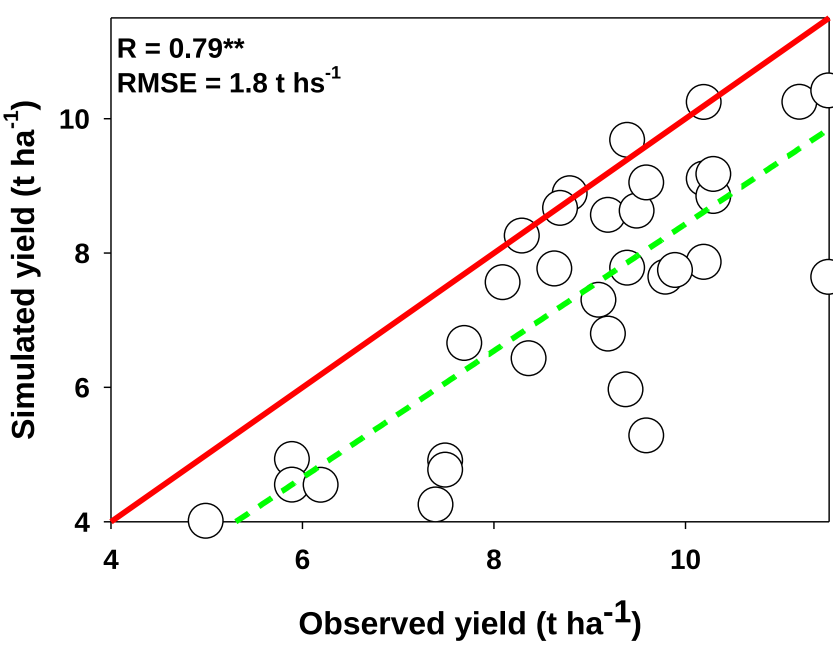


SI figure 3.5. Mean temperature around observed and de-trended day of heading (one week before and two weeks after heading) computed across all cropland grid cells in Germany.

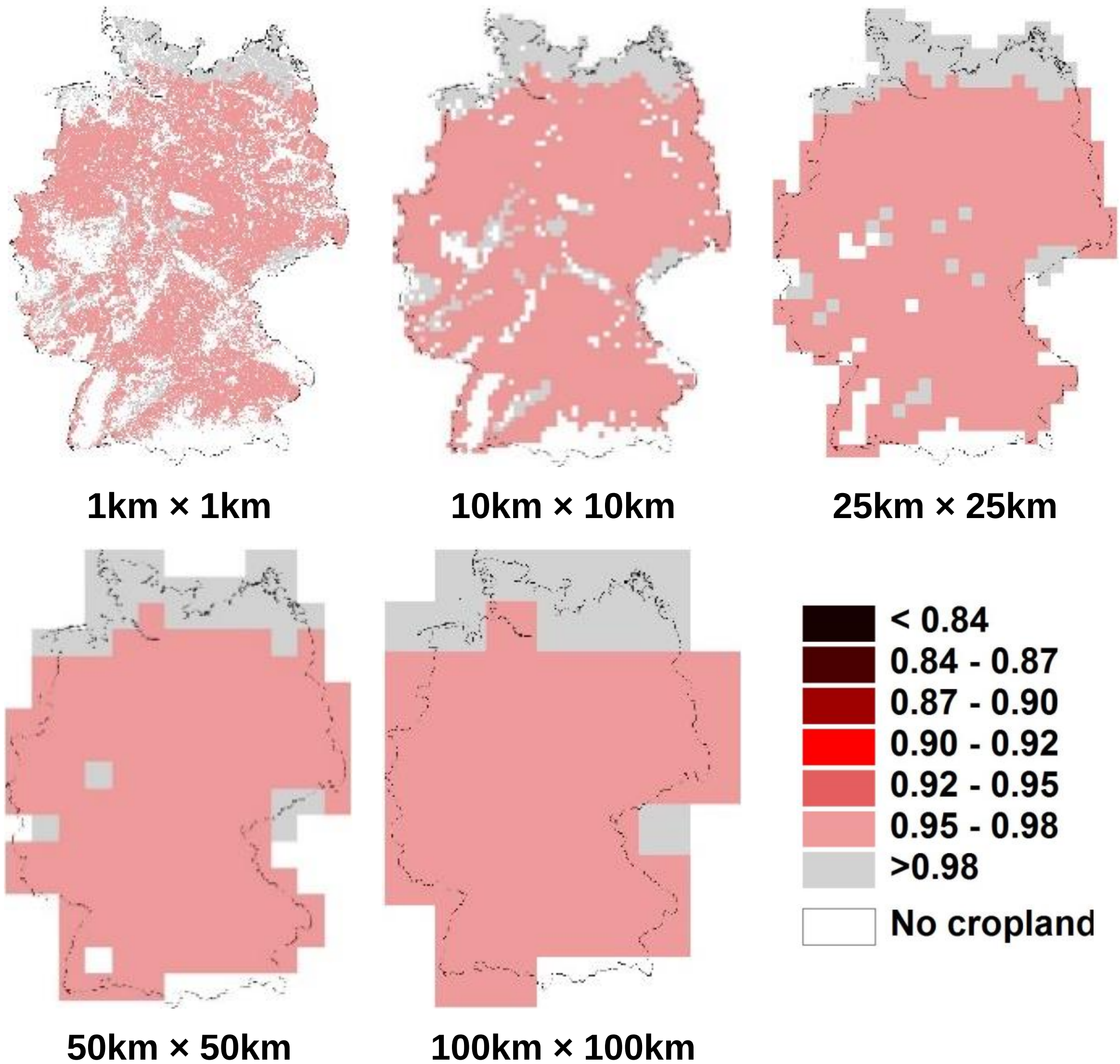
Supplementary materials for Chapter 4



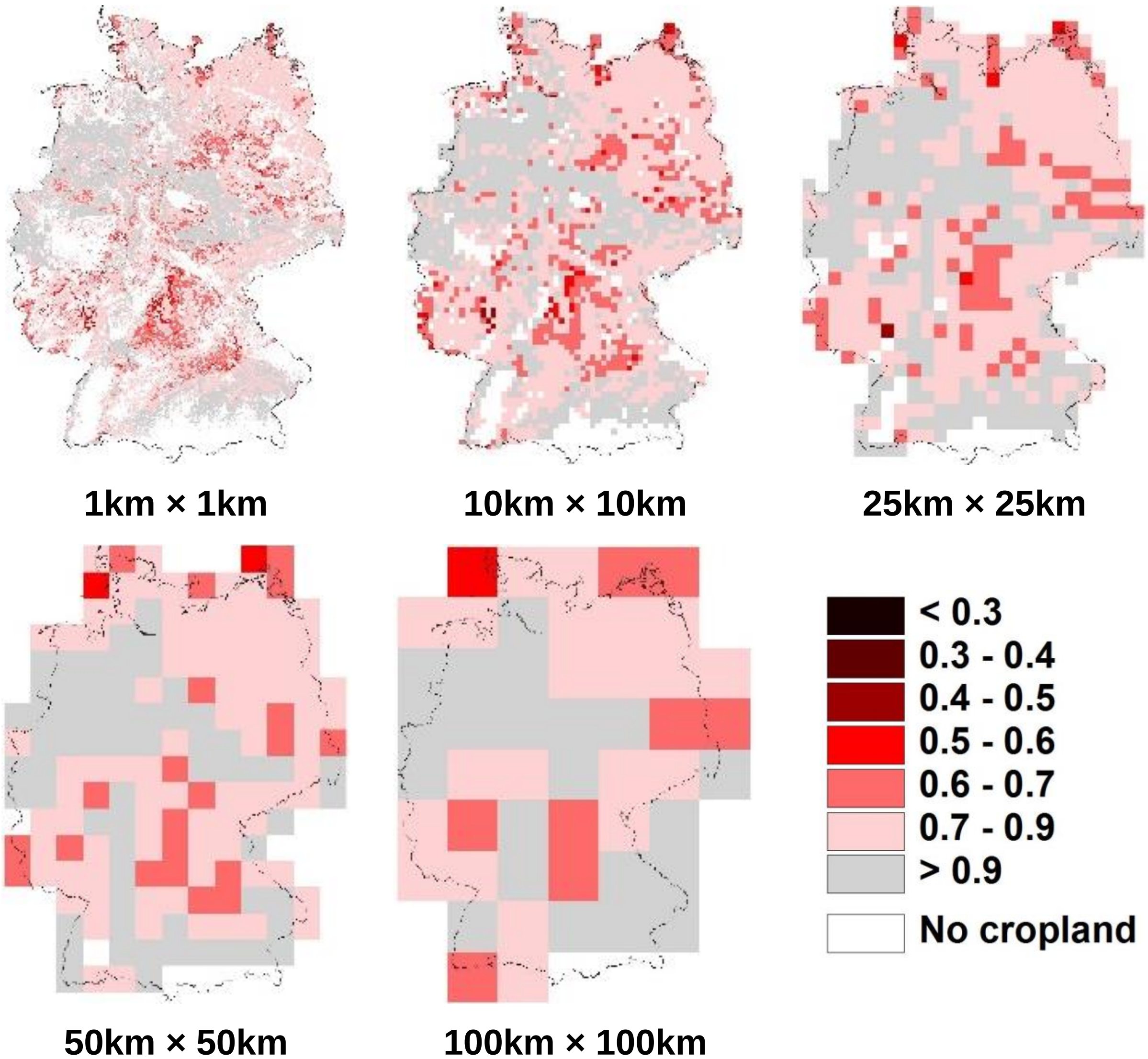
SI figure. 4.1. The relationship between heat stress reduction factor (HSRF) calculated from maximum daily temperature (Max_T) and day temperature (Day_T) and relative yield for the period 2001-2011 for three locations in Germany.



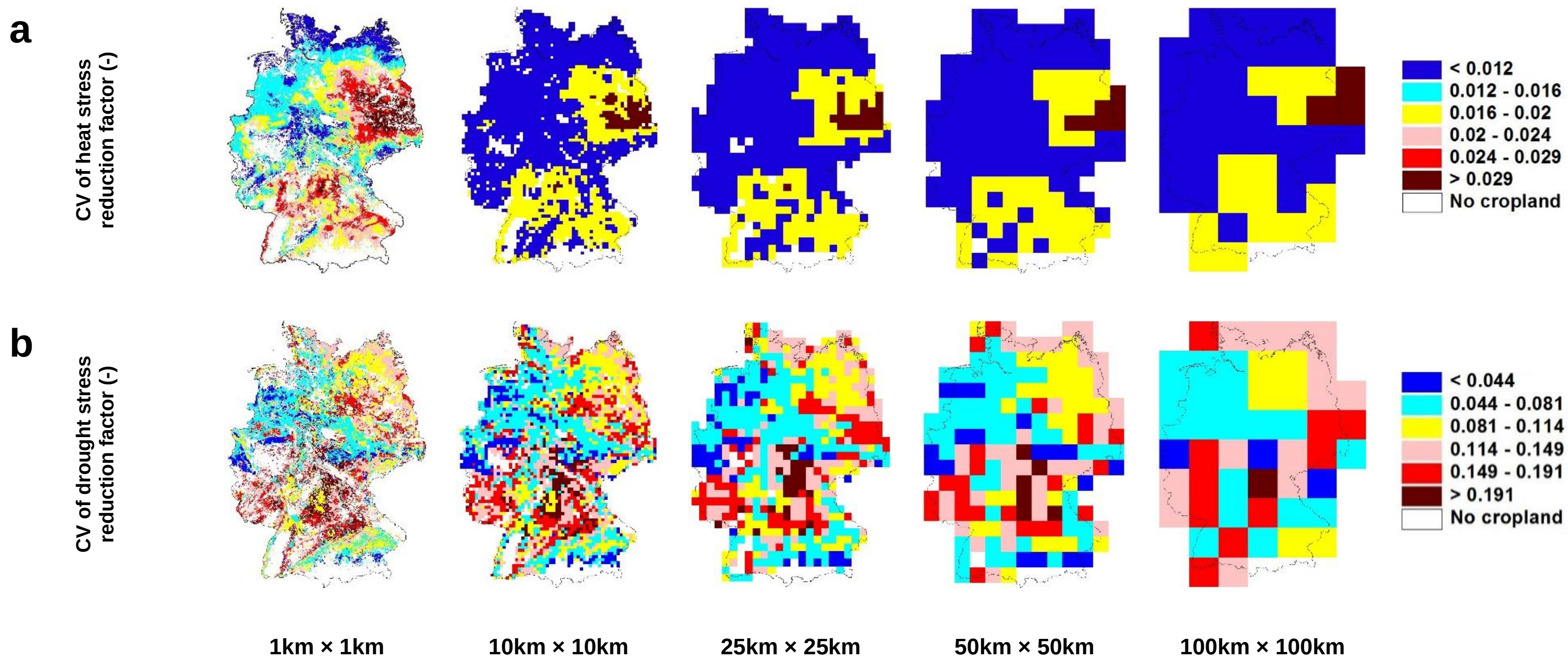
SI figure. 4.2. 1:1 Simulated vs. observed yields of winter wheat at three locations (2001-2011) in the state of Saxony Germany.



SI figure. 4.3. Heat stress reduction factors for Germany at different resolutions (mean 1980-2011). A low reduction factor means high heat stress (Legend of the fig. S3 is same as fig. 4).



SI figure. 4.4. Drought stress reduction factors for Germany at different resolutions (mean 1980-2011). A low reduction factor means drought stress (Legend of the fig. S4 is same as fig. 5).



SI figure. 4.5. The coefficient of variation (CV) of heat (a) and drought (b) stress reduction factors calculated (1980-2011) for all spatial resolutions at pixel level.