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Wheat and maize yield development in Bavaria until 2045
Usage of statistical models for predictions

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„Alle reden vom Wetter, aber keiner unternimmt was dagegen.“

(Karl Valentin)

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List of abbreviations

abbreviation	meaning
afc	Available field water capacity of agricultural soils [mm]
SW	Available soil water content [mm]
ha	Hectare
dt ha^{-1}	Deciton per hectare
SCA	Soil-Climate-Area
t_max/T_{MAX}	Daily maximum air temperature [°C]
t_min/T_{MIN}	Daily minimum air temperature [°C]
t_avg/T_{AVG}	Daily average air temperature [°C]
VP	Vapour pressure [kPa]
VPD	Vapour pressure deficit [kPa]
Prec	Sum of precipitation [mm day^{-1}]
ET_c	Potential evapotranspiration from a crop canopy [mm day^{-1}]
ET_o	Reference evapotranspiration FAO56 [mm day^{-1}]
Rad	Global radiation [KJ m^{-2} day^{-1}]
Cal	Aggregation of variables based on the calender
Phen	Aggregation of variables based on the phenology
RMSE	Root mean square error
MAE	Mean absolute error

Zusammenfassung

Da die Weltbevölkerung wächst, nimmt auch die Nachfrage nach Nahrungsmitteln zu. Deshalb muss die Nahrungsmittelproduktion bis 2050 steigen. Darüber hinaus stellen witterungsbedingte Ertragsschwankungen, die laut Klimaprojektionen in Zukunft zunehmen werden, ein erhöhtes Produktionsrisiko für die Landwirtschaft dar. Gerade bei ertragsstarken Systemen mit hohem Input, wie z.B. in Bayern, ist wenig bekannt, wie Witterungsschwankungen die Ertragsvolatilität beeinflussen. Deshalb muss ein besseres Verständnis der wetterbedingten Ertragsvolatilität, die auch ein Produktionsrisiko für Bayern birgt, gewonnen werden.

Vor diesem Hintergrund, war/ist das Ziel dieser Studie, die möglichen zukünftigen Auswirkungen des Klimawandels auf die Erträge von Winterweizen (*Triticum aestivum* L.) und Silomais (*Zea mays* L.) in Bayern einzuschätzen. In der vorliegenden Studie wurden statistische Modelle berechnet, die auf historischen Weizen- und Maiserträgen von 1991 – 2015 in verschiedenen bayerischen Landkreisen basieren. Die Modelle wurden so konzipiert, dass sie sowohl die Durchschnittserträge als auch die jährlichen Ertragsvariationen reproduzieren. Die Erträge wurden auf der Ebene der Landkreise und der Boden-Klima-Räume modelliert und verglichen. Durch die Modelle wurden abiotische Faktoren wie die nutzbare Feldkapazität, das Temperaturmaximum und -minimum, die Globalstrahlung und das Sättigungsdefizit als diejenigen Faktoren identifiziert, die die unterschiedlichen mittleren Ertragsniveaus zwischen den bayerischen Standorten, Landkreisen und Boden-Klima-Räumen, und die zwischenjährlichen Ertragsschwankungen innerhalb der Standorte erklären. Alle anderen ertragsbeeinflussenden Faktoren, wie z.B. das Management, wurden als konstant angenommen.

Um die Auswirkungen des Klimawandels auf Winterweizen- und Silomaiserträge in Bayern bis 2045 zu projizieren, wurde das Klimaszenario A1B genutzt. Dabei wurden drei Zeiträume verglichen: 1985 - 2015, 2005 - 2035 und 2015 - 2045. Die Ertragsmodellierungen wurden anhand dreier statistischer Ansätze berechnet: Zeitreihenmodelle, Paneldatenmodelle und cross-section Modelle. Anhand der Modelle wurde zusätzlich untersucht, ob die Einbeziehung phänologischer Phasen im Gegensatz zu kalenderaggregierten Faktoren und die zeitvariable Aggregation von Faktoren die Modellierung verbessern.

Das Panelmodell war das effektivste Modell für Ertragsvorhersagen in Bayern. In Hinblick auf den Nash-Sutcliffe Modell-Effizienz-Koeffizienten (NSE), nach dem die Modellgüte bewertet wurde, erreichte das cross-section Modell die höchste Modellgüte mit einem NSE = 0,84 und R^2-Werten von 0,88 bis 0,96 für Weizen auf der Ebene der Boden-Klima-Räume. Für Mais wurde ein durchschnittlicher NSE-Wert von 0,69 ermittelt, das R^2 lag bei 0,69. Das Bestimmtheitsmaß für das Panelmodel betrug bei Winterweizen für die Aggregationsebene der Boden-Klima-Räume $R^2 = 0,75 - 0,80$, für Mais lag dieser Wert bei $R^2 = 0,63 - 0,67$. Auf Landkreiseben wurden für Weizen

$R^2 = 0{,}49 - 0{,}55$ beobachtet, für Mais lagen R^2 Werte zwischen 0,58 und 0,62. Im Zeitreihenmodell waren die NSE-Werte negativ, was bedeutet, dass Mittelwerte bessere Ertragsschätzungen lieferten als das Modell selbst. Insgesamt lieferte das Weizenmodell bessere Ertragsprognosen als das Maismodell, und zwar sowohl für mittlere Erträge als auch hinsichtlich der Ertragsvolatilität.

Es konnte ein Aggregationseffekt beobachtet werden, der Erträge für größere Flächen, also der Boden-Klima-Räume, besser vorhersagen konnte. Der beobachtete Aggregationseffekt war jedoch nur bei Weizen vorhanden. Da die quadratische Ergänzung der Faktoren zu einer hohen Kollinearität der Faktoren führte, waren die geschätzten Koeffizienten nur für Bayern und unter der Annahme gültig, dass sich die Beziehungen zwischen den Faktoren in Zukunft nicht ändern werden. Jedoch waren die Faktoren, die als natürliche Zahlen zur Berechnung von Ertragsvorhersagen verwendet wurden, untereinander nicht kollinear. Der Einbezug phänologischer Phasen in die Modellierung führte zu keiner Verbesserung der Vorhersagen. Auch die zeitvariable Aggregation von Umweltfaktoren verbesserte die Modellergebnisse nicht wesentlich. Die Aggregation von abiotischen Faktoren auf monatlicher Basis wurde als ausreichend zur Berechnung statistischer Panelmodelle in Bayern betrachtet.

Die Erträge zwischen 2000 und 2020 werden laut Projektionen in Bayern leicht ansteigen. Im Mittel werden sich Klimaänderungen bis zum Jahr 2035 nicht negativ auf Erträge auswirken. Bis zur Mitte des Jahrhunderts werden die projizierten Klimaänderungen in Bayern laut Panelmodel zu Ertragsreduktionen um ca. 10% im Vergleich zum Zeitraum 1985 - 2015 führen. Insgesamt waren die Panelmodelle die im Rahmen dieser Arbeit berechnet wurden in der Lage, den Einfluss der Klimaänderungen für künftige Erträge in Bayern abzuschätzen. Extremereignisse wurden jedoch nicht berücksichtigt, sodass in Jahren mit sehr ungünstigen Wetterbedingungen Erträge noch stärker schwanken bzw. reduziert sein werden.

Die durchschnittlichen Ertragsunterschiede zwischen bayerischen Boden-Klima-Räumen ließen sich sehr gut durch den Median der nutzbaren Feldkapazität in den Boden-Klima-Räumen erklären. Die Ertragsvariabilität zwischen den Jahren kam hingegen durch Witterungsunterschiede während der Vegetationszeit zustande. Weizen benötigt in ganz Bayern im Laufe seiner Vegetationszeit eine ähnlich hohe Wassermenge. Hieraus wurde geschlussfolgert, dass eine Kultur im Vegetationszeitraum im Verhältnis zur nutzbaren Feldkapazität umso mehr Wasser benötigt, desto geringer die Pufferfähigkeit des Bodens ist. Es wurde weiter geschlussfolgert, dass der Beitrag der Pufferkapazität der Böden umso geringer ist, je mehr Wasser eine Kultur während der Vegetationsperiode im Verhältnis zur nutzbaren Feldkapazität benötigt. Aus diesem Grund war der positive Zusammenhang zwischen nutzbarer Feldkapazität und mittleren Maiserträgen in den bayerischen Boden-Klima-Räumen weniger stark. Durch die höhere Evapotranspiration, der höheren Biomasse Akkumulation und dadurch, dass Mais eine sommerannuelle Kultur ist, benötigt er mehr Wasser während des Vegetationszeitraums, als Weizen. Die Pufferfähigkeit der Böden kam hier also folglich nicht so stark zum Tragen wie beim Weizen. In Bayern hing die Höhe der Maiserträge noch stärker als bei den Weizenerträgen von der Witterung ab.

Insgesamt liefert die vorliegende Studie mittels Benutzung von Panelmodellen Berechnungen zu Ertragsprognosen für den Raum Bayern. Die Modelle sind jedoch nur für den bayerischen Raum gültig und können nicht auf andere Räume angewendet werden. Zukünftige Forschungsprojekte könnten neuronale Netze oder prozessbasierte Modelle berücksichtigen, um weitere Fragestellungen zu untersuchen.

Summary

Since world population grows, the demand for food also increases. Therefore, food production must rise by 2050. In addition, weather-related yield variabilities pose an increased production risk for the agricultural sector. According to climate projections, weather-induced yield variabilities will increase in the future. Especially in high-yielding, high-input systems, such as in Bavaria, Germany, little is known how weather variability influences yield volatility. Thus, an improved understanding of weather-related yield volatility also entailing a production risk for the federal state of Bavaria must be obtained.

Against this background, the aim of this study was to assess the possible future effects of climate change on winter wheat (*Triticum aestivum* L.) and silage maize (*Zea mays* L.) yields in Bavaria. Statistical models were calculated based on historical wheat and maize yields from 1991 - 2015 in the Bavarian counties. The models were designed to reproduce average yields as well as the inter-annual variability of yields. Yields were modelled and compared on the county and Soil-Climate-Area level. Furthermore, the modelling identified abiotic factors such as available field water capacity, temperature maximum and minimum, radiation sum and vapor pressure deficit, which explained the different mean yield levels across Bavarian sites and the inter-annual yield variations within sites. All other factors that influenced yields, such as management, were assumed to be constant.

The climate scenario A1B was used to predict climate change impacts on winter wheat and silage maize in Bavaria until 2045. Thus, three time periods were compared: 1985 – 2015, 2005 – 2035 and 2015 – 2045. For the yield modelling three statistical approaches were used: Time-series models, panel data models and cross-section models. In addition, the models investigated whether the inclusion of phenological phases in contrast to calendar-aggregated factors besides the time variable aggregation of factors improved the modelling performance.

The panel model was the most effective model for yield predictions in Bavaria. For cross-section models, the highest model performance was obtained, with a Nash-Sutcliffe model efficiency coefficient (NSE), according to which the model quality was assessed, NSE = 0.84 and R^2-values from 0.88 to 0.96 for wheat at the Soil-Climate-Area level. For maize, an average NSE of 0.69 was obtained and the R^2-value was 0.69. For the panel model the coefficients of determination were $R^2 = 0.75 - 0.80$ for winter wheat and $R^2 = 0.63 - 0.67$ for maize for the aggregation level of the Soil-Climate-Areas. At county level, $R^2 = 0.49 - 0.55$ for wheat and R^2 values of 0.58 and 0.62 were obtained. The NSE of both crops were negative according to time-series models. A negative NSE reveals that mean values provide better yield estimates than the model itself. The wheat model provided better overall yield predictions for both, average yields and yield variability than the maize model.

An aggregation effect could be observed which allowed a better prediction of yields for larger areas, namely the Soil-Climate-Areas. However, the observed aggregation effect was only present for wheat. Since the quadratic additions of factors resulted in a high overall collinearity among the factors, the estimated coefficients are only valid for Bavaria and on the assumption that the relationships between the factors would not change in the future. However, the factors used as natural numbers to calculate yield predictions were not collinear among each other. Furthermore, the inclusion of factors based on phenological phases instead of calendar phases and the combination of environmental factors at different time intervals did not improve the model predictions. The aggregation of abiotic factors on a monthly basis was regarded as adequate as a basis for statistical panel models in Bavaria.

According to the modelled predictions, yields between 2000 and 2020 will increase slightly in Bavaria. Thus, climate change in Bavaria will on average, not negatively affect yields until 2035. By mid-century, up to the year 2045, the projected climate changes for Bavaria will, based on the panel model, result in yield reductions of about 10% compared to the period 1985 – 2015. Overall, the panel models developed in this thesis were able to estimate the impact of climate change on future yields in Bavaria. However, extreme events were not included, which means that in years with very unfavorable weather conditions, yields will be more variable or reduced.

Average yield differences across Bavarian Soil-Climate-Areas could be explained very well by the different level of median available field water capacity across Soil-Climate-Areas. However, inter-annual yield variability resulted mainly from differences in weather conditions during the growing season. Wheat requires a similar amount of water throughout Bavaria during its vegetation period. It was concluded that the more water a crop requires during the growing season in relation to the available field water capacity, the less contribution of the buffering capacity of soils is observed. For this reason, the positive correlation between available field water capacity and average maize yields was less strong among the Bavarian Soil-Climate-Areas. Due to higher evapotranspiration, higher biomass accumulation and as maize is a summer crop, it requires more water during the growing season than wheat. Therefore, the buffering capacity of soils was less evident for maize than for wheat. In Bavaria, maize yields were even more dependent on weather conditions than wheat yields.

In sum, this study provides yield predictions for the federal state of Bavaria by using panel models. However, the models are only valid for the Bavarian region and are not applicable to other regions. Future research projects may consider neural networks or process-based models to extend these investigations.

1 Introduction

1.1 Identification of relevant abiotic factors influencing yields of silage maize and winter wheat in Bavaria

Climate change negatively affect wheat and maize production in many regions throughout the world (Porter et al., 2014). The uncertainty of climatic conditions also creates a risk for agricultural production in Germany (Gornott and Wechsung, 2016). Bavaria is the largest producer of wheat and silage maize in Germany (Statistisches Bundesamt, 2018). Since the global demand for agricultural products, particularly wheat and maize, is expected to rise, and production uncertainty is increasing (Michèle, 2018), it is also important for the federal state of Bavaria, which represents the largest agricultural area in Germany, to assess production risks. It is well known that environmental conditions, especially temperature, influence the phenology of plants (Heuer et al., 1978; Hodges, 1990; Kirby et al., 1987, 1987; McMaster and Smika, 1988; McMaster and Wilhelm, 2003; Spinoni et al., 2015). Changes in the timing of phenological phases of crops could have direct impact on final yields (Chmielewski et al., 2004). An important challenge in a world where the demand for agricultural products is increasing and climate conditions are changing, is therefore, to understand the influence of phenology on the final yield as well as the influence of environmental variables on phenology.

In recent decades, many studies focused on changing phenology due to changing environmental factors (Chmielewski et al., 2004; Sacks and Kucharik, 2011; Tao et al., 2006). In the past the focus was directed more on trees and less on arable crops (Menzel and Fabian, 1999). Numerous studies addressed changing climatic factors, their relation to phenology and the yield level concerning regions such as China and the USA (Sacks and Kucharik, 2011; Tao et al., 2006). Studies in Germany regarding changing phenology as a result of predicted climate changes were undertaken (Chmielewski et al., 2004; Estrella et al., 2007; Siebert and Ewert, 2012). Furthermore, studies that investigated site-specific interactions of weather, climate and phenology on yield components were reported for Germany (Chmielewski and Köhn, 2000). The focus of the studies was placed on the temporal change of the phenology and included possible spatial heterogeneity in phenology. Often phenology was explained by climatic variations, however the relationship to yield levels was not documented (Chmielewski et al., 2004; Estrella et al., 2007). Several studies described relationships between global wheat yield levels and abiotic factors such as temperature, precipitation levels and solar radiation. Asseng et al. (2011a) investigated the effect of temperature on yield of various locations in the world including Germany. Using simulation models, they were able to separate the sole effect of temperature on yields. They concluded that a variation of ±2 °C of the mean temperature during the growing season in the main wheat growing regions in Australia, could result in grain reductions of up to 50%. For Germany, yield reductions could not be quantified as precisely as for Australia, but the authors concluded with higher temperatures during grain filling in Germany, yields were also reduced (Asseng et al., 2011a). Ciais et al. (2005) observed a negative relationship between precipitation deficit and yield in Europe. Lobell and Ortiz-Monasterio (2007) investigated the impact of temperature minimum and maximum and solar radiation on yield at three locations in the USA. They found a positive relationship for all three factors. For Germany, Erekul and Köhn (2006) investigated the effect of weather and soil conditions on yield components of winter wheat. They found that adverse weather conditions as in the dry year 2003, led to reduced ear densities and that silty sand soils in Thyrow reacted more sensitively to adverse weather conditions than loamy sandy soils in Berge. Thus the cultivation of wheat on very light sandy soil was exposed to a higher production risk. For maize studies have been reported which analyzed the relationship between phenology, yield and abiotic factors such as soil temperature, solar radiation and temperature. Radiation for example, revealed a positive relationship with yield (Loomis and Williams, 1963; Muchow, 1989; Muchow et al., 1990), whereas maximum temperatures above 32°C especially during the grain filling phase reduced yields (Muchow, 1989; Runge, 1968). Higher soil temperatures resulted in higher grain yields for temperate climates (Stone et al., 1999). Whilst studies on the relationship between abiotic factors and the duration of phenological phases, or on how the duration of phenological phases influenced yields have been conducted, such information is not available for Bavaria. To date, relationships between the median available field water capacity and average yields in Bavaria were not investigated. Only the effects of soil moisture anomalies on maize yields were investigated at county level for Germany for the period 1999 – 2015 (Peichl et al., 2018).

1.2 Evaluation of optimal time intervals using statistical models

Wheat and maize, the two most cultivated crops in Europe, Germany and Bavaria, pose major challenges to agriculture due to an increasing population and changes in the global and regional climate (Bundesanstalt für Landwirtschaft und Ernährung, 2018; Eurostat, 2019a, 2019b; Statistisches Bundesamt, 2018). Over the next few years, agriculture will have to develop strategies and methods to ensure the sustained nutrition of the entire population subjected to changing conditions. By 2050, the earth's population will rise to 9.1 billion people. This requires an increase in food production (FAO, 2009). At the same time, climatic extremes and severe weather events are increasing, posing a greater risk for farmers and thus threatening food production security (Handmer et al., 2012). In southern Germany wheat yields are expected to decline moderately due to climate change by the middle of the 21st century (Kersebaum and Nendel, 2014). In an environment where the climate is changing, it is crucial to assess the effects of climate change on yield. Therefore, the usage of crop models is essential. However, yield predictions depend to a great extent on input data (Albers et al., 2017; Hoffmann et al., 2016; Kuhnert et al., 2017; Maharjan et al., 2019).

Crops models are used to evaluate how agricultural yields can be affected by climate change (Porwollik et al., 2017). Two different approaches were established in crop modelling: process-based models and statistical models. Statistical models use statistical regressions to link historical yield outcomes to historical weather aggregates and extrapolate from observed associations to do yield predictions under an altered projected climate (Schlenker and Roberts, 2009; Roberts et al., 2017). Process-based models need data and/or assumptions about soils, management practices, daily weather variables and feeds these through process-based mathematical models of plant growth and seed formation (Roberts et al., 2017; Muchow et al., 1990; Jones et al., 2003; Keating et al., 2003) Crop models prevailed for five decades (Boote et al., 2013) and were initiated by the pioneering work of de Wit (1965) and Monteith (1965a, 1965b). They simulated the main processes of crop growth and development using numerical models. But they required extensive data on the environment, soil, management and the cultivar (Lobell and Burke, 2010). Today there are numerous models reflecting different complexities (Asseng et al., 2011b; Challinor et al., 2009; Edreira et al., 2018; Kersebaum and Nendel, 2014). They differ, among others, with regard to the investigated areas and the spatial, spatio-temporal and temporal resolutions of the input variables. Global studies on the influence of climate change on crop yields were conducted (Asseng et al., 2011b; Rosenzweig and Parry, 1994), but also individual countries (Kersebaum et al., 2009) as well as groups of countries (Mäkinen et al., 2018), as well as regions within a country (Langensiepen et al., 2008) or individual sites (Kersebaum and Nendel, 2014) were investigated. The influence of the spatial resolution of input variables on simulating yield levels, were analyzed in Hoffmann et al. (2016) for North Rhine-Westphalia and in Nendel et al. (2013) for Thuringia. Zhao et al. (2016) evaluated the spatial sampling on simulated yields for winter wheat and silage maize. The effects of data aggregation on simulated crop yields in temperate and mediterranean climates as well as the impact of climate data aggregation at different spatial resolutions for cropland were evaluated by Maharajan et al. (2019) and Kuhnert et al. (2017). Spatial and temporal uncertainties of crop yield aggregations were assessed by Porwollik et al. (2017). All these different models were used to predict yield and to evaluate the impact of climate change on yield. The effect of temporal aggregation of weather input data on model results were the subject of different studies. Nonhebel (1994) and van Bussel et al. (2011b) for example used daily weather data instead of using averages. Other studies used input parameters such as the mean temperature during the vegetation period (e.g. Lobell and Burke, 2010b) or mean aggregated weather information, averaging information over several months (Gornott and Wechsung, 2015). Some studies aggregated the input variables according to the reproductive and vegetative phases (Gornott and Wechsung, 2016), others according to phenological phases (Ortiz-Bobea and Just, 2013). Others considered annual averages during the vegetation period (Lobell and Burke, 2010), monthly averages (Reidsma et al., 2007) or both monthly and yearly averages (Isik and Devadoss, 2006). Albers et al. (2017) aggregated weather variables such as the sum of solar radiation during phenological phases. By contrast, high-resolution temperature data and their distribution during the course of a day as well as between days were used by Schlenker and Roberts (2009) to explain the yield levels of soy, corn and cotton. To the best of our knowledge, no systematic analysis was undertaken to identify whether time variable factors can better predict yields. Furthermore, to our knowledge it was not demonstrated whether statistical models described yield levels better when input variables were calculated on the basis of phenological data or calendar-based data.

1.3 Yield predictions of winter wheat and silage maize in Bavaria

Extreme events will occur more frequently in the future as a result of climate change, with agriculture being one of the sectors most vulnerable to climate change. Weather determines crop yields and their variability considerably (Handmer et al., 2012; Porter and Semenov, 2005; Semenov and Porter, 1995; Wheeler et al., 2000). This affects both the macro level with its effects at the global level and the micro level with its effects at the regional/country level. Therefore, the uncertainty of climatic conditions also creates a risk for agricultural production in Germany (Gornott and Wechsung, 2016), with Bavaria being the largest producer of wheat and silage maize in Germany (Statistisches Bundesamt, 2018). If yield levels in Bavaria decrease, this can have an impact on the micro-level i.e. the income stability of farmers, but also on the macro-level because it contributes to global food security. Hence, food security was linked to our ability to adapt agricultural systems to extreme events (Handmer et al., 2012). As extremes will increase in the future and thus have an impact on our yield levels, it is of decisive importance to assess the risk that we could face in the future. Crop models offer a method for estimating future yields due to climate change.

Within crop modelling, two different approaches were developed. Process-based models will be outlined first. Typically, process-based models were tested based on experimental trials. Experimental trials were based on the knowledge about crop physiology as well as soil information. Thus, the calibration of such models was difficult because of unknown and uncertain parameters. The uncertainty of parameters could be disregarded and parameters were fitted until they produce values which were similar to observations (Lobell and Burke, 2010). Nevertheless, numerous process-based models of different complexities exist today for various questions (Asseng et al., 2011b; Boote et al., 2013; Challinor et al., 2009; Edreira et al., 2018; Kersebaum and Nendel, 2014; Nonhebel, 1994; Priesack et al., 2012; Semenov and Porter, 1995; van Bussel et al., 2011b). The second approach to assess the influence of climate on agricultural yields are statistical models (Gornott and Wechsung, 2016; Holzkämper et al., 2012; Iizumi et al., 2013; Kern et al., 2018; Lobell et al., 2011b; Schlenker and Roberts, 2009). Statistical models were not as frequently used as process-based models to capture the influence of abiotic factors on yield levels (Oury, 1965). In contrast to process-based models, statistical models explained the yield level with weather without considering sub-models such as an integrated phenology model. Generally, statistical models can be differentiated into two types. The first type uses so-called production functions, which take external effects like fertilizer prices into account (Gornott and Wechsung, 2016, 2015; Hoch, 1962). The second type of statistical models uses statistical regressions to explain historical yields with climatic data (Hansen, 1991; Holzkämper et al., 2012; Lobell and Burke, 2010; Lobell and Field, 2007; Schlenker and Lobell, 2010; Shi et al., 2013). Based on these relationships, predictions for future yields were subsequently calculated taking climatic change conditions into consideration (Roberts et al., 2017). Numerous studies considered the interaction of weather and crop yields (e.g. Chen et al., 2004; Lobell and Burke, 2010b) and they differed in many aspects. The distinction was done between the investigated area, the input parameters, the aggregation of the input parameters and the regression technique used to analyze yield levels. The effects of elevated temperatures on the world's most commonly grown crops were assessed (Lobell and Field, 2007). Changes in yield levels due to altered temperatures and reduced precipitation in sub-Saharan Africa were predicted by Barrios et al., (2008) and Lobell and Burke (2010). While another study used statistical models to predict the yield volatility of winter wheat and silage maize in Germany (Albers et al., 2017). Furthermore, statistical models that predicted yield levels for silage maize and winter wheat were available at the county level for Germany. (Gornott and Wechsung, 2016, 2015). Wheat yield levels of individual farms were predicted by Heimfarth et al. (2012). Some studies only used time-series regressions to model crop yields (Choudhury and Jones, 2014; Iglesias and Quiroga, 2007), whereas in other studies several regression techniques were considered (Albers et al., 2017; Chen et al., 2004; Gornott and Wechsung, 2015, 2016; Lobell et al., 2011b; Lobell and Burke, 2010). Most studies used precipitation and temperature as input parameters and explanatory variables (e.g. Hansen, 1991; Lobell et al., 2011; Lobell and Burke, 2010b; Reidsma et al., 2007). However, there were also studies that included further/other explanatory variables within their models. These were, for example, the potential evapotranspiration (Gornott and Wechsung, 2016) or the vapor pressure deficit (Lobell et al., 2014). The influence of soil moisture as an explanatory variable was included in Kaylen et al. (1992). The author developed a soil moisture index which represented the total rainfall for six months prior the beginning of the growing season (Kaylen et al., 1992), whereas Yang et al. (1992) defined the soil moisture as the sum of precipitation during the growing season plus the preseason precipitation (Yang et al., 1992). To the best of our knowledge, no study that involved changes in the available soil water content during the vegetation period in Bavaria was conducted. Although models with integrated production functions were calculated for German counties (Gornott and Wechsung, 2016, 2015), no research was started to the best of our knowledge to investigate correlations between yields and abiotic factors in Bavaria using statistical models.

2 Objectives

The objectives of this thesis are stated individually for the different sections 4.2 to 4.4.

Section 4.2 is based on the first hypothesis that the different levels of the median available field water capacities present in the Soil-Climate-Areas of Bavaria, can explain the yield differences across Soil-Climate-Areas. The second hypothesis is that yield is influenced by the duration of phenological phases whereas phenological phases are influenced by environmental factors, and thus yields are influenced by both the duration of phenological phases and environmental factors. The objectives of this thesis are to identify relationships between the duration of phenological phases and abiotic factors, to identify relationships between yields and the duration of phenological phases. Furthermore, to correlate yields with abiotic factors present during phenological phases, and to determine those abiotic factors and phenological phases that were correlated with high or low yields.

Section 4.3 is based on the hypothesis that factors calculated on the basis of short time intervals, such as the calculation of the ten-day average temperature, result in more precise yield predictions than factors based on longer time intervals, such as the calculation of the monthly average temperature. The objectives are to test time variable factors and their ability to predict yields, to evaluate whether the predictive ability of models increases if time intervals are based on phenology-based instead of calendar-based time intervals, and to define a suitable time interval for the aggregation of factors for the modelling of yields in Bavaria.

To predict yields for Bavaria up to 2045, the objectives in Section 4.4 are: to apply different approaches of statistical modelling, compare them with each other and to identify the model that can adequately reproduce yield level and variability. Based one these findings, yield preditcions for all Soil-Climate-Areas and counties of both crops until 2045 were calculated. Additionally it was investigated whether the inclusion of a further abiotic factor, the available soil water content, could improve statistical crop yield modelling.

To meet these objectives, different methodologies, spatial aggregation levels, time intervalls, etc. were considered throughout the different sections. Table 1 gives an overview of the various approaches.

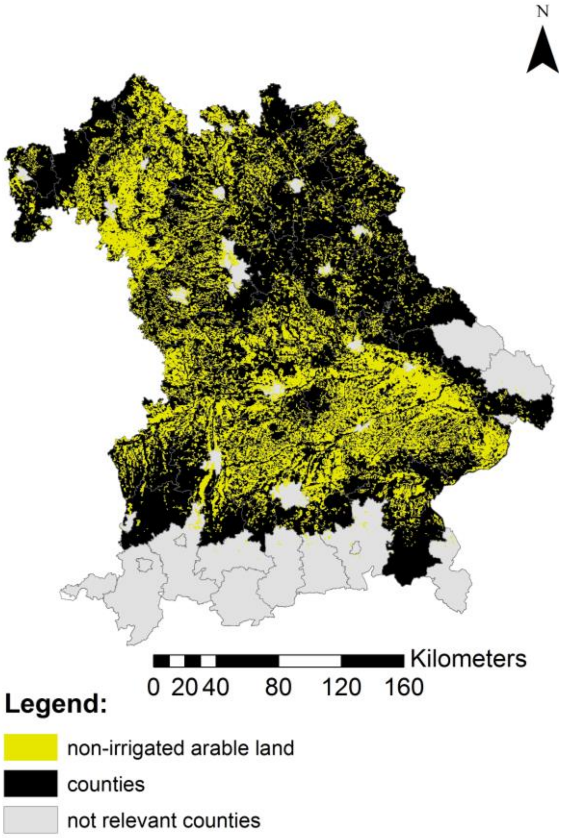
Table 1: Overview of target, procedure and used methodology in different sections of this thesis.

Section	Objectives	Statistical procedure	Target	Independent variables	Geographic unit	Time span
4.2	Explain yield variability between regions in Bavaria by the amount of median available field water capacity	Linear Regression	Average Yield	Median available field water capacity	Soil-Climate-Areas	1991-2015
	Correlation of the duration of phenological phases with abiotic factors	Linear Regression	Phenological phase	Abiotic factors during phenological phases	Soil-Climate-Areas	Each single phenological phase per year
	Correlation of yields with the duration of phenological phases	Linear Regression	Yield	Duration of each phenological phase in days	Soil-Climate-Areas	Average duration of each single phenological phase between 1991 - 2015
	Correlation of yields with abtiotic factors during phenological phases	Linear Regression	Average yield, high yield, low yield	Abiotic factors during phenological phases	Soil-Climate-Areas	Phenological phases per year 1991 - 2015
4.3	Inter-annual yield variability	Multiple linear regression	Yield variability	Temperature, simulated available soil water content. Time variable factors	Counties	**Phenology**: units and phenological phases **Calender**: days, month, year
4.4	Yield predictions for each Soil-Climate-Area	Time-series analysis	Yield variability, yield level	Abiotic factors: weather, simulated available soil water content	Soil-Climate-Area	Monthly 1991 - 2015
	Yield predictions for all Soil-Climate-Areas and counties together	Panel analysis	Yield variability, yield level	Abiotic factors: weather, simulated available soil water content	Soil-Climate-Area, counties	Monthly 1985 - 2045
	Yield predictions for all Soil-Climate-Areas and counties together	Panel analysis	Yield variability, yield level of average-, high- and low yields between 1991 - 2015	Abiotic factors: weather, simulated available soil water content	Soil-Climate-Area	Monthly 1991 - 2015
	Average yield predictions of all Soil-Climate-Areas	Cross section model	Yield	Average abiotic factors: weather, simulated available soil water	Soil-Climate-Area	Monthly 1991 - 2015

3 Materials and Methods

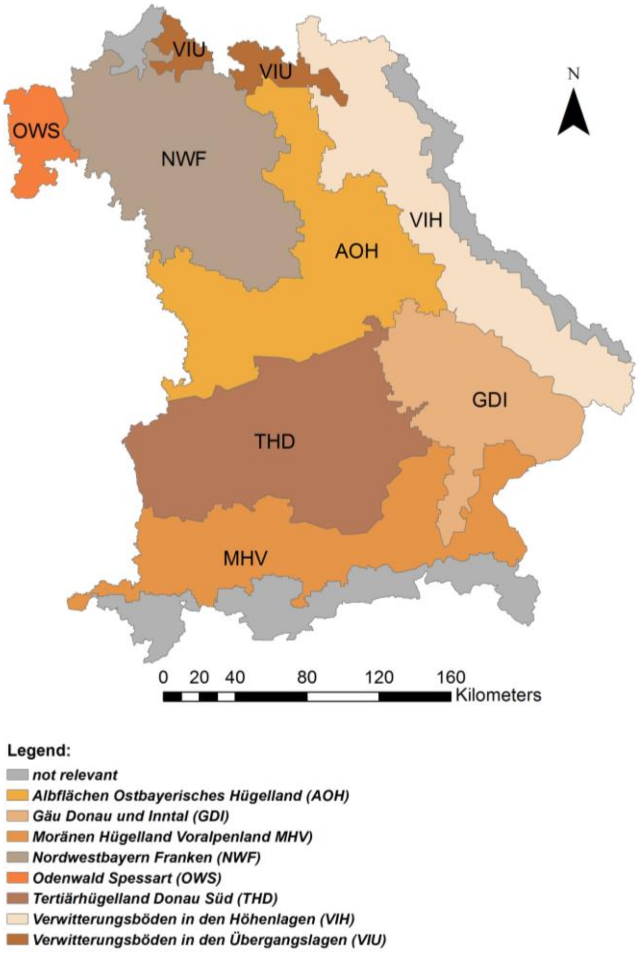
3.1 Definition of the study area, site selection and upscaling method

The study area covers the federal state of Bavaria in Germany. Within the framework of the European project "Nomenclature of territorial units for statistics" (NUTS), Bavaria is divided into three political-administrative zones. The federal state of Bavaria is defined as NUTS 1. NUTS 2 consists of seven districts (Regierungsbezirke = districts). The NUTS 3 include 96 counties (Landkreise = counties) (Eurostat, 2015). The present work was based on agricultural areas in Bavaria. The European project "Coordination of Information on the Environment" (CORINE) provides a comprehensive data set on land cover and land use in Bavaria in a resolution of 1:100,000. The information was obtained from satellite data. One of the main classes of CORINE data is agricultural land use, for which arable land is a subcategory. Arable land is also divided into subcategories. The subclass non-irrigated arable land represents the areas in Bavaria in which the two crops winter wheat and silage maize were grown, excluding cities from the analysis (European Environment Agency, 1995). By intersecting the non-irrigated arable land with the counties in Bavaria, the relevant counties for this thesis, which were in total 60, were selected by using ArcMap 10.5 (Map 1).



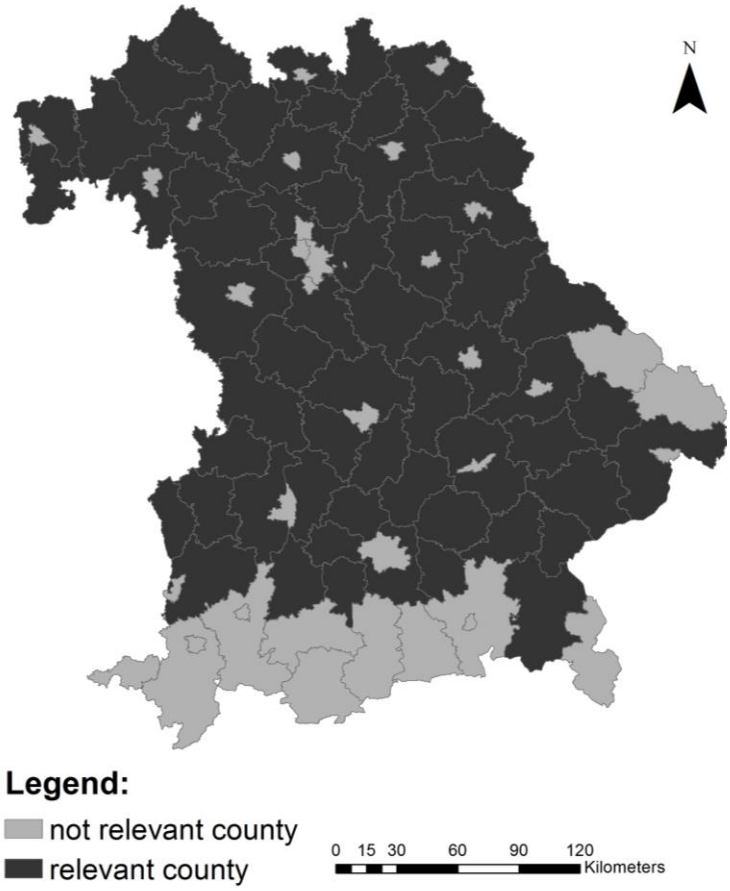
Map 1: Selected counties for yield analyses in Bavaria (own illustration according to Eurostat, 2015 & European Environment Agency, 1995).

Furthermore, the counties were spatially aggregated by using ArcMap 10.5. Soil-Climate-Areas form the aggregation level (Map 2).



Map 2: Relevant Soil-Climate-Areas (own illustration according to Roßberg et al., 2007).

The advantage of this classification was the definition of areas focusing on homogenous location conditions for agricultural production instead of political-administrative borders which followed other principles (Roßberg et al., 2007). In total, eight Soil-Climate-Areas of relevance for this study were selected for Bavaria. The allocation of the counties to Soil-Climate-Areas was based on the biggest share of a county’s area within a Soil-Climate-Area. A list of the 60 selected counties for this thesis and the corresponding Soil-Climate-Area can be found in the Supplemental Section A. All relevant counties are illustrated in Map 3.



Map 3: Selected counties for yield analyses in Bavaria.

3.2 Yield data of Bavaria

Wheat yields and silage maize yields from 1991 to 2015 at county and state scale were taken from the Bavarian Statistical State Office (Bayerisches Landesamt für Statistik, 2016a, 2016b). The *Ernte-, Betriebsberichterstattung (EBE): Feldfr., Grünland* includes average yields indicated in decitons per hectare of different crops and forage plants with an annual reference for different administrative levels. The final yields were estimated by so-called harvest and farm rapporteurs or calculated by a weighted arithmetic mean in which a value which refered to a larger harvest area got a greater weight than a value that refered to a smaller harvest area. The information of the farms about their cultivation and their expected yield was reported on a voluntary basis; only agricultural businesses larger than 4 ha were included. Farms that spaned several administrative areas were counted for that administrative unit in which the head office of the establishment was located. The yield estimates and calculations refered to a moisture content of 14% for cereals and 35% dry matter for silage maize in decitons per hectare (Statistisches Bundesamt, 2018, 1982b, 1982c). Figures 1 and 2 show the yield development for winter wheat and silage maize in Bavaria from 1991 - 2015.

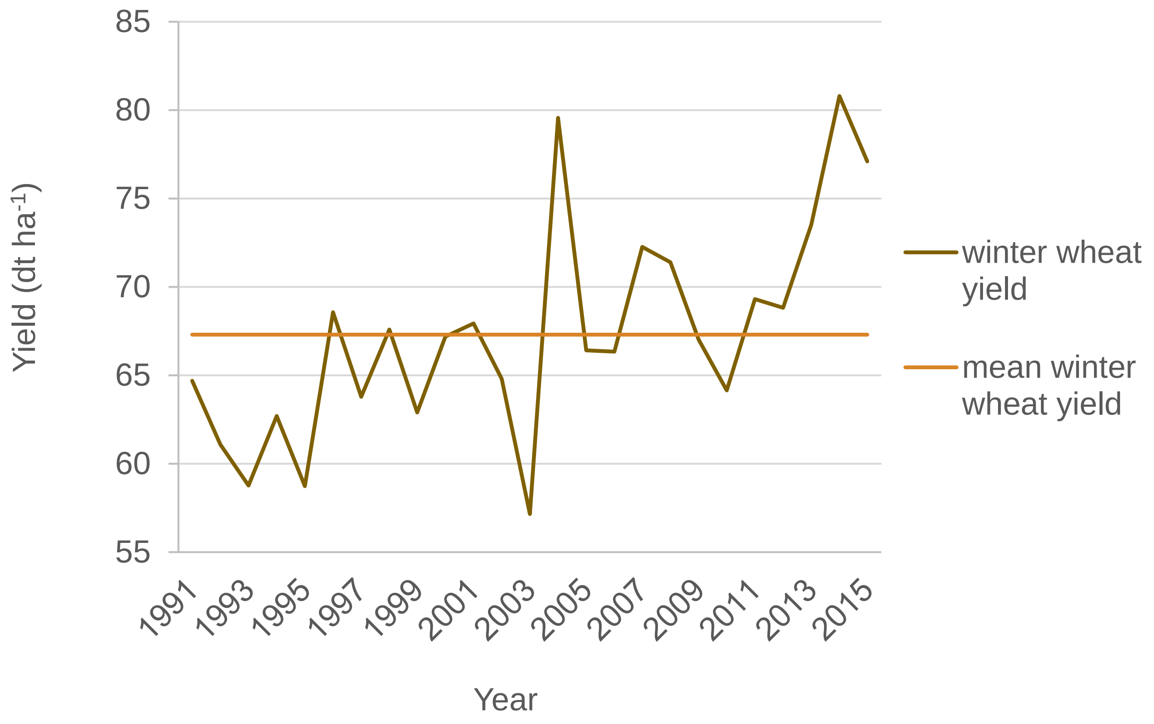


Figure 1: Development of winter wheat yields and average winter wheat yields in Bavaria from 1991 to 2015 (Bayerisches Landesamt für Statistik, 2016a).

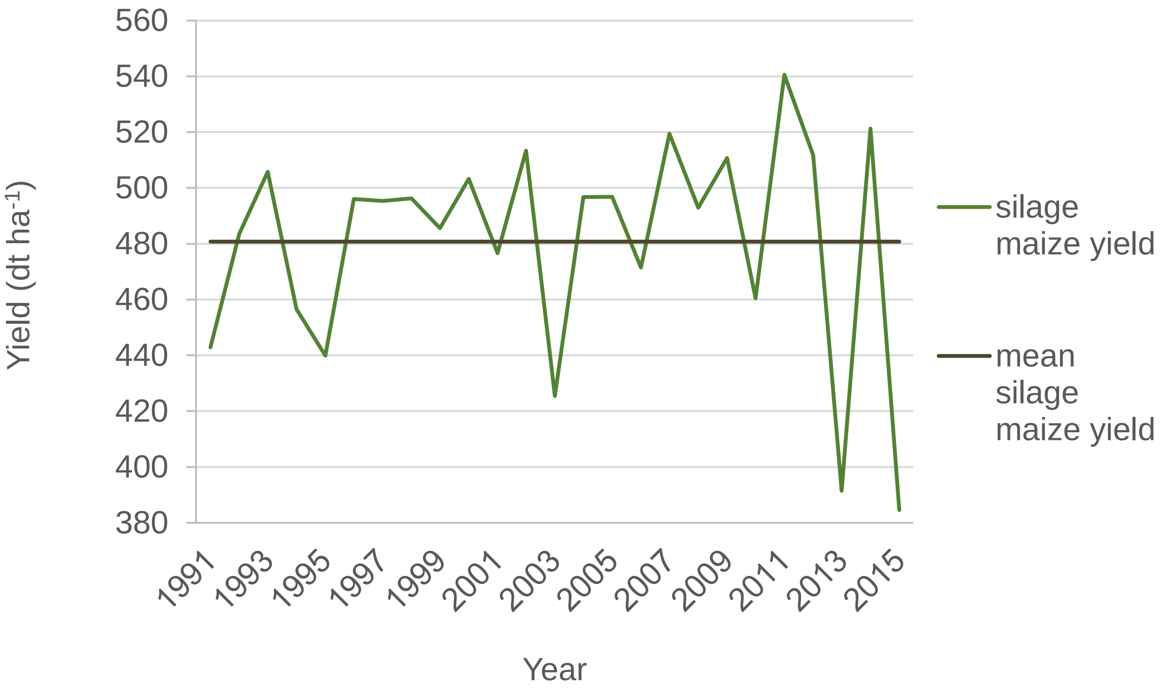


Figure 2: Development of silage maize yields and average silage maize yields in Bavaria from 1991 to 2015 (Bayerisches Landesamt für Statistik, 2016b).

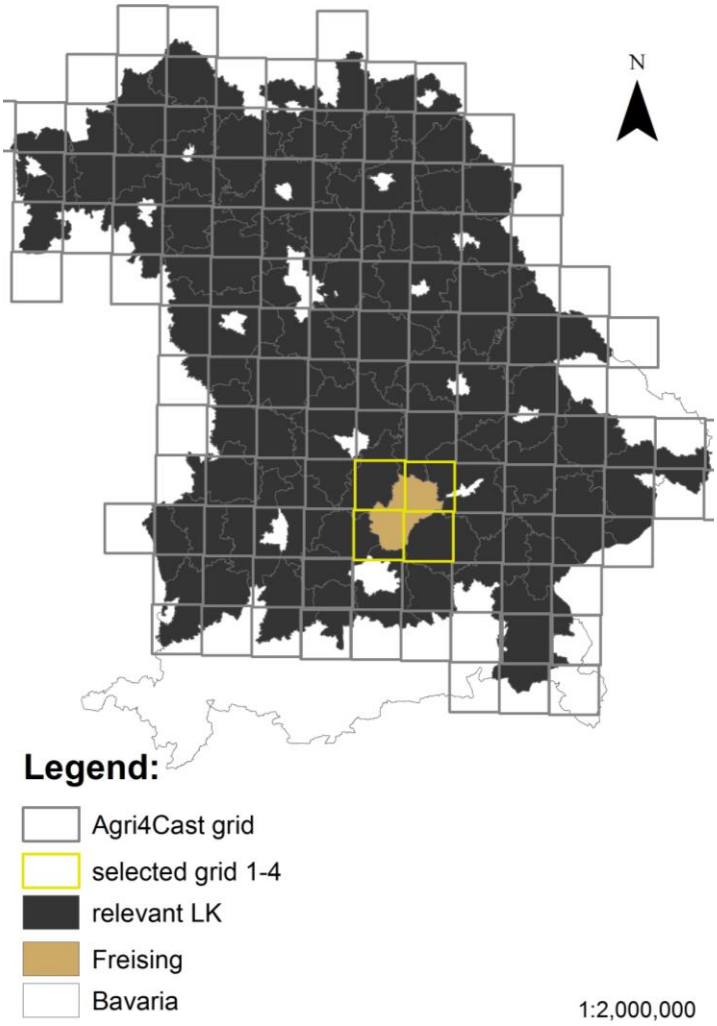
Yield data of the Soil-Climate-Areas were calculated by using the average value of all counties belonging to a Soil-Climate-Area. If a county was divided by several Soil-Climate-Areas, it was assigned to the Soil-Climate-Area with which it shared the largest area. The Soil-Climate-Area *Odenwald Spessart* of the year 2005 was used to illustrate the calculation. *Odenwald Spessart* was formed by the two counties *Aschaffenburg* and *Miltenberg*. In 2005, the wheat yield was 68.1 dt ha^{-1} in *Aschaffenburg* and 73.5 dt ha^{-1} in *Miltenberg*. This resulted in a wheat yield of 70.8 dt ha^{-1} for the year 2005 in *Odenwald Spessart*.

3.3 Climate and further variables

Historical climate data were obtained from the Joint Research Centre (JRC) of the European Union. The JRC’s Monitoring of Agricultural ResourceS (MARS) developed Gridded Agro-Meteorological Data for Europe (Agri4Cast). The database contained different meteorological parameters from stations interpolated on a 25 km x 25 km grid. Daily meteorological parameters are available for the period of 1975 until the last complete year, in this case 2019 (EC-JRC-AGRI4CAST, 2012). The daily values of the following variables were extracted from the database:

- maximum air temperature [°C] = t_max
- minimum air temperature [°C] = t_min
- mean air temperature [°C] = t_avg
- vapor pressure [kPa] = VP
- sum of precipitation [mm day^{-1}] = prec
- potential evapotranspiration from a crop canopy [mm day^{-1}] = ET_c
- global radiation in [KJ m^{-2} day^{-1}] = Rad

Daily climate data were required for each county because the underlying yield data for this study were available on county level as well. Since not every county provided an official measurement station, daily values of the above mentioned climate variables were calculated for every county using the Agri4Cast grid. The recalculation was done via the percentage area share that a grid shared with a single county. Map 4 and Table 2 illustrate the recalculation using the county *Freising* as an example.



Map 4: Grid selection of the Agri4Cast raster for the county *Freising* (own illustration according to (EC-JRC-AGRI4CAST, 2012 & Eurostat, 2015). LK indicates county.

Table 2: Percentage of the area of the county *Freising* covered by each grid (numbered from top left, starting with 1).

county	Percentage	Latitude	Longitude	selected grid
Freising	16.07	48.56499	11.57798	1
Freising	34.24	48.55967	11.91647	2
Freising	36.77	48.34014	11.57093	3
Freising	12.93	48.33484	11.90792	4

A database query was started in MSAccess 2016 via the geographical coordinates given in Table 2 which selected the Agri4Cast data for the same coordinates (latitude and longitude must match). Additionally, the day of the relevant grids had to match so that one value for each weather variable was calculated for each day and county. Table 3 shows the selected cells (green) using the example of *Freising*. Finally, the percentages of Table 2 were used to determine the weighting of each grid that was included in the calculation. The result was generated by a SQL statement in MSAccess2016 and was available for each county on every day, starting from 01.01.1990 - 31.12.2015. In this example, the maximum temperature in *Freising* during the 1st of January 2005 was 5.8°C. The same methodology was used to calculate the values for all weather variables of all counties and Soil-Climate-Areas.

Table 3: Extract of Agri4Cast-data. Green cells are the selected cells for the calculation of the maximum temperature in °C in *Freising* on 1st of January 2005.

LATITUDE	LONGITUDE	DAY	TEMPERATURE_MAX
47.88511	11.89111	20050101	4.7
50.14858	10.58058	20050101	6.2
48.33484	11.90792	20050101	6.2
49.70041	9.88219	20050101	7.1
48.55967	11.91647	20050101	6.2
50.14288	11.27998	20050101	6
49.9082	11.96989	20050102	5.8
47.9	10.55473	20050102	6.2
47.90118	10.22056	20050102	6
48.56499	11.57798	20050101	4.8
50.14288	11.27998	20050102	5.7
50.59233	11.29219	20050102	5.6
48.34014	11.57093	20050101	5.6
49.69757	9.18924	20050102	5.9
48.57478	10.56218	20050102	5.9

3.3.1 Calculation of growing degree days (GDD)

Plant development is directly dependent on the temperature during the vegetation period. Therefore, plants need a specific amount of heat to develop from one biological phase to another. The calculation of growing degree days (GDD) is a common method for determining and predicting the stages of different phenological phases (McMaster and Wilhelm, 1997; Miller et al., 2001). The general formula includes the average daily temperature (T_{AVG}), calculated from the maximum (T_{MAX}) and minimum daily temperature (T_{MIN}), and a basic temperature (T_{BASE}). T_{MIN} is summed with T_{MAX}, divided by two. The basic temperature (T_{BASE}) is subtracted from the average temperature:

$$GDD = \left[\frac{T_{MAX} + T_{MIN}}{2}\right] - T_{BASE}$$

T_{BASE} is the specific minimum daily average temperature that a plant needs to grow. T_{BASE} can vary according to regions or study designs (Porter and Gawith, 1999). Mc Master and Smika (1988) investigated in a study nine different T_{BASE} values for winter wheat – ranging from -2°C to 9°C. For

Germany and the two alpine states Switzerland and Austria, T_{BASE} varied between 0°C and a few degrees above freezing. Holzkämper (2015) indicated 0°C as base temperature, whereas Reiner (1992) pointed out 3°C and Albers et al. 4°C (2017). Based on the conclusion that the lower the baseline temperature, the smaller was the RMSE (McMaster and Smika, 1988), and since most studies assumed a minimum baseline temperature of 0°C, 0°C was set as T_{BASE} for the calculation of GDD for winter wheat.

Different values for T_{BASE} can also be found for the calculation of GDD for maize. Holzkämper and Fuhrer (2015) indicated 6°C for Switzerland, Cross and Zuber (1972) mentioned 10°C for the USA. The German Maize Committee (Deutsches Maiskomitee e. V., 2017) specified 8°C for maize in the calculation of GDD. Based on the recommendation of the German Maize Committee, 8°C was defined as T_{BASE} for the calculation of GDD for silage maize.

For the calculation of GDD up to the desired time, GDD was summed up and resulted in a specific temperature sum for each phenological phase. McMaster and Wilhelm (1997) summarized the different common calculation methods for small grain cereals and for maize. For cereals like wheat, if T_{AVG} fell under T_{BASE}, T_{AVG} should be set equal to T_{BASE}. For maize normally an upper-temperature threshold was used (McMaster and Wilhelm, 1997). Since the German Maize Committee did not give any recommendations for an upper temperature threshold, this was assumed to be at T_{MAX} = 30°C (McMaster and Wilhelm, 1997).

$$If\colon \left[\frac{(T_{MAX} + T_{MIN})}{2}\right] < T_{BASE}$$

$$Then\colon \left[\frac{(T_{MAX} + T_{MIN})}{2}\right] = T_{BASE}$$

In contrast, for maize, if T_{MAX} or T_{MIN} fell under T_{BASE}, $T_{MAX/MIN}$ was set to T_{BASE} in both cases.

$$If\colon T_{MAX} < T_{BASE} \qquad Then\colon T_{MAX} = T_{BASE}$$

$$If\colon T_{MIN} < T_{BASE} \qquad Then\colon T_{MIN} = T_{BASE}$$

The upper temperature threshold for maize results from:

$$If\colon T_{MAX} > 30°C \qquad Then\colon T_{MAX} = 30°C$$

The temperature sum of the GDD for a specific phenological phase was composed as follows:

$$GDD_x = \sum_{i=1}^{x} T_{AVGi} - T_{BASE}$$

with GDD_x: the temperature sum of the growing degree days until day_x or $date_x$, T_{AVGi}: the daily average temperature and T_{BASE}: the base temperature.

3.3.2 Calculation of vapor pressure deficit (VPD)

The daily vapor pressure deficit (VPD) was calculated as saturation vapor pressure (es) minus actual vapor pressure (ea). The climate variables provided by the JRC included ea. The saturation vapor pressure derived from air temperature was calculated with the following formula (Murray, 1967):

$$es = \frac{e_{(Tmax)} + e_{(Tmin)}}{2}$$

where:

$$e_{(Tmax)} = 0.6108 \exp\left[\frac{17.27\, T_{max}}{T_{max} + 237.3}\right]$$

and:

$$e_{(Tmin)} = 0.6108 \exp\left[\frac{17.27\, T_{min}}{T_{min} + 237.3}\right]$$

thus:

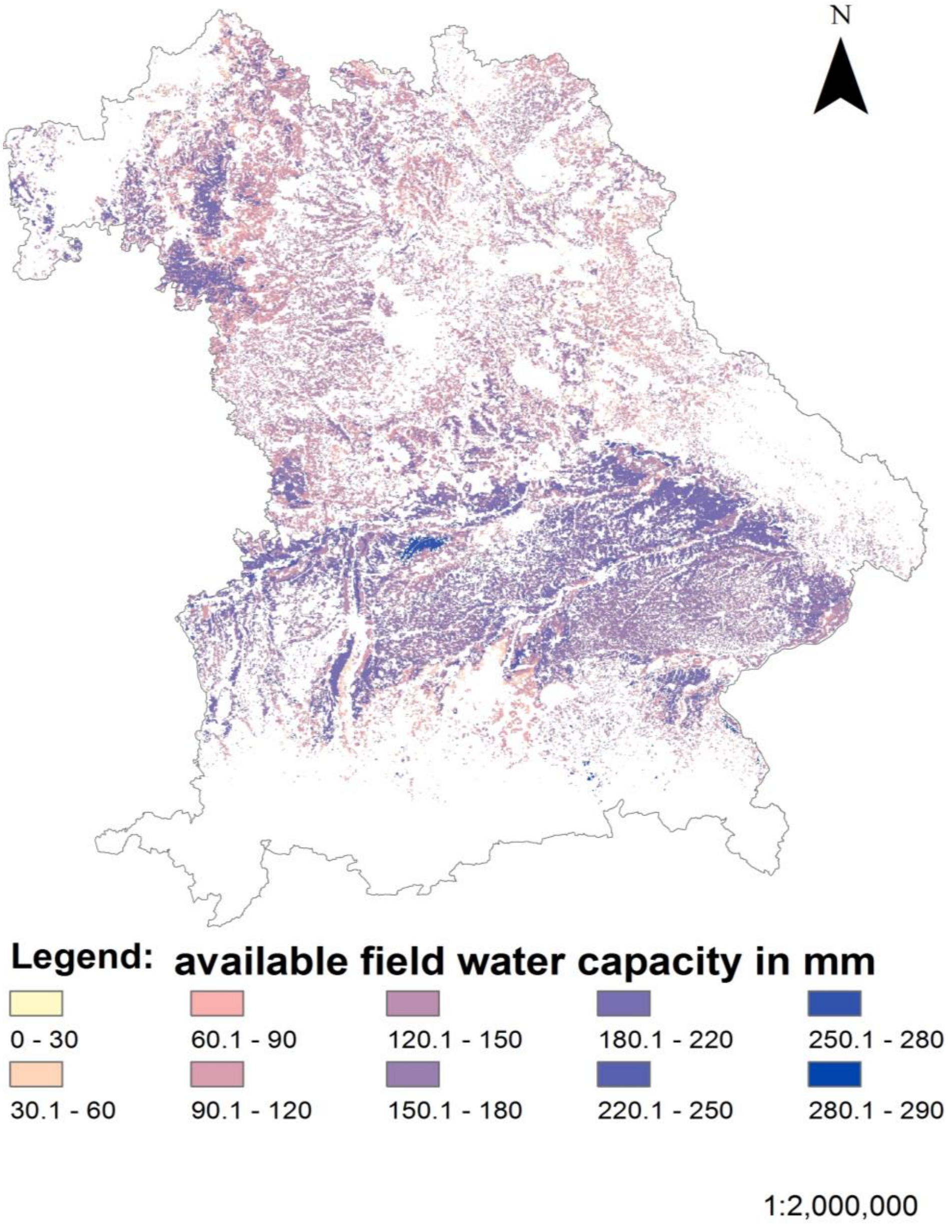
$$VPD = \mathrm{es} - \mathrm{ea}$$

VPD was calculated after Jensen et al., (1990).

3.4 Soil data and the calculation of the available soil water content

Soil data were used to determine the available field water capacity (afc) in mm present in agricultural soils in Bavaria. Available field water capacity is the amount of water that a soil can store or the amount of water that is available for use by plants (Deutsche Landwirtschafts-Gesellschaft, 1979; Ehlers, 1996; Stahr et al., 2020). For Bavaria, the information about the various soil types was collected and systematized by the soil survey of the federal state (*Bodenkundliche Landesaufnahme*). Model profiles were created that represented soil structures with typical soil properties and parameters. Typical soil properties recorded were the number of horizons, the upper and lower horizon limits, the maximum investigation depth, afc, soil texture and the skeleton content (BayStUV, 2018).

A total amount of 992 model profiles were available for Bavaria. The model profiles, which also included information on the afc of Bavarian soils, were used to define regions in which certain soil properties predominated (BayStUV, 2018). As the maximum investigation depth of the model profiles was limited to 1 m, but the effective root penetration depth of the two investigated crops can be more than 1 m, the afc of selected soils was increased by 50% (Jasper, 2016). To obtain only the afc of agricultural soils in Bavaria, the information of the afc for all soils were intersected with non-irrigated arable land of the CORINE classification (European Environment Agency, 1995) (Map 5). The values minimum, maximum, mean, median and standard deviation for the two levels of aggregation, counties and Soil-Climate-Areas, were produced with ArcMap 10.5 using the spatial statistics tool and the intersection of county/Soil-Climate-Areas with the afc.



Map 5: Available field water capacity of agricultural soils in Bavaria (own illustration according to BayStUV, 2018; Jasper, 2016).

The available soil water content was simulated daily for each county and each Soil-Climate-Area. The underlying assumption was that at the beginning of the vegetation period the median value of the afc of each county or Soil-Climate-Area was always filled up. The beginning of the vegetation period for wheat was set to the 1st of March, for maize to the 21st of April. For the available soil water content calculations which were based on the phenology of the plant, the time of sowing was assumed as the starting value for calculating the available soil water content. The calculation of the simulated available soil water content (SW) was done by using daily precipitation and evapotranspiration. The following simplifying assumptions were made:

- The available soil water content could not exceed the value of the median afc in mm.
- Precipitation sums below 1 mm per day did not contribute to the filling up of the available soil water content.
- The interception was 10% of the total daily precipitation (Hoyningen-Huene, 1983).
- Surface runoff amounted to 20% of total daily precipitation (Kennel, 2004). These assumptions were independent from precipitation amount and orography and were considered as an average for Bavaria.

Interception of rain by crops was set to the same value to simplify the calculations. Higher values than 10% were also indicated in the literature (Hoyningen-Huene, 1983), but were not considered in this thesis. The daily changes of the available soil water content were therefore calculated on the basis of precipitation minus surface runoff, interception and evapotranspiration.

3.5 Phenological data

The German Weather Service (DWD) provides observation data on the phenology of crops (DWD, 2018a). For each crop, a file is available which entails information about the location, the reference year and the observed phase of a crop. In addition to the information provided, there were entries on the quality level of the observation and the date of entry (Gregorian day) of a specific crop into a particular phenological phase. The observations take place in a defined area, whereby the observations of one year always took place at the same location and were subject to a plausibility check when the data were transmitted (DWD, 2018b). The observers are voluntary helpers, who adhere to precise observation criteria (DWD, 1991). For this work phenological data for the observation period 1990-2015 of the DWD for winter wheat and 1991-2015 for maize (silage harvest, the specific harvesting method was indicated in the raw data) were used. All entries had a quality level of one, two, seven and ten, respectively. The entries were either formally checked, systematically checked and corrected or checked and corrected. Furthermore, only observations from which the entry date of one phase to another was not questioned or corrected (corresponds to quality level one or two) were included in this thesis (DWD, 2018a). The crop specific phases as well as the corresponding BBCH coding are given in Tables 4 and 5.

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Table 4: Phenological phases recorded by DWD for winter wheat (DWD, 1991). BBCH stages indicate the development stages according to the (Biologische Bundesanstalt für Land- und Forstwirtschaft, Bundessortenamt und CHemische Industrie, 1989).

Phase	BBCH – identification key	Phase number
Beginning of sowing	00	1
Beginning of emergence	10	2
Beginning of stem elongation	31	3
Beginning of heading	51	4
Beginning of milk ripening	75	5
Beginning of hard ripening	87	6
Harvesting	-	7

Table 5: Phenological phases recorded by DWD for silage maize (DWD, 1991). BBCH stages indicate the development stages according to the (Biologische Bundesanstalt für Land- und Forstwirtschaft, Bundessortenamt und CHemische Industrie, 1989).

Phase	BBCH – identification key	Phase number
Beginning of sowing	00	1
Beginning of emergence	10	2
Beginning of stem elongation	31	3
Beginning of tassel emergence	53	4
Beginning of flowering (male)	61	5
Beginning of milk ripening	75	6
Beginning of dough ripening	83	7
Beginning of hard ripening	87	8
Harvesting	-	9

After the preselection, a total of 445 stations with seven phases were available for winter wheat. Based on them the yearly mean of the Gregorian day for each Soil-Climate-Area and each phenological phase was calculated. The result for each Soil-Climate-Area was the Gregorian day on which, for example, the beginning of emergence or the beginning of milk ripening in a certain year occured. A plausibility check was also carried out. The phenological phase of milk ripening follows the phenological phase of flowering for maize. Consequently, the beginning of milk ripening could not begin earlier during the vegetation period than the beginning of flowering. If the day of the beginning of milk ripening was indicated before the day of the beginning of flowering within the vegetation period, this error was corrected. The day of the beginning of the incorrectly dated phenological phase was calculated and replaced by the mean value of the beginning of the corresponding phenological phase determined from neighbouring sites and replaced accordingly. The counties were assigned to the values of the Soil-Climate-Areas in which they were located, since the stations were not equally distributed across all counties. Thus, every phenological phase of all counties that were located in the same Soil-Climate-Area, started at the same day within a year.

A total of 451 stations with nine phenological phases was available for maize. While for maize cultivation all times from sowing to harvesting (silage harvesting = beginning of dough ripening) were used for the further analysis, for wheat cultivation the phases from sowing to hard ripening were considered. Since there are no physiological processes that influence the yield level of wheat between hard ripening and harvesting, this phenological phase is excluded from the analyses. The term phenological phase was used here as the time between two phenological entry dates. For silage maize there were six phase intervals, for winter wheat, there were five.

3.6 Statistical analyses and calculations

3.6.1 Statistics with RStudio

The analyses were performed with the help of the statistical package in R or RStudio. First, the development of yields of the Soil-Climate-Areas over the considered period were derived. Yield differences among the eight Soil-Climate-Areas were tested by ANOVAs as well as the stability of yields of the Soil-Climate-Areas. In Section 4.2 the climatic factors were determined which exerted a positive or negative effect on the yield depending on the phenological phase. In Section 4.3, daily values were combined into blocks of different lengths of days. It was examined whether they affect the model’s predictive ability. In Section 4.4, three different statistical models (time-series models, panel data models and cross-section models) were calibrated, validated and tested for model efficiency to calculate yield predictions considering climate change effects.

3.6.2 Yield data

The Soil-Climate-Areas’ yields between 1991 and 2015 were analyzed regarding their yield developments and differences. Within all Soil-Climate-Areas data were analyzed using a linear function with the factors Soil-Climate-Area and year. ANOVAS were calculated in order to reveal the significance of factors. The means were distinguished via Tukey’s HSD test. The test for normal distribution was performed with the Shapiro-Wilk test, whereas the Breusch-Pagan test was used to test the homogeneity of the variances (= homoscedasticity).

Increases in yields over time are due to breeding and technical progress. These factors, which determine the increase (= trend) in the data, were omitted. No distinction was made between technical and breeding progress. Progress is assumed to be an annual constant. Linear functions for all eight Soil-Climate-Areas and all 60 counties of both crops were determined. By using the linear function:

$$\mathrm{Y_e} = \beta_0 + \beta_1 * X_t + \varepsilon_i$$

the expected yield is calculated ($\mathrm{Y_e}$), whereby β_0 is the point of intersection of the determined linear function with the y-axis, β_1 is the slope and X_t the year. The term ε_i represents the random error term. Detrended yields are thus calculated:

$$\mathrm{Y_d} = \mathrm{Y} - \beta_1 * \mathrm{z}$$

where Y is equal to the actual yield of one year, β_1 is the slope of one county or Soil-Climate-Area and z is the number of the year. In the observation period 1991-2015, the year 2000 is, therefore, assigned to the number 10.

The absolute yield deviations in dt ha^{-1} thus result from:

$$\mathrm{Y_{abs}} = \mathrm{Y} - \mathrm{Y_e}$$

Relative yield differences can be calculated by using the following formula:

$$\mathrm{Y_{rel}} = \frac{\mathrm{Y} - \mathrm{Y_e}}{\mathrm{Y_e}} * 100$$

Yield stability over the study period based on Soil-Climate-Areas and counties are investigated on the basis of Knapp and van der Heijden (2018). These authors distinguish between relative and absolute yield stability. This enables direct comparison of locations with low and high yield levels.

The absolute yield stability represents the standard deviation of one analyzed location (e.g. *Gäu Donau Inntal*) over the investigated time period in this thesis. The relative yield stability corresponds to the coefficient of variation of a location. The coefficient of variation can be calculated as follows:

$$\mathrm{CoV_{i,t}} = \frac{\mathrm{STD_{i,t}}}{\mathrm{Mean\ Yield_{i,t}}}$$

Whereas i is the analyzed location (e.g. a county or Soil-Climate-Area), t is the observation period (1991-2015), CoV is the coefficient of variation and STD equals the standard deviation.

3.6.3 Relevant abiotic factors and phenological phases

Section 3.5 explained the criteria used to select the phenological data, the phases which are recorded by the DWD and how the input data for each phase were determined or calculated. This section investigates the influence and interaction of phenology, meteorology and soil data to search for relationships between climatic parameters, phenology, soil and yield.

The vegetation period of silage maize and winter wheat was divided into phenological phases. The beginning and duration were determined by the dates of the phenological observations. Five phenological phases were selected for winter wheat and six for silage maize. Climate variables were calculated for the individual phases. Depending on the variable, the mean value, the maximum or the sum was calculated (Table 6).

Table 6: Calculated abiotic variables for each phenological phase.

Parameter	Aggregation of Parameter	Abbreviation	Unit
Abiotic Factor 1	Averaged mean temperature	t_avg	[°C]
Abiotic Factor 2	Mean of simulated soil water	SW	[mm]
Abiotic Factor 3	Mean of maximum temperature	t_max	[°C]
Abiotic Factor 4	Mean of minimum temperature	t_min	[°C]
Abiotic Factor 5	Mean of vapor pressure deficit	VPD	[kPa]
Abiotic Factor 6	Sum of pot. evapotranspiration from crop canopy	ETc	[mm]
Abiotic Factor 7	Mean total global radiation	Rad_avg	[kJ m^{-2}]
Abiotic Factor 8	Sum of precipitation	prec	[mm]
Abiotic Factor 9	Sum of water balance (ETc - precipitation)	WB	[mm]
Abiotic Factor 10	Maximum of Growing Degree Days	GDD	[GDD]
Abiotic Factor 11	Minimum of simulated soil water	SW_min	[mm]
Abiotic Factor 12	Sum of total global radiation	Rad_sum	[kJ m^{-2}]

For two abtiotic factors, two different calculation possibilities were included to examine which correlated better with yields. These were the minimum and mean value for the simulated available soil water and the sum and mean value of radiation. A further interest of this thesis was to be able to relate high and low yields to abiotic factors. Since extreme values often lead to high or low yields, some factors in addition to the mean value, were correlated as minimum or maximum with yields. Furthermore, some abiotic factors were aggregated over several phenological phases, since the water requirement of maize for example is particularly high due to higher biomass accumulation in the time between tassel emergence and dough ripening. To correlate the phenological phases of high water requirements with maize yields, abiotic factors were calculated over this three water intensive phenological phases (DWD, 1991). Further investigated relationships with yield were the duration of a phenological phase in days. For a better understanding of factors leading to high or low yields, correlations of abtiotic factors with extreme yield years were calculated. Extreme yield years were either yields that were higher than the 90th percentile of a yield distribution of a site between 1991 and 2015, or yields that were lower than the 10th percentile of a yield distribution of a site between 1991 and 2015 (Schönwiese et al., 2005; Soja and Soja, 2003).

3.6.4 Time intervals and their aggregation

Different time intervals of the predictors were calculated to investigate the model performance regarding the temporal aggregation of predictors. Two predictors, the average temperature (t_avg) and the simulated available soil water content (SW), with different time resolutions were used for the model building. A definition for the simulated soil water content can be found at 3.4. The usage of only two predictors enabled a clearer and simpler comparison between the different models regarding their time aggregation. The response variable of the model consisted of county yields from 1991-2015 (= 1500 records). The model was based on the following calculation:

$$Y_{i,t} = \beta_{i,0} + \beta_1 \, t\_avg_{i,t} + \beta_2 \, SW_{i,t} + \varepsilon_{i,t}$$

where $Y_{i,t}$ was the predicted yield for one county$_i$ in a certain year. The term $\beta_{i,0}$ represented an intercept for each county$_i$, t_avg$_i$ and SW$_i$ represented the average temperature respectively the simulated available soil water content in one county for a certain time interval t in a specific year. The term β_0 - β_2 represented a model parameter to be fitted and ε an error term. Two predictors, the average temperature and the simulated available soil water content aggregated over different time intervalls were initially included in each model. The RMSE were used to evaluate the model performance.

The main differentiation between the models was made on the one hand by different temporal aggregations on the other hand regarding the vegetation period. The resulting different time intervals were defined either by the calendar (hereafter referred to as "calendar") or by phenological observations (hereafter referred to as "phenology"). With the calendar consideration for winter wheat, the yield-relevant beginning ofvegetation was fixed on the 1st of March of each year, for silage maize on the 21st of April. The end of a vegetation year was fixed on the 31st of July for wheat and the 15th of October for maize. In the “phenology” model, the vegetation period varied from one year to another and began with sowing and ended with harvesting. Because sowing and harvesting are not fixed to a date, but depend on other factors such as the cultivar, each "phenological" year lasts a different length of time. In the “calendar” method, however, this time was always the same. In total, 153 vegetation days were available for the wheat "calendar days" and 178 for the maize "calendar days". The time intervals and thus also the aggregation of the predictors for the "calendar" methodology were:

- one day
- two days
- five days
- ten days
- 15 days
- one month
- whole vegetation period (wheat: 1st of March – 31st of July, maize: 21st of April – 15th of October

By defining different time intervals for the calculation of predictors, the vegetation period was divided into various units. For a better understanding of the division of a vegetation period, the ten- and five-day interval was used as an exampel. According to the "calendar" methodology, maize has a total of 178 vegetation days, while wheat has in total 153 vegetation days. For splitting the total number of vegetation days into ten-day intervals, 17 (178:10 = max. 17) units were obtained for the vegetation period of maize, and 15 (153:10 = max. 15) units for the vegetation period of wheat. Using a five-day interval, 35 (178:5 = max. 35) units were obtained for the vegetation period of maize and 30 (153:5 = max. 30) units for the vegetation period of wheat. In total, this resulted to the following number of units per vegetation period and crop for the five time intervals:

- 1 day = wheat: 153 units, maize: 178 units
- 2 days = wheat: 75 units, maize: 89 units
- 5 days = wheat: 30 units, maize: 35 units
- 10 days = wheat: 15 units, maize: 17 units
- 15 days = wheat: 10 units, maize: 11 units

With the "phenology" method, the total number of vegetation days varied from year to year. Thus the calculation of the predictors could not be based on equally long time intervals as in the "calendar" method because a different number of predictors would be obtained in different years and this would have rendered the calculation of a regression difficult. However, since the aggregation of predictors based on equally long time intervals finally only split the vegetation period into a different number of units, the vegetation period in the "phenology" methodology was divided into the same number of units that resulted from the calculations in the "calendar" methodology. For winter wheat, this approach resulted in dividing the vegetation period into the following units:

- 153 units
- 75 units
- 30 units
- 15 units
- 10 units
- one phenological phase
- whole vegetation period

Since silage maize did not always have 178 vegetation days as assumed with the "calendar" method and thus a vegetation period could not be divded into 178 units, the minimum number of vegetation days that occurred between 1991 and 2015 was chosen as smallest unit. For silage maize, this approach resulted in dividing the vegetation period into the following units:

- 118 units
- 89 units
- 35 units
- 17 units
- 11 units
- one phenological phase
- whole vegetation period

Because wheat is sown in Bavaria in October, the two predictors' t_avg and SW were taken into account in the "phenology" methodology from the 1st of October onwards. The available soil water content simulations started with the 1st of October, here it was also assumed that the available field water capacity was filled up at the beginning. However, the option of involving the two predictors from October onwards, was tested with fewer time intervals. The evaluated time intervals were 10 days, 1 month and the whole vegetation period. Furthermore, the model performance of different time intervals was also tested for high and low yield years, again with fewer time intervals. Considered time intervals were 10 days, 1 month and the whole vegetation period for the "calender" methodology. For the "phenology" methodology the corresponding units were used, hence 15 units for wheat and 17 units for maize. Furthermore each phenological phase and the whole vegetation period was considered.

3.6.5 Statistical models

Statistical models use statistical regressions to link historical yield outcomes to historical weather aggregates and extrapolate from observed associations to do yield predictions under an altered projected climate (Schlenker and Roberts, 2009; Roberts et al., 2017). Statistical models used in this thesis were a time-series model, a panel model and a cross-section model. The differences of the calcualtions of statistical models used in this thesis are presented in section 3.6.5.1-3.6.5.4 (Gornott and Wechsung, 2016, 2015; Lobell and Burke, 2010). All monthly values from 1991 to

2015 depending on the target value, maximum, minimum and mean were firstly included in all models. The stepwise (both) selection method selec

ted the significant ($p < 0.05$) factors for yield predictions. Based on significant predictors, yield predictions were calculated for Soil-Climate-Areas and counties until the year 2045. The difference among the time-series model, the panel model and the cross-section model was: the time-series model calculated for each site an own model. The panel model calculated for all county yields one model and for all Soil-Climate-Areas yields one model. Whereas the cross-section model provided one model that was able to predict the average yields across counties and one model that was able to predict the average yields across Soil-Climate-Areas.

3.6.5.1 Time-series models

Time-series models and their parameters were estimated separately and independently for each Soil-Climate-Area or county. The predictors were aggregated on the basis of a static vegetation period. If monthly values of the individual predictors would have been included in the model, this would result in more predictors than observation points (= 25 observed yields) which rendered in a impossible calculation. By comparing the β coefficients of each model, differences in the response regarding abiotic factors could be identified. This reveals spatial heterogeneity (Gornott and Wechsung, 2015). The basic functional form of each model was:

$$Y_t = \beta_0 + \beta_1 * X_t + \beta_2 * K_t + \beta_3 * Z_t + \cdots + \varepsilon_t$$

Where Y_t was the yield in a particular year t, X_t, K_t and Z_t were abiotic factors selected by the model in a particular year t (the number of statistically significant parameters may vary per Soil-Climate-Area). The terms β_0 - β_3 were model parameters that changed with each calculation. Ɛ represented an error term.

3.6.5.2 Panel models

The yields of all eight Soil-Climate-Areas for 25 years (200 yields) as well as county yields for 25 years (1500 yields) were used to estimate panel data models. The model's β coefficients were estimated for all Soil-Climate-Areas or counties. The panel model was based on the following formula:

$$Y_{i,t} = \beta_{i,0} + \beta_1 X_{i,t} + \beta_2 K_{i,t} + \beta_3 Z_{i,t} + \beta_4 X^2{}_{i,t} + \beta_5 K^2{}_{i,t} + \beta_6 Z^2{}_{i,t} + \cdots + \varepsilon_t$$

Quadratic terms of the predictors were included for the purpose of reflecting possible nonlinearities in the relationships between yield and the selected predictors (Lobell and Burke, 2010). Furthermore a model with fixed effects was considered. The β values were estimated to be the same for all sites in the panel functions. Assuming that the coefficients across all administrative districts, i.e. between Soil-Climate-Areas and between counties were the same, it was implicitly supposed that the response of plants with regard to abiotic factors was the same across all locations. The differences of the modeled yields resulted from different levels of the abiotic factors in each Soil-Climate-Area. Different sensitivies of cultivars regarding abiotic factors could be neglected by the model. The terms $X_{i,t,}$ $K_{i,t}$ and $Z_{i,t}$ are values of abiotic factors of a particular month of a particular Soil-Climate-Area i in a particular year t. The term $Y_{i,t}$ represents the yield of one Soil-Climate-Area i in a certain year t. Here, again, Ɛ describes an error term.

3.6.5.3 Cross-section models

Average yields were estimated on the basis of average predictors in each Soil-Climate-Area within a year. Thus, the resulting cross-section model was estimated using the following formula:

$$Y_{i,avg} = \beta_{i,0} + \beta_1 X_{i,avg} + \beta_2 K_{i,avg} + \beta_3 Z_{i,avg} + \cdots \dots \dots \dots + \varepsilon_t$$

Cross-sectional regressions emphasize the differences between Soil-Climate-Areas. Squared terms were not included because of the feasibility of the calculation. If quadratic terms were included, the model could not be calculated due to too many predictors. In contrast to the panel and time-series model, average yields serves as the basis of calculations. The term $Y_{i,avg}$ was calculated as an average value of one Soil-Climate-Area$_i$ between 1991 and 2015. The terms $X_{i,avg,}$ $K_{i,avg}$ and $Z_{i,avg}$ were monthly averages of the years 1991 - 2015 and were calculated for each Soil-Climate-Area$_i$ seperatly.

3.6.5.4 Models for high, low and average yields

The models from 3.6.5.1 - 3.6.5.3 included all yields from every county and every Soil-Climate-Area from 1991 - 2015. The following method tested whether yield predictions became more robust if one seperate panel model was calculated based on high, low and average yields. In practice, years that had negative yield deviations (= low yields) are particularly important. Low yields were defined as those yields that were smaller than the 10th percentile of a yield distribution of a studied area (Soja and Soja, 2003). High yield years were analogous to low yield years, except that all yields of a site that were larger than the 90th yield percentile were selected. This resulted in 20 Soil-Climate-Area/yield combinations for low yields, 20 Soil-Climate-Area/yield combinations for high yields and 160 Soil-Climate-Area/yield combinations for average yields. This resulted in a total of three panel models. Quadratic terms were not considered, because a model based on too many predictors and too few target variables is not reasonable.

3.6.6 Model validation, model quality and statistical tests

The k-fold cross validation method was used to test the predictive power of the models. In the k-fold cross validation, the data set is divided into k folds. The skipped fold serves as the validation data set, the other folds serve as the test set (Abu-Mostafa et al., 2012). The process was repeated until each fold was used as test and validation set. In this thesis, the data set was usually broken down into five equal folds. The time-series resulted in five folds consisting of five years each (n = 25). In the panel models, these were five folds consisting of forty years (n = 200). As validation methodology the leave one out method was choosen for cross-section-models. The validation of high, low and average yield years was calculated from six (favourable/ unfavorable) or four folds (mean yield years). High and low yield years were six folds consisting of four years each (n = 24). The validation of average yield years was done by four folds consisting of 38 years each (n = 152).

The models should be able to reproduce the yield level and its volatility. The root mean square error (RMSE), the corrected coefficient of determination (Adjusted R² in the following only referred to as R²) and the Nash-Sutcliffe Model Efficiency Coefficient (NSE) were calculated as coefficients for the model quality. The RMSE indicates the mean error of the model in dt ha^{-1}, the coefficient of determination R² indicates how well the volatility of the model was explained by the tested abiotic factors. In addition to the correlation coefficient, the NSE is a useful index that describes the goodness of fit of the model (McCuen et al., 2006; Nash and Sutcliffe, 1970). The NSE accepts values between $-\infty$ and 1.0 (perfect fit). If the NSE is in a negative range, this means that the mean value of the observations (i.e. the mean value of observed yields) provides better yield predictions than the calculated model. For interpretations of the NSE, it should be considered that it does not react sensitively to systematic over- or underestimations of the model (Krause et al., 2005).

The statistical tests that were performed were the following: The test for normal distribution of residuals was performed using the Shapiro-Wilk test. Multicollinearity was evaluated by calculating the Variance Inflation Factor (VIF) test. The autocorrelation was tested using the Durbin-Watson method, and heteroscedascidity was evaluated using the Breusch-Pagan test.

3.7 Climate models used for yield predictions

The yield prediction was based on simulated climate data (future weather data) provided by the Joint Research Center (JRC) of the European Union (FOODSECURITY -MARS4CAST, 2015). As with the climate variables used in section 3.3, the resolution of a grid size of 25 km x 25 km was available. The data could be used for the purpose of yield modelling and included three time horizons (2000, 2020 and 2030 +/- 15 years). The model data provided by the JRC were calculated based on three climate models. One climate model was calculated by the Danish Meteorological Institute, one ran by the Swiss Federal Institute of Technology and one conducted by the UK Met Office. The institutes generated for each time horizons 30 synthetic years using the ClimGen weather generator. The assumed scenario was A1B (Duveiller et al., 2017). The A1B scenario assumes that there will be no rethinking of anthropogenic climate change worldwide and that "business as usual" will be conducted. The scenario is based on data which was provided by the Special Report on Emission Scenarios (SRES) (Nakićenović et al., 2000). More recently the SRES scenarios were replaced by representative concentration pathways (RCPs) (van Vuuren et al., 2011). For the purpose of this thesis the usage of A1B Scenarios instead of for example RCP 4.5 was regarded as sufficient. Furthermore, the SRES A1B scenario was considered because short-time horizons (until 2045) were targeted. For this time scale, differences in temperature were considered as moderate. Furthermore the A1B scenario was already implemented in other studies and was considered to be the most likely scenario for the near future (Duveiller et al., 2017). The data was dynamically downscaled and bias corrected by regional climate models (RCMs) (Duveiller et al., 2017). The calculation of the environmental parameters from raster to values for Soil-Climate-Areas and counties was done in the same way as in 3.3. The parameters provided by the JRC:

- sum of precipitation [mm day^{-1}] = prec
- maximum air temperature [°C] = t_max
- minimum air temperature [°C] = t_min
- total global radiation [KJ m^{-2} day^{-1}] = Rad
- Reference evapotranspiration [mm day^{-1}] FAO56 = ET_o
- vapor pressure deficit [kPa] = VPD

The parameters for modelling the influence of climate change on yields were calculated as in 3.3 and 3.4. and by calculating the arithmetic mean based on the climate models considered here. Only the simulated available soil water content was calculated slightly different than in 3.4. The calculation difference was the evapotranspiration which refered to the potential evapotranspiration from a crop canopy in mm day^{-1} in 3.4, whereas for modelled climate data the FAO reference evapotranspiration mm day^{-1} was provided. The sum of FAO reference evapotranspiration in mm is greater than the sum of the potential evapotranspiration from a crop canopy in mm (FAO, 1977).

4 Results

4.1 Yield data

Yield developments and yield differences, as well as results from detrending are illustrated in the following section using the spatial aggregation level of Soil-Climate-Areas. The period analysed always refers to the period 1991-2015. Results depicting the yield data at the county level are provided in the supplemental section E with tables, yield results of Soil-Climate-Areas further illustrated in the supplemental section B as figures.

4.1.1 Yield developments

For wheat, the average yield of 72.6 dt ha^{-1} in 25 years was highest in the Soil-Climate-Area *Gäu Donau und Inntal*. The lowest yield of 62.8 dt ha^{-1} was observed in the Soil-Climate-Area *Verwitterungsböden in den Höhenlagen*. For silage maize the Soil-Climate-Area *Gäu Donau und Inntal* also showed the highest average yield with 497.9 dt ha^{-1}. The lowest average yield of 461.7 dt ha^{-1} was observed in the Soil-Climate-Area *Verwitterungsböden in den Übergangslagen*. The difference between the highest and lowest average yield in 25 years was higher for winter wheat (15.6%) than for silage maize (7.9%). Tables 7 and 8 indicate the average yields per Soil-Climate-Area in descending order.

Table 7: Average winter wheat yields of all Soil-Climate-Areas between 1991 and 2015 indicated in descending order.

No.	Soil-Climate-Area	Years	Yield in dt ha^{-1}
1	*Gäu Donau und Inntal*	1991-2015	73
2	*Tertiärhügelland Donau Süd*	1991-2015	72
3	*Odenwald Spessart*	1991-2015	69
4	*Moränen Hügelland Voralpenland*	1991-2015	67
5	*Albflächen Ostbayerisches Hügelland*	1991-2015	66
6	*Nordwestbayern Franken*	1991-2015	64
7	*Verwitterungsböden in den Übergangslagen*	1991-2015	63
8	*Verwitterungsböden in den Höhenlagen*	1991-2015	63

Table 8: Average silage maize yields of all Soil-Climate-Areas between 1991 and 2015 indicated in descending order.

No	Soil-Climate-Area	Years	Yield in dt ha^{-1}
1	*Gäu Donau und Inntal*	1991-2015	498
2	*Tertiärhügelland Donau Süd*	1991-2015	493
3	*Moränen Hügelland Voralpenland*	1991-2015	488
4	*Albflächen Ostbayerisches Hügelland*	1991-2015	484
5	*Odenwald Spessart*	1991-2015	470
6	*Nordwestbayern Franken*	1991-2015	467
7	*Verwitterungsböden in den Höhenlagen*	1991-2015	465
8	*Verwitterungsböden in den Übergangslagen*	1991-2015	462

The tables illustrate that in the south of Bavaria higher yields were observed than in the north. An exception to this is found for wheat yields of *Odenwald* Spessart in northwestern Bavaria. On a long-term average, this Soil-Climate-Area achieved the third-highest yield.

The yield developments of both crops are depicted in Figures 3 and 4. For reasons of simplicity, the Soil-Climate-Area with the highest and lowest yield per crop and the mean value for all Soil-Climate-Areas in the period examined are indicated. The individual yield developments of all Soil-Climate-Areas are shown in the Supplemental Section B.

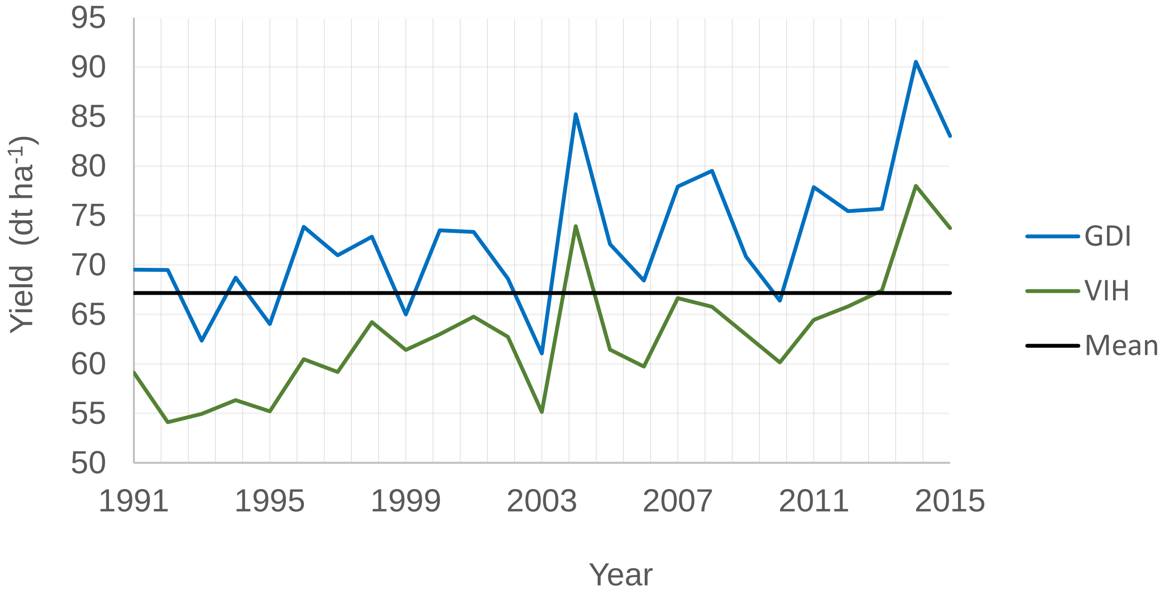


Figure 3: Yield development of winter wheat in the Soil-Climate-Areas *Gäu Donau und Inntal (GDI)* and *Verwitterungsböden in den Höhenlagen (VIH)* between 1991 and 2015. The horizontal line represents the average yield of all years from all Soil-Climate-Areas.

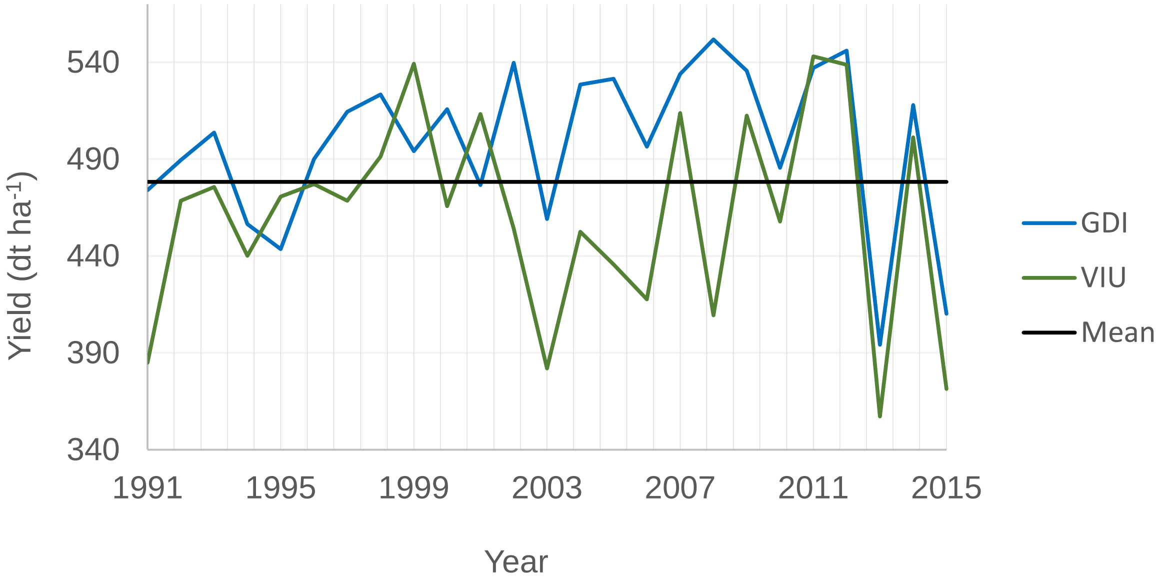


Figure 4: Yield development of silage maize in the Soil-Climate-Areas *Gäu Donau und Inntal (GDI)* and *Verwitterungsböden in den Übergangslagen (VIU)* between 1991 and 2015. The horizontal line represents the average yield of all years from all Soil-Climate-Areas.

For wheat, increasing yields are generally observed. The yield development of the presented Soil-Climate-Area in general shows a parallel course, whereby the Soil-Climate-Area with the lowest yield, *Verwitterungsböden in den Höhenlagen*, compared to the Soil-Climate-Area with the highest yield, *Gäu Donau und Inntal*, is shifted downwards. The average yield of all Soil-Climate-Areas between 1991 and 2015 was 67 dt ha^{-1}. For silage maize, no increase in yield over time was observed. Furthermore, the yield development of the Soil-Climate-Area showed no clear trend, but varied largely with years. There was no clear offset between high yield and low yield Soil-Climate-Areas. On average, the yield from all Soil-Climate-Areas in the 25-year period was 478 dt ha^{-1}. Years that were well below the average of yields of all Soil-Climate-Areas between 1991 and 2015, probably indicate that they were influenced by unfavorable environmental conditions affecting the yield level. The year 2003, for instance, was an exceptionally hot and dry year for Germany. In this year the yield fell below the average yield.

4.1.2 Detrended yields

Detrending was used to eliminate the influence of technical progress that increased yields, for example through breeding progress over time. With this procedure, weather-related influences on yield differences were emphasized. For silage maize, no increase in yield due to technical progress could be observed; therefore non-detrended yields were used for further processing the silage maize data.

Figure 5 shows trend-corrected wheat yields for the Soil-Climate-Area *Albflächen Ostbayerisches Hügelland*. For wheat, normalized (= detrended = trend-corrected) yields were used in the further work. The trend correction revealed that the yields in 2014 were lower than in 2004. If real yields were used, the yield level of 2014 would be higher. This example reveals that the higher yield in 2014 resulted from progress made, for example, by breeding or agronomic advances. However, due to the detrending, the volatility between the years remains the same (Figure 5).

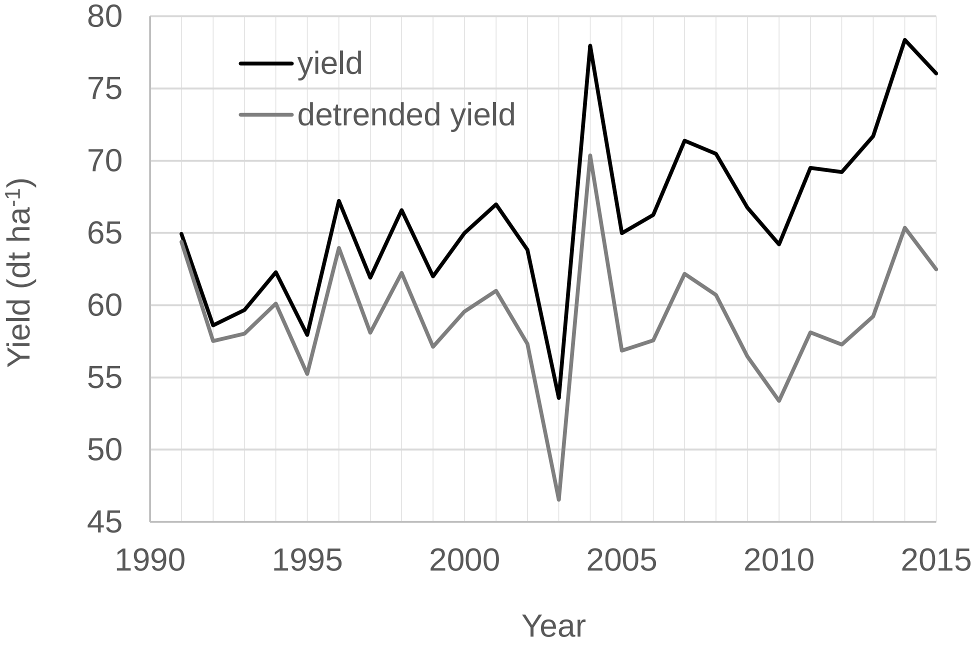


Figure 5: Actual and trend corrected wheat yields for the Soil-Climate-Area *Albflächen and Ostbayerisches Hügelland* for the time period between 1991 and 2015.

4.1.3 Differences among yields in the Soil-Climate-Areas

The analysis of the ANOVA showed that the yields across the Soil-Climate-Areas were significantly different ($p \leq 0.05$) for both crops. The yields of Soil-Climate-Areas which were not significantly different from each other were assigned to the same group (corresponding letters are shown above the box-plots in Figures 6 and 7. Classifications into different classes were made when the yield difference between two Soil-Climate-Areas was higher than 2.3 dt ha^{-1} for winter wheat and 18.8 dt ha^{-1} for silage maize. Figure 6 and 7 show the distribution of Soil-Climate-Area yields over 25 years in ascending order. Yield differences among the Soil-Climate-Areas are highlighted by the Maps 6 and 7.

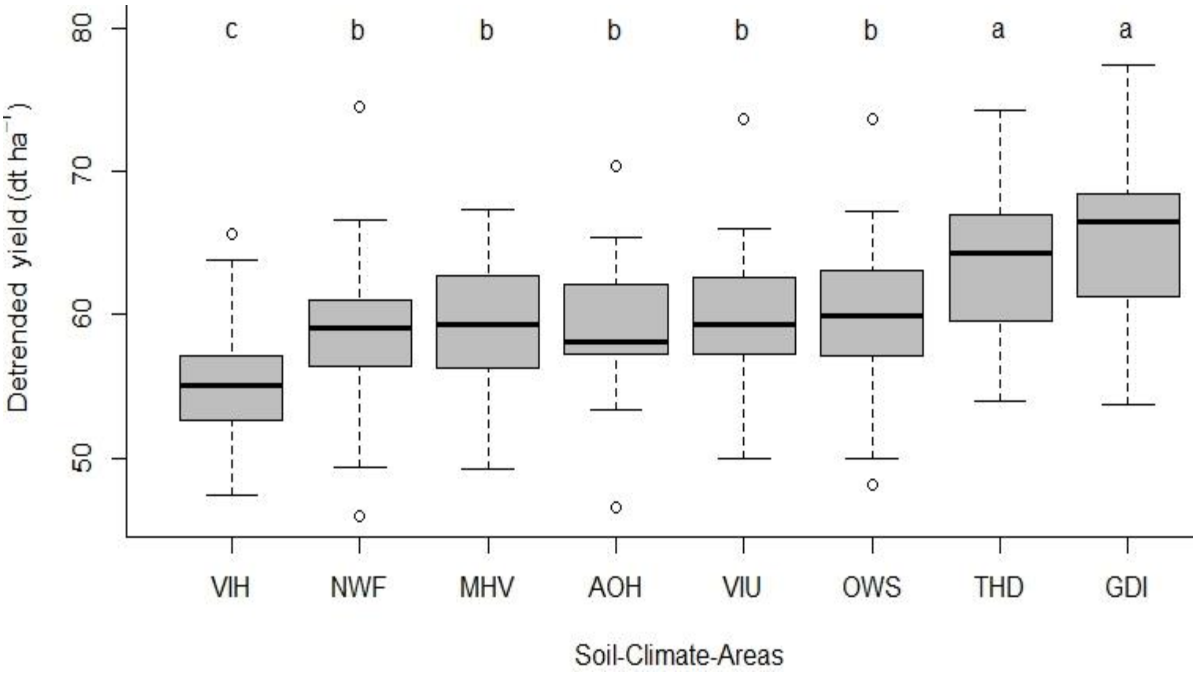
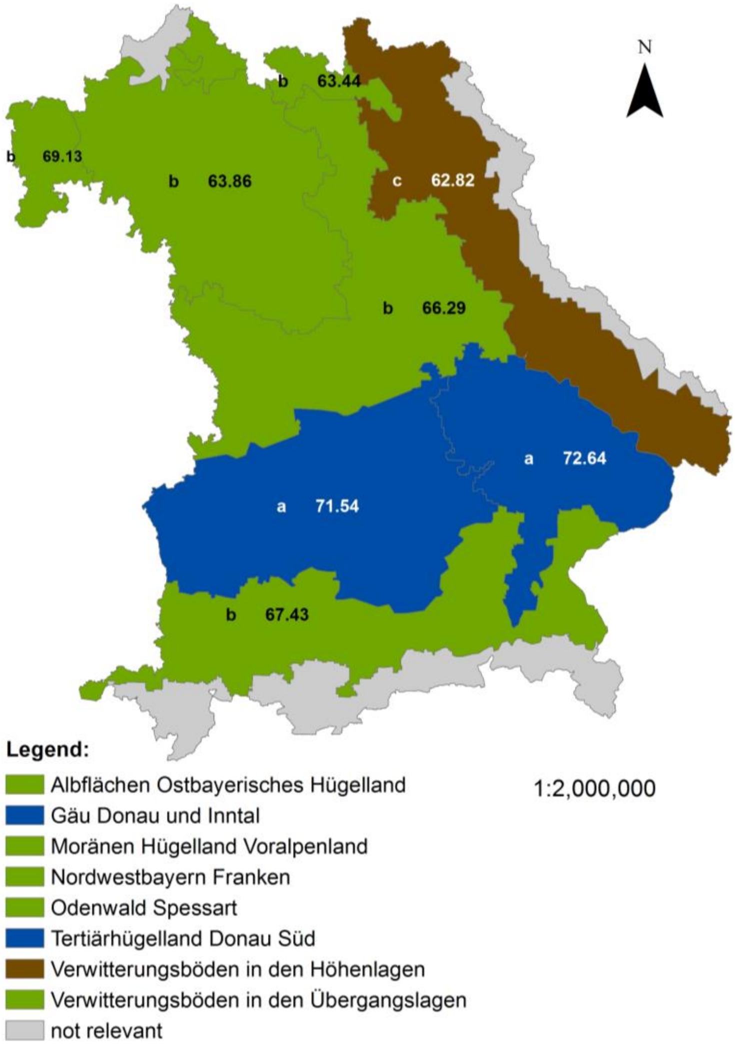


Figure 6: Box plots illustrating the detrended winter wheat yields of the Soil-Climate-Areas between 1991 and 2015. Different letters (a, b and c) indicate significant differences among yields at $p \leq 0.05$ according to the h.s.d. test.



Map 6: Differences among average detrended wheat yields of Soil-Climate-Areas between 1991 and 2015. The yields among Soil-Climate-Areas with different letters are significantly ($p < 0.05$) different. The numbers in Soil-Climate-Areas indicate the mean yields in dt ha^{-1} during the observation period.

Three yield classes could be identified for wheat. The first class, labelled with the letter "a", achieved the highest yields, with average yields of more than 60 dt ha^{-1}. This group is located in the south of Bavaria. The second class, labelled with the letter "b", is located in the north and north-west of Bavaria and achieved average yields of 58-60 dt ha^{-1}. An exception within class “b” was *Moränen Hügelland Voralpenland*, which is located in south Bavaria. The last class included the Soil-Climate-Area *Verwitterungsböden in den Höhenlagen* indicated with the letter "c" and an average yield of 55 dt ha^{-1}. Higher yields were generally obtained in south Bavaria than in the north of Bavaria. Whereas the northwestern part of Bavaria achieved higher yields than the north-east of Bavaria.

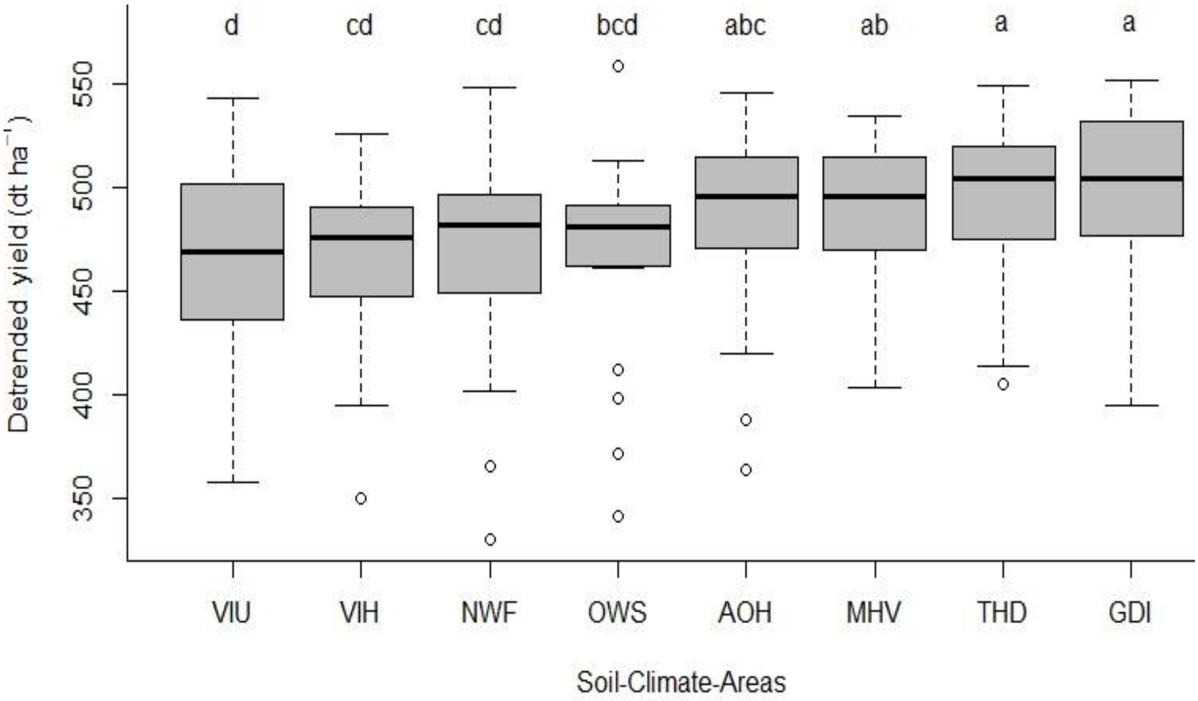
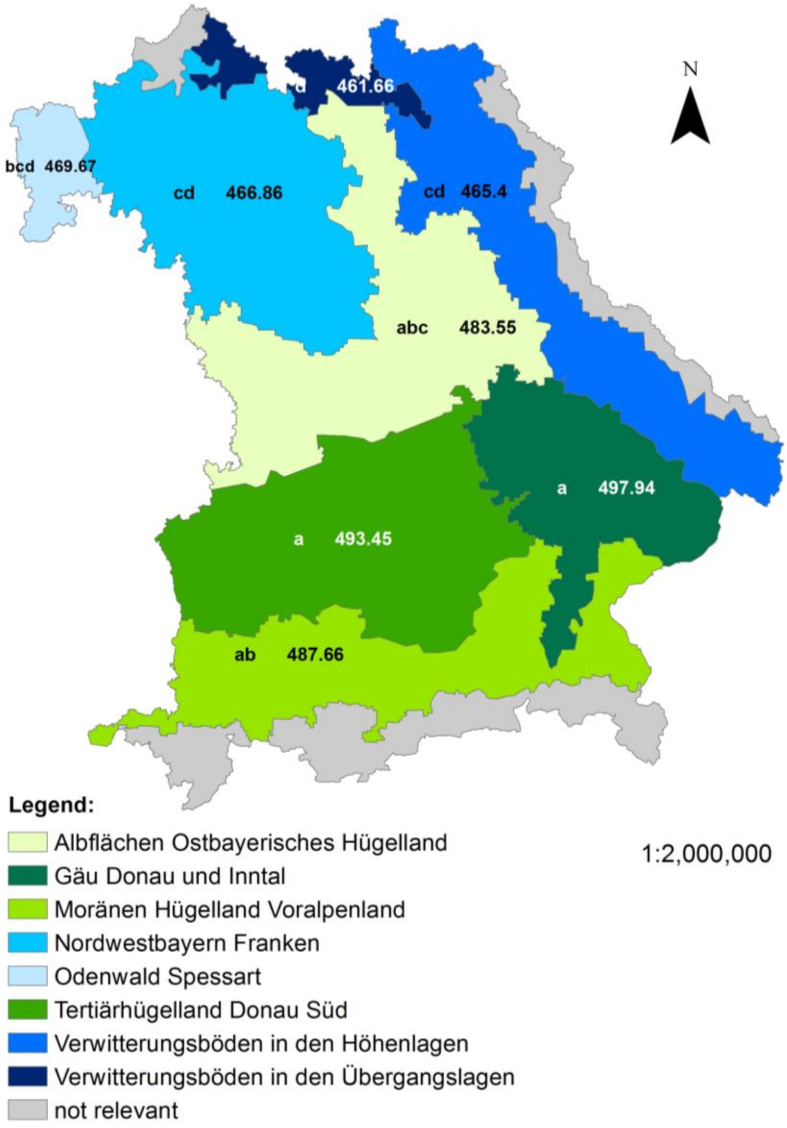


Figure 7: Box plots illustrating silage maize yields of the Soil-Climate-Areas between 1991 and 2015. Different letters (a, ab, abc, bcd, cd and d) indicate significant differences among yields at $p \leq 0.05$ according to the h.s.d. test.



Map 7: Differences among average maize yields of Soil-Climate-Areas between 1991 and 2015. The yields among Soil-Climate-Areas with different letters are significantly ($p < 0.05$) different. Numbers in Soil-Climate-Areas indicate the mean yields in dt ha^{-1} during the observation period.

Two main classes could be distinguished for silage maize. They were labelled with the letters "a" for south Bavaria and "d" for the north of Bavaria. All classes which contained these two letters were significantly different ($p \leq 0.05$). The south of Bavaria with the four blue Soil-Climate-Areas (Map 7) achieved on average higher yields than 490 dt ha^{-1}. The north of Bavaria with the four green Soil-Climate-Areas resulted in average yields of 460-470 dt ha^{-1}. For both crops generally higher yields were achieved in the south compared to the north of Bavaria.

4.1.4 Stability of yields

The evaluation of the yield stabilities was based on both absolute and relative values of the two crops (Figures 8 - 11).

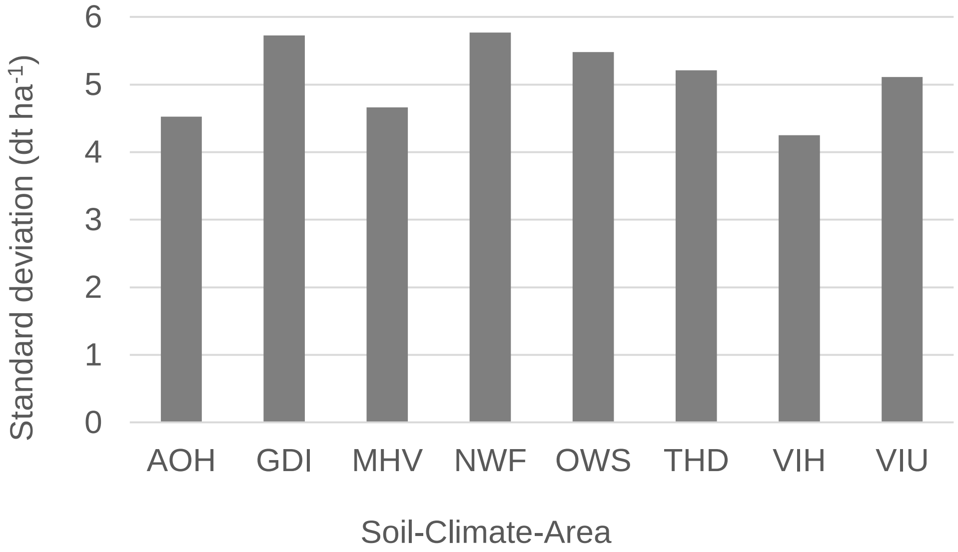


Figure 8: Absolute yield stability of Soil-Climate-Areas in Bavaria from 1991-2015 for winter wheat.

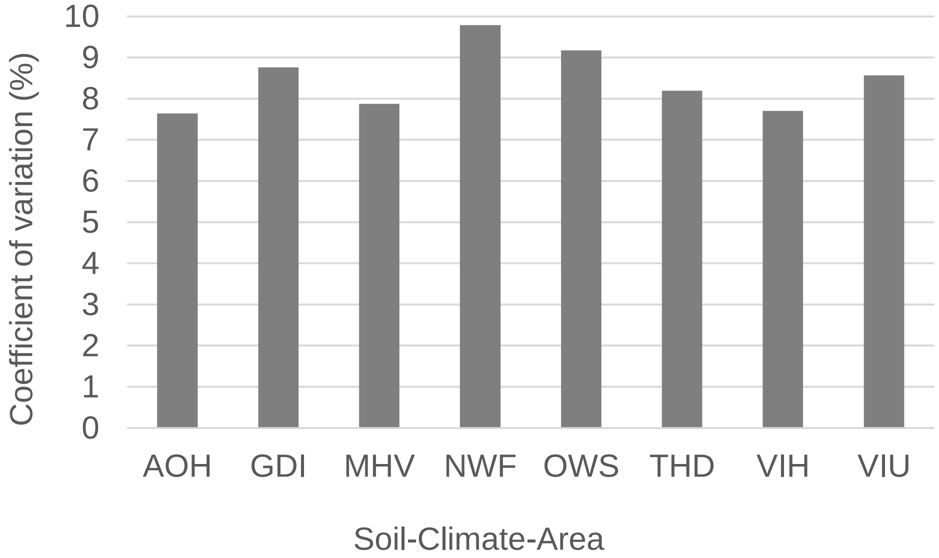


Figure 9: Relative yield stability of Soil-Climate-Areas in Bavaria from 1991-2015 for winter wheat.

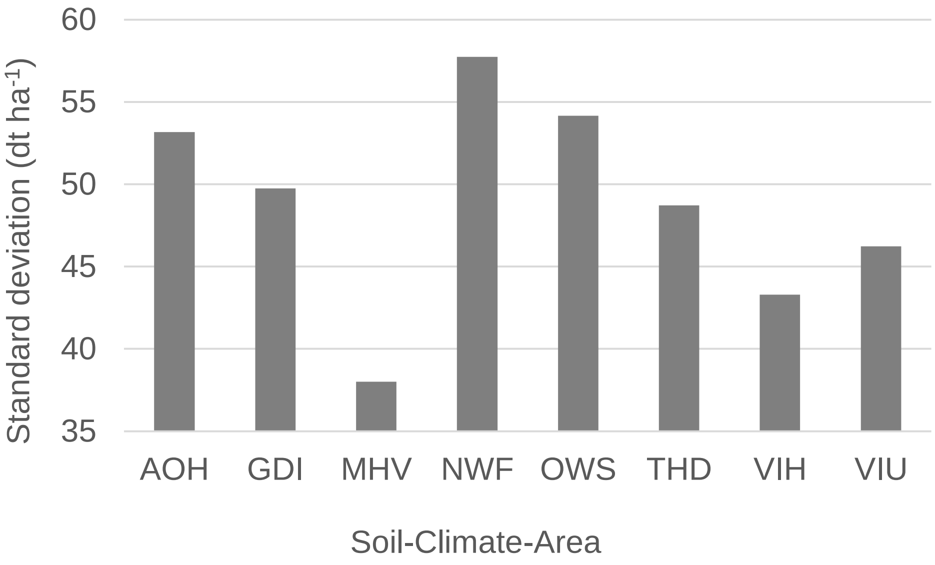


Figure 10: Absolute yield stability of Soil-Climate-Areas in Bavaria from 1991-2015 for silage maize.

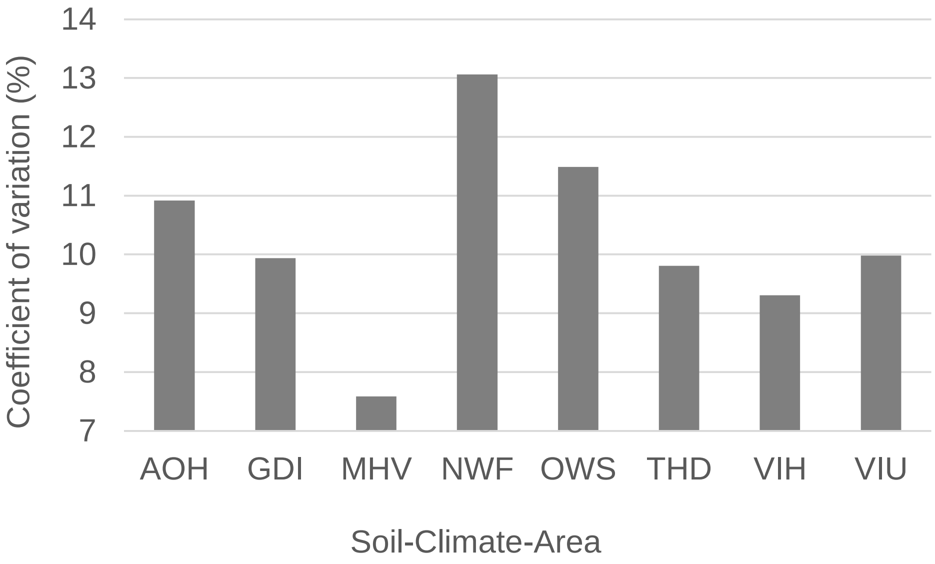
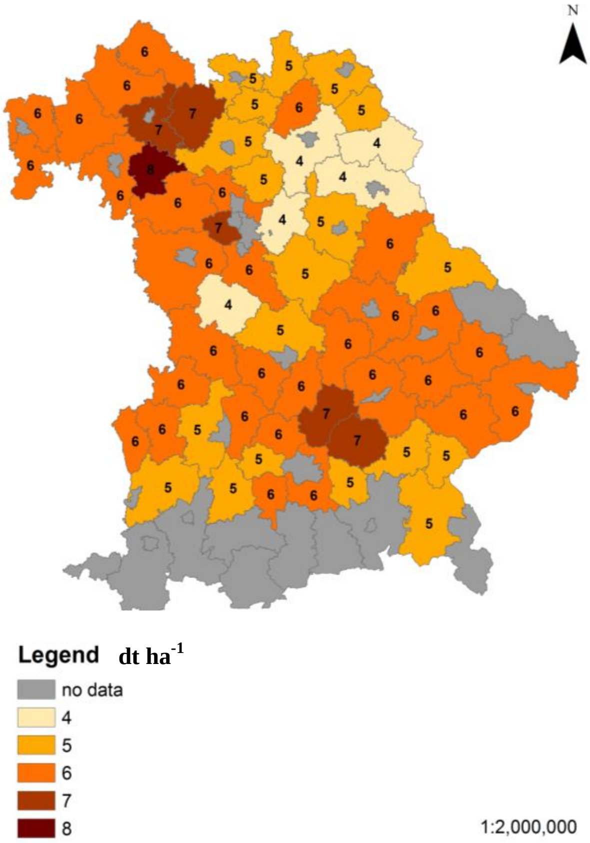


Figure 11: Relative yield stability of Soil-Climate-Areas in Bavaria from 1991-2015 for silage maize.

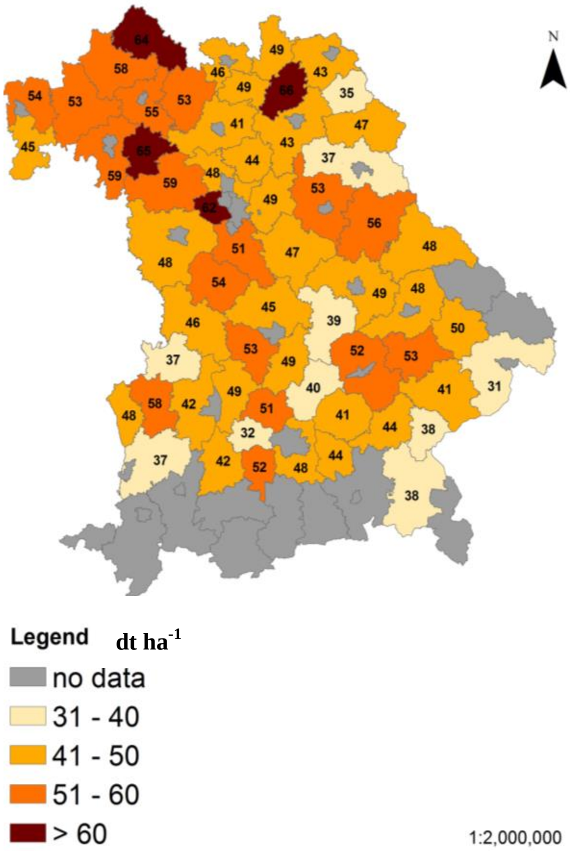
Winter wheat showed no major difference between the Soil-Climate-Areas in both the relative (Figure 9) and absolute (Figure 8) yield stability. With a standard deviation of 4.25 dt ha^{-1}, the absolute yield stability was highest in the Soil-Climate-Area *Verwitterungsböden in den Höhenlagen*. The relative yield stability - which allows an objective comparison with respect to the yield level - was highest in *Albflächen Ostbayerisches Hügelland* depicting a coefficient of variation of 7.6%. The second most stable yield was observed in the Soil-Climate-Area *Verwitterungsböden in* *den Höhenlagen* characterized by a very similar coefficient of variation of 7.7%. The most unstable wheat yields could be observed in the Soil-Climate-Area *Nordwestbayern Franken*. The coefficient of variation was 9.8 %. In general, the differences in the relative yield stability of wheat were not significantly different and amounted only to 2.2% among the Soil-Climate-Areas.

Silage maize, on the other hand, revealed something different. The differences ranged from 7.6% relative yield stability (Figure 11) in *Moränen Hügelland Voralpenland* to 13.1% in *Nordwestbayern Franken*. *Moränen Hügelland Voralpenland* also showed the lowest standard deviation of 38 dt ha^{-1} with regard to the absolute yield stability (Figure 10). Other Soil-Climate-Areas with high relative yield instabilities were *Albflächen Ostbayerisches Hügelland* (10.9%) and *Odenwald Spessart* (13%). Furthermore, the Soil-Climate-Areas *Gäu Donau Inntal*, *Tertiärhügelland Donau Süd*, *Verwitterungsböden in den Höhenlagen* and *Verwitterungsböden in den Übergangslagen* revealed a similar relative yield stability with values between 9.3% and 10%. The difference in relative yield stability between the Soil-Climate-Areas was higher for silage maize (5.5%) than for winter wheat (2.2%). Generally, the relative yield stability of maize (mean relative yield stability over all Soil-Climate-Areas 10.3%) was lower than that of wheat (mean relative yield stability over all Soil-Climate-Areas 8.5%).

The spatial aggregation of the Soil-Climate-Areas did not indicate a possible heterogeneity between counties within a Soil-Climate-Area. To estimate the climate sensitivity of individual counties, absolute and relative yield stabilities of both crops were calculated for all counties (Map 8 and 9). The lowest relative yield stability for winter wheat could be observed in the counties *Fürth* (14.4%), *Haßberge* (12.3%) and *Erlangen-Höchstadt* (12.2%). The most unstable winter wheat yields were observed in northwestern Bavaria for both the relative and absolute yield stability. Other counties with unstable relative yields were the county *Schwandorf* (11%), as well as the two counties *Freising* (10.8%) and *Starnberg* (10.7%), which could be assigned to eastern and southern Bavaria. Regarding absolute yields the two counties *Erding* and *Freising* (both 7 dt ha^{-1}) showed a low yield stability for southern Bavaria. In northern Bavaria *Haßberge*, *Schweinfurt* and *Fürth* (all of them had an absolute stability of 7 dt ha^{-1}), as well as *Kitzingen* (8 dt ha^{-1}) were characterized by a low absolute yield stability. The relatively most stable yields were achieved in *Tirschenreuth* (6.9%, 4 dt ha^{-1}) and in *Nürnberger Land* (6.9%, 4 dt ha^{-1}). This county is located directly next to one of the most unstable counties (*Erlangen-Höchstadt* 12.2%, 6 dt ha^{-1}). Stable yields were achieved in northeast Bavaria (*Neustadt Waldnaab* (7.4%, 4 dt ha^{-1}), *Tirschenreuth* (6.9%, 4 dt ha^{-1}), in the middle of Bavaria (*Weißenburg Gunzenhausen* 7.4%, 4 dt ha^{-1} *Eichstätt* 7.6%, 5 dt ha^{-1}) and in the southwest of Bavaria (*Unterallgäu* 7.6%, 5 dt ha^{-1}, *Augsburg* 7.7%, 5 dt ha^{-1}). Stable absolute yields could further located in northeast Bavaria (*Bayreuth*, *Tirschenreuth*, *Neustadt an der Waldnaab* and *Nürnberger Land*, all with 4 dt ha^{-1}). The absolute yields for winter wheat did not vary as much as the relative yield stabilities across Bavaria.

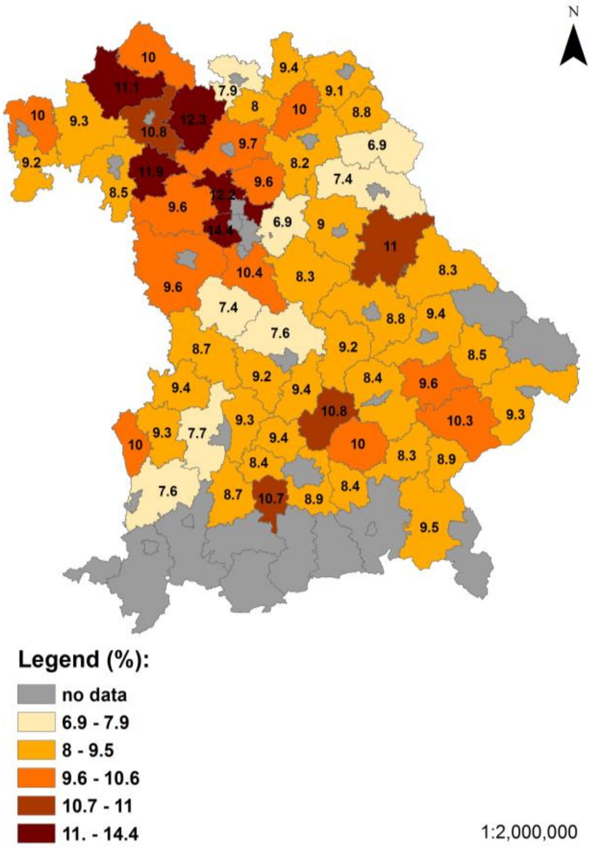


Map 8: Absolute yield stabilities (dt ha^{-1}) of winter wheat per county. The number in a county indicates the specific absolute yield stability.

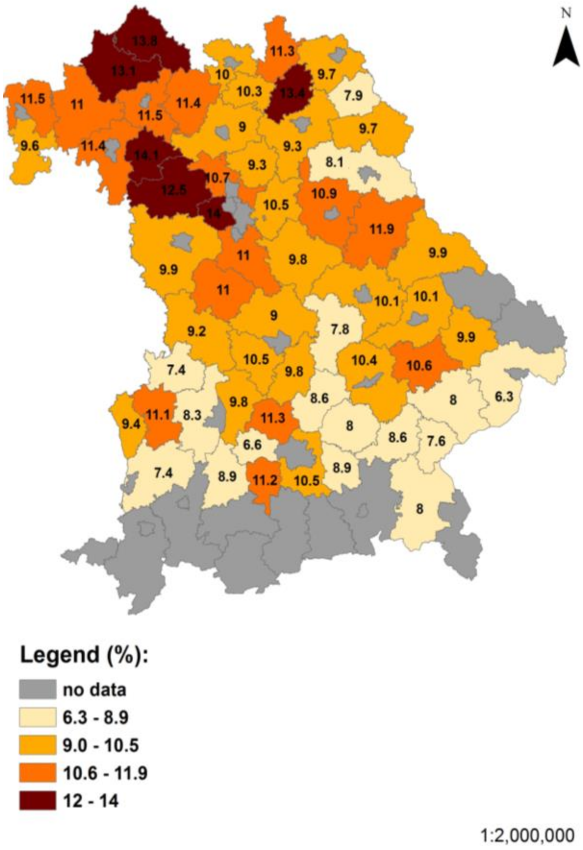


Map 9: Absolute yield stabilities (dt ha^{-1}) of silage maize per county. The number in a county indicated the specific absolute yield stability.

Similar patterns could be detected for silage maize. Unstable yields in northwestern Bavaria (*Kitzingen* 14.1%, 65 dt ha^{-1}, *Fürth* 14%, 62 dt ha^{-1}, *Rhön Grabfeld* 13.8%, 64 dt ha^{-1} and in *Neustadt an der Aisch* 12.5%, 59 dt ha^{-1}) were identified. The county *Kulmbach* (13.1%, 66 dt ha^{-1}) in north-eastern Bavaria represented another county with a low relative yield stability. For silage maize differences between northern (more unstable yields) and southern Bavaria (more stable yields) were identified. The most stable yields were achieved in *Passau* (6.3%, 31 dt ha^{-1}), *Fürstenfeldbruck* (6.6%, 32 dt ha^{-1}), *Unterallgäu* (7.4%, 37 dt ha^{-1}), *Dillingen an der Donau* (7.4%, 37 dt ha^{-1}) and *Altötting* (7.6%, 38 dt ha^{-1}). For southern Bavaria unstable yields were observed in *Starnberg* (11.2%, 52 dt ha^{-1}), *Dachau* (11.3%, 51 dt ha^{-1}), *Günzburg* (11.1%, 58 dt ha^{-1}) and *Dingolfing Landau* (10.6%, 53 dt ha^{-1}).



Map 11: Relative yield stabilities (%) winter wheat per county. The number in a county indicates the specific yield stability.



Map 10: Relative yield stabilities (%) of silage maize per county. The number in a county indicates the specific yield stability.

In summary, it was evident that the crop yields of counties with low absolute yields, low relative yields were observed as well. The yield stability in northern Bavaria was lower than in southern Bavaria. Since the higher yield stability was possibly related to a higher available field water capacity in southern Bavaria, the median afc was correlated with the relative and absolute yield stability of the counties and the Soil-Climate-Areas of both crops (Figures 13 - 15).

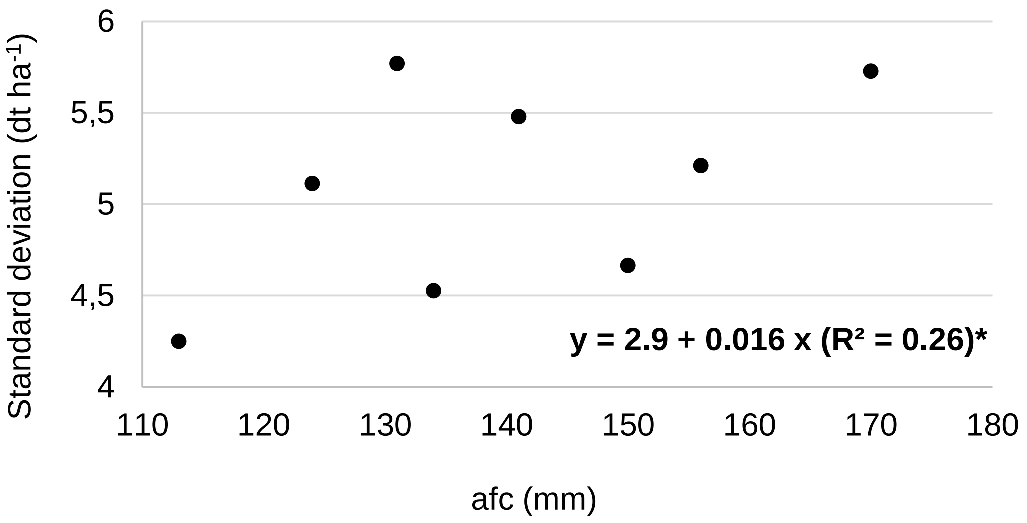


Figure 12: Relationship between the standard deviation (= absolute yield stability) of winter wheat and the median available field water capacity of the Soil-Climate-Areas. Statistical significance as indicated by p-value: * $p < 0.05$.

For winter wheat the absolute yield stability and afc were moderately correlated with each other. The higher the afc in a Soil-Climate-Area, the lower was the yield stability. Thus, the variability of those Soil-Climate-Areas that represent higher afc was higher than the yield variability of the Soil-Climate-Areas characterized by low median afcs. A correlation between afc and relative yield stability was hardly evident for both crops ($r = 0.01$ for winter wheat, $r = 0.04$ for silage maize). However, tendencies for both crops could be identified: For winter wheat, the relative yield stability was higher with increasing median afc. With silage maize, the relative yield stability increased with a higher median afc of a Soil-Climate-Area. The absolute yield stability of silage maize was not correlated to the median afc in the Soil-Climate-Areas. In contrast other results were obtained within the counties. For silage maize, 23% of the variance of yields in Bavarian counties was explained through the median afc. The relative yield stability increased with increasing afc of a county (Figure 13). 16% of the variance in Bavarian county yields was explained by the level of afc in counties (Figure 14). Here too, the absolute yield stability increased, the higher a county’s afc was. There were hardly any relationships observed for county yields of winter wheat. The relationships between the absolute/relative yield stability and the afc were very low. However, the same tendencies could be observed for the counties as for the Soil-Climate-Areas. Relative and absolute yield stabilities of winter wheat decreased with higher afc. For winter wheat there was no apparent tendency for high afcs to lead to higher yield stabilities or vice versa. This statement could be made for both the Soil-Climate-Areas and the counties. For maize, on the other hand, it was observed for both study areas that yield stability increased with higher afcs.

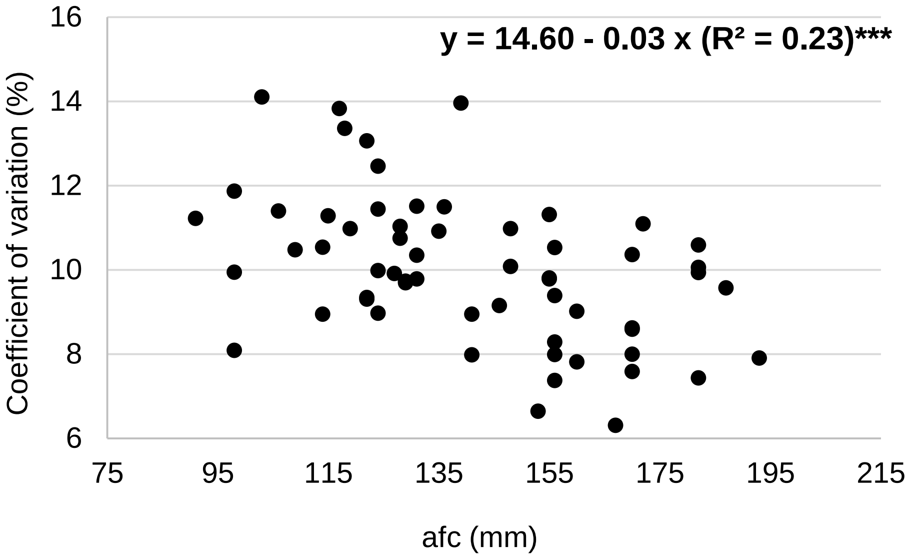


Figure 13: Relationship between the coefficient of variation (= relative yield stability) of silage maize and the median available field water capacity of the investigated counties in Bavaria. Statistical significance as indicated by p-value: ***$p < 0.001$.

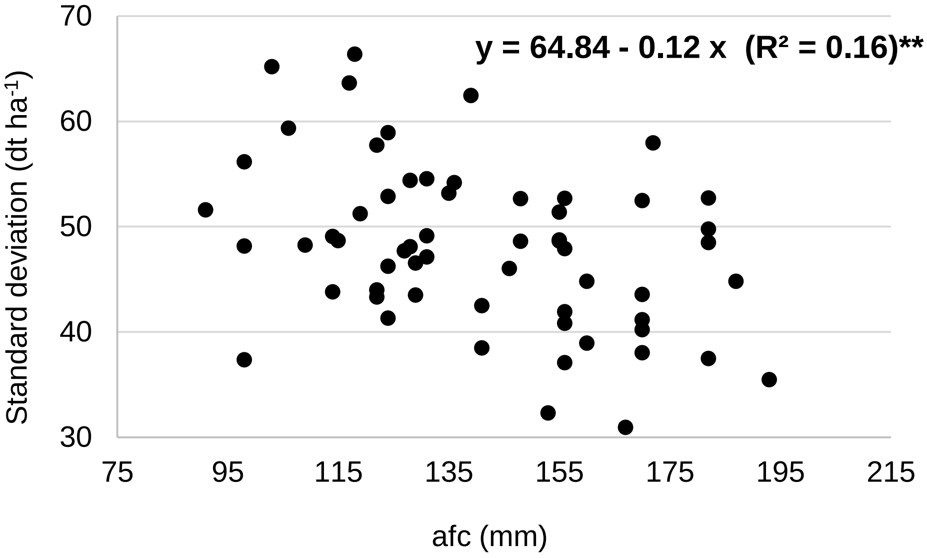


Figure 14: Relationship between the standard deviation (= absolute yield stability) of silage maize and the median available field water capacity of the investigated counties in Bavaria. Statistical significance as indicated by p-value: **$p < 0.01$.

4.1.5 Low and high yields among Soil-Climate-Areas and counties

Low yields were defined as smaller than the 10th percentile within a yield distribution of a Soil-Climate-Area or county, high yields were higher than the 90th percentile within a yield distribution (see 3.2). For each Soil-Climate-Area and cultivar, high and low yields were identified. In total, there were thus three years per Soil-Climate-Area that represent a low yield and three years that represent a high yield. Of the total of 200 yields (eight Soil Climate Areas with 25 years each), 24 Soil-Climate-Areas were classified as high yields and 24 as low yields for each cultivar, wheat and maize. Figures 15 and 16 show the frequencies of SCA-years that were regarded as high or low.

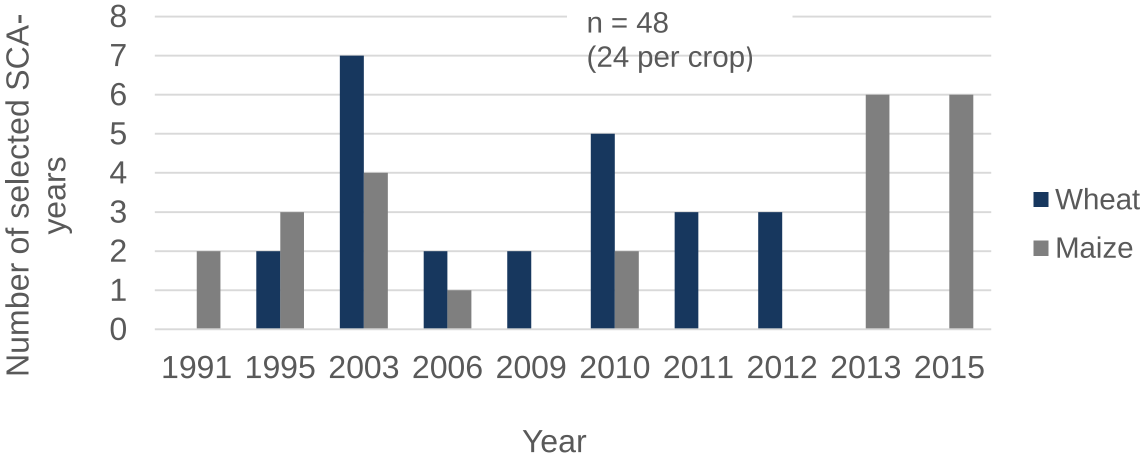


Figure 15: Frequencies of years identified as low yield years of all silage maize and winter wheat yields.

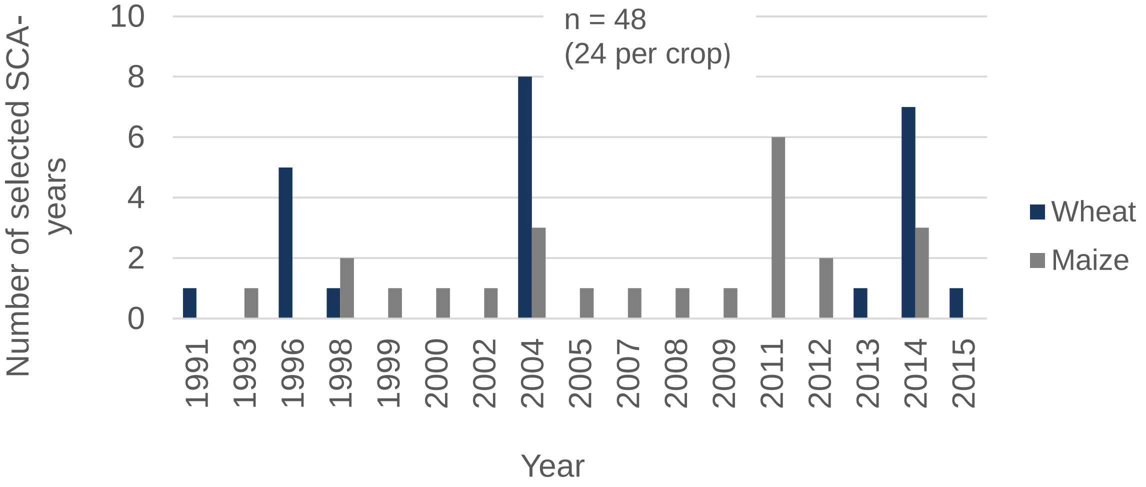


Figure 16: Frequencies of years identified as high yield years of all silage maize and winter wheat yields.

Different years revealed to be low in yield for wheat and maize. For maize, in the years 2013 and 2015 six low yields were identified. While for wheat the year 2003 was selected seven times, maize was classified as low four times. Another low yield year for wheat was in 2010. Those years that depicted most frequently low yield years for wheat were also characterized as low yield years for maize, namely in 2003 and 2010. However, the years 2013 and 2015 being often selected as low yield years for maize, were not classified to be low yield years for wheat.

High yield years were as well assessed differently for maize and wheat. While the selection of wheat for high yields per SCA was concentrated on few years 1996: five, 2004: eight, 2014: seven, the selection of high yield years of maize was more evenly distributed over many years, whereby the year 2011 revealed a peak in high yields with six Soil-Climate-Areas identified as high yield. Furthermore, the years 2004 and 2014 can be regarded as high-yield years.

4.2 Relationships between abiotic factors, phenological phases and yields of silage maize and winter wheat in Bavarian Soil-Climate-Areas

The influence of weather conditions on phenological phases are illustrated in this section using Soil-Climate-Areas. Phenological phases referred to are given in Tables 4 and 5. The investigated factors in section 4.2.1 describe the relationship between available field water capacity and yield. Section 4.2.2 addresses the relationship between the duration of phenological phases and climatic factors. The relationship between weather conditions and yields during each phenological phase is addressed in section 4.2.4 whereas the correlation of the length of one phenological phase to the yield is described in section 4.2.3. Section 4.2.5 assesses whether one specific climatic factor (factors used here were the same as used in 4.2.4) resulted in high or low yields.

4.2.1 Influence of the median available field water capacity on yield in Bavaria

This section addresses the research question whether the median level of available field water capacity in mm of Bavarian Soil-Climate-Areas can explain the yield variabilities of wheat and maize among Soil-Climate-Areas from 1991 - 2015. The median of the available field water capacity (afc) of each Soil-Climate-Area was correlated with the average maize yield or detrended wheat yield of each Soil-Climate-Area across 25 years. The yield variability of both crops within the Soil-Climate-Areas from 1991-2015 was closely related to the median amount of available field water capacity in each Soil-Climate-Area.

For wheat, the detrended yield variability in Soil-Climate-Areas was explained by the median afc by 81%. According to the linear model, yield increased by 0.15 dt ha^{-1} for one additional mm of afc (Figure 17).

The yield variability of silage maize in Soil-Climate-Areas was explained by 56% with the median afc (Figure 18). According to the linear model, yield increased by 0.87 dt ha^{-1} per one incremental mm of afc.

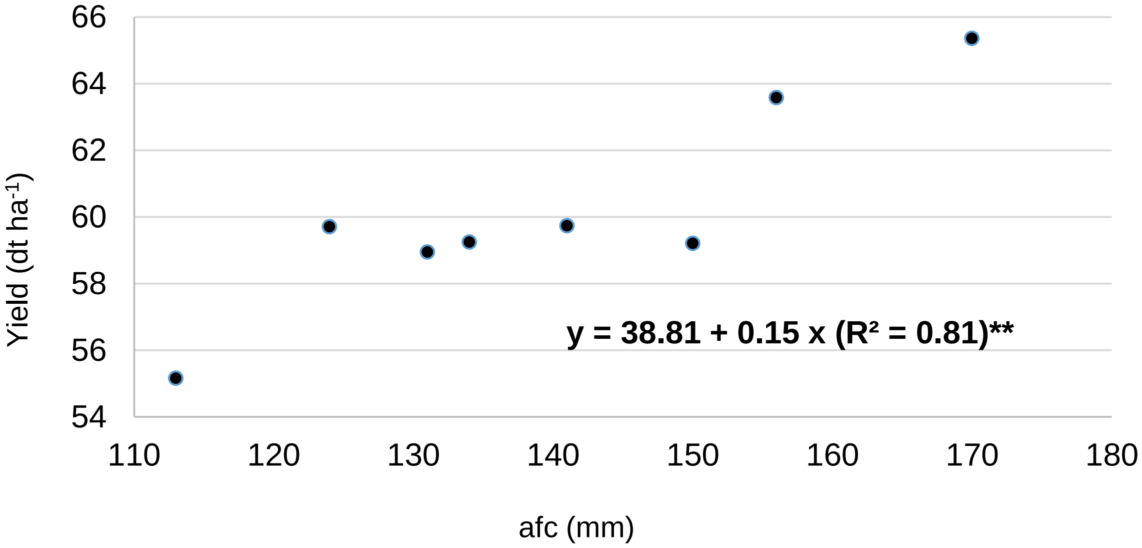


Figure 17: Relationship between the mean detrended yield of winter wheat and the median afc of the Soil-Climate-Areas. Statistical significance as indicated by p-value: **p < 0.01.

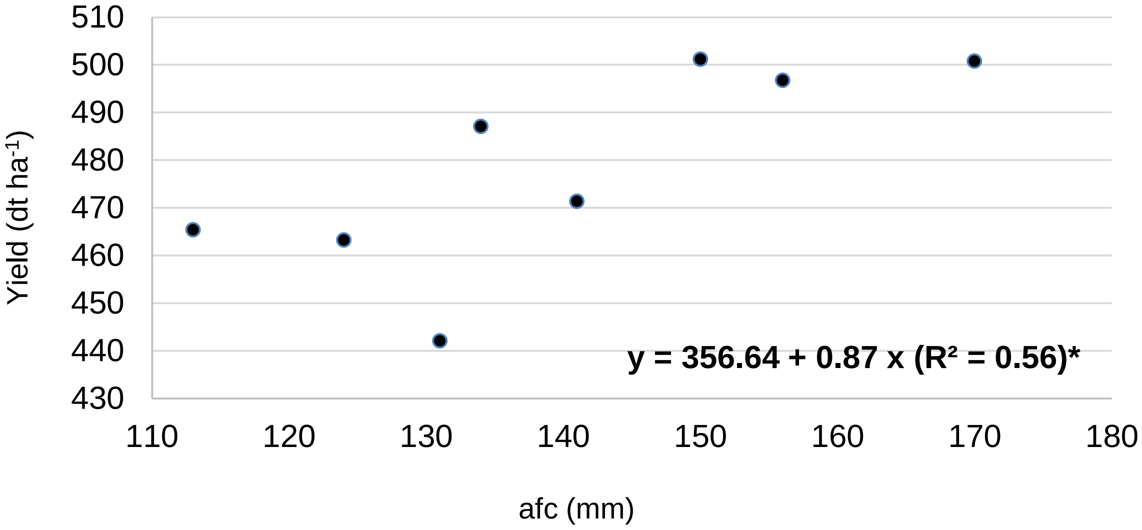


Figure 18: Relationship between the mean yield of silage maize and the median afc of the Soil-Climate-Areas. Statistical significance as indicated by p-value: *p < 0.05.

4.2.2 Relationships between climatic variables and the duration of phenological phases in Bavaria

In this section, each phenological phase was considered individually within five phenological phases for wheat and six phenological phases for maize for the Soil-Climate-Areas. For each phenological phase and Soil-Climate-Area, only the environmental variable which was identified to have the highest correlation with the duration of a phenological phase in days and a minimum level of significance of $p \leq 0.05$ was considered. Each climatic variable was correlated with each phenological phase of each Soil-Climate-Area individually. With eight Soil-Climate-Areas and six phenological phases, this analysis provided a total of 48 considered factors that were used to explain the duration of a phenological phase in a Soil-Climate-Area for silage maize. For wheat there were in total 40 considered environmental variables, since there was one phenological phase less. The analysis revealed for silage maize that the sum of radiation was the variable that most frequently was correlated with the duration of a phenological phase. The sum of radiation was identified as the highest correlated factor 31 times out of 48 possible selection factors. The individual tables depicting the correlation coefficient per crop for each environmental factor, each phenological phase and the significance level are indicated in the Supplemental Tables C1-C4. The second variable that was identified to have the highest correlation with the duration of a phenological phase in days was the temperature with average, maximum or minimum values. For maize, the temperature was identified 11 times as the factor with the highest correlation coeffcient. Thus in 42 out of 48 considered factors, the temperature and the radiation sum were identified to have the highest correlation with the duration of a phenological phase of silage maize. Similar observations could be identified for wheat. Here, too, the radiation sum was the environmental factor which was correlated with the duration of a phenological phase most often with 20 out of the 40 factors selected. Temperature was identified as the second most frequently correlated factor which was in total 15 times out of 40 factors selected. Temperature was more often identified as highest correlated factor with wheat yields than with maize yields. In total, this factor was identified 20 times as the most correlated factor with the duration of phenological phases of wheat, whereas temperature was identified only 11 times for maize as the best correlated factor. The values of the correlation coefficients were different for both crops and varied depending on the phenological phase. Taking just one factor into consideration, for wheat, correlation coefficients ranged from $r = 0.48$ during the first phenological phase to $r = 0.63$ during the third phenological phase. The correlation coefficient of one phenological phase in a Soil-Climate-Area was calculated as an average of all correlation coefficients that had the highest value in each Soil-Climate-Area in each phenological phase. For maize, this calculation resulted in a lowest value with $r = 0.56$ during the fifth phenological phase and $r = 0.79$ beeing the highest value identified for the second phenological phase. Overall, the duration of a phenological phase could be described very well by temperature and radiation sum; the individual factors showed high correlations concerning the duration of a phenological phase.

4.2.3 Relationships between the duration of phenological phases and the yield in Bavaria

The results are restricted to phases and Soil-Climate-Areas that are at least at a significance level of 0.05. Thus, the yield level was related to the duration of individual phenological phases as follows:

Winter wheat:

- Beginning of stem elongation to beginning of heading:

  For *Nordwestbayern Franken* a positive correlation with r = 0.35 was found.

- Beginning of heading to beginning of milk ripening:

  Albflächen Ostbayerisches Hügelland showed a positive correlation with r = 0.2

- Beginning of milk ripening to beginning of yellow ripening:

  In *Gäu Donau Inntal*, as well as in *Verwitterungsböden in den Höhenlagen* a positive correlation between the duration of this phenological phase and yield was found. The correlation for *Gäu Donau Inntal* was 0.17, for *Verwitterungsböden in den Höhenlagen* the correlation was 0.25.

Winter wheat yields in the Soil-Climate-Areas of Bavaria revealed only positive correlations with the duration of vegetation phases. Positive correlations were more frequent with three times in northern Bavaria than in southern Bavaria where a correlation was observed one time. Negative correlations between the duration of phenological phases and yield did not exist for the whole of Bavaria within the time period 1991 - 2015.

Silage maize:

- Beginning of emergence to beginning of stem elongation:

  For *Verwitterungsböden in den Höhenlagen* a correlation coefficient of 0.21 was identified.

- Beginning of stem elongation to beginning of tassel emergence:

  In *Tertiärhügelland Donau Süd* the correlation between yield and the length of this phenological phase was positive with r = 0.21.

- Beginning of flowering to beginning of milk ripening:

In this phase, four Soil-Climate-Areas showed positive relationships. The strongest correlation could be observed for *Albflächen Ostbayerisches Hügelland*, amounting up to a correlation of r = 0.46. In *Verwitterungsböden in den Höhenlagen* and *Tertiärhügelland Donau Süd* the correlation coefficient was 0.23. In *Nordwestbayern Franken* it was slightly lower with r = 0.21.

- Beginning of milk ripening to beginning of dough ripening:

  One positive correlation was observed for *Moränenhügelland Voralpenland* with r = 0.23.

Silage maize yields in the Soil-Climate-Areas of Bavaria revealed also only positive correlations with the duration of vegetation phases. The correlations were relatively homogeneously distributed over northern and southern Bavaria, whereby more positive correlations were detected for maize than for wheat.

4.2.4 Relationships of abiotic factors during phenological phases and yield in Bavaria

To determine the relationship between weather or soil factors during phenological phases with yield, correlations for each abiotic factor during a phenological phase were calculated for each Soil-Climate-Area between 1991 and 2015. Five phenological phases were identified for wheat whereas silage maize had six phenological phases. The results are presented in Tables 9 and 10.

Table 9: Significant correlation coefficients of each variable during phenological phases with winter wheat yields in Soil-Climate-Areas in Bavaria from 1991-2015.

Albflächen Ostbayerisches Hügelland

	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Sowing - Emergence												
Emergence - Stem elongation								🟩 0.16 *				
Stem elongation - Heading				🟥 0.23 *	🟥 0.16 *							
Heading - Beg. milk ripening	🟥 0.2*		🟥 0.16 *	🟥 0.23 *	🟥 0.21 *							🟩 0.19 *
Beg. milk ripe. - Beg. yellow ripe.												

Gäu Donau und Inntal

	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Sowing - Emergence		🟥 0.16 *										
Emergence - Stem elongation												
Stem elongation - Heading				🟥 0.24 *	🟥 0.19 *							🟩 0.16 *
Heading - Beg. milk ripening				🟥 0.23 *	🟥 0.23 *							
Beg. milk ripe. - Beg. yellow ripe.	🟥 0.25 *		🟥 0.16 *	🟥 0.39 ***	🟥 0.32 **							

Moränen Hügelland Voralpenland

	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Sowing - Emergence						🟥 0.19 *						
Emergence - Stem elongation												
Stem elongation - Heading					🟥 0.21 *							
Heading - Beg. milk ripening												
Beg. milk ripe. - Beg. yellow ripe.	🟥 0.28 **		🟥 0.17 *	🟥 0.39 ***	🟥 0.36 **							

Tertiärhügelland Donau Süd

	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Sowing - Emergence												
Emergence - Stem elongation												
Stem elongation - Heading				🟥 0.23 *	🟥 0.21 *	🟩 0.17 *						🟩 0.26 **
Heading - Beg. milk ripening				🟥 0.17 *								
Beg. milk ripe. - Beg. yellow ripe.	🟥 0.17 *			🟥 0.20 *								

Odenwald Spessart

	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Sowing - Emergence												
Emergence - Stem elongation												
Stem elongation - Heading	🟥 0.16 *											
Heading - Beg. milk ripening				🟥 0.16 *	🟥 0.2 *							
Beg. milk ripe. - Beg. yellow ripe.												

Nordwestbayern Franken

	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Sowing - Emergence												
Emergence - Stem elongation												
Stem elongation - Heading	🟥 0.18 *		🟥 0.22 *									
Heading - Beg. milk ripening				🟥 0.18 *								
Beg. milk ripe. - Beg. yellow ripe.												

Verwitterungsböden in den Höhenlagen

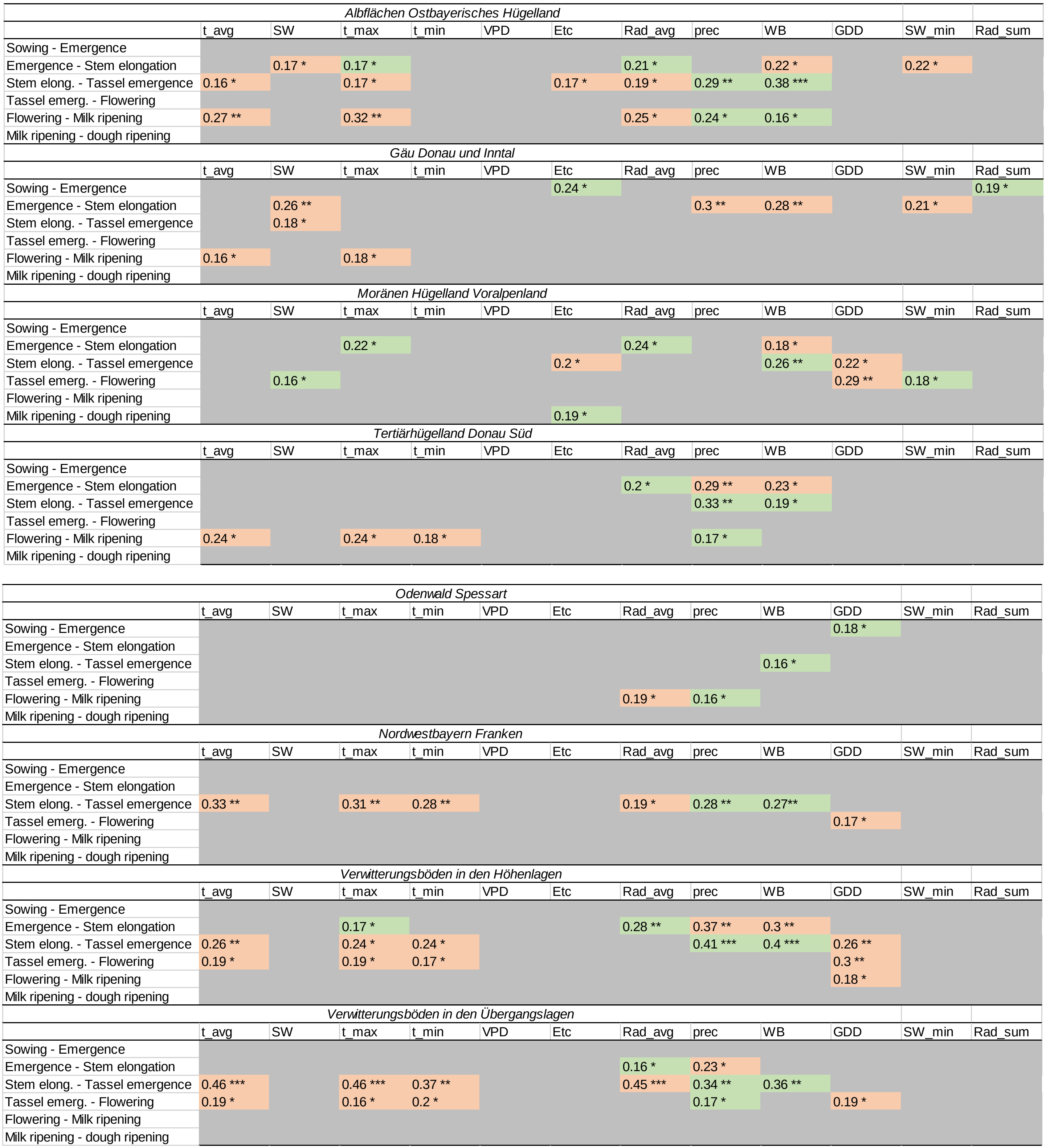
	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Sowing - Emergence												
Emergence - Stem elongation												
Stem elongation - Heading												
Heading - Beg. milk ripening	🟥 0.29 **		🟥 0.23 *	🟥 0.33 **	🟥 0.34 **							
Beg. milk ripe. - Beg. yellow ripe.												

Verwitterungsböden in den Übergangslagen

	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Sowing - Emergence	🟩 0.17 *			🟩 0.21 *	🟩 0.17 *							
Emergence - Stem elongation												
Stem elongation - Heading	🟥 0.16 *	🟩 0.17 *	🟥 0.19 *					🟩 0.22 *	🟩 0.21 *			
Heading - Beg. milk ripening	🟥 0.18 *			🟥 0.21 *								
Beg. milk ripe. - Beg. yellow ripe.												

Statistical significance as indicated by p-value: *p < 0.05, **p < 0.01, ***p < 0.001.
Given numbers are correlation coefficients of significant environmental variables during a phenological phases.
Green coloration: positive correlation.
Red coloration: negative correlation.

Table 10: Significant correlation coefficients of each variable during phenological phases with silage maize yields in Soil-Climate-Areas in Bavaria from 1991-2015.



Albflächen Ostbayerisches Hügelland

	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Sowing - Emergence												
Emergence - Stem elongation		0.17 *	0.17 *				0.21 *		0.22 *		0.22 *	
Stem elong. - Tassel emergence	0.16 *		0.17 *			0.17 *	0.19 *	0.29 **	0.38 ***			
Tassel emerg. - Flowering												
Flowering - Milk ripening	0.27 **		0.32 **				0.25 *	0.24 *	0.16 *			
Milk ripening - dough ripening												

Gäu Donau und Inntal

	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Sowing - Emergence						0.24 *						0.19 *
Emergence - Stem elongation		0.26 **						0.3 **	0.28 **		0.21 *	
Stem elong. - Tassel emergence		0.18 *										
Tassel emerg. - Flowering												
Flowering - Milk ripening	0.16 *		0.18 *									
Milk ripening - dough ripening												

Moränen Hügelland Voralpenland

	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Sowing - Emergence												
Emergence - Stem elongation			0.22 *				0.24 *		0.18 *			
Stem elong. - Tassel emergence						0.2 *			0.26 **	0.22 *		
Tassel emerg. - Flowering		0.16 *								0.29 **	0.18 *	
Flowering - Milk ripening												
Milk ripening - dough ripening						0.19 *						

Tertiärhügelland Donau Süd

	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Sowing - Emergence												
Emergence - Stem elongation							0.2 *	0.29 **	0.23 *			
Stem elong. - Tassel emergence								0.33 **	0.19 *			
Tassel emerg. - Flowering												
Flowering - Milk ripening	0.24 *		0.24 *	0.18 *				0.17 *				
Milk ripening - dough ripening												

Odenwald Spessart

	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Sowing - Emergence										0.18 *		
Emergence - Stem elongation												
Stem elong. - Tassel emergence									0.16 *			
Tassel emerg. - Flowering												
Flowering - Milk ripening							0.19 *	0.16 *				
Milk ripening - dough ripening												

Nordwestbayern Franken

	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Sowing - Emergence												
Emergence - Stem elongation												
Stem elong. - Tassel emergence	0.33 **		0.31 **	0.28 **			0.19 *	0.28 **	0.27**			
Tassel emerg. - Flowering										0.17 *		
Flowering - Milk ripening												
Milk ripening - dough ripening												

Verwitterungsböden in den Höhenlagen

	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Sowing - Emergence												
Emergence - Stem elongation			0.17 *				0.28 **	0.37 **	0.3 **			
Stem elong. - Tassel emergence	0.26 **		0.24 *	0.24 *				0.41 ***	0.4 ***	0.26 **		
Tassel emerg. - Flowering	0.19 *		0.19 *	0.17 *						0.3 **		
Flowering - Milk ripening										0.18 *		
Milk ripening - dough ripening												

Verwitterungsböden in den Übergangslagen

	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Sowing - Emergence												
Emergence - Stem elongation							0.16 *	0.23 *				
Stem elong. - Tassel emergence	0.46 ***		0.46 ***	0.37 **			0.45 ***	0.34 **	0.36 **			
Tassel emerg. - Flowering	0.19 *		0.16 *	0.2 *				0.17 *		0.19 *		
Flowering - Milk ripening												
Milk ripening - dough ripening												

Statistical significance as indicated by p-value: *p < 0.05, **p < 0.01, ***p < 0.001.
Given numbers are correlation coefficients of significant environmental variables during a phenological phases.
Green coloration: positive correlation.
Red coloration: negative correlation.

All significant correlation coefficients for winter wheat yields and the selected abiotic factors are presented in Table 9. During the final phenological phase, which was equivalent for the period between the beginning of milk ripening to the beginning of yellow ripening, no factor was significantly correlated with yields in the northern Soil-Climate-Areas *Odenwald Spessart, Verwitterungsböden in den Höhenlagen* and *Übergangslagen, Nordwestbayern Franken* and *Albflächen Ostbayerisches Hügelland*. The correlations of the southern Soil-Climate-Areas *Albflächen Ostbayerisches Hügelland, Gäu Donau und Inntal* sowie *Moränen Hügelland Voralpenland* were nearly always negatively correlated with yield. The only exception to this was made by the potential evapotranspiration from a crop canopy between the beginning of stem elongation and beginning of heading in *Tertiärhügelland Donau Süd*. It was positively correlated r = 0.17 at the 0.05 significance level. The highest negative correlation between an abiotic factor and yield was delivered by the variable t_min with correlation coefficients amounting up to r = -0.39 at the 0.05 significance level between the beginning of milk ripeness and the beginning of yellow ripeness in *Gäu Donau und Inntal* as well as for *Moränen Hügelland Voralpenland*. However, minimum temperature showed also negative correlations in the northern Soil-Climate-Areas up to r = -0.33 at the 0.01 significance level in *Verwitterungsböden in den Höhenlagen*. Negative correlations in northern Bavaria were also observed during later phenological phases, e.g. between the phenological phase that started with the beginning of heading and ended with the beginning of milk ripening which corresponded to phase four. The other remaining Soil-Climate-Areas which were assigned to the north of Bavaria, showed negative correlation coefficients for the abiotic factor minimum temperature as well. In *Albflächen Ostbayerisches Hügelland* correlation coefficients of r = -0.23 at the 0.05 significance level could be observed for two phenological phases which started with the beginning of stem elongation and ended with the beginning of heading and started with the the beginning of heading and ended with the beginning of milk ripening. In *Verwitterungsböden in den Übergangslagen* minimum temperature showed negative correlations r = -0.21 at the 0.05 significance level for one phenological phase of wheat which was recorded with the beginning of heading and the beginning of milk ripening. Comaparatively was the case for *Nordwestbayern Franken* and *Odenwald Spessart* during this phenological phase with correlation coefficients of -0.18 and -0.16 at a significance level $p < 0.05$ for the minimum temperature for both Soil-Climate-Areas. A further abiotic factor, vapor pressure deficit, showed also negative correlations in the Soil-Climate-Areas during three phenological phases, whereas the highest negative correlation r = -0.36 at a significance level $p < 0.01$ could be observed for *Moränen Hügelland Voralpenland* during the last investigated phenological phase which corresponded to the beginning of milk ripening until the beginning of yellow ripening. Similar negative correlations for the same variable during the same vegetation phase were detected for *Gäu Donau und Inntal*. However, for other phenological phases negative correlations between yield and vapor pressure deficit were identified. They cover the period between the beginning of stem elongation and the beginning of milk ripening with correlation coefficients from -0.16 to -0.34 at least at a significance level of 0.05 in nearly all Soil-Climate-Areas except of *Nordwestbayern Franken* where no correlation between vapor pressure deficit and yield was observed. In *Verwitterungsböden in den Übergangslagen*, a positive correlation coefficient of 0.17 between yield and vapor pressure deficit during the phase between sowing and emergence was observed. Further positive relationships between abiotic factors and yields could be detected particularly for precipitation, water balance, ETcrop and soil water, although not in all Soil-Climate-Areas and not during all phenological phases. *Verwitterungsböden in den Übergangslagen* was found to be among the Soil-Climate-Area with the most positive correlations. In contrast to negative correlations, positive correlations for wheat were found less frequently and were associated with earlier vegetation phases like from sowing to emergence and from stem elongation to heading.

For maize, both negative as well as positive correlations between yield and abiotic factors were observed (Table 10). During the first phenological phase which began with sowing and ended with the beginning of emergence, negative correlations could be identified in *Gäu Donau und Inntal* between yields and the simulated available soil water content (SW) with $r = -0.16$ at a level of significance $p < 0.05$ and in *Moränen Hügelland Voralpenland* between crop specific evapotranspiration (ETc) and yield with $r = -0.19$ at a significance level $p < 0.05$. However, positive correlations during the first phenological phase could be identified for *Verwitterungsböden in den Übergangslagen* between yields and average temperature, minimum temperature and vapor pressure deficit. The corresponding correlation coefficients are in the same order as abiotic factors indicated in the text as $r = 0.17$, r: = 0.21, and $r = 0.17$, at the 0.05 significance level for all three factors. The second investigated phenological phase which started with the beginning of emergence and ended with the beginning of stem elongation revealed positive and negative correlations between yields and abiotic factors again. Apart from this, two Soil-Climate-Areas *Odenwald Spessart* and *Nordwestbayern Franken* were identified for which no significant relationships between abiotic factors and yields from the beginning of emergence until the beginning of stem elongation could be detected. The strongest correlations during the second phenological phase were identified for *Verwitterungsböden in den Höhenlagen* between yields and precipitation and revealed a negative relationship $r = -0.37$ and a significance level of $p < 0.01$. This negative relationship was also found for other Soil-Climate-Areas with correlation coefficients ranging from -0.23 in *Verwitterungsböden in den Übergangslagen* to -0.3 in *Gäu Donau und Inntal*. For radiation, on the other hand, a positive correlation was observed for yields in five Soil-Climate-Areas. The coefficient of correlation ranged from 0.16 in *Verwitterungsböden in den Übergangslagen* to 0.28 in *Verwitterungsböden in den Höhenlagen* with a minimum level of significance $p < 0.05$. In contrast to the second phenological phase, the sum of precipitation during the third phenological phase which was defined by the beginning of stem elongation until the beginning of tassel emergence delivered for five Soil-Climate-Areas positive effects on yields with r-values ranging from 0.28 in *Nordwestbayern Franken* to 0.41 in *Verwitterungsböden in den Höhenlagen* at a significance level of at least 0.05. For two Soil-Climate-Areas a positive correlation between yield and the precipitation sum during the third phenological phase was not identified, but the water balance (WB) could be detected to have a positive correlation in *Moränen Hügelland Voralpenland* r = 0.26 and in *Odenwald Spessart* r = 0.16). Whilst the influence of temperature (mean, minimum and maximum) on yield in the third phenological phase was negatively correlated, especially for Soil-Climate-Areas in northern Bavaria like *Verwitterungsböden in den Übergangslagen* with correlation coefficients for average temperature being -0.46 and -0.33 for *Nordwestbayern Franken.* During the fourth phenological phase the time between the beginning of tassel emergence and the beginning of flowering only few correlations with yields were identified. Four Soil-Climate-Areas showed negatively correlated growing degree days (GDD) with correlation coefficients between -0.17 in *Nordwestbayern Franken* and -0.3 in *Verwitterungsböden in den Höhenlagen*. Further negative correlation coefficients were found in two Soil-Climate-Areas *Verwitterungsböden in den Höhenlagen* r = t_avg/t_max: -0.19, r = t_min: -0.17 and in *Verwitterungsböden in den Übergangslagen* r = t_min -0.2, r = t_max: -0.16, r = t_avg: -0.19) for temperature. Positive correlations during the forth phenological phase were identified in two Soil-Climate-Areas. In *Moränen Hügelland Voralpenland* the minimum simulated available soil water content showed a correlation coefficient of 0.18, in *Verwitterungsböden in den Übergangslagen* a value of 0.17 for precipitation while the significance level of both factors was $p < 0.05$. A similar finding was obtained for the fifth phenological phase, the beginning of flowering until the beginning of milk ripening and sixth phenological phase, the beginning of milk ripening until the beginning of dough ripening.. Temperature and radiation were the factors that were generally negatively correlated with the yield, whereas precipitation and simulated soil water were generally identified as being positively correlated factors during these phases. The correlation coefficients varied from -0.32 for t_max to 0.24 for precipitation in *Albflächen Ostbayerisches Hügelland* during the fifth phase.

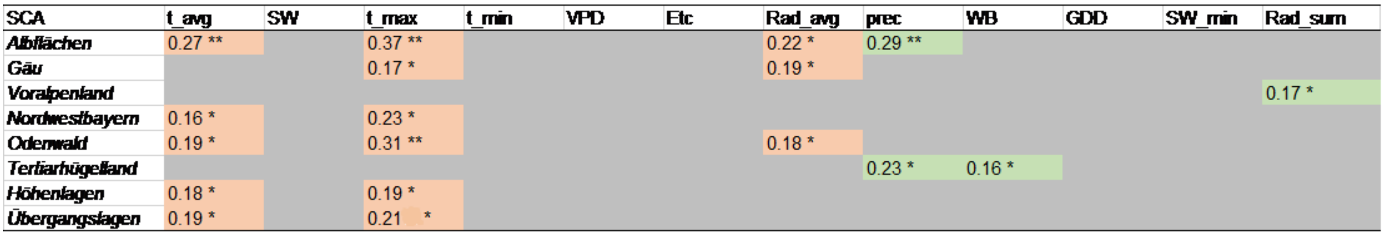
In summary, it was found that the following variables appear to be influencing the yield of both crops and the entire vegetation period:

- Temperature (the mean, the maximum and the minimum, whereby the maximum and minimum temperatures appeared to have a higher overall influence).
- Simulated available soil water content / the water balance which is part of the equation for the simulated available soil water content
- Radiation
- Vapor pressure deficit

The correlations of three particularly high/low abiotic factors with yield were evaluated as well. The maximum temperature and solar radiation as well as the minimum simulated available soil water content were used for this purpose. The inclusion of particularly high or low abiotic factors or extreme values into the calculation of correlations with yield did not reveal stronger correlations.

Since the water requirement of maize is particularly high due to strong biomass accumulation in the time between tassel emergence and dough ripening, correlations were calculated for this period as well (Table 11).

Table 11: Significant correlation coefficients of each environmental variable between tassel emergence and dough ripening with silage maize yields in Soil-Climate-Areas in Bavaria from 1991-2015.



SCA	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Albflächen	0.27 **		0.37 **				0.22 *	0.29 **				
Gäu			0.17 *				0.19 *					
Voralpenland												0.17 *
Nordwestbayern	0.16 *		0.23 *									
Odenwald	0.19 *		0.31 **				0.18 *					
Tertiärhügelland								0.23 *	0.16 *			
Höhenlagen	0.18 *		0.19 *									
Übergangslagen	0.19 *		0.21 *									

Statistical significance as indicated by p-value: *p < 0.05, **p < 0.01, ***p < 0.001.
Given numbers are correlation coefficients of significant environmental variables during a phenological phase.
Green coloration: positive correlation.
Red coloration: negative correlation.

The thesis showed more factors that showed a negative correlation with yield, whereby only factors that had a minimum significance level of $p < 0.05$ were considered. It became apparent, that the maximum temperature between tassel emergence and dough ripening, except in *Voralpen* and *Tertiärhügelland*, was always negatively correlated with yield in the Soil-Climate-Areas. The correlations were higher for the northern Soil-Climate-Areas than for the southern Soil-Climate-Areas. Also the average temperature was usually negatively correlated with yield. A correlation for the average radiation which was negative, could only be identified for three Soil-Climate-Areas. Positive correlations could be observed in *Albflächen* and in *Tertiärhügelland* for precipitation. As a further factor which was positively correlated with yield, the radiation sum in *Voralpenland* was identified. Further correlations are shown in the Supplemental Section C.

4.2.5 Relationships between abiotic factors and high and low yield levels in Bavaria

By correlating abiotic factors with low or high yields, those factors were determined that led to distinctly high or low yields in Soil-Climate-Areas in Bavaria. Results are given in Tables 12 - 15.

Table 12: Significant correlation coefficients of abiotic factors with low wheat yields. Those Soil-Climate-Areas whose yields were lower than the 10th percentile were selected.

	SW	t_min	VPD	SW_min
Correlation coefficient phase 1	0.34**			0.32**
Correlation coefficient phase 2	0.48***			0.41***
Correlation coefficient phase 3	0.35**			0.34**
Correlation coefficient phase 5		0.19*	0.28**	

Given numbers are correlation coefficients (r) of significant environmental variables during a phenological phase.
Statistical significance as indicated by p-value, *p < 0.05, **p < 0.01, ***p < 0.001.

Table 13: Significant correlation coefficients of abiotic factors with high wheat yields. Those Soil-Climate-Areas whose yields were greater than the 90th percentile were selected.

	t_avg	SW	t_max	t_min	SW_min	Rad_sum
Correlation coefficient phase 1	-0.23*	0.29**	-0.23*	-0.19*	0.23*	0.17*
Correlation coefficient phase 2		0.27**				

Given numbers are correlation coefficients (r) of significant environmental variables during a phenological phase.
Statistical significance as indicated by p-value, *p < 0.05, **p < 0.01, ***p < 0.001.

Table 14: Significant correlations coefficients of abiotic factors with high maize yields. Those Soil-Climate-Areas whose yields were greater than the 90th percentile were selected.

	SW	ETc	SW_min	Rad_sum
Correlation coefficient phase 1	0.33**		0.26*	
Correlation coefficient phase 6		0.27**		0.27**

Given numbers are correlation coefficients (r) of significant environmental variables during a phenological phase.
Statistical significance as indicated by p-value, *p < 0.05, **p < 0.01, ***p < 0.001.

Table 15: Significant correlations coefficients of abiotic factors with low maize yields. Those Soil-Climate-Areas whose yields were lower than the 10th percentile were selected.

	SW	Rad_avg	prec	WB	SW_min
Correlation coefficient phase 2	0.33**	-0.26*		0.18*	0.32**
Correlation coefficient phase 3	0.45***		0.41	0.26*	0.44***
Correlation coefficient phase 4	0.4***				0.4***
Correlation coefficient phase 5			0.22*		
Correlation coefficient phase 6			0.24*	0.31**	

Given numbers are correlation coefficients (r) of significant environmental variables during a phenological phase.
Statistical significance as indicated by p-value, *p < 0.05, **p < 0.01, ***p < 0.001.

The mean of the simulated available soil water content during each phenological phase was selected most frequently as the factor related with high or low yields for both crops. The level of low yields = yields smaller than the 10th percentile of winter wheat was predominantly correlated with the mean simulated available soil water content in the first three phenological phases which comprised the beginning of sowing until the beginning of stem elongation, with correlation coefficients ranging from 0.34 in the first phenological phase to 0.47 in the second phenological phase. In later phenological phases, between the beginning of milk ripening and the beginning of yellow ripening, the mean vapor pressure deficit and the mean minimum temperature were correlated with low winter wheat yield. The correlation coefficients were 0.19 and 0.28. All correlations for winter wheat yields were positive.

For high winter wheat yields = yields greater than the 90th percentile, the first phenological phase, the beginning of sowing to beginning of emergence was relevant as factor being correlated with yield. The correlation coefficients ranged from 0.17 for the radiation sum to 0.29 for the mean simulated available soil water content during sowing and emergence. Temperature, radiation, vapor pressure deficit and simulated available soil water content during sowing and emergence were correlated with high winter wheat yields. The correlations were both negative for temperature and positive for the simulated available soil water content and radiation. A further abiotic factor that was correlated with winter wheat yield was the simulated available soil water content during the second phenological phase r = 0.27. In general slight differences were observed regarding correlations of abiotic factors with high and low winter wheat yield. While high yield correlations with abiotic factors were more likely to be observed at the beginning of the vegetation phase, low yield correlations with abiotic factors were observed both at the beginning and at the end of the vegetation phase.

Similar observations could be made between high maize yields and abiotic factors where correlations could be identified both at the beginning (beginning of sowing - beginning of emergence) and the end (beginning of milk ripening - beginning of dough ripening) of the vegetation period. All correlated factors were based on positive correlations related to high silage maize yields with correlation coefficients of r = 0.33 for the simulated available soil water content during the first phenological phase or r = 0.27 for the crop evapotranspiration and radiation sum during the last phenological phase.

Low silage maize yields were influenced by a number of factors. All phenological phases, were correlated with low yields. At the beginning of the vegetation phase, between the beginning of emergence and the beginning of tassel emergence, the level of simulated available soil water content was correlated with low yields from r = 0.33 to r = 0.45. In later vegetation phases, between the beginning of flowering and the beginning of milk ripening, low maize yields were correlated with the sum of precipitation r = 0.22 and the water balance r = 0.31. But also in earlier phases of the vegetation period, between the beginning of emergence and the beginning of tassel emergence, the water balance with r = 0.18 and r = 0.26 was correlated with yield. In the third phenological phase which corresponded to the beginning of stem elongation until the beginning of tassel emergence, precipitation was correlated with low maize yields with r = 0.41. The only negative correlation between an abiotic factor and low yield that was identified, was the radiation sum between the beginning of emergence and beginning of stem elongation with a correlation coefficent of r = -0.26.

4.3 Evaluation of optimal time intervals using statistical models

4.3.1 Modelling yields using time variable factors

To determine an adequate time interval for yield modelling, the mean RMSE of all counties from 1991 – 2015 are presented for the "calendar" and "phenology" methodology (Figures 19 - 22).

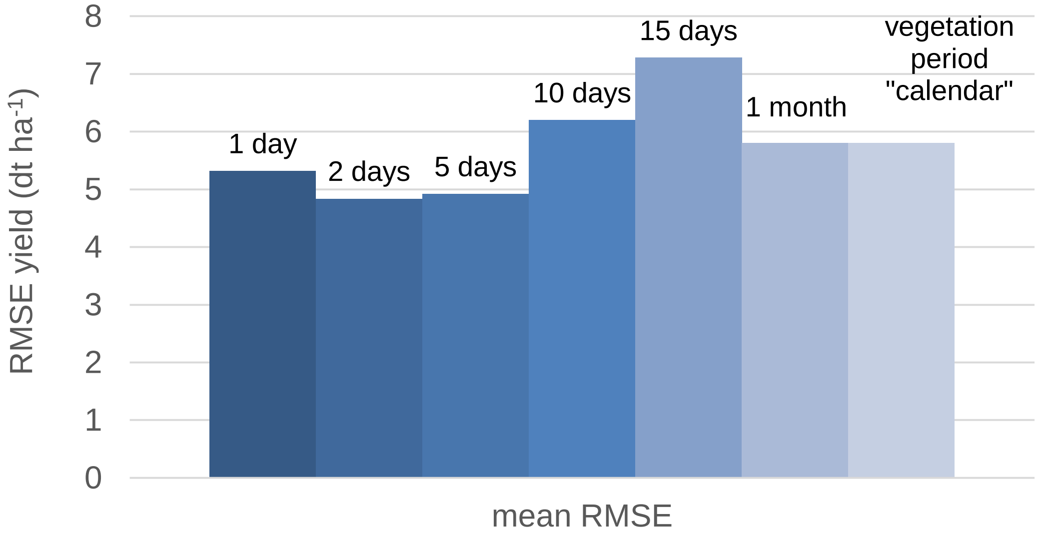


Figure 19: Mean RMSE´s of modeled wheat yields of all counties from 1991-2015 for different time aggregations using the “calendar” methodology.

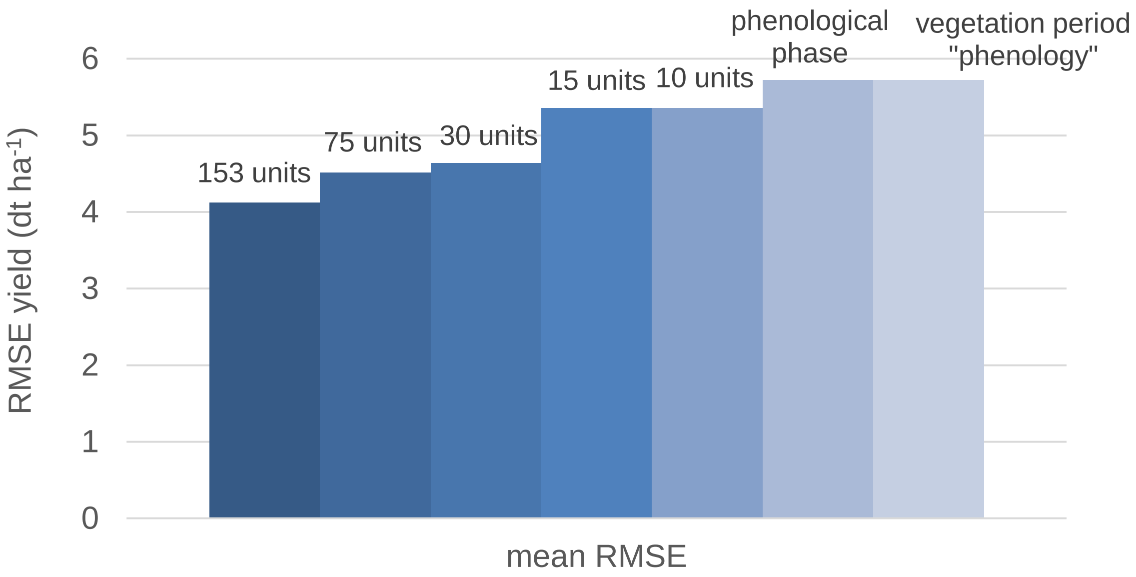


Figure 20: Mean RMSE´s of modeled wheat yields of all counties from 1991-2015 for different time aggregations using the “phenology” methodology.

Since vegetation periods can vary in duration from year to year, calculating the predictors using the same time periods would result in a different number of predictors per year. Therefore, the vegetation days of each year were divided into units of equal size with the aim of establishing the same number of predictors for each year. The units were formed out of a different number of days depending on the duration of the vegetation period of a year.

The differences between modelled wheat yields based on different time aggregations of the predictors were not significant for either method (alpha = 0.05). Only the time interval of 15 days used in the "calendar" methodology was significantly different and predicted yields with higher RMSE than other time aggregations. Meanwhile, no significant differences between winter wheat models were found when different vegetation periods were assumed (October to July vs. March to July). Moreover, the predictors aggregated on the basis of different time intervals did not reveal major differences in RMSE. For maize similar results were observed. There were no significant differences between modelled yields based on different time aggregations (alpha = 0.05).

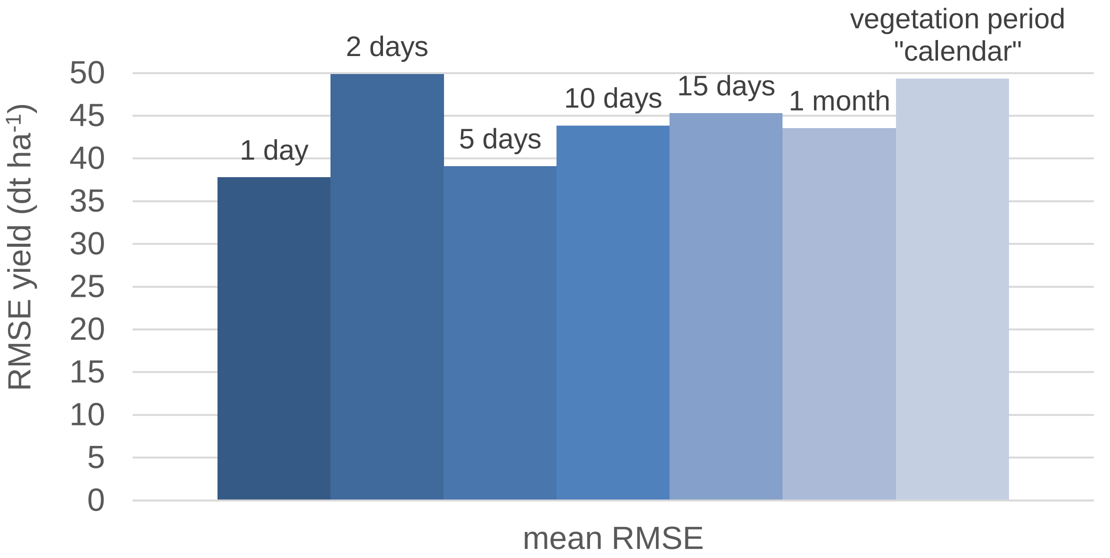


Figure 21: Mean RMSE´s of modeled maize yields of all counties from 1991-2015 for different time aggregations using the "calendar" methodology.

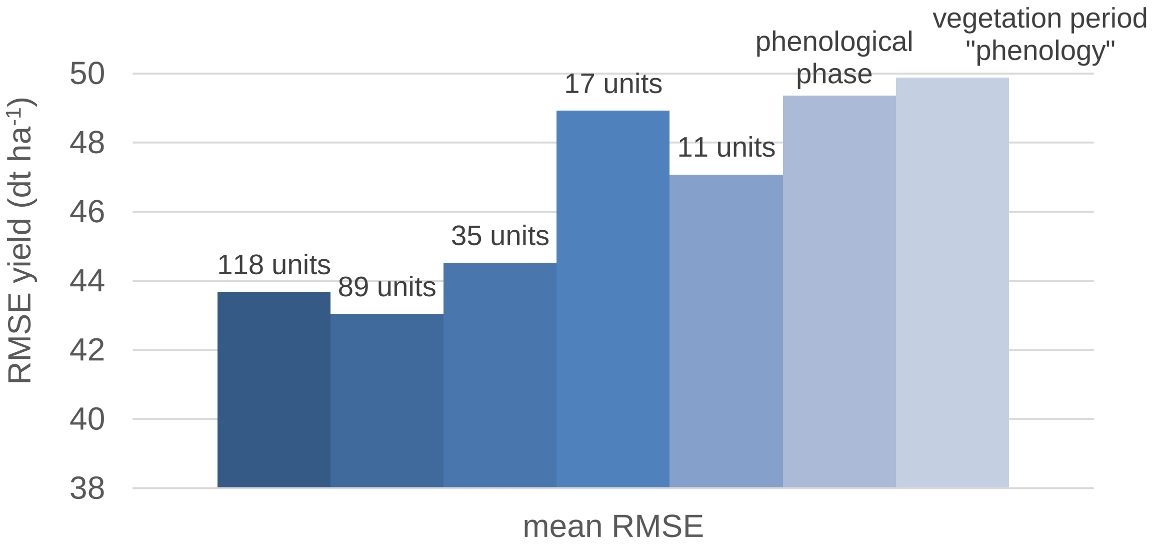


Figure 22: Mean RMSE´s of modeled maize yields of all counties from 1991-2015 for different time aggregations using the "phenology" methodology.

4.3.2 Differences between the methodologies "calendar" and "phenology" to predict yields

The purpose of this analysis was to test if the yield prediction performance of models was improved if the growing season was determined on the basis of actually observed phenological phases rather than on calendar days. Figures 23 and 24 show yield predictions for wheat and maize using two factors t_avg and simulated soil water as examples. Even though the two factors were not able to predict actual yields between 1991 and 2015, a comparison of the two methods "calendar" and "phenology" could be made. Neither method performed better than the other in predicting crop yields. However, as the calculation of the predictors using the "phenology" method was more complex, the "calendar" method was preferred for the further analysis.

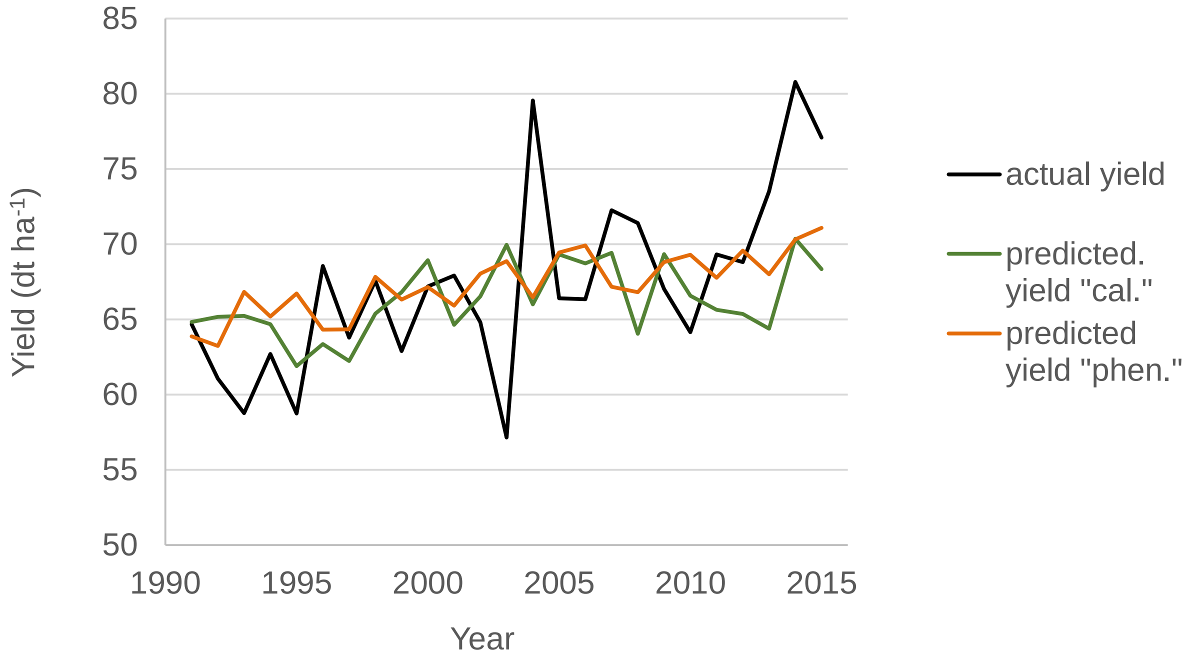


Figure 23: Average predicted and actual wheat yields from 1991-2015 over all time intervals and all counties using the “calendar” (cal) or “phenology” (phen) methodology.

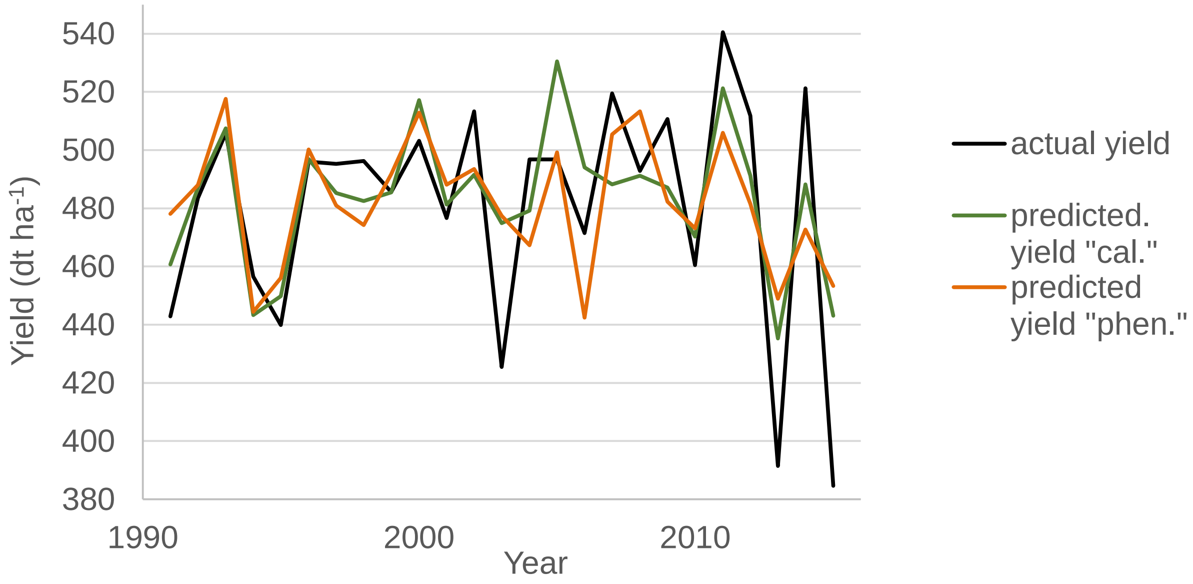


Figure 24: Average predicted and actual maize yields from 1991-2015 over all time intervals and all counties using the “calendar” (cal) or “phenology” (phen) methodology.

4.3.3 Time intervals and their ability to depict yield developments

To test whether certain time aggregations of factors could better reproduce the yield history in Bavaria between 1991 and 2015, all of the yield predictions based on the generated time intervals were compared with actual yields. Figures 25 - 32 illustrate the results using two time spans, 2 days or 75 units for winter wheat or 2 days and 89 units for silage maize, and one month or one phenological phase. Since phenological years can vary regarding the number of days, units were formed using the "phenology" method. To enable a comparison of the two methods, the phenological period was divided into units of equal size s in the "phenology" method. All results of the respective time intervals are presented in the appendix (Supplemental Figures section 4.3 D1 – D4). The predicted yields that included phenology deviated more from the actual yields than the predictions based on the calendar method. The yield development of both crops was fairly well described if months were taken into account as time intervals. For wheat yields the last years were better reproduced by the 2-day time interval than for the monthly values. In the case of monthly values the first years of yield developments were better reproduced. The yield development processes were not reproduced comparably well by all-time intervals. The monthly intervals seemed suitable for both crops.

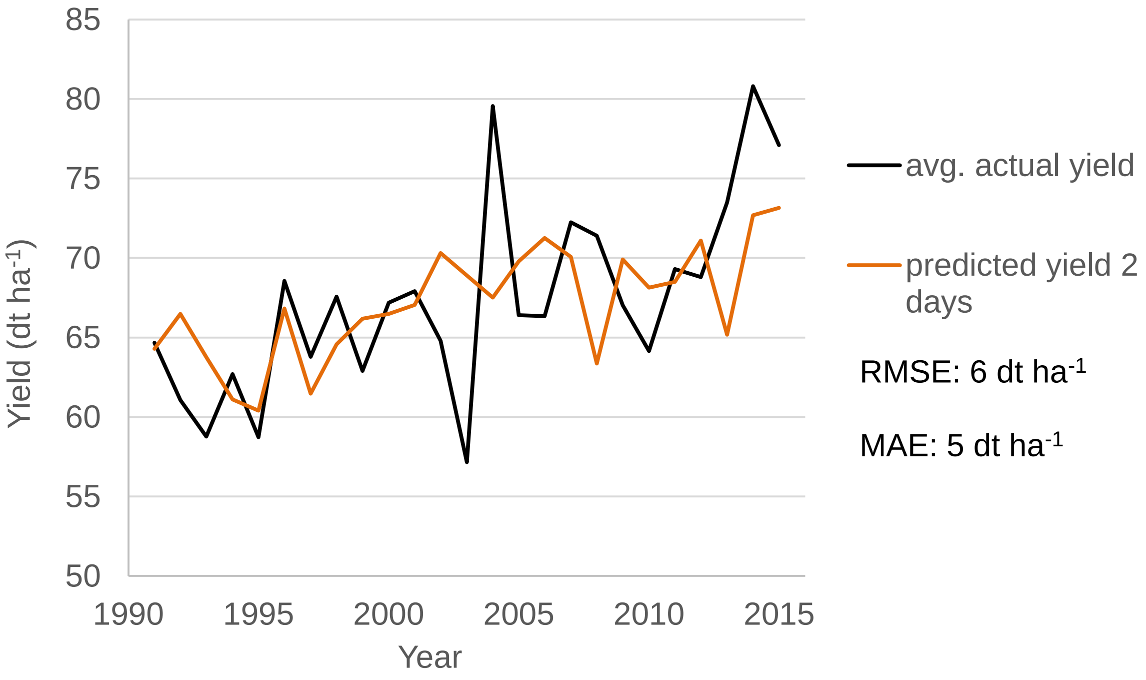


Figure 25: Mean yield vs. mean predicted yield of wheat for all counties from 1991-2015 based on a time interval of 2 days using the “calendar” method.

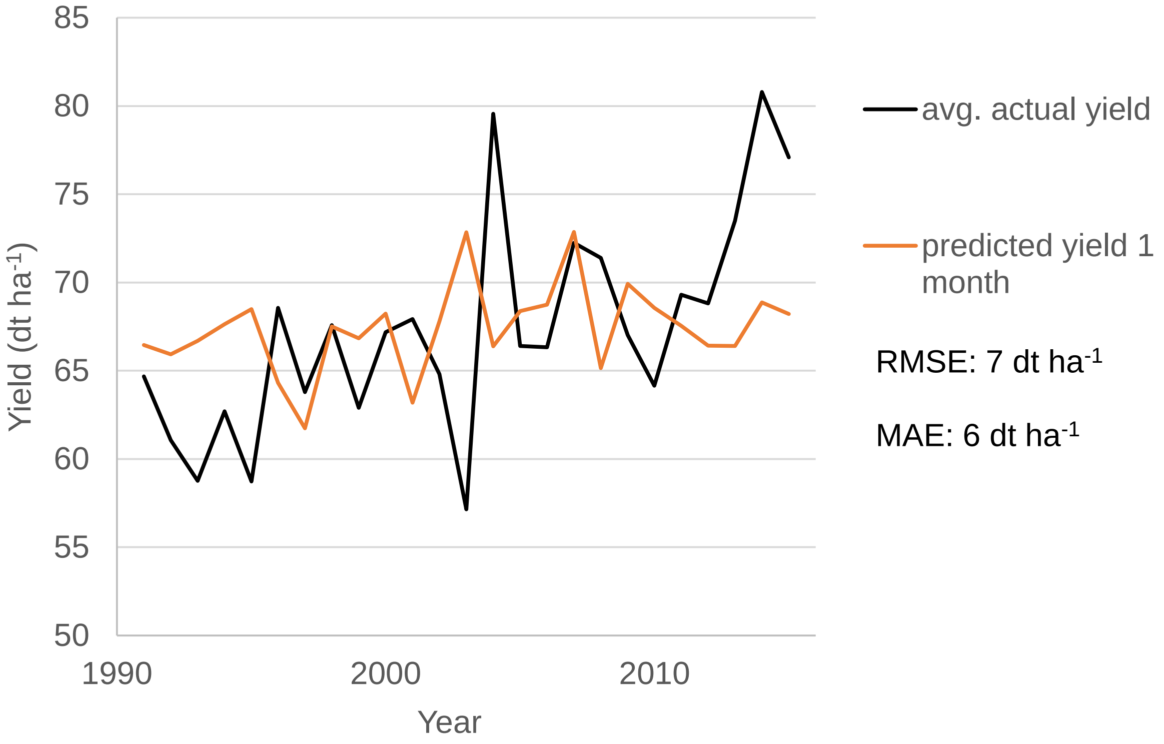


Figure 26: Mean yield vs. mean predicted yield of wheat for all counties from 1991-2015 based on a time interval of 1 month using the “calendar” method.

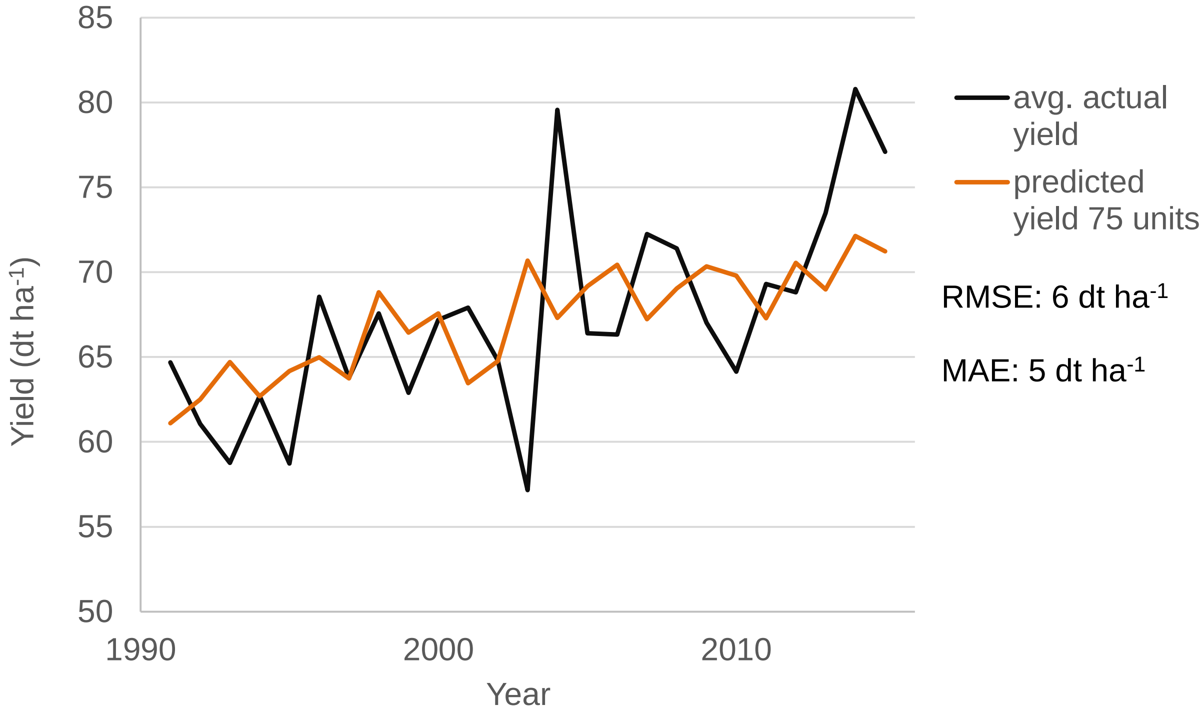


Figure 27: Mean yield vs. mean predicted yield of wheat for all counties from 1991-2015 based on 75 time units using the “phenology” method.

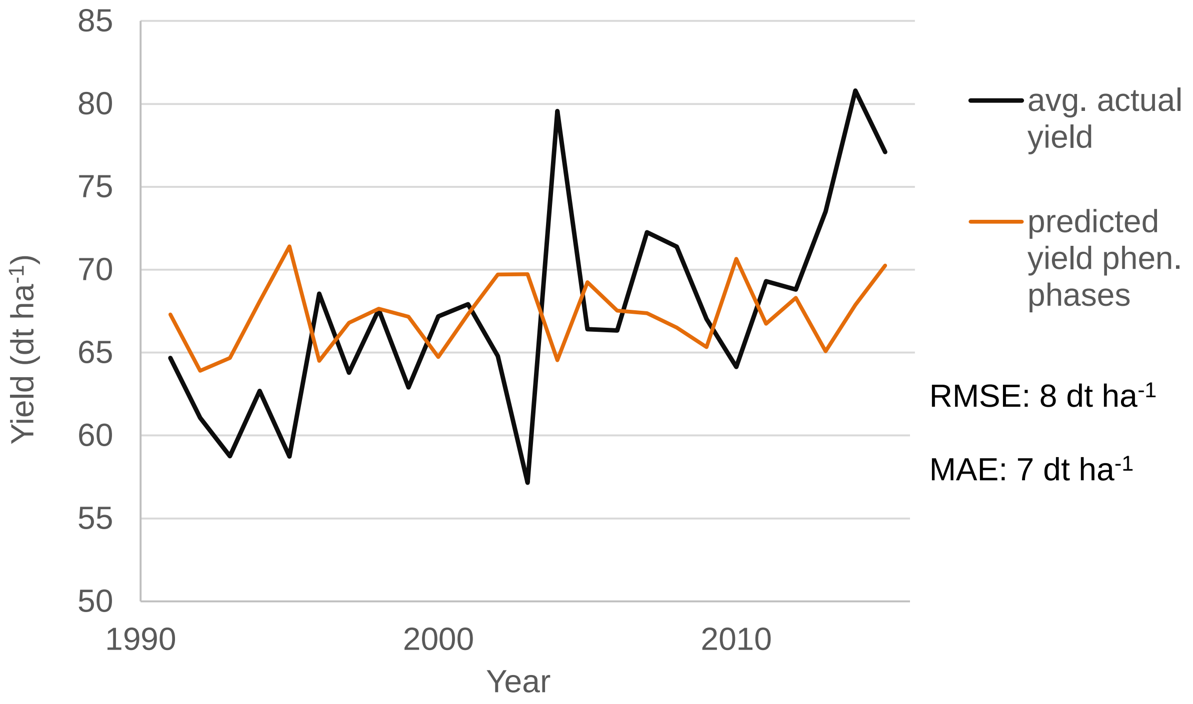


Figure 28: Mean yield vs. mean predicted yield of wheat for all counties from 1991-2015 based on phenological phases using the "phenology" method.

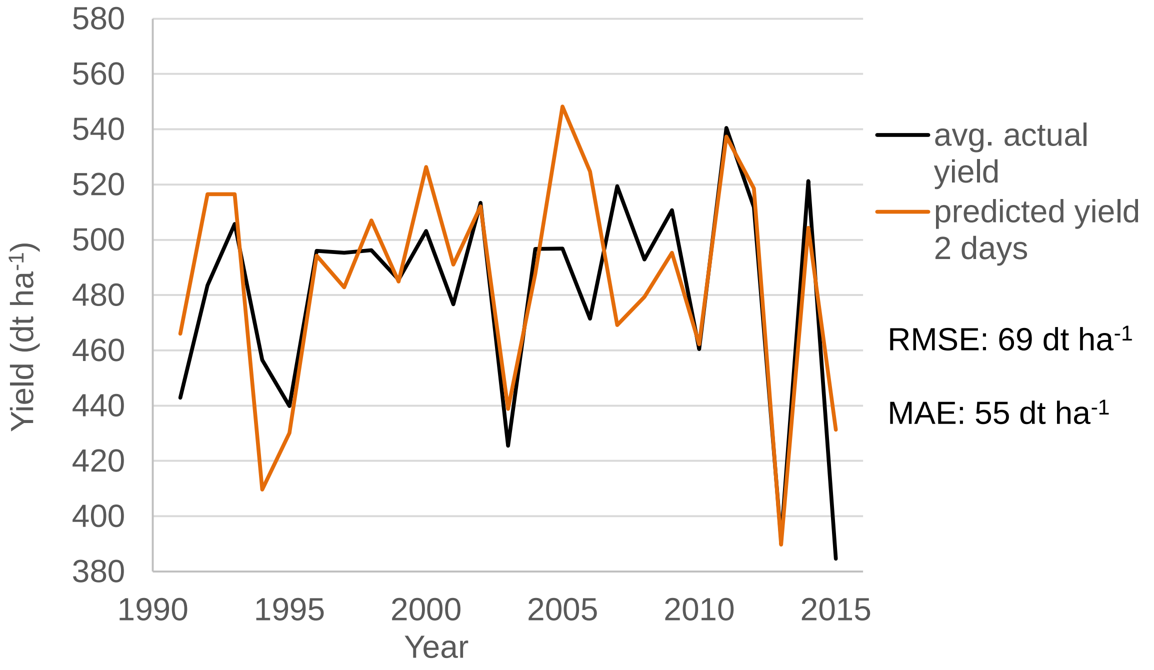


Figure 29: Mean yield vs. mean predicted yield of maize for all counties from 1991-2015 based on a time interval of 2 days using the "calendar" method.

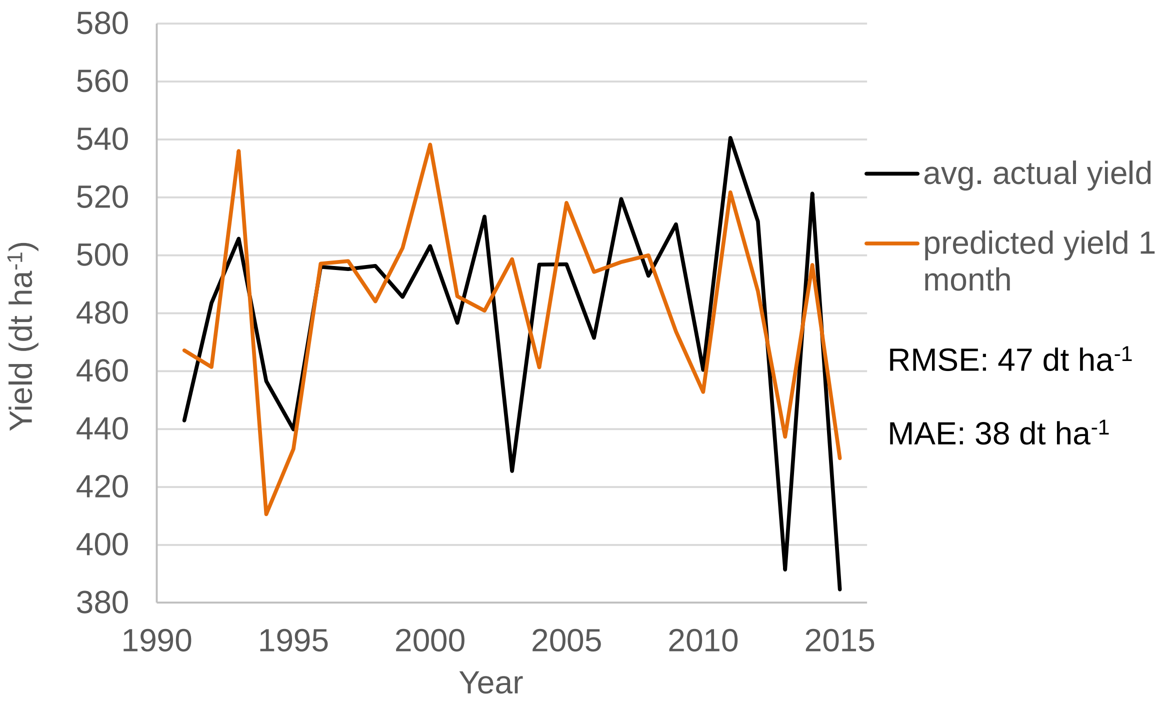


Figure 30: Mean yield vs. mean predicted yield of wheat for all counties from 1991-2015 based on a time interval of 1 month using the “calendar” method.

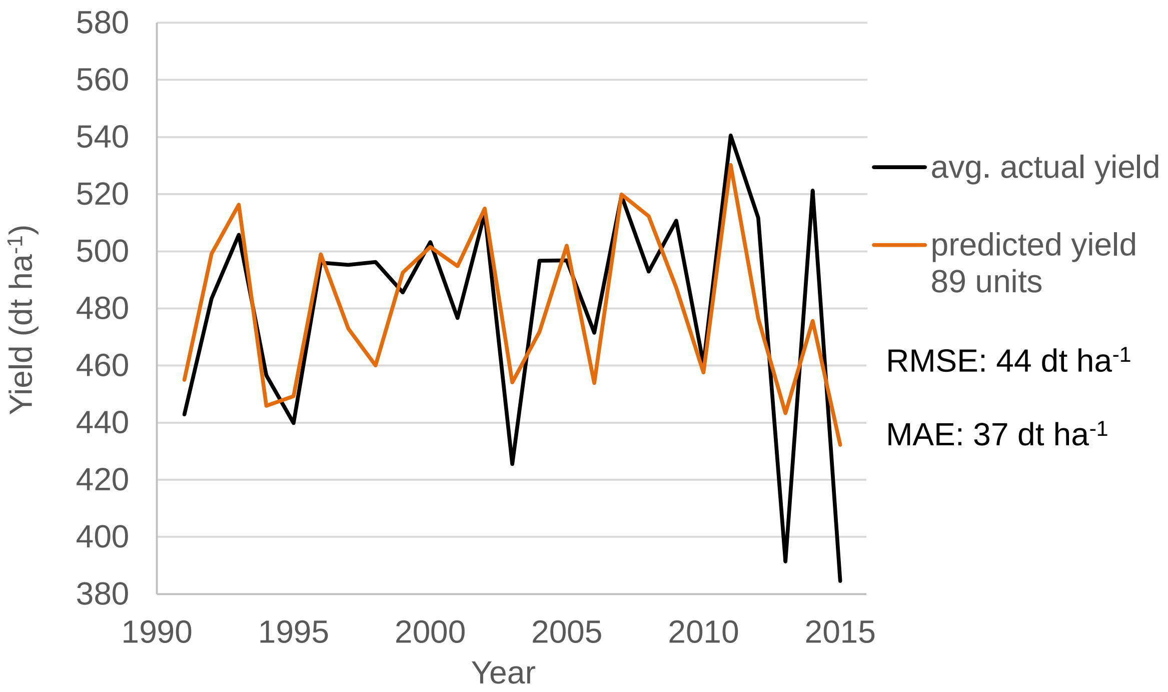


Figure 31: Mean yield vs. mean predicted yield of maize for all counties from 1991-2015 based on 89 time units using the “phenology” method.

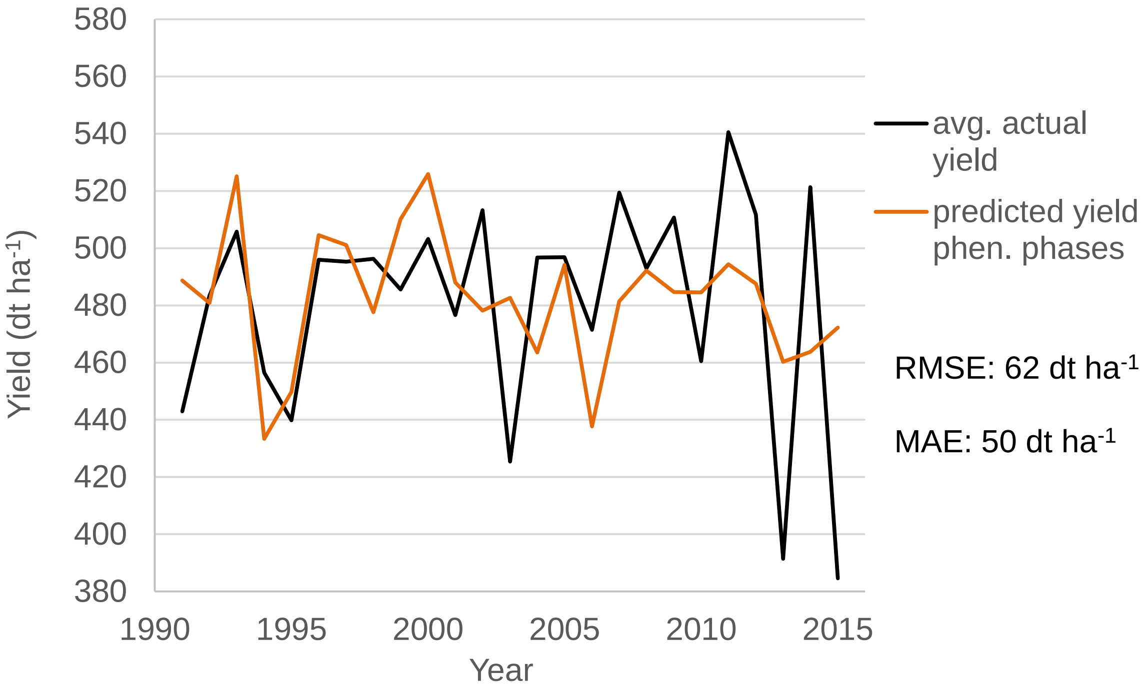


Figure 32: Mean yield vs. mean predicted yield of maize for all counties from 1991-2015 based on phenological phases using the “phenology” method.

4.4 Yield predictions of winter wheat and silage maize in Bavaria

4.4.1 Model performance, validation and evaluation

This section compares the results of different model validations using measured/interpolated weather and yield data from 1991-2015 to determine the model that best predicted yield. The model that best predicted yields and their variations was then used for yield predictions. The three parameters R^2, RMSE and NSE were used to assess the model quality.

4.4.1.1 Time-series model

The time-series model of winter wheat in the Bavarian Soil-Climate-Areas did not deliver satisfactory results. Although the R^2 was between 16% (*Moränenhügelland Voralpenland*) and 46% (*Odenwald Spessart*), the NSE was in a negative range, which means that the average of all yields in the Bavarian Soil-Climate-Areas between 1991 and 2015, will estimate yields better than an individual time-series model for each Soil-Climate-Area. However, it should be mentioned that this observation was not valid for all Soil-Climate-Areas and all years, as some predicted Soil-Climate-Areas and years also had positive NSE coefficients for both wheat and maize (Table 16). Similiar observations were obtained for silage maize. The R^2 varied between 14% (*Gäu Donau und Inntal sowie Tertiärhügelland*

Donau Süd) and 63% (*Nordwestbayern Franken*). The NSE was also in a negative range for silage maize. The same observations were made for time-series models at the county level. Here, too, the NSE was on average negative for both crops. In summary, no satisfactory yield predictions could be made with time-series models for both crops in the study areas during the whole considered period (1991 – 2015).

Table 16: Examples of annual yield predictions for Soil-Climate-Areas using time-series models for wheat and maize.

Crop	Soil-Climate-Area	Year	Yield (dt ha^{-1})	Predicted yield (dt ha^{-1})	R²	RMSE (dt ha^{-1})	Correlation coefficient	MAE (dt ha^{-1})	NSE
Wheat	*Albflächen Ostbay. Hügelland*	1994	60.11	57.29	0.61	5	0.78	4	0.05
Wheat	*Gäu Donau und Inntal*	2012	63.09	62.78	0.79	2	0.89	2	0.61
Wheat	*Gäu Donau und Inntal*	1995	61.21	67.37	0.13	6	0.36	6	- 4.01
Maize	*Albflächen Ostbay. Hügelland*	2006	478.6	473.83	0.88	20	0.94	18	0.81
Maize	*Nordwestbayern Franken*	2009	462.1	437.37	0.23	46	0.48	36	- 0.21
Maize	*Tertiärhügelland Donau Süd*	1991	509.7	493.54	0.09	68	-0.3	53	- 1.22

4.4.1.2 Panel model

The validation of the panel model for winter wheat of all Soil-Climate-Areas showed an average R² of 0.74, an NSE of 0.72 and a RMSE of 2.8 dt ha^{-1}. For silage maize the average values were R² = 0.66, RMSE 30.8 dt ha^{-1} and NSE 0.6. Figure 33 andFigure *34:* show the detrended and predicted yields as well as the model quality (R², RMSE, NSE) of both crops for the Soil-Climate-Area *Albflächen Ostbayerisches Hügelland*. The model quality of the individual Soil-Climate-Areas is given Tables 17 and 18 and did not show large differences among Soil-Climate-Areas. Yields and their volatility could be predicted better for winter wheat than for silage maize since the NSE as well as the R² of winter wheat was higher than for silage maize. The predicted yields of both models did not systematically over- or underestimate the actual yields, as the predictions were both above as well as below the actual yield.

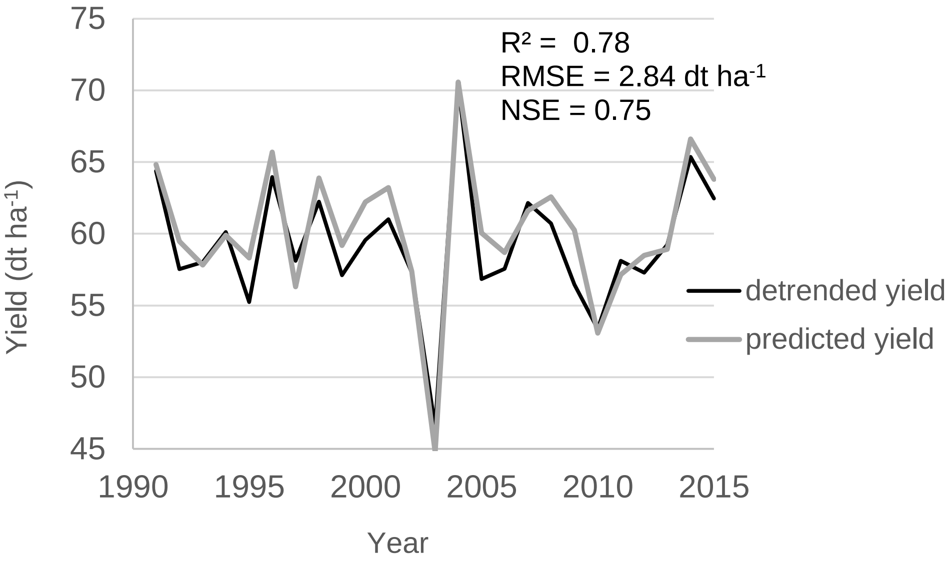


Figure 33: Panel model results of detrended and predicted yields for winter wheat in *Albflächen Ostbayerisches Hügelland* from 1991-2015.

Table 17: Panel model results for winter wheat (RMSE is in dt ha^{-1}, values of Soil-Climate-Areas are means from 1991-2015).

Soil-Climate-Area	R²	RMSE	NSE
Albflächen Ostbayerisches Hügelland	0.78	2.8	0.75
Gäu Donau und Inntal	0.77	2.9	0.75
Moränen Hügelland Voralpenland	0.75	2.8	0.74
Nordwestbayern Franken	0.80	2.6	0.78
Odenwald Spessart	0.78	2.8	0.76
Tertiärhügelland Donau Süd	0.78	2.8	0.76
Verwitterungsböden in den Höhenlagen	0.78	2.8	0.76
Verwitterungsböden in den Übergangslagen	0.77	2.8	0.75

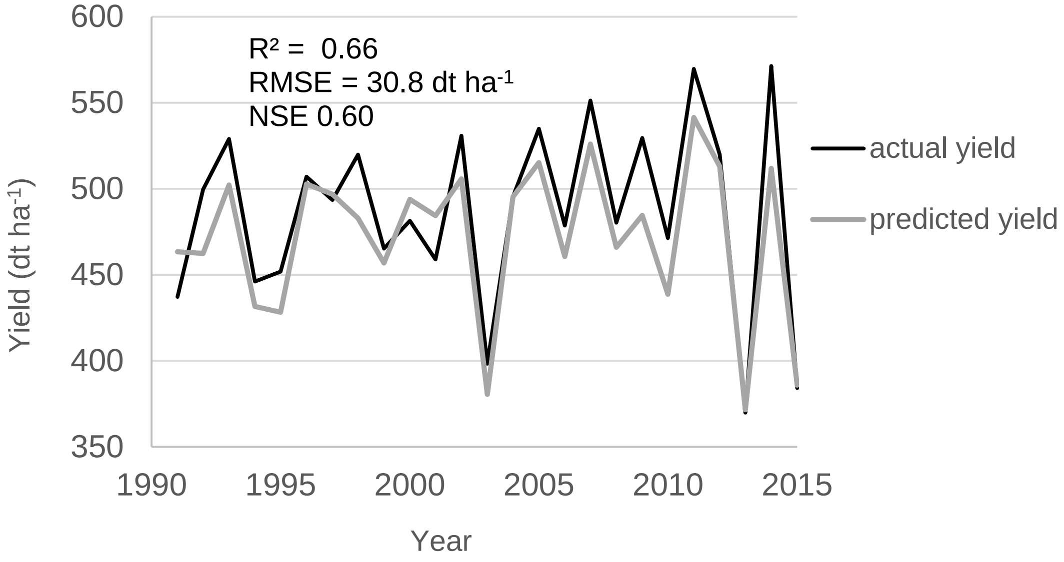


Figure 34: Panel model results of detrended and predicted yields for silage maize in *Albflächen Ostbayerisches Hügelland* from 1991-2015.

Table 18: Panel model results for silage maize (RMSE is in dt ha^{-1}, values of Soil-Climate-Areas are means from 1991-2015).

Soil-Climate-Area	R²	RMSE	NSE
Albflächen Ostbayerisches Hügelland	0.66	30.8	0.60
Gäu Donau und Inntal	0.66	31.1	0.61
Moränen Hügelland Voralpenland	0.63	30.2	0.57
Nordwestbayern Franken	0.66	31.0	0.60
Odenwald Spessart	0.67	30.8	0.64
Tertiärhügelland Donau Süd	0.67	31.1	0.62
Verwitterungsböden in den Höhenlagen	0.64	30.6	0.57
Verwitterungsböden in den Übergangslagen	0.65	30.8	0.58

The validation of the panel model of all counties showed on average an R²-value of 0.62 for winter wheat, an RMSE of 4 dt ha^{-1} and an NSE of 0.61. The model quality between the counties did not differ much. The R² of individual counties varied from 0.61 in *Kulmbach* to 0.62 in *Dingolfing-Landau*. The prediction error of the wheat panel model for yields from 1991-2015 within the counties was 4 dt ha^{-1}. The NSE was between 0.60 in *Kulmbach* and 0.62 in *Dingolfing-Landau*. The validation of the panel model of all counties for silage maize delivered on average R² and NSE both of 0.66 and an RMSE of 30.4 dt ha^{-1}. The model quality between the counties varied even less here. The R² reached values from 0.65 in *Pfaffenhofen* to 0.67 in *Kelheim*, the RMSE was between 29.9 dt ha^{-1} in *Passau* and 30.9 dt ha^{-1} in *Rottal-Inn*. The NSE ranged between 0.64 in *Pfaffenhofen* and 0.67 in *Neuburg-Schrobenhausen*.

Generally it was possible to calculate reliable yield predictions for both crops at both spatial aggregation levels throughout the investigated time period using panel models. Yet, in terms of the results of the panel models for the two spatial levels of aggregation that are the subject of this thesis, the calculated yield predictions for the Soil-Climate-Areas were generally more precise than the yields calculated for the counties and this for both crops. The differences between the results in the yield prediction of the two spatial levels of aggregation, Soil-Climate-Areas and counties, were higher for winter wheat than for silage maize.

4.4.1.3 Cross-sectional model

Tables 19 and 20 show the results of the cross-sectional models for both crops.

Table 19: Cross-sectional model results for winter wheat (yields and RMSE are in dt ha^{-1}, values of Soil-Climate-Areas are means from 1991-2015).

Soil-Climate-Area	Detrended Yield	Predicted Yield	R²	RMSE	NSE
Albflächen Ostbayerisches Hügelland	59.2	59.3	0.92	0	0.84
Gäu Donau und Inntal	65.4	66.7	0.88	1	0.84
Moränen Hügelland Voralpenland	59.2	59.5	0.92	0	0.84
Nordwestbayern Franken	58.9	57.2	0.96	2	0.84
Odenwald Spessart	59.7	61.2	0.95	1	0.84
Tertiärhügelland Donau Süd	63.6	62.5	0.93	1	0.84
Verwitterungsböden in den Höhenlagen	55.2	56.7	0.91	2	0.84
Verwitterungsböden in den Übergangslagen	59.7	59.0	0.93	1	0.84
Mean	**60.1**	**60.3**	**0.9**	**1**	**0.84**

Table 20: Cross-sectional model results for silage maize (yields and RMSE are in dt ha^{-1}, values of Soil-Climate-Areas are means from 1991-2015).

Soil-Climate-Area	Yield	Predicted Yield	R²	RMSE	NSE
Albflächen Ostbayerisches Hügelland	487.0	469.8	0.68	11.1	0.68
Gäu Donau und Inntal	500.7	495.1	0.70	10.9	0.70
Moränen Hügelland Voralpenland	501.2	509.4	0.69	11.0	0.69
Nordwestbayern Franken	442.0	464.2	0.68	11.6	0.68
Odenwald Spessart	471.3	469.7	0.70	10.9	0.70
Tertiärhügelland Donau Süd	496.7	491.3	0.70	10.9	0.70
Verwitterungsböden in den Höhenlagen	465.3	463.3	0.70	10.9	0.70
Verwitterungsböden in den Übergangslagen	463.2	464.7	0.70	10.9	0.70
Mean	**478.4**	**478.4**	**0.69**	**11.00**	**0.69**

The average yields for winter wheat were very well predicted by the cross-sectional models. The cross-sectional model estimated a maximum error of 2 dt ha^{-1} (RMSE = 2). The model quality was also very good with NSE = 0.84. The yield variability could also be reproduced very well with R² = 0.93. The differences between the Soil-Climate-Areas with regard to the values R², RMSE and NSE were very small. For silage maize, on the other hand, a different result was obtained. On average the yield variations were reproduced less effectively than for winter wheat, but still well with R² = 0.69. The differences between the Soil-Climate-Areas with regard to the RMSEs as well as with regard to the R² were not larger than for winter wheat. The lowest R² of 0.68 was observed in *Nordwestbayern Franken*, the highest with 0.70 in five Soil-Climate-Areas. On average, the predicted yields deviated by 11 dt ha^{-1} and 2.3% from the actual yields, whereas variations of -22,2 dt ha^{-1} and -5% in *Nordwestbayern Franken* up to 17.2 dt ha^{-1} and 3.5% in *Albflächen Ostbayerisches Hügellamd* were observed between the predicted yields and the mean yields of all Soil-Climate-Areas between 1991 and 2015. The model quality with an NSE of 0.69 is regarded as satisfactory (Moriasi et al., 2007). Therefore, the cross-section model was suitable for predicting silage maize and wheat yields for Soil-Climate-Areas. Significant predictors for estimating yields were the available soil water content and precipitation for wheat, for maize only the available soil water content was significant at $p < 0.05$.

A different result was observed regarding the spatial aggregation on the county level. The R² for winter wheat yields was on average 0.48, similar like the NSE, wheareas the RMSE was 4 dt ha^{-1}. Due to the poor model quality (low NSE) of the cross-section model of winter wheat, a calculation of a separate model was regarded as not suitable. Similar results were observed for maize. Here too, the calculation of a cross-section model was regarded as not suitable. The mean NSE and R² were both 0.43, the average RMSE of the model was 16 dt ha^{-1}. Significant predictors at the minimum significance level of $p < 0.05$ were the sum of radiation and the average amount of available soil water content whereas for maize yields the radiation sum and the maximum temperature were identified as significant factors ($p < 0.05$).

4.4.1.4 Panel models for high, low and average yields

A prediction of low yield years being as accurate as possible is of particular interest. For this reason, the prediction ability of three different panel models was evaluated by calculating one panel model for high, low and medium yield years. For each Soil-Climate Area, yields between 1991 and 2015 that were below the 10th percentile were classified as low. This resulted in 25 Soil-Climate-Area/year combinations for each panel model of low/high yields. The average panel model was calculated from the remaining Soil-Climate-Area/year yield combinations = 200. The same methodology was used for the county/year combinations. Here, 180 county/year combinations each for high and low yield years, as well as 1140 county/year combinations for average yield years were selected. The NSE for low yield years of the Soil-Climate-Areas was negative for both crops with winter wheat NSE = -0.1 and silage maize NSE = -1). This means that the model predicted low yields worse than the calculation of an arithmetic mean out of all yields using this model. Therefore, the usage of a separate model to predict low yield years more accurately is not recommendable. Similar results were observed for the counties models. Although county level modelling was possible, the predictions of the whole panel model were better than one separate model for high, low and average yield years because the model had a higher NSE, except for the average winter wheat model. An overview of model qualities are presented by Tables 21 and 22.

Table 21: Model quality for different winter wheat county models.

Panel model	R²	RMSE (dt ha^{-1})	NSE
high yields	0.58	4	0.54
low yields	0.4	3.8	0.34
average yields	0.63	3.6	0.63
all yields	0.62	4	0.62

Table 22: Model quality for different silage maize county models.

Panel model	R²	RMSE (dt ha^{-1})	NSE
high yields	0.23	22.8	0.1
low yields	0.61	23.6	0.56
average yields	0.42	27	0.4
all yields	0.66	30.4	0.66

4.4.1.5 Statistical tests

The statistical tests revealed that the model residuals were normally distributed, the test for autocorrelation differed depending on the study area. No autocorrelation was observed in the Soil-Climate-Areas, whereas autocorrelation was present in the counties. The same can be said for heteroscedasticity, it was present in the counties, not in the Soil-Climate-Areas. For both heteroscedascidity and autocorrelated data, the estimated parameters were inefficient for the counties, so new parameters considered for heteroscedasticty and autocorrelation were estimated. For this purpose, the "vcovHAC" function from the package "sandwich" of the statistical software RStudio was used. The newly estimated parameters were used for yield predictions for wheat and maize at the county level. For the test of multicollinearity the squared predictors were excluded. Thus only minor dependencies between the predictors were observed.

4.4.2 Selected variables for yield predictions

The abiotic factors which used for yield predictions in Bavaria were the mean maximum temperature = t_max, the mean simulated available soil water content = SW, the sum of radiation = Rad_sum and the mean vapor pressure deficit = VPD, as well as their squared terms. For winter wheat a further predictor was added, the mean minimum temperature = t_min. Nevertheless, only those monthly aggregated predictors that were identified as significant, using a stepwise regression technique for each model separately, were incorporated into the calculation of the individual panel models. The numbers behind each predictor indicated the month e.g. VPD7 = average vapor pressure deficit in July which exerted a statistical significanct influence on yield levels in Bavaria. The individual variables/predictors used to calculate panel models for both crops and both spatial aggregation levels with their values of Beta, standard error, level of significance and standardized β coefficients are presented in Tables 23 - 26 while the number behind each variable indicates the average or sum of that variable per month e.g. 5 = May, 6 = June etc, whereas the calculation method average or sum was variable dependent. The standardized β coefficients values show the relative contribution of each independent variable in the prediction of the yield levels. The standardized β coefficients thus also provide information on how strong the influence of one predictor on yield was compared to other predictors used in the model for yield predictions, while the standard error reflects the degree of uncertainty for getting a reliable estimate of a variables influence on yields. Statistical significance is indicated by the p-value, whereas * indicates a statistical significance of $p < 0.05$, ** $p < 0.01$ and *** indicates $p < 0.001$. The regression coefficient refer to the unstandardized regression coefficients or weights, which were included in the regression equation. The +/- sign in front of the regression coefficient or the standardized β coefficient show whether the influence of this predictor on yield levels was negative or positive.

Table 23: Coefficients and the significance of variables (predictors) using a stepwise regression technique withinin the panel model calculated for the Soil-Climate-Areas' wheat yields from 1991-2015.

Variables	Regression coefficient	Standard Error	Significance	Standard. β coefficients
Intercept	-112.30	33.50	***	
$(Rad\_sum3)^2$	-4.86^{-10}	3.99^{-11}	***	-0.93
$(Rad\_sum4)^2$	7.41^{-11}	1.39^{-11}	***	0.60
$(Rad\_sum6)^2$	-2.91^{-10}	8.31^{-11}	**	-2.86
$(Rad\_sum7)^2$	-2.59^{-10}	5.86^{-11}	***	-3.38
$(SW4)^2$	-3.72^{-4}	1.44^{-4}	*	-0.26
$(t\_max5)^2$	-0.12	0.01	***	-1.69
$(t\_min5)^2$	0.12	0.03	***	0.39
$(VPD5)^2$	-118.10	19.49	***	-1.79
$(VPD6)^2$	-22.89	7.29	***	-0.43
$(VPD7)^2$	23.29	5.49	***	0.61
Rad_sum6	3.82^{-4}	9.66^{-5}	***	3.18
Rad_sum7	2.74^{-4}	6.66^{-5}	***	2.96
SW3	0.35	0.04	***	1.03
SW7	-0.07	0.01	***	-0.26
t_max3	2.16	0.49	***	0.86
t_min3	-2.34	0.56	***	-0.69
t_min4	2.29	0.25	***	0.52
t_min7	-9.56	0.44	***	-0.77
VPD3	63.13	11.53	***	0.57
VPD4	-64.15	9.94	***	-0.90
VPD5	140.70	18.38	***	2.64

Table 24: Coefficients and the significance of variables (predictors) using a stepwise regression technique within the panel model calculated for the Soil-Climate-Areas' maize yields from 1991-2015.

Variables	Regression coefficient	Standard Error	Significance	Standard. β coefficients
Intercept	-133.80	101.50	*	
t_max6	66.60	11.31	***	2.66
t_max8	-5.59	1.26	***	-0.25
(t_max4)²	-1.86	0.35	***	-2.48
(Rad_sum10)²	1.56^{-9}	7.43^{-10}	*	0.18
(SW6)²	-0.01	1.67^{-3}	***	-0.56
(SW8)²	0.01	1.57^{-3}	***	0.31
Rad_sum5	2.12^{-4}	5.32^{-5}	***	0.26
SW10	0.58	0.25	*	0.20
SW4	0.69	0.18	***	0.24
SW6	0.57	0.25	*	0.40
SW9	-1.12	0.34	**	-0.38
VPD7	-212.1	19.94	***	-0.53

The number of predictors used for yield predictions of the Soil-Climate-Areas were greater for wheat (21 variables in Table 23) than for maize (12 variables in Table 24). The yield level of winter wheat was slightly more influenced by negative factors than by positive ones with eleven predictors with a negative sign vs. ten predictors with a positive sign. For maize, a total of twelve predictors, five negative and seven positive, were identified as statistically significant for yield prediction whereby these predictors influenced yields more often positive than negative. However, the degree of influence of the predictors on yield levels differed. The standardized β coefficients in Tables 23 – 26 contain information about the degree of influence of a predictor on yield levels for both crops and both spatial aggregation levels. The higher the value of a predictor, the greater its influence on the yield level and vice versa. Therefore, the factor that exerted the strongest positive influence on wheat yield in Soil-Climate-Areas was the VPD in May, whereas the most negative impact was exerted by too high radiation in July (Table 23). For silage maize the maximum temperature in June was identified as the predictor with the strongest impact on yield in Soil-Climate-Areas (Table 24). If the temperature was too high in June, the response of maize yields was negative, but a certain amount, probably up to a certain threshold, of maximum temperature in June was needed to reach higher yields.

At county level more predictors were identified as statistically significant for the purpose of yield predictions than at the Soil-Climate-Area-level with 28 significant predictors for wheat (Table 25) and 30 signifcant predictors for maize (Table 26). The number of predictors that exerted negative or positive effects on yields at the county level was quite balanced for wheat with 15 positive predictors and 13 negative, whereas for maize the number of predictors that positively influenced yield levels was more frequently identified as statistically significant with 17 positive and 13 negative. The predictors that showed the strongest positive influence on yields were the average maximum temperature in July for wheat and August for maize. However, this effect changed if the temperature was too high, as indicated by the predictors that had the most negative impact on yields. These were the squared maximum temperature in July for wheat and in August for maize.

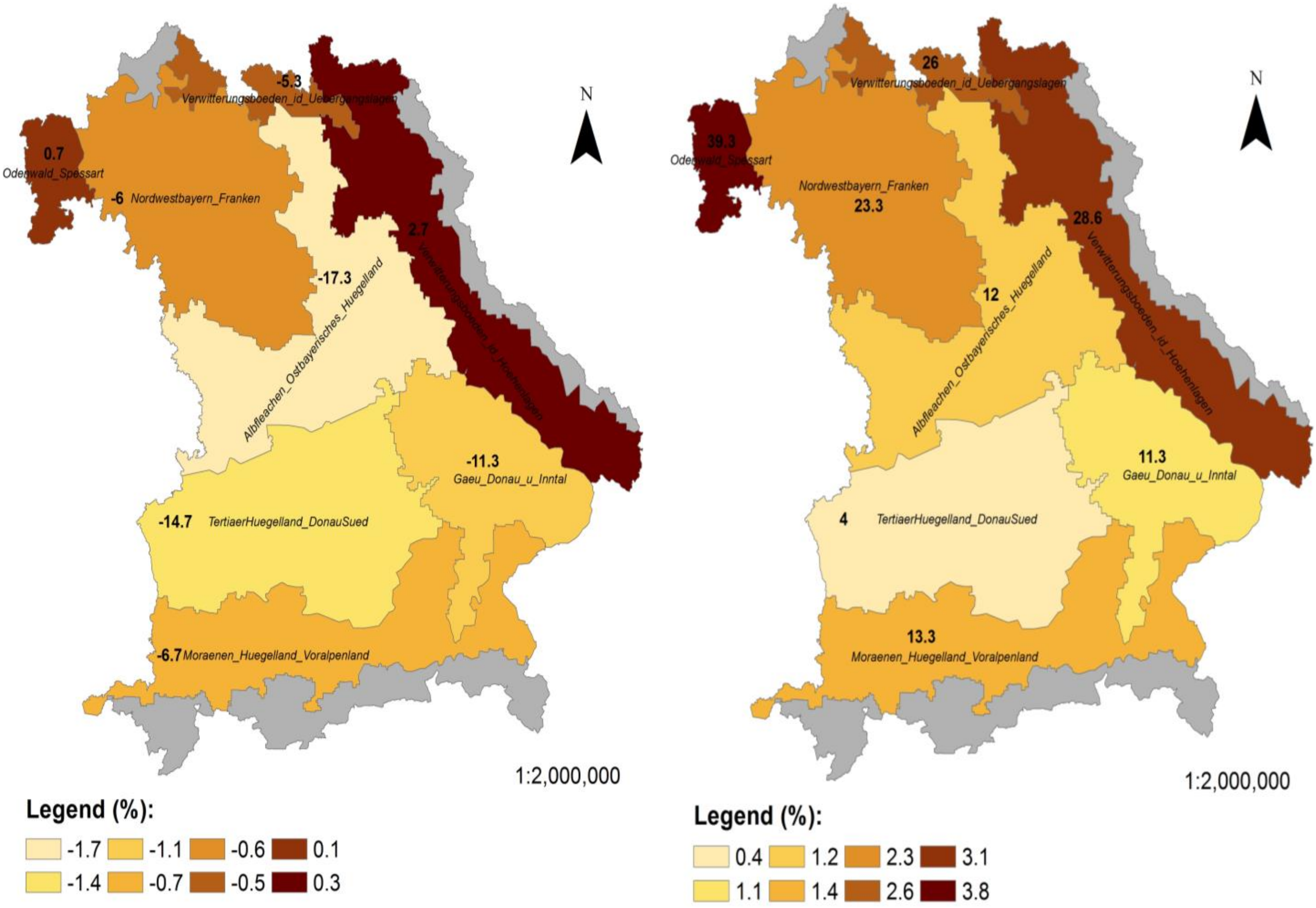
Table 25: Coefficients and the significance of variables (predictors) using a stepwise regression technique within the panel model calculated for the counties' wheat yields from 1991 – 2015.

Variables	Regression coefficient	Standard Error	Significance	Standard. β coefficients
Intercept	-134.80	2.46^{1}	***	
t_max3	-3.46	5.87^{-1}	***	-1.16
t_max4	4.21	8.37^{-1}	***	1.34
t_max5	5.85	1.12	***	1.84
t_max6	9.46	1.22	***	2.67
t_max7	9.77	1.46	***	3.27
t_min3	0.98	2.97^{-1}	***	0.25
t_min6	1.41	3.16^{-1}	***	0.26
$(t\_max3)^2$	0.18	3.08^{-2}	***	1.09
$(t\_max4)^2$	-0.11	2.72^{-2}	***	-1.11
$(t\_max5)^2$	-0.12	3.19^{-2}	***	-1.41
$(t\_max6)^2$	-0.23	2.65^{-2}	***	-2.98
$(t\_max7)^2$	-0.21	3.02^{-2}	***	-3.52
$(t\_min3)^2$	-0.26	4.57^{-2}	***	-0.16
$(t\_min5)^2$	-0.08	1.65^{-2}	***	-0.24
$(Rad\_sum3)^2$	3.99^{-10}	8.26^{-11}	***	1.39
$(Rad\_sum5)^2$	1.58^{-10}	3.00^{-11}	***	1.64
$(Rad\_sum7)^2$	1.70^{-10}	3.21^{-11}	***	2.05
$(SW3)^2$	1.08^{-3}	2.36^{-4}	***	1.16
$(SW4)^2$	-6.48^{-4}	1.40^{-4}	***	-0.69
$(SW7)^2$	-2.16^{-4}	6.18^{-5}	***	-0.07
$(VPD3)^2$	1.01	4.84^{-1}	*	0.04
Rad_sum3	-2.03^{-4}	4.78^{-5}	***	-1.18
Rad_sum5	-1.92^{-4}	3.16^{-5}	***	-1.85
Rad_sum6	2.32^{-5}	7.07^{-6}	**	0.20
Rad_sum7	-1.52^{-4}	3.80^{-5}	***	-1.51
SW3	-0.21	6.41^{-2}	**	-0.84
SW4	0.1	3.15^{-2}	**	0.51
SW5	0.05	9.25^{-3}	***	0.28

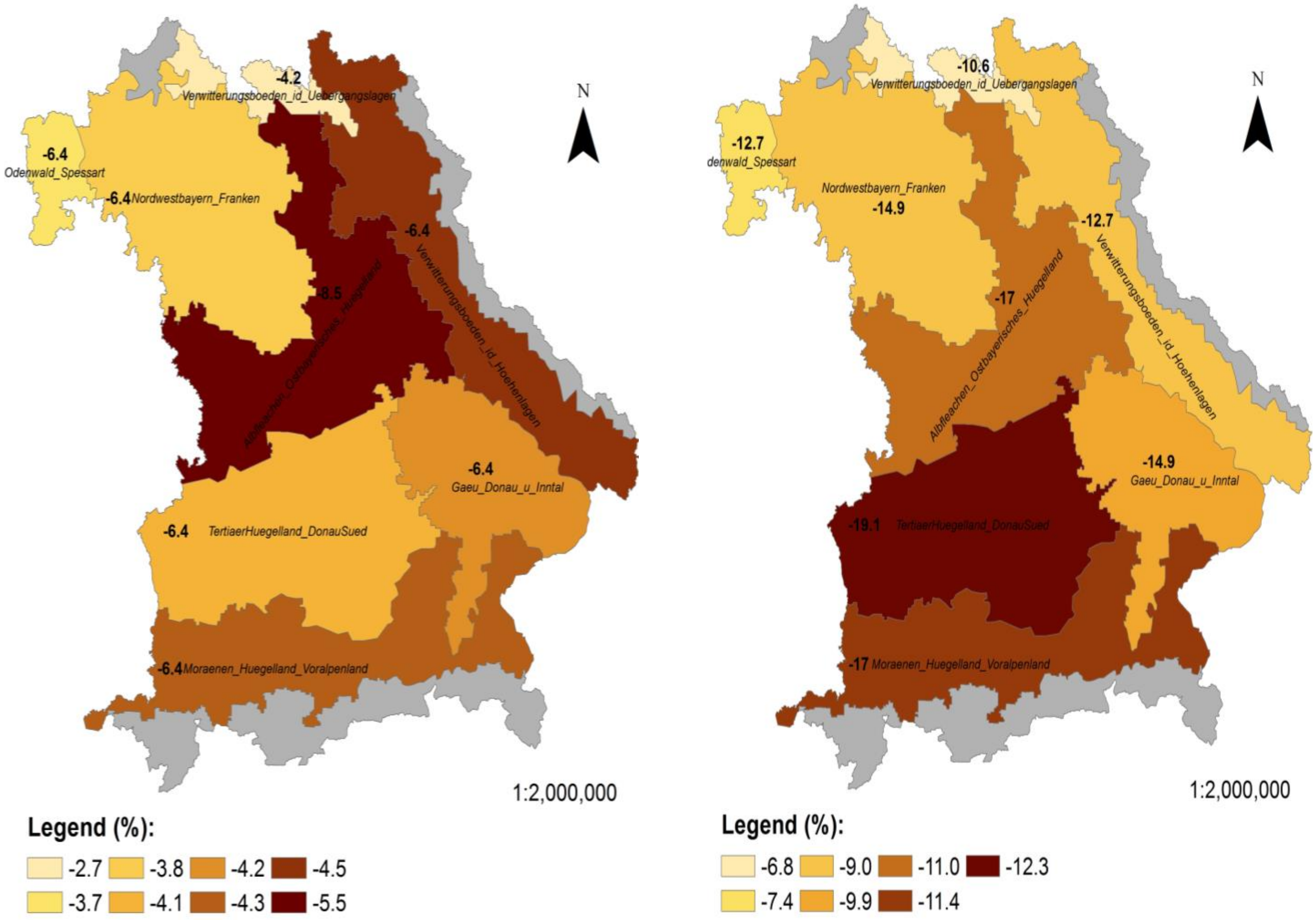
Table 26: Coefficients and the significance of variables (predictors) using a stepwise regression technique within the panel model calculated for the counties' maize yields from 1991-2015.

Variables	Beta	Standard Error	Significance	Standard. β coefficients
Intercept	-860.50	1.78^{2}	***	
t_max4	29.56	4.79	***	1.75
t_max5	24.97	9.13	**	1.19
t_max6	6.29	1.09	***	0.21
t_max7	46.20	10	***	2.02
t_max8	58.01	11.6	***	2.34
t_max9	-8.01	1.97	***	-0.34
$(t\_max4)^{2}$	-0.72	0.13	***	-1.52
$(t\_max5)^{2}$	-0.53	0.25	*	-0.94
$(t\_max7)^{2}$	-1.26	0.20	***	-2.68
$(t\_max8)^{2}$	-1.37	0.23	***	-2.72
$(t\_max10)^{2}$	0.26	0.05	***	0.32
$(Rad\_sum7)^{2}$	1.21^{-10}	3.62^{-11}	***	0.19
$(Rad\_sum8)^{2}$	1.24^{-9}	$4.35-^{10}$	**	1.06
$(Rad\_sum9)^{2}$	3.82^{-10}	9.34^{-11}	***	0.25
$(SW6)^{2}$	-2.28^{-3}	3.17^{-4}	***	-0.24
$(SW8)^{2}$	4.01^{-3}	6.75^{-4}	***	0.21
$(SW9)^{2}$	-4.60^{-3}	1.29^{-3}	***	-0.21
$(SW10)^{2}$	3.66^{-3}	8.11^{-4}	***	0.22
$(VPD4)^{2}$	-313.30	79.44	***	-0.20
$(VPD5)^{2}$	-123.90	19.93	***	-0.15
$(VPD6)^{2}$	422.40	94.98	***	0.95
$(VPD7)^{2}$	135.80	15.45	***	0.33
$(VPD8)^{2}$	47.22	13.04	***	0.12
Rad_sum8	-1.16^{-3}	$4.45-^{4}$	**	-0.96
Rad_sum10	-4.40^{-4}	1.25^{-4}	***	-0.17
SW5	0.31	0.04	***	0.20
SW9	-0.50	0.12	***	-0.22
VPD6	557.60	117.90	***	1.00
VPD9	-148.50	26.97	***	-0.31
VPD10	57.24	25.37	*	0.12

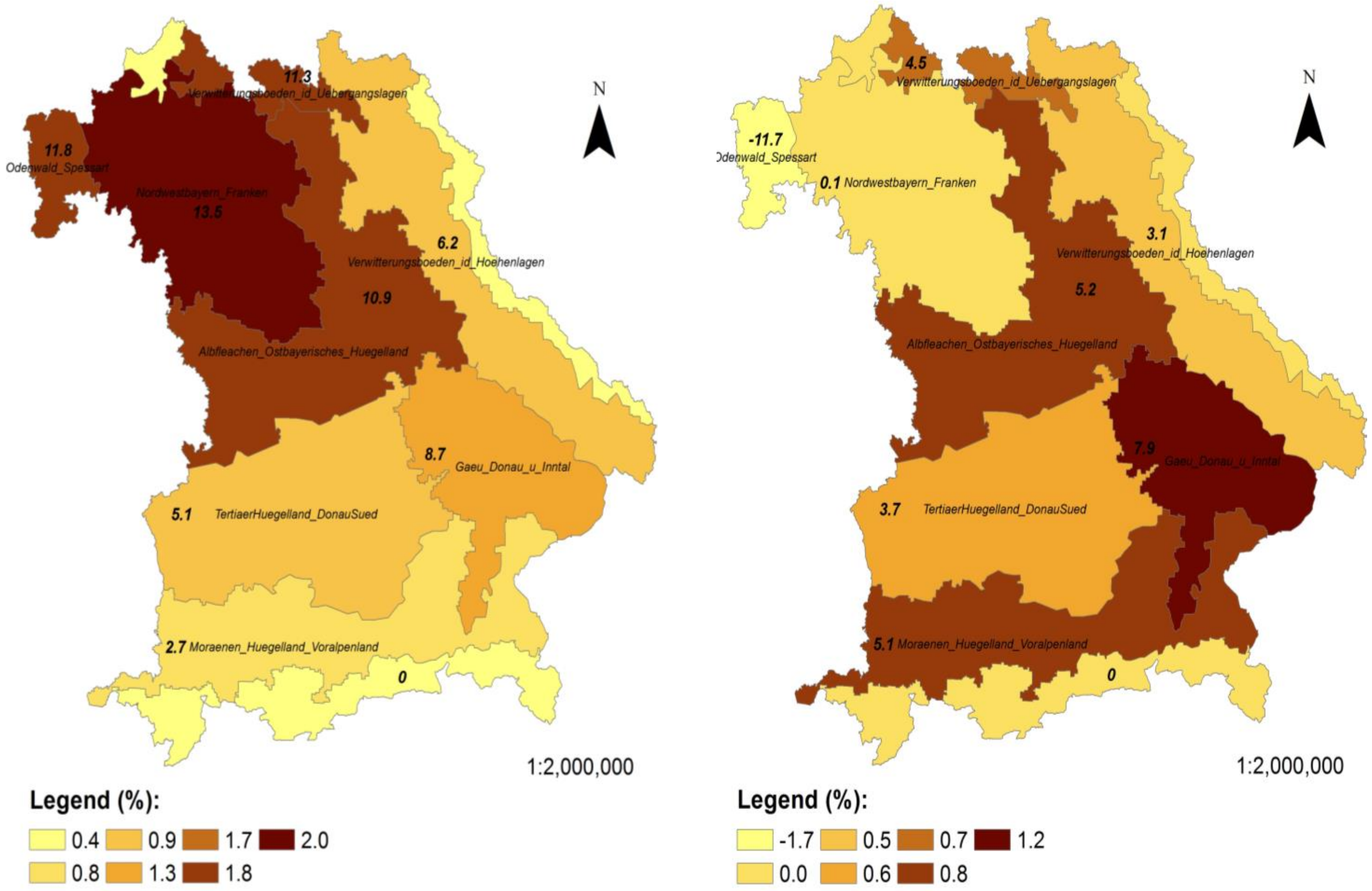
Based on the predictors from Tables 23 - 26 yield predictions from panel models were calculated. Thus, a total of four panel models were developed, which were furthermore suitable for estimating the possible future influence of climate change on yield levels in Bavaria. The possible future influence of climate change on yields in Bavaria could be estimated through the incorporation of modelled climate data in the four panel models which were developed. The modelled climate data considered in this thesis provided three time periods. The baseline period 2000, 2020 and 2030 each period +/- 15 years. The predicted percentage and absolute yield change caused by the change of one predictor in the Bavarian Soil-Climate-Areas between the base line period 2000 and the two other time periods 2020 and 2030 were illustrated by the Maps 12 - 15. The selection of the predictors shown by the Maps 12 - 15 were based on those predictors, which had the strongest positive or negative influence = highest/lowest standardized β coefficients in Tables 23 and 24 on wheat or maize yields in the Soil-Climate-Areas between 1991 and 2015, whereby squared values of predictors were not considered for the selection. This resulted in the selection of a total of four predictors. The predictor that influenced silage maize yields most positively between 1991 and 2015 was the mean maximum temperature in June. The most negative impact on silage maize yields in the Bavarian Soil-Climate-Areas was the vapor pressure deficit in July in Table 24 with the highest/lowest standardized β coefficient excluding all squared values of predictors. For wheat the predictor which was identified as the most positive yield influencing one was the sum of the solar radiation of the Soil-Climate-Areas in June, whereas the factor with the most negative influence on yields in Soil-Climate-Areas was the VPD in April as shown in Table 23 with the highest/lowest standardized β coefficient excluding all squared values of predictors.



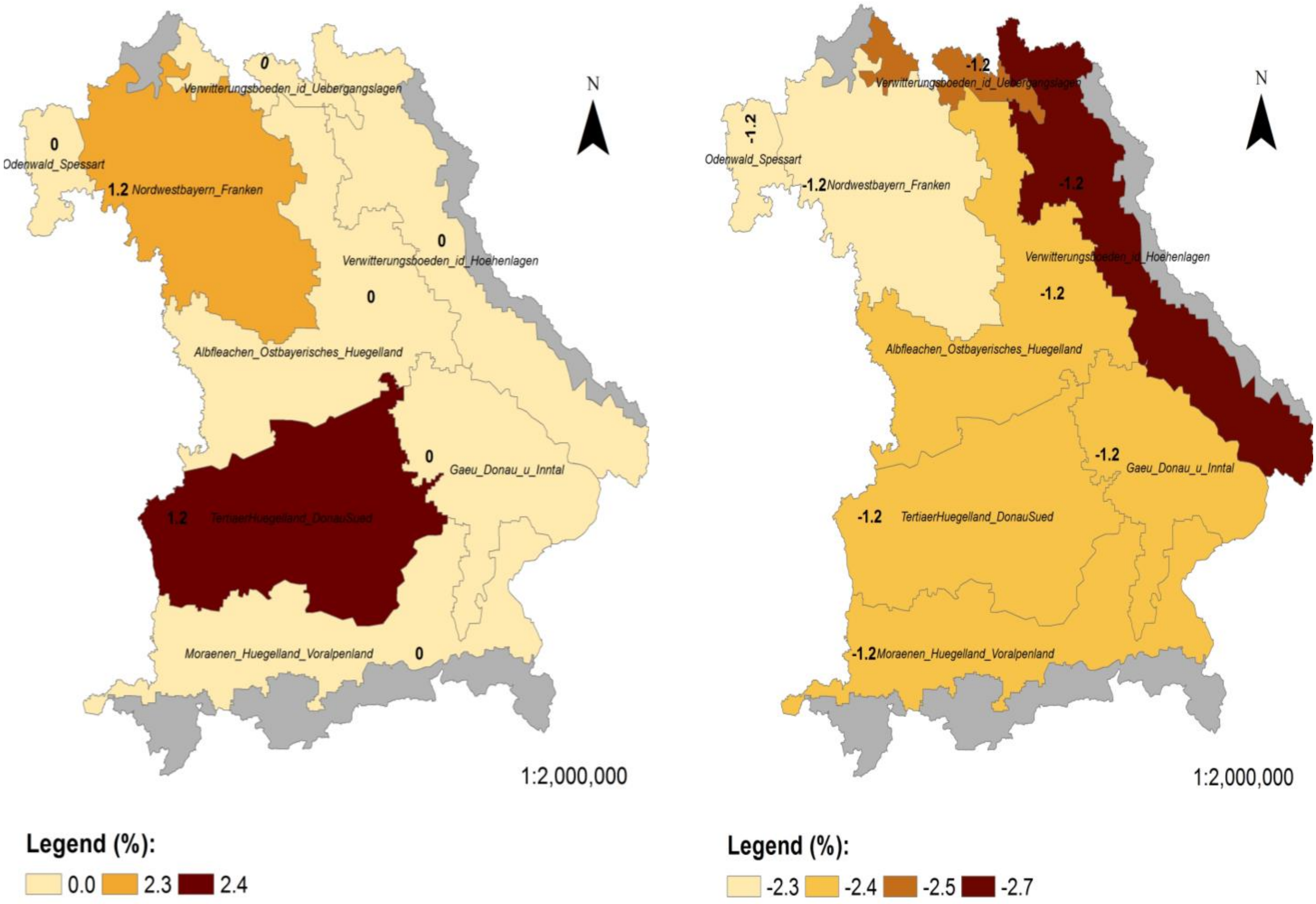
Map 12: Influence of the average maximum temperature in June on silage maize yield between the baseline period (2000) and 2020 (left) and from 2000 to 2030 (right). Numbers within a Soil-Climate-Area indicate absolute yield changes in dt ha^{-1}, whereas numbers in the legends indicate relative yield changes in dt ha^{-1}.



Map 13*:* Influence of the average vapor pressure deficit in July on silage maize yield between the baseline period (2000) and 2020 (left) and from 2000 to 2030 (right). Numbers within a Soil-Climate-Area indicate absolute yield changes in dt ha^{-1}, whereas numbers in the legends indicate relative yield changes in dt ha^{-1}.



Map 14: Influence of the sum of solar radiation in June on winter wheat yield between the baseline period (2000) and 2020 (left) and from 2000 to 2030 (right). Numbers within a Soil-Climate-Area indicate absolute yield changes in dt ha^{-1}, whereas numbers in the legends indicate relative yield changes in dt ha^{-1}.



Map 15: Influence of the mean vapor pressure deficit in April on winter wheat yield between the baseline period (2000) and 2020 (left) and from 2000 to 2030 (right). Numbers within a Soil-Climate-Area indicate absolute yield changes in dt ha^{-1}, whereas numbers in the legends indicate relative yield changes in dt ha^{-1}.

Both crops showed that high temperatures/radiation sums at certain time points led to higher yields. In the case of silage maize, higher temperatures in June led to higher yields. According to the climatic scenario used in this thesis, the maximum temperature in June increased slightly from the period 2000 to 2020. The yield was therefore higher in the Soil-Climate-Areas if only the maximum temperature in June was used for the prediction in this time period. In the period 2000 to 2030 the temperature increased even more. So the percentage increase of the yield by this factor was 0.4 - 3.8% in *Tertiärhügelland* and in *Odenwald Spessart*. This means to account for an increase of the yield between 4.0 dt ha^{-1} and 39.3 dt ha^{-1} this factor alone would be used for the yield prognosis. At this point the quadratic relationship should be considered again: if temperatures are too high in June, the yields will decrease. The increase in wheat yields will be most strongly affected by the future increase in the radiation sum in June. According to the climate model, the radiation sums will increase in both time periods 2020 and 2030 compared to 2000. The only exception is the Soil-Climate-Area *Odenwald Spessart* in the model of 2030. Here the average radiation sum decreased in June, which resulted in a yield reduction of 1.7% compared to the period of 2000. In all other Soil Climate Areas a yield increase of 0.01 - 1.8% could be observed between 2000 and 2020 or 2000 and 2030 with 0.01% in *Nordwestbayern* for the period 2030 and 1.8% in *Odenwald* for the period 2020.

The VPD accounted for negative yield changes in April (wheat) and July (maize). In the period 2000 to 2020, the maize yield decreased due to this factor from -2.7 to -5.5% in *Verwitterungsböden in den Übergangslagen* and in *Albflächen*. In the period 2000 to 2030, yields declined even more from -6.8% to -12.3% in *Verwitterungsböden in den Übergangslagen* and in *Tertiärhügelland*. For wheat, the VPD hardly changed in April, which means that this did not have a major impact on yield. From 2000 to 2020 the VPD remained almost unchanged or decreased in *Nordwestbayern Franken* and in *Tertiärhügelland*. The decrease in VPD resulted in an increase in yield of 2.3%. From 2000 to 2030 the VPD increased in April, which is why yields in all Soil-Climate-Areas were approximately 2% lower.

4.4.3 Yield predictions

Yield predictions were developed on the basis of climate scenarios provided by MARS (Monitoring Agricultural RessourceS), the Department of the European Commission's Science and Knowledge Service, the Joint Research Centre (JRC) (FOODSECURITY -MARS4CAST, 2015). To reveal differences in yield over time, average absolute yields of Soil-Climate-Areas in dt ha^{-1} are presented in Figure 35 for wheat and Figure 37 for maize for the time periods 2000, 2020 and 2030 considered in this thesis with each point of time +/- 15 years. Furthermore, mean relative yield changes of the Soil-Climate-Areas for the same time periods as before are presented in the Figure 36 for wheat and Figure 38 for maize. The yield predictions on the county level and the limits of the 95% confidence interval of Soil-Climate-Areas and counties yields are given in the Supplemental Tables E1 and 2.

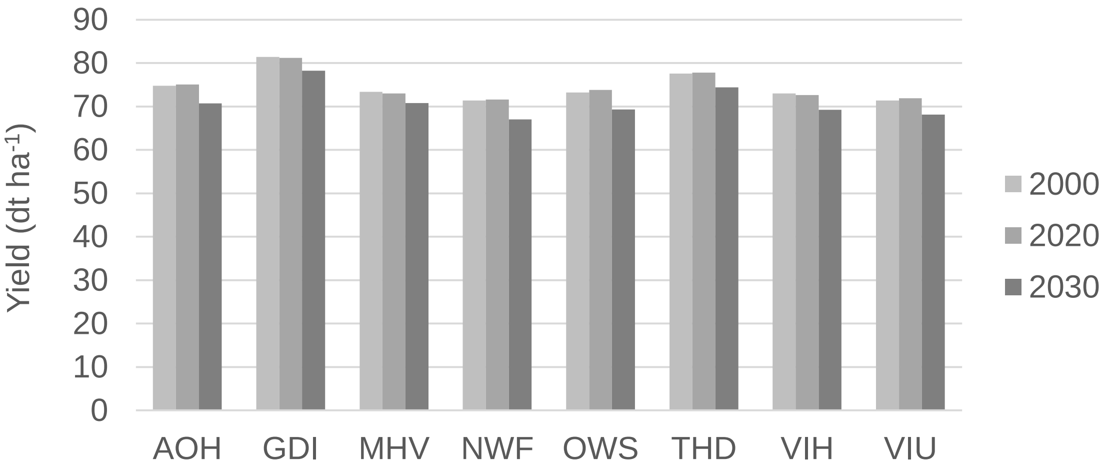


Figure 35: Mean wheat yields of Soil-Climate-Areas for the climate scenarios of 2000, 2020 and 2030.

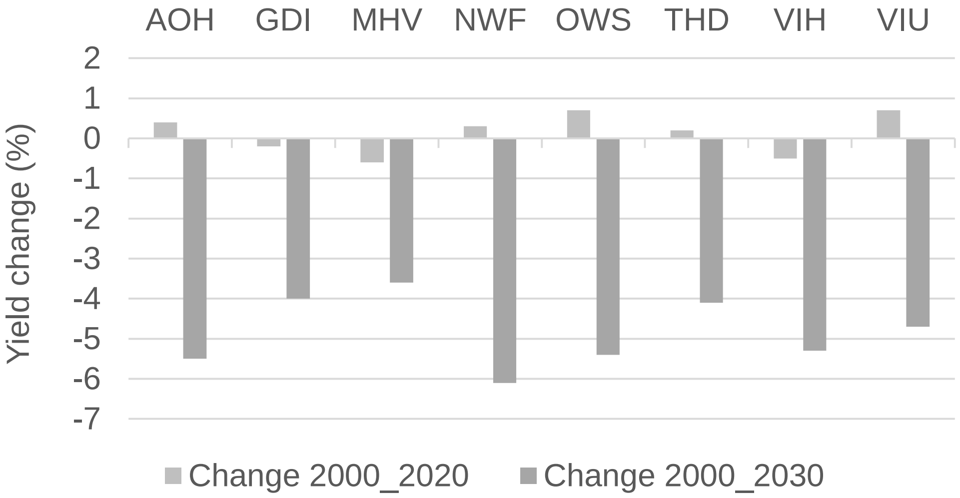


Figure 36: Change of mean wheat yields in Soil-Climate-Areas between 2000 and 2020 and 2000 and 2030.

The level of wheat yields in the Soil-Climate-Areas between 2000 and 2020 revealed hardly any difference. In some Soil-Climate-Areas like in *Gäu Donau und Inntal*, *Moränenhügelland Voralpenland* and *Verwitterungsböden in den Höhenlagen* there was a slight decrease of the average yield of -0.14 dt ha^{-1} and -0.2% in *Gäu* to -0.46 dt ha^{-1} and -0.5% in *Moränenhügelland*. In the other five Soil-Climate-Areas, a slight increase in yield was predicted. This increase was on average between 0.13 dt ha^{-1} and 0.2% in *Tertiärhügelland* and 0.52 dt ha^{-1} and 0.7% in *Odenwald*. Between 2000 and 2030, yields were expected to decline in all Soil-Climate-Areas according to the yields prediction. The yield decreased on average by -2.7 dt ha^{-1} in *Moränenhügelland* to -4.4 dt ha^{-1} in *Nordwestbayern Franken*, which indicates a percentage change from -3.6 to -6.1 percent.

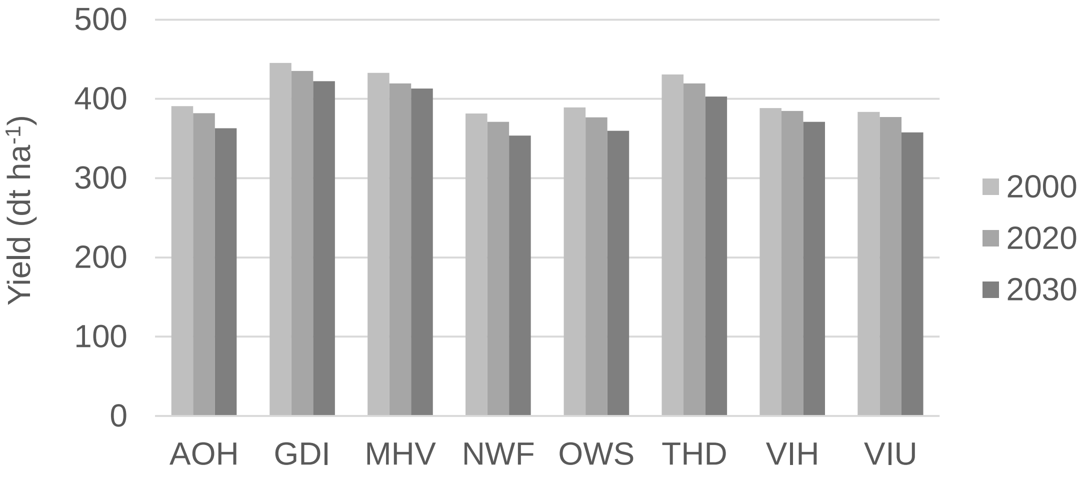


Figure 37: Mean maize yields of Soil-Climate-Areas for the climate scenarios of 2000, 2020 and 2030.

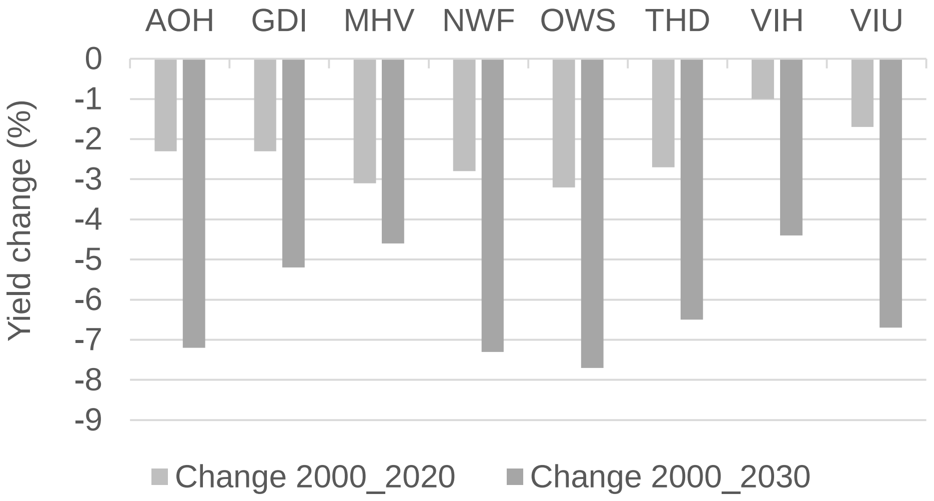


Figure 38: Change of mean maize yields in Soil-Climate-Areas between 2000 and 2020 and 2000 and 2030.

The predicted level of maize yields for both periods showed a decline, which were predicted to be stronger in the later future. Between 2000 and 2020, the average yield droped from -3.8 dt ha^{-1} in *Verwitterungsböden in den Höhenlagen* to -13.5 dt ha^{-1} in *Moränenhügelland.* This equals a percentage change of -1% to -3.1%. Between 2000 and 2030, yields fell even more. According to predictions, the average yield decreased from -17.3 dt ha^{-1} in *Verwitterungsböden in den Höhenlagen* to -29.8 dt ha^{-1} in *Odenwald* which equals a percentage change of -4.4% to -7.7%. For 2045, the decline in the average yield of the Soil-Climate-Areas for both crops were predicted to be less than 10%. For maize, the decline was stronger than for wheat. Between 2000 and 2020, wheat showed hardly any decline in yield, whereas a decline could already be observed for maize in the same period.

The yield developments in the counties for winter wheat were similar to those of the Soil-Climate-Areas and showed only a very small difference between 2000 and 2020. Forty of the 60 counties showed yield differences of less than +1% and -1%. Only in one county, in *Erlangen-Höchstadt*, a negative yield development of -1.36% was observed. A positive yield development was expected for the remaining 19 counties, it varied from 1.04% in *Bad Kissingen* to 3.75% in *Tirschenreuth*. Between 2000 and 2030, eleven counties had a yield difference of less than one percent. Three counties had a negative yield development of -1.21% in *Fürth*, -0.5% in *Würzburg* and -0.42% in *Erlangen Höchstadt*. With more than half of the counties, 34, the yield increased between 1% and 3%. The highest percentage yield increase between 2000 and 2030 was expected in *Unterallgäu* with 6.03% and in *Tirschenreuth* with 6.54%.

The yield developments in the counties for silage maize showed a different picture than those of the Soil-Climate-Areas. With the exception of three counties *Neu-Ulm with* -1.11%, *Traunstein* with -0.44% and *Fürstenfeldbruck* with -0.13%, yields increased between 2000 and 2020. The increase ranged from 0.89% in *Günzburg* to 10.48% in *Bamberg*. Between the two time periods 2000 and 2030, all silage maize yields developed positively according to the modelling. The lowest increase here was observed in *Miltenberg* with 3.36%, the highest in *Tirschenreuth* with 12.99%. Only seven of the 60 counties showed an increase in yield of more than 10% compared to 2000 with *Neuburg-Schrobenhausen, Freising, Kulmbach, Neustadt an der Waldnaab, Landsberg am Lech, Bamberg and Tirschenreuth.*

5 Discussion

5.1 Data

5.1.1 Yield data

Yield data reported in this thesis reflect the average harvest values of a county. Furthermore, the information of the farms about their cultivation and their expected yield is voluntary; only agricultural farms larger than 4 ha are included. In addition farms that span several administrative areas were accounted to the administrative unit in which the head office of the establishment was located (Statistisches Bundesamt, 1982a). This represents a potential source of error. Also the fact that only fields larger than 4 ha were included in the statistics may lead to biases. The historically determined division of the heritage in Bavaria led to a small parceling of fields. The official county yields of the Bavarian Statistical State Office were calculated using the weighted average, hence larger fields had more influence on the official figure than smaller fields (Statistisches Bundesamt, 1982c). In addition, the quality of the harvest results and farm reporting field crops is also influenced by the number of farms or reporters involved and the coverage of the targeted areas. The aim is to maintain the largest possible area coverage. However, it is becoming increasingly difficult to recruit expert rapporteurs (Statistisches Bundesamt, 2015). Despite some sources of error, the statistics of the Bavarian Statistical State Office can be used as a basis for the calculations.

Detrending of time series in the agronomic context was carried out because the increase in yields follows a positive trend and is therefore in agreement with Lobell (2010) mainly due to breeding and technical advances. This implies that if there is no positive trend in a data series detrending was not necessary for silage maize in the investigated area and period. Basically, several methods can be used to detrend crop yields (Lobell et al., 2005; Lobell and Field, 2007; Ye et al., 2015). A common approach is to calculate first differences which represent differences in values from one year to the next. A second approach is the inclusion of a temporal trend in the regression between non-detrended yields and climate. A third approach is the correction with a cubic-spline trend, which considers nonlinear technological trends (Lobell and Field, 2007). Since knowledge about the development of technological progress is not provided and a fitting of the trend using a spline function did not result in better fits, applying the cubic-spline method was not considered more advantageous than assuming a linear trend. Including time as another factor in the regression of climate and yield was regarded as disadvantageous, since the explained variance of yields, was reflected in closer relationships. The inclusion of time as a further factor suggests that abiotic factors explain differences in yield very well, mainly due to the relationship between yield increase and time, rather than to the explained variance of yield and abiotic factors. The first difference methodology could also be regarded as unsuitable for the purpose of yield prediction. Although it served the purpose of assessing individual factors in reducing or increasing yields, projections for the future were difficult to establish. This was due to the fact that differences existed between two years. Therefore, the last known year always served as the basis for the calculation of the next year, which required many individual calculation steps and made the method inefficient in terms of yield prediction. The selection of the trend model represented a critical point in yield modelling. As the yield level was divided into at least two parts, one that resulted from the trend, i.e. from technological/breeding progress and another one that resulted from the non-trending or oscillation of the yield curve, e.g. variations of natural factors. The detrending methods estimated these two factors differently, so that different results are possible (Ye et al., 2015). Nevertheless, the effect on yield modelling using different detrending methods can be considered as being very low (Lobell and Field, 2007).

Soil-Climate Areas differed in yield levels. Three yield level groups (Figure 6) of Soil-Climate-Areas were identified for wheat and two for maize (Figure 7). The high yield group for wheat could be attributed to the higher available field water capacity of the selected Soil-Climate-Areas (*Gäu Donau und Inntal*: afc 170 mm, *Tertiärhügelland*: afc: 156 mm) compared to the medium yield group level (*Albflächen Ostbayerisches Hügelland*: afc: 134mm or *Nordwestbayern Franken:* afc: 131mm) or the lower yield group (*Verwitterungsböden in den Höhenlagen*: afc: 113 mm). This observation was supported by the relationship between available field water capacity and yield as described in 4.2.1. Two main groups were identified for maize. Here, too, the different levels of afc at the beginning of the vegetation period explained the two groups. This observation was supported by results described in 4.2.1. However the correlation was less close for maize.

Interannual yield variability is mainly a consequence of annual differences in weather conditions (Chen et al., 2004). Globally, regional yield variabilities can be explained by weather differences accounting for about one third of the variability, with large regional differences. With wheat and maize in Germany, for example, the yield variability was not present or only to a very small extent (coefficient of variance of yield: 0 - 0.05) caused by differences in weather (Ray et al., 2015). Also, the results presented in sections 4.1.3 and 4.1.4 showed that interannual yield differences and interannual yield variability were greater than yield differences and variabilities between the study areas. Moreover, from the yield data it is evident that if weather conditions in a certain time period (e.g. months, one year, two years) exert negative impact(s) on yields, they generally occurred throughout Bavaria and were not regionally present. Therefore, it is likely that the differences observed between winter wheat and maize yields at the county- and Soil-Climate-Area-level could not be fully explained by differences in weather conditions between study areas. Thus other environmental or management factors must have influenced the yield stability as also reported by

Schauberger et al. (2016). The results presented in section 4.1.4 reveal that the yield stabilities of winter wheat in Bavaria were similar. The coefficient of variation for the Soil-Climate-Areas varied between 7.7% and 9.8% (Figure 9). A comparable situation was observed for the yield stability of maize in the Soil-Climate-Areas, where coefficients of variation varied between 7.6% and 13.1% (Figure 11). The differences among Soil-Climate-Areas were higher for maize yield stabilities compared to the wheat yield stabilities. Since yield variability could be minimized by spatial aggregation effects, county-based results offered an additional indication for the observed yield variabilities in Bavaria between 1991 and 2015. The coefficient of varation for county wheat yields was between 6.9% in *Tirschenreuth* and *Nürnberger Land* and 14.4% in *Fürth* (Map 11) for maize the coefficient varied between 6.3% in *Passau* and 14% in *Fürth* or 14.1% in *Kitzingen* (Map 10).

The analyses showed that differences between yield variabilities were reduced through spatial aggregation. Additionally, it is likely that the yield variability was rather due to management practices and different soil conditions instead of different weather conditions. The relative yield stability between 1991 and 2015 for wheat at the county level was 6.9% (*Nürnberger Land*), while the lowest yield stability of 14.4% was observed for *Fürth* (Map 11). However, both counties border the city of *Nürnberg* and are not far from each other. Therefore, the possibility of major weather differences explaining the large difference in yield stability can be excluded. Similar observations were made for silage maize, even though the counties with the highest and lowest yield variability were not directly adjacent. Nevertheless, some districts with a high yield stability (6.6% *Fürstenfeldbruck*) were directly adjacent to districts with a low yield stability (11.3% *Dachau*) (Map 11). If other environmental factors were used to explain the yield stability the median afc of counties (afc in *Nürnberger Land:* 114 mm, afc in *Fürth:* 139 mm, afc in *Fürstenfeldbruck:* 153 mm, afc in *Dachau:* 155 mm) did not differ significantly. Management practices probably exerted the greatest influence on yield stability if neighbouring districts showed different yield stabilities. This observation is also supported by findings of Porter and Semenov (2005) who stated that management contributes much more to yield variability than those factors beyond our control. Apart from management, there are other factors that are able to explain the yield stability in Bavaria. Bakker et al. (2005) identified soil, weather and management as factors influencing wheat yield variability in Europe. Ray et al. (2015; 2016) analysed wheat and maize with regard to yield stability and confirmed also the soil, weather and managment as being relevant. Therefore, as a further yield variability influencing factor, the soil or the afc in Bavaria can be considered. Figure 12 depicts a R^2 of 0.26 and thus a weak positive relationship between absolute yield stability in Bavaria and the level of afc existing in the Soil-Climate-Areas. A quarter of the variability of the yield stabilities could be explained by the median level of afc in Soil-Climate-Areas. This was similarly apparent (R^2 of 0.23 as shown in Figure 13) for the relative yield stability of maize and the level of afc for the counties in Bavaria. However, since relationships were only found for wheat in Soil-Climate-Areas and for silage maize in counties, the influence of afc could also have a smaller impact on yield stability. A study examining the main growth zones of China, in terms of yield stability of maize, concluded that soil did not contribute to the explained yield stability (Zhao and Yang, 2018). Another study that analyzed the variability in regional soft wheat yields as a function of climate, soil and economic variables concluded that the correlation coefficient between yield and plant available soil water was 0.64 at the county level and 0.74 at the NUTS 2 level (Bakker et al., 2005). This aggregation level is comparable in scale to the Soil-Climate-Areas. However, soil properties that were teken into consideration by Zhao and Yang (2018) were bulk density, organic carbon, pH-value, total N, drained upper limit and 15 bar lower limit and not afc as in this work.

The observed north-south gradient in Bavaria should be taken into account. For both crops a north-south gradient was observed, whereby generally more stable yields were achieved in the south than in the north of Bavaria. One reason for this could be the higher afc in soils of south Bavaria. The other reason is a higher precipitation in the south of Bavaria caused by the orography. Both factors which indicate a higher water availability for plants might explain the observed higher yield stability in the south of Bavaria during adverse weather conditions such as dry periods.

5.1.2 Environmental data

The use of the environmental data provided by MARS (Monitoring Agricultural ResourceS) of the Joint Research Centre (JRC) of the European Union offered the advantage that a complete data set could be used for the purpose of this thesis. The station data of the DWD were not located in each Bavarian county. Here one would has to rely on the nearest neighbor of the county with an existing weather station, which automatically leads to sources of error, since the same meteorological parameters would be linked with different yields. The MARS unit calculated interpolations out of weather measurements from station data to obtain a regular raster (grid) with a resolution of 25 km * 25 km over Europe (EC-JRC-AGRI4CAST, 2012). After the grids were converted to county and Soil-Climate-Area values, the measured weather data of the DWD and the interpolated data from MARS were compared and the deviations were rated as being low. Even with precipitation, which is known to cause most errors, the values of the local point measurements of the DWD were comparable to the calculated values of a county. Overall, the environmental data provided by JRC were assessed as being comparable as or even more complete than the data provided by DWD.

5.1.3 Phenological data

The input data collected for the phenological phases may include several sources of error. On the one hand, the phases are rather collected by non-experts according to observation instructions by DWD. Although the Monitoring Guidelines (DWD, 1991) provide a detailed description of the individual phases to be observed, a fully accurate determination and classification of all data cannot be guaranteed. Furthermore, only a few selected phases were documented. To obtain a complete overview of the plant development a detailed recording of the growth cycle would be necessary. A development of at least 50% of the crops was also expected when the entry data was recorded. It was difficult to reliably determine for example the average degree of maturity of a field without technical aids. The cultivation of different winter wheat or silage maize cultivars was also disregarded. Furthermore two of the phases were based also on the farmer’s decision. Sowing and the harvest dates are chosen at dates considered by farmers to be optimum regarding soil and weather conditions. Consequently the phases following sowing, such as heading, depend partly on the farmers decision on sowing dates (Estrella et al., 2007). However, the phenological phase of heading is still strongly influenced by temperature (Menzel et al., 2006). Although the data submitted was checked and corrected, the observations with poorer quality characteristics (DWD, 2018b) represented unreliable data points. On the other hand, the question was whether a more precise recording of the phenological development of winter wheat and silage maize would be advantageous within the given framework. The method used offered a comprehensive observation system that provided a good overview of plant development without large financial resources. More detailed descriptions of the development of the individual cultivars could be found in scientific papers. The environmental parameters collected by DWD were recorded at various measuring stations throughout Germany with standardized procedures. Only the monitoring of the phenological phases without additional monitoring of the environmental parameters was considered. All in all, the DWD data provided a solid basis for the entry data of a wide variety of crops that were recorded throughout Germany for decades.

5.1.4 Soil data

The available field water capacity of the agricultural soils (afc) of Bavaria was derived from the soil survey of the State of Bavaria. The underlying model profiles represent the main soil type for a specific region. Other soil types and their properties had to be disregarded just because of data availability. Another aspect to be considered is a possible groundwater influence of a site resulting in capillary rise which had to be disregarded because of missing data availability. As only agricultural areas were relevant for the analysis, CORINE Landcover data was used to determine the agricultural areas. These are based on aerial or satellite images. The minimum size of an agricultural area to be mapped is 10 ha (European Environment Agency, 1995). Smaller areas were grouped in other categories. This implies that the calculation of the available field water capacity of agricultural areas contained only fields that were larger than or equal to 10 ha. These fields again classified by CORINE as agricultural areas were used to calculate the median afc of agricultural areas of a county or Soil-Climate-Area. Since yields on county/Soil-Climate-Areas were already aggregated, the aggregation of the afc on county/Soil-Climate-Areas was regarded as an appropriate approach for this thesis. Yield differences that existed between the counties/Soil-Climate-Area could be related to the different levels of afc in a county/Soil-Climate-Area. This approach considered the heterogeneity regarding afc within Bavaria and thus provides a possible explanation for differences in yield.

The calculation of the available soil water content was based on some simplified assumptions and served to simulate soil water content as the year progressed. As underlying basic assumptions a filled up available field water capacity and the crop specific evapotranspiration simulating the extraction of the soil water were used. Furthermore, other effects such as interception and surface runoff were integrated in the model. A similar method to calculate the soil water content is described by Rattalino Edreira et al. (2018). Here evapotranspiration, surface runoff and deep drainage were used as soil water content reducing factors. Although the simplified model of this thesis did not consider deep drainage, interception was included which in turn was not taken into account in the study by Rattalino Edreira et al. (2018). In comparison to process-based models, the approach developed in this thesis did not use a wide range of parameters (e.g. Priesack et al., 2012, 2008); the simplified model was intended to assess whether the inclusion of the level of the simulated soil water content during the progress of the vegetation period could reveal yield differences.

5.1.5 Climate models

The target group of the database used here are crop modelers who assess the impact of climate change on agricultural development in the near future. For this purpose, three realizations were provided. They differed mainly in the projected precipitation levels. Since the effects of climate change projections on crop yields are uncertain (Godfray et al., 2010), an approach trying to minimize the uncertainties of climate models which has already been applied by Asseng et al. (2013) was used. In the study by Asseng et al. (2013), the value that predicted yield levels with minimum uncertainties among all models was the mean of all yields resulting from different crop models. To account for uncertainties between climate models, a similar approach was used in this thesis. The mean values for all abiotic factors of these three ENSEMBLES were calculated and yield predictions were made on the basis of means derived from these three ENSEMBLES. Another aspect that indicated that the dataset could be used was based on the experience that it had been used as well in previous modelling studies evaluating the impact of climate change on e.g. yield levels (Donatelli et al., 2015) or contributing to the Fifth Assessment Report of the IPCC (Kovats et al., 2014). Moreover, the baseline period did not show large differences compared to the observed weather data (Donatelli et al., 2015), which indicates a reliable dataset.

The following apects needed to be critically assessed: The data set used the older scenario scheme - in this case the A1B scenario. This will be replaced in the near future by the newer representative concentration pathways (RCP) methodology. Nevertheless, there is no reason why the A1B scenario should not be used for crop modelling (Duveiller et al., 2017). Furthermore, the projections may be more influenced by interannual variability than by long-term trends (Maraun, 2013). However, since the observed weather variables did not show large differences regarding the distribution of the variables in the baseline period, the method represented a suitable compromise (Duveiller et al., 2017). Finally, the short-term time horizon up to 2045 is discussed. The relatively short time horizon may not sufficiently cover possible consequences of climate change on yield in the long term. However, on the other hand, the uncertainties of climate projections increase with time (Kirtman et al., 2013) and the uncertainty in modelling increases if climate projections were not included during the models calibration process (Wallach, 2011). Consequently, uncertainties within models are greater the further they project the future and smaller if they are calibrated using the parameters projected for the future. Therefore, to avoid producing statistical artifacts, changes in abiotic factors that allow predictions of future yields were considered until the year 2045.

5.2 Identification of relevant abiotic factors during phenological phases influencing yields of silage maize and winter wheat in Bavaria

5.2.1 Influence of the median available field water capacity on yields in Bavaria

In the last years, numerous studies demonstrated a strong influence of the soil water content or plant available soil water on yield levels (Bakker et al., 2005; Eitzinger et al., 2003; Lawes et al., 2009; Olesen et al., 2000; Rattalino Edreira et al., 2018; Wu et al., 2019). The soil water balance variation can often explain differences in crop yield levels (Batchelor et al., 2002). Another study showed that the explained variation between soft wheat yields and soil water available to plants amounted to 0.73 on the NUTS2 level for Germany (Bakker et al., 2005). The NUTS2 level regards a scale comparable to the Soil-Climate-Areas considered in this thesis. The explained variationof 0.81 between the median available field water capacity and the average wheat yields of the Soil-Climate-Areas for the period 1991-2015 as shown in Figure 17 reveals even closer relationships. However, for maize, the explained variability between the median available field water capacity and yield levels of Soil-Climate-Areas for the period 1991-2015 was smaller with $R^2 = 0.56$ (Figure 18). Another study found a higher explained variation of 91% ($p < 0.001$) between plant available soil water and precipitation amount from 30 days before and 20 days after flowering (Calviño et al., 2003). The investigated region of the study was located in the Argentinean Pampa region. The maximum water availability for plants in the Argentinean Pampa region was specified to be 180 mm, which is similar to Bavaria. Furthermore, the average precipitation amount of 750 mm – 850 mm (Krishna, 2015) is comparable to the one in Bavaria (900 mm) (Bayerisches Landesamt für Umwelt, 2020). An indication for the higher explained variance could be the non-linear functions that were applied in the study of Calviño et al. (2003), whilst in section 4.2.1 linear relationships were considered. A different study which was carried out on four locations in Illinois from 1969 to 1971 revealed that the weekly plant available stored soil moisture investigated for a period of ten weeks, could explain 58% of the variation in maize yields (Leeper et al., 1974). Another study that analyzed the effect of soil moisture anomalies on silage maize yields in Germany between 1999 and 2015 found that models were improved by including soil moisture anomalies, whereby the effect of each variable was dependent on the month (Peichl et al., 2018). In Bavaria, the driver of differences among average yield levels between 1991 and 2015 are mainly due to the available field water capacity. There were, of course, other factors such as the weather or management which influenced the different average yield levels, but the influence of these seemed to be less significant. It is postulated that in Bavaria technology and management is at a high level and competitive.

The question arises why the explained variability of wheat yields is higher than that of silage maize. This could be due to spatial aggregation. In Jasper's master thesis (2016), relationships between maize and afc were observed at 82% for administrative districts (*Regierungsbezirke*) and for wheat at 70%. The explained variance between yield levels and median afc in this thesis based on Soil-Climate-Areas which are regarding scale comparable to *Regierungsbezirke* were observed for maize at 56% and for wheat at 81% between 1991 and 2015. Therefore it was concluded that the spatial aggregation is of importance to account for factors influencing yield. The geographical division of Bavaria into Soil-Climate-Areas according to Roßberg et al. (2007) is strongly generalized by the formation of weather and soil clusters. Nevertheless, Soil-Climate-Areas offer a good basis regarding agriculturally influencing variables, as soil and climate-specific factors are taken into account. The fact that the variability of wheat yields can be better explained by afc than for maize yields, could be due to the fact that soil clusters were formed on the basis of their influence on winter wheat yields when the Soil-Climate-Areas were classified. A further explananation is illustrated in Figure 18. In this figure one data point is far from the linear regression (*Nordwestbayern Franken*). If the regression is calculated without this data point, it reaches a level of 74% which explaines the variability of yields. Nevertheless, the explained variability between yield levels and the median afc levels for maize is lower than for wheat. This initially contradicts the conclusion that summer cereals in particular are vulnerable to drought and therefore more dependent on soil water storage than winter cereals (Eitzinger et al., 2003). Also, the fact that winter wheat needs less water during the vegetation period, 250-350 mm, than maize, which needs between 350 and 400 mm, seems to contradict these results (Brouwer and Heibloem, 1986). However, Ehlers (1996) indicated that the water use efficiency of maize is higher than that of wheat. In Germany, for example, an average maize yield of 200 dt ha^{-1} dry matter is expected to use about 250 mm, whereas an average wheat yield of 120 dt ha^{-1} dry matter is expected to roughly need the same amount of water (Ehlers, 1996). This might contribute to the lower explanatory power between the median available field water capacity and the yield level of maize in the Bavarian Soil-Climate-Areas. Obviously, due to the higher water use efficiency of maize, the initial water availability is not as important for the average yield level as it is for wheat. A further indicator that may explain the different dependencies between the median afc and wheat or maize yields could be the carbon cycle of the plants. Being a C_4 plant, maize has a higher radiation use efficiency (Monteith et al., 1977). As a result, it can convert more dry matter per unit of radiation. In adverse weather conditions, plants close their stomata. This protects the plant from dehydration, but at the same time they cannot photosynthesize and cannot form dry matter (Ehlers, 1996). Since the radiation use efficiency of maize is higher, it can keep its stomata longer closed and still produce dry matter compared to wheat. This protects maize better against dehydration, which is why the soil water content for maize might not be as decisive as for wheat. A further explanation for the different relationships between the median available field water capacity and the mean yield among Bavarian Soil-Climate-Areas from 1991 to 2015 could be that the available field water capacity was not filled up every year at the beginning of the vegetation period of maize, whereas the available field water capacity was filled up at the beginning of wheat growth. There might be several reasons why the median afc was not filled up at the beginning of the vegetation period of maize. One reason could be that a previously grown intercrop could have used some of the soil water resources. Another reason could be that maize fields are often bare until late spring and not or only partly covered by vegetation. This increases soil evaporation, causing the level of median afc to drop even further if there is not enough rainfall between sowing and onset of plant growth (Ehlers, 1996). Although the rainfall maximum in Bavaria is observed during the summer months (Bayerisches Landesamt für Umwelt, 2020), the soil water could be less filled up by lack of precipitation during summer. Precipitation in summer often occurs in the form of short and heavy storms. If the soil is already unsaturated, the water may move more slowly vertically downward, so that less water can infiltrate into the soil. The soil water storage may thus become poorly refilled and water runs off (Rippel et al., 2014), or may be lost by interception (Ehlers, 1996). Another drawback of short and heavy rain showers is that the water use efficiency of plants is lower compared to average rainfall occurring over a longer period of time. Larger amounts of precipitation are used less effectively by plants because of fast movement of excess water to deep and unavailable layers in the soil (van Keulen and Wolf, 1986). The effect of a less filled up soil water capacity due to heavy precipitation is higher for maize than for wheat since wheat is harvested in early to mid August in Bavaria and maize remains in the fields until mid October. So, heavy precipitation events occur more often during the growing season of maize than wheat and thus are less effective for maize. To conclude, afc has to be regarded as the yield-dominant factor in Soil-Climate-Areas in Bavaria. This holds true for both crops. The median afc seems, however, to be more important in explaining different yield levels for wheat than for maize in the Soil-Climate-Areas.

5.2.2 Correlations between abiotic factors, duration of phenological phases and yield in Bavaria

The duration and timing of various phenological phases of crops were identified as yield-determining factors to a large extent (Bonelli et al., 2016; Cirilo and Andrade, 1994; Ewert et al., 1996; Jamieson et al., 1998; Porter and Semenov, 2005). The phenology, and in particular the duration of various phenological phases are influenced by both abiotic and genetic factors (Cleland et al., 2007; Kirby et al., 1987; Porter et al., 1987; Richardson et al., 2013; van Bussel et al., 2011a). Furthermore, the length of a phenological phase can be influenced by crop management, by adjusting the sowing date or the cultivar selection (Rezaei et al., 2018; van Bussel et al., 2015, 2011a). To ensure high and stable yields in the long term, environmental variables that are strongly associated with the duration of a phenological phase were identified. The correlation between the duration of phenological phases and yields enabled the identification of phenological phases that were strongly related to yield. As a result, phenological phases that are actually negatively related to yield could be matched with environmental variables which could shift or lengthen these phenological phases. This, in turn, could reduce the negative correlation between the duration of phenological phases and yield. The results obtained in section 4.2.2 indicate that the duration of a phenological phase showed the highest correlation coefficients for the radiation sum and temperature with a correlation coefficient which was generally at $r = 0.5$, with some values reaching up to $r = 0.85$. This observation agrees with several other scientific studies which identified temperature and day length or photoperiod as the two determining factors in the development of crops (Kirby et al., 1987; McMaster et al., 2008; Porter et al., 1987; Siebert and Ewert, 2012; van Bussel et al., 2015, 2011a; Yan and Wallace, 1998). The two factors: radiation sum and temperature are strongly collinear, why an estimation which factor influences the length of a phenological phase and how strongly, cannot finally be ascertained. However, the different photoperiodicity of the crops could contribute to a better understanding of the relationship existing to the duration of a phenological phase (Asseng et al., 2013; Bassu et al., 2014; Porter et al., 1987; van Bussel et al., 2015). For both crops, the radiation sum was the factor that showed the strongest correlation regarding the duration of a phenological phase. Another factor used to indicate relationships between phenology and abiotic factors is the concept of GDD. Menzel and Fabian (1999) as well as Rötzer and Chmielewski (2001) confirmed that temperature rather than GDD is an important influencing factor on phenology. Holzkämper et al. (2015), on the other hand, used GDD for the prediction of the beginning of phenological phases or the phenological duration. The fact that both factors, GDD and temperature, are correlated to phenology is consistent with the study of Heuer et al. (1978) and Wilson et al. (1995). However, this study reveals that the radiation sum and temperature show closer relationships with phenology than GDD. Critical of the degree-day concept is that the photoperiodicity of a plant is not considered (Bonhomme, 2000), which could be an explanation for lower correlations of GDD with the duration of phenological phases. Several factors influence the phenological response as well as water stress. In this thesis, precipitation was identified as a third factor which showed high correlations with the duration of a phenological phase, with coefficients up to r = 0.6, especially during phases in which much biomass was accumulated. This finding agrees with the study of Bradley et al. (2011) or Hodges (1990). Apart from abiotic factors, other factors such as crop management could provide a further link to phenology. By adjusting the sowing date or the cultivar selection, the duration of a phenological phase could be influenced as well (Estrella et al., 2007; Rezaei et al., 2018; van Bussel et al., 2015, 2011a).

The remarkable difference between wheat and maize was that temperature for wheat was more often the factor that showed the closest relationships with the duration of a phenological phase compared to maize. One reason for this becomes evident from the relationship between dry matter formation and radiation. Maize produces much more dry matter than wheat. As a result, it needs more radiation even if the radiation use efficiency is higher. Therefore, the highest correlation between the duration of a phenological phase and radiation was more frequently observed for maize than for wheat. Nevertheless, the radiation sum was also identified for wheat as the factor that could best explain the relationship to the duration of a phenological phase. This contradicts the study of Hodges (1990), who found that during the growth cycle of maize, daylengths are less important than temperature effects. Bonhomme et al. (1994) and Birch et al. (1998) concluded that maize cultivars that were adapted to temperate regions show lower or no sensitivity to the photoperiod. The high interannual variability in temperature in Europe resulted as a consequence of the low sensitivity to the photoperiod of maize (van Bussel et al., 2015).. The critical daylength marks the transition between vegetative growth and flowering and varies significantly between cultivars (Thomas and Vince-Prue, 1996). However, the thresholds for the base and optimal temperature do not differ as much between cultivars, why the influence of radiation on the phenology is higher in this thesis. It is difficult to separate both effects of temperature and solar radiation on crop yields because they are collinear. One example for the interaction of the two factors is that temperature determines the amount of radiation intercepted by crops (Wilson et al., 1995). Temperature affects leaf canopy development (Hardacre and Turnbull, 1986; Reid et al., 1990; Stone et al., 1999), and thus the fraction of radiation intercepted, as well as the duration and efficiency of the interception of maize (Wilson et al., 1995). This effect can may explain that an influence of the duration of a phenological phase and of radiation was observed more frequently for maize. Furthermore, non-linear growth and development responses should be integrated when investigating potential impacts of climatic factors on phenology (Semenov and Porter, 1995). Overall, this thesis can adequately account for the relationship between the length of a phenological phase and the two influential environmental factors; temperature and radiation for the Soil-Climate-Areas in Bavaria as well as the two most cultivated crops, wheat and maize. These findings agree with the study from van Bussel et al. (2015) yet with the restriction that the length of the vegetation phase of winter wheat delivered better results with temperature and day length (= radiation) than for maize. In this thesis, other contrary observations were made as well. The identified correlations were higher for maize than for wheat. However, since the former study was carried out on a global scale and the observation applied particularly to warm regions (van Bussel et al., 2015), the results of this thesis do not necessarily conflict with results from van Bussel et al. (2015). All in all the results from this work are consistent with other studies that linked environmental parameters and phenology (Bradley et al., 2011; Estrella et al., 2007; Ibáñez et al., 2010; Menzel and Fabian, 1999; Rötzer and Chmielewski, 2001).

If environmental factors were associated with the duration of a phenological phase, a relationship should be existent between the duration of a phenological phase and yield since environmental factors influence yield (Asseng et al., 2011a; Challinor et al., 2009; Gornott and Wechsung, 2016; Kersebaum et al., 2009; Lobell and Field, 2007; Rosenzweig and Parry, 1994; Siebert et al., 2017). The analysis given in section 4.2.3 confirmes this. Basically, the concept of GDD serves to derive the phenological phase of a crop (Bonhomme, 2000; Holzkämper et al., 2015; McMaster and Smika, 1988; McMaster and Wilhelm, 1997). The entry from one phenological phase to another depends not only on temperature but also on other factors such as the cultivar type (Rezaei et al., 2018; Slafer and Rawson, 1995) or day length (Prasad et al., 2008). The duration of a phenological phase provided information on sensitive phenological phases for the yield of the two crops. This knowledge could be used to breed future cultivars for longer or shorter phenological phases or to alter sowing dates. However, the duration of early phenological phases showed no correlations with wheat yield levels. For silage maize the duration of early phenological phases were correlated with yield levels and particularly the beginning of emergence. The duration of a phenological phase was obviously only decisive for the yield level when adverse environmental conditions such as heat were present. Frost in early stages of plant development did not seem to affect the yield level. The results reveal that a reduction of the duration of the kernel filling phase for maize had the greatest effect on yield level (Maytín et al., 1995). The sensitivity during flowering (Araus et al., 2012; Rattalino Edreira and Otegui, 2013; Sánchez et al., 2014) in maize is also recognized by the duration of this specific phenological phase. The longer the phase between flowering and beginning of milk ripening, the higher the yield. Also for wheat, an increased sensitivity between the beginning of milk ripening and the beginning of hard ripening was observed. Under adverse weather conditions, such as a lack of water supply or temperatures above the optimum of 25°C (Wardlaw, 1974) during the grain filling phase wheat shows too early ripening (Porter and Gawith, 1999; Stone and Nicolas, 1995). The phase of hard ripening is thus reached much earlier, which means a shortened phenological phase in days. All in all, yield levels show significant correlations with the duration of phenological phases in days and thus particularly sensitive phases can be identified.

5.2.3 Correlations between yield and abiotic factors during phenological phases

Many studies stress the relationship between environmental variables during a phenological phase and yield level (Kern et al., 2018; Kirby et al., 1987; Porter et al., 1987; Prasad et al., 2008; Richardson et al., 2013; Sánchez et al., 2014; Sarto et al., 2017; Siebert and Ewert, 2012; Strer et al., 2018; van Bussel et al., 2011a). High temperatures, respectively heat stress or drought may result in substantial negative impacts on crop yield (Barnabás et al., 2008; Lobell et al., 2013; McMaster and Wilhelm, 2003). Observations in this thesis are supported by negative correlations between yield and temperature as shown in Tables 9 and 10. For winter wheat, statistically significant negative correlation coefficients became apparent, especially the temperature during the fourth phenological phase, which includes the beginning of heading until the beginning of milk ripening. This resulted in a negative correlation of $r = -0.33$ ($p < 0.01$) with wheat yields in Bavaria. Since the heat sensitivity of wheat is higher in the period during and after flowering (Prasad et al., 2008; Stratonovitch and Semenov, 2015), it is assumed that the results from Table 9 have to be interpreted as a negative effect of heat occurring between flowering and milk ripening and affecting the yield level of winter wheat in the Soil-Climate-Areas in Bavaria. These results are consistent with findings from other studies (Prasad et al., 2008; Russell and Wilson, 1994; Sarto et al., 2017; Wheeler et al., 1996). The negative correlation coefficients of temperature with a correlation up to -0.39 ($p < 0.01$) in the fifth phenological phase, which included the beginning of milk ripening to hard ripening, are also consistent with findings in other studies (Prasad et al., 2008; Sarto et al., 2017). However, the fact that wheat needs water particularly in the third phenological phase, during the development of the flag leaf (Sarto et al., 2017), is supported by the results presented in Table 9. Both precipitation and the water balance correlated positively with yields in some Soil-Climate-Areas with coefficients up to 0.22 ($p < 0.05$). According to the study of Singh (1981) the most critical phase of wheat concerning soil moisture is between the beginning of emergence and the beginning of heading. A further point, which became apparent in the analysis, was that predominantly negative correlations associated with temperature were obtained for this data set. These findings were consistent with the study of Roberts et al. (2017) in which negative impacts caused by heat correlated more strongly with the yield level than other factors. However, it remained unclear whether the negative correlation was only caused by high temperatures or was accompanied as well as by drought. In some few cases, positive relationships were found concerning soil moisture/precipitation, although these were mostly found on sites with soils which have a rather low water storage capacity in Bavaria like in the *Verwitterungsböden in den Übergangslagen* with a median afc of 124 mm. However, positive correlations were not found on all sites with a low soil water content capacity. This could be an indicator that the negative correlation between temperature and wheat yields in Bavaria is rather due to heat than to drought. The research of Semenov and Shewry (2011) concluded from their modeled results that heat, not drought, will increase the vulnerability of wheat in Europe. They assumed the same soil conditions for all locations with an afc of 131 mm. The level of afc indicated by Semenov and Shewry (2011) was comparable or slightly higher than the afc values of the northern Soil-Climate-Areas, *Verwitterungsböden in den Höhenlagen, Verwitterungsböden in den Übergangslagen, Nordwestbayern Franken, Albflächen Ostbayerisches Hügelland.* The southern Soil-Climate-Areas and *Odenwald*, which is located in the northwestern part of Bavaria, revealed higher afc values. The Soil-Climate-Areas which indicated higher afc than those reported by Semenov and Shewry (2011) were: *Odenwald Spessart, Moränenhügelland, Gäu and Tertiärhügelland.*

For silage maize, similarly to winter wheat, heat during flowering resulted in negative correlation coefficients. This observation was consistent with findings from other studys (Estrella et al., 2007; Sánchez et al., 2014), whereas precipitation during this phase correlated positively with yield (Table 10). The positive correlation between precipitation and yield in Bavaria contradicts with findings from Gornott and Wechsung (2015), who assumed sufficient precipitation for silage maize in Bavaria. Nevertheless, maize is susceptible to a lack of moisture in the vegetative phase (Çakir, 2004), therefore precipitation in the phase between stem elongation and tassel emergence was positively correlated with maize yields. As maize is heat sensitive during the beginning of flowering and beginning of milk ripening, a positive feedback with precipitation in this phase for cooling purposes may be useful. If more soil moisture is available, the plant could achieve a better cooling effect by transpiration. On the contrary a reduction in water availability in plants leads to stomatal closure which results in reduced photosynthesis, influencing plant development (Chaves, 1991; Ort et al., 1994). However, it was observed that the stability of maize yields was lower when high temperatures during and after flowering were prevailing than before (Shim et al., 2017). This was partly in contrast to the results given in Table 10, where high temperatures between stem elongation and tassel emergence showed stronger negative correlations to yield than in the following phases. Also, the fact that the simulated available soil water content was not identified as a significant factor correlating with yield is in contrast to another study (Kern et al., 2018). The observation that the simulated soil water content showed hardly any significant correlations, but precipitation did, could be an indication that this parameter was not correctly calculated with regard to phenology. In Kern et al. (2018) the simulated soil water content was included in the modelling as a statistically significant factor for the months July and August. Since, however, not the months but phenological phases were considered here, this could explain the difference between the results. Another aspect that may lead to differences is that the study was carried out in Hungary, where the climate is much more continental than in Bavaria. The summers are drier, so the variation of the soil water content during the vegetation period certainly has a higher influence on yield than in Bavaria. The predominantly positive correlation between yield and precipitation for maize in the Soil-Climate-Areas and the negative correlation for temperatures may indicate that drought rather than heat was a yield limiting factor for maize. The Hungarian study confirmed this assumption, in which soil moisture correlated positively with maize yields in months with little precipitation (Kern et al., 2018). Furthermore, the observation that maize reacted more sensitive to dry conditions than to heat agrees with other results (Jin et al., 2016; Lobell et al., 2011a; Webber et al., 2018).

Finally, correlations underlying this analysis will be discussed. It is known that both wheat and maize have temperature optima up to which increased temperatures are beneficial to growth and that after exceeding the optimum, negative relationships are found leading to lower yields (Diepenbrock et al., 2016; Porter and Gawith, 1999; Sánchez et al., 2014; Wardlaw, 1974). Therefore, a possible quadratic relationship should be included in an upcoming analysis. Moreover, calculations of weather indices such as heat days, which also allow to test for correlations between yield and the environment, would be plausible. However, in this study, no indices were intentionally calculated, as the statistical modelling should be based on simple relationships between environmental factors and yield. Differences regarding correlations between abiotic factors and yield within Soil-Climate-Areas - if not already mentioned - were not remarkable. The analysis supported existing findings on yield limiting factors during phenological phases for both crops in Bavaria. Furthermore, the analysis showed different negative correlations between temperature and wheat yield and temperature and maize yield. The correlation coefficients between maize and temperature were more negative than the coefficients between wheat and temperature.

In practice, there is a high interest in identifying those factors during phenological phases which have a particularly strong correlation with low or high yields in Bavaria. The results from section 4.2.5 were related to high or low yields in the Bavarian Soil-Climate-Areas. For wheat, a strong positive correlation between the median available soil water content during phenological phases and low yield was observed. This indicated if soil water contents are too high in the first three phenological phases, low yields can be observed in the Bavarian Soil-Climate-Areas. On the other hand, positive correlations between soil water content in the first two phenological phases and high wheat yields in Bavarian Soil-Climate-Areas were observed. From these two observations it could be concluded that high median soil water contents during the first three or two phenological phases were associated with both low and high yields, so that a correlation with high yields could be observed up to a certain level of the soil water content and the correlation was reversed above a certain level of the soil water content. That the excess of water in general was a major constraint for crop yields was observed by Setter and Waters (2003). However, the sensitivity of crops to excess water differs at different stages of growth (Cannell et al., 1980; Shao et al., 2013). In the study of Cannell et al. (1980) it was found that wheat reacted most sensitive to the excess of soil water soon after germination. Singh (1981) however identified as most critical phase of wheat concerning soil moisture the period between the beginning of emergence and the beginning of heading. Both studies revealed that the excess of water was associated with low yields, especially in the earlier phenological phases, which agrees with the results of this thesis. On the other hand, the fact that water is needed at the beginning of germination (Nickl et al., 2014) is also supported by the results of this thesis. Another correlation that was highlighted was the negative correlation between temperature and high wheat yields between sowing and emergence. The negative correlation was related to the vernalization requirements. Similar correlations between low maize yields and soil water contents were observed for maize. Between emergence and flowering, high soil water contents were related to low maize yields. Here, too, this could be explained by excessive soil water contents.

5.3 Evaluation of optimal time intervals using statistical models

5.3.1 Evaluation of time variable factors regarding model results

Typically regression-based yield modelling approaches use average weather data over the entire growing season or average values of particular months (Hansen, 1991; Lobell, 2010; Lobell and Burke, 2010; Schlenker and Lobell, 2010; Schlenker and Roberts, 2009). While recent process-based crop growth models studies address the influence of the spatial and temporal aggregation effect on yield levels (Batchelor et al., 2002; Heimfarth et al., 2012; Hoffmann et al., 2016; Kuhnert et al., 2017; Maharjan et al., 2019; Porwollik et al., 2017), statistical yield modelling had hardly investigated effects of the temporal aggregation of input variables (Schlenker and Roberts, 2009; van Bussel et al., 2011b). One study aggregated climate variables over different time intervals to explore the effects of temporal aggregation of predictor variables on grain maize yields in Switzerland using statistical crop models (Holzkämper et al., 2012). The results of this thesis (Figures 19 - 22) reveal that different findings were obtained depending on different temporal aggregations of predictor variables used for statistical crop modelling. However, the variations were small. Considering the longer computational time required for the evaluation of using weather variables with a higher temporal resolution, the results cannot not be regarded as economical. The analysis showed that the established method of using annual averages or monthly averages within statistical yield modelling was appropriate, whereas monthly averages provided better results than annual values. This observation corresponds with the results of the study carried out by Holzkämper et al. (2012). Scian (2004) reported for wheat that the coefficient of variation in the 10 day model was generally higher than for the model which was based on crop phases. This thesis used the RMSE as a model quality parameter. For maize the RMSE of 44 dt ha^{-1} for the 10 day model performed better than the crop phase model which delivered an RMSE of 49 dt ha^{-1}. Contrary to this, the results for wheat were lower for the crop phase model with an RMSE of 5.8 dt ha^{-1} and were higher for the 10-day model with an RMSE of 6 dt ha^{-1}. Results reported by Scian (2004) were not consistent. For truncated models for example the predictive equation revealed to be better for phenological phases than for 10 days intervals. Evidence that the model results for time intervals were not always consistent indicated that factors other than the temporal aggregation of abiotic factors could be more important for yield. Variable disaggregation increases the risk of overfitting and therefore the results of temporally disaggregated predictor variables like e.g. ten days periods were probably not better than monthly aggregations of abiotic factors. Furthermore the model bias can be increased through the disaggregation of abiotic factors because of increased problems of multicollinearity which could result in biased model coefficients. Apparently, the intervals of the temporal aggregation of abiotic factors were related to the sample size. The sample size of 1500 used in this thesis meets the requirement of being large enough for testing different time intervals (Holzkämper et al., 2012). Concerning autocorrelation and multicollinearity it can be assumed that abiotic factors will show the same multicollinearities in the future or at another location, i.e. another county in Bavaria. The increase in temperature for example leads to an increase in radiation. A further explanation for similar results obtained from different temporal aggregations of abiotic factors could be due to the response variable, namely the yield. It was available only once for each year and each county. If single values of a weather variable had the same effect on yield as the value of the aggregate of this weather variable - no matter at what time it occured in the vegetation period - aggregated values could be used instead of single values for linear models. However, individual values reflected the variability of abiotic factors. Experimental results and simulations have shown that the change in temperature variability has the same effect on the development and growth of wheat as the change in the mean value (Porter and Semenov, 2005). If the variability of an environmental factor has the same effect on growth and development of a crop as the mean of the same environmental factor, the inclusion of the variability may not improve the model. This statement is consistent with results from this thesis. In contrast, other studies argued that the inclusion of the variability of environmental factors is necessary to predict the impact of climate change on crop development and yield (Moriondo et al., 2011; Rigby and Porporato, 2008; Semenov and Porter, 1995). Only a few days of extreme temperatures above 32°C around the flowering stage can drastically reduce the yield of crops (Semenov and Shewry, 2011; Wheeler et al., 2000). Changes in the variability of temperature can influence dry matter production of wheat. Both, high and low temperatures, decrease the rate of dry matter production of wheat and can cause production to stop (Grace, 1988). Maize for example responds to temperatures above 36°C during flowering with a reduced pollen viability (Decker et al., 1986). Moreover, in another study, which evaluated the influence of the temporal aggregation of abiotic factors, other output factors such as biomass were included in addition to the yield level (van Bussel et al., 2011b). This supports the assumption that one output variable per year and location is not sufficient to use weather data with a higher temporal resolution. The challenge to assess the influence of the temporal aggregation of abiotic factors on the quality of yield predictions is that yields are only observed once a year. Weather, on the other hand, is recorded continuously throughout the year and can have different effects on yield prediction due to various temporal aggregation possibilities of abiotic factors (Blanc and Schlenker, 2017). In addition to this aspect, the frequently assumed linear relationship between input and output variables is considered as being critical, since Schlenker and Roberts (2009) already demonstrated a non-linear relationship between the usage of daily temperature and yield. They described non-linear relationships between daily weather data and yield levels. Concerning further analyses the need to recognise the importance of variability and its interaction with the nonlinear plant growth aspects will have to remain in the focus (Porter and Semenov, 2005). Hence, it has to be emphasized that the results in section 4.3.3 cannot better reflect yield volatility the finer the temporal aggregation of the input variables is and thus the variability has to be taken into account. Perhaps this is due to the above mentioned assumed linear relationship between input and output variables, or, as already postulated, due to the same influence of a value on the response variable no matter how it was aggregated over time. The limited benefit of variable disaggregation found in this thesis could also probably be due to the fact that statistical models are necessarily extremely simplified compared to process based models (Holzkämper et al., 2012). Process-based models use variables that are dissaggregated to daily values and are a common method for quantifying the influence of climate variability on crop yields (Siebert et al., 2017). But many statistical studies considere climate predictor variables aggregated over monthly or seasonal periods and they could capture climate-yield relationships (Albers et al., 2017; Chen et al., 2004; Gornott and Wechsung, 2015; Kern et al., 2018; Lobell, 2010; Lobell and Burke, 2010; Lobell and Field, 2007; Lobell and Ortiz-Monasterio, 2007; Michel and Makowski, 2013; Roberts et al., 2017; Shi et al., 2013). All in all monthly aggregates of abiotic factors were used for further modelling approaches in this thesis because this allowed to establish relationships based on monthly values between abiotic factors and yield levels. Furthermore, there were no large differences in the results of the temporal aggregates, why the choice of monthly aggregates as predictors seemed appropriate.

5.3.2 Influence of the selection of the vegetation period on model results

The inclusion of phenology showed no improvement in the predictability of yields. On the one hand, this could be due to the data basis of the phenological data, which could be subject to errors with regard to the duration of a phase or the entire vegetation period. The discussion about the quality of phenological data in section 5.1.3 denied this argument as a possible reason why yield modelling was not improved by considering phenological phases. Rather, other studies indicated that harvest or sowing times may have been delayed due to machine availability or that sowing and harvesting times were also dependent on environmental conditions (Estrella et al., 2007; Rezaei et al., 2018). Instead, reasons for similar model results were seen in the relationship between environmental variables and phenology. Several other studies already identified environmental factors as main driver of the phenological development of crops (Chmielewski et al., 2004; Chmielewski and Köhn, 2000; Estrella et al., 2007; Menzel and Fabian, 1999; Siebert and Ewert, 2012; van Bussel et al., 2015). Consequently, abiotic factors aggregated on the basis of the phenological calendar were not able to predict crop yields better than abiotic factors aggregated on the basis of the calendar, because the assumed calendar dates overlapped with the phenological development of a crop. In the case of wheat in particular, modelling was not better when the whole vegetation period, which lasted from about the beginning of October to the end of July, was taken into account. The important time period for modelling purposes started at March. In addition the yield volatility was not better reflected by the phenologically represented vegetation period than by an assumed vegetation period from March to July. The results of the two methods “phenology” and “calendar” did not differ very much, why the evaluation of the phenological data set for the further usage in statistical yield modelling was not considered to be better. However, this result was consistent with results reported by Dixon et al. (1994) who showed that a spatially and temporally differentiated classification on the basis of phenological developmental stages showed only a minor effect on the predictive capabilities of statistical models. Compared to the study by Scian (2004) regression models referring to a calendar period provided better fits than models that took phenological phases into account. And in the study of Scian (2004) it was concluded that the explained variability of yields in crop models was higher for 10-day models than that from models based on crop phases. There were several other reaons why the inclusion of abiotic factors based on phenology did not improve modelling results. Although the relationship between, for example, temperature and phenological development is well known (Cleland et al., 2007; Estrella et al., 2007; Heuer et al., 1978; Hodges, 1990; Maytín et al., 1995; McMaster and Smika, 1988; McMaster and Wilhelm, 1997; Menzel and Fabian, 1999; Shim et al., 2017; Tao et al., 2006), other factors like changes in management, modified sowing dates and changing cultivars could overlay the phenological development and thus the climate signal (Liu et al., 2010, 2013; Rezaei et al., 2018). It is not possible to determine which factor, the environment, the cultivar or changed sowing dates, finally altered phenological phases. In particular, information on changes in variety characteristics in relation to their phenological development is very limited (Rezaei et al., 2018). This thesis did not account for changes in the choice of varieties over time although the choice of cultivars influence the duration of phenological phases (Hilden et al., 2005; Liu et al., 2010, 2013; Rezaei et al., 2018; Xiao et al., 2016). In Finland the vegetation period for wheat was extended by about 10 days due to a new cultivar (Hilden et al., 2005). In northern China, the reproduction phase of maize was extended by about four days per decade due to cultivar change and was thus considered as adaptation strategy to climate change (Xiao et al., 2016). By assuming that the varieties did not change, yield simulations based solely on abiotic factors during phenological phases could generate errors and were therefore possibly not better than yield simulations based on calendars.

5.4 Yield predictions of winter wheat and silage maize in Bavaria

5.4.1 Evaluation of statistical model performance

The statistical models used in this thesis: time-series, panel models and cross-section models were based on previous research using these or comparable model subtypes to predict yields (Lobell et al., 2011b; Lobell and Burke, 2010; Michel and Makowski, 2013; Roberts et al., 2017). However, the implementation of time series models for yield predictions did not provide satisfactory results for both aggregation levels, Soil-Climate-Areas and counties. Although similarly high R^2 values were achieved compared to other studies (Gornott and Wechsung, 2016, 2015; Lobell, 2010; Lobell and Burke, 2010), the negative NSE indicated that the mean of the time-series estimated the yield better than the model used. It is worth noting that in the studies of Lobell (2010) and Lobell and Burke (2010) the NSE was not used as a quality measure, therefore a statement about the quality of the predictions from these studies cannot be made. In contrast in the analyses of Gornott and Wechsung (2015, 2016), NSE values for time-series models in Bavaria were obtained. These were NSE = 0.77 for time-series models of wheat and NSE = 0.64 for panel data models of maize (Gornott and Wechsung, 2015), and NSE = 0.72 for wheat and NSE = 0.67 for maize (Gornott and Wechsung, 2016). Nevertheless, one reason why time-series models were not successfully calculated in this thesis might be the large number of independent factors or degrees of freedom that initially served as input parameters. Since each study area had only 25 yield data, it would have been useful for the purpose of the study to limit the number of predictors to a few. The number of predictors used to fit a model should be less than a fourth of the number of samples (Harrell, 2015). However, the usage of less predictors for the model calculation would mean that the time-series models would not be comparable with panel and cross-section models calculated for Bavaria. Yet one aim of this study was to allow for a comparison of models and their predictive ability. Therefore, the time series model was not modified and not used for future yield predictions in this thesis. However with less predictor variables a calculation would have been possible.

The panel models revealed that yield modelling for wheat and maize was possible in Bavaria. They were able to adequately reproduce the yield history for different counties and Soil-Climate-Areas with one set of parameters for each crop and each spatial aggregation level. For the modelling of yields in Bavaria abiotic factors with a monthly temporal resolution and their quadratic terms were used. In contrast to other statistical models, the panel models allow for the inclusion of fixed effects (Blanc and Schlenker, 2017). The application of fixed effects in a panel model allows to control unobservable variables in the regression (Hoch, 1962; Mundlak, 1961). In this thesis the fixed effects were group specific which means that unobserved factors are constant over time within each group. The groups in this thesis consisted either of counties or Soil-Climate-Areas. An example for a known time invariant factor of a county is the median available soil water capacity of this county. The usage of group fixed effects absorbs any time-invariant confounding variation which means that these factors do not have to be included in the panel model. A further advantage of fixed effects is, if limited knowledge about factors influencing the response variable exists and these factors are time-invariant they will not affect modelling (Blanc and Schlenker, 2017). Nevertheless, time-invariant confounding variations across groups, such as the median available field water capacity (Hu and Si, 2013, 2016; Mittelbach and Seneviratne, 2012) influence the dependent variable. If only one factor, such as the median available field water capacity, has been relevant for the yield of a county or Soil-Climate-Area and no other factors influence yield, the result would always be the same yield level per county or Soil-Climate-Area. The temporal invariance of the median available field water capacity would have ensured this. In practice, it was observed that yields are volatile. This volatility is caused among other things by the variation of the weather. In panel models one underlying assumption is that the response regarding one predictor is the same for all sites (Blanc and Schlenker, 2017). The response was expressed by the beta coefficient. Differences in the response variable were therefore only obtained by the different values of the predictor itself. Different cultivars of a crop, however, may have shown different thresholds with respect to abiotic factors, e.g. temperature. The panel model used in this thesis simulated that the two crops wheat and maize had the same threshold values throughout Bavaria and thus it was simulated that the same cultivars were grown. However, in Bavaria, different expressions of abiotic factors were observed. Consequently, for panel models differences in yield response were observed for Soil-Climate-Areas and counties in Bavaria. Modelled maize yields reacted spatially more heterogeneous than wheat yields. The panel models captured wheat yields better than those models which were calculated for maize. This observation covered both average yields and the variability of yields. Opposite observations were obtained by Gottschalk et al. (2018) who applied a process-based eco-hydrological model for the entire state of Germany. Both average yields and yield variability were simulated better for maize than for wheat (Gottschalk et al., 2018). However, results obtained from statistical modelling by Gornott and Wechsung (2016, 2015) predicted for Germany the mean as well as the variability of wheat yields better than those for silage maize. Both, the observations and the simulations revealed lower interannual variability for wheat than for maize. This suggested that wheat was more capable of dealing with variable weather than maize (Webber et al., 2018). Furthermore, several studies have shown that maize reacted more sensitive to drought stress than wheat (Daryanto et al., 2016; Gottschalk et al., 2018; Webber et al., 2018). Especially in the last few years of the crop statistics that was used in this thesis, low yields were observed for maize. In these years a severe spring dryness combined with high temperatures could be observed. Warming during the vegetative stage of maize leads to a reduction in the length of the growing period. The reduced length of the growing period has a negative impact on crop production and yield (Liu et al., 2010; Lobell and Field, 2007). The volatility of the predicted maize yields were particularly high in *Nordwestbayern Franken*. Here a lower median available field water capacity was observed than in many other Soil-Climate-Areas. This indicated that maize was particularly sensitive to drought and that the model was not able to sufficiently capture this sensitivity. Maize yields were overestimated in low yield years.

Individual models for high, low and medium years did not result in more accurate yield predictions than all years combined in a single model, as the variation of yield levels were higher in the overall model. A higher variability of yield levels ensures that the model can predict poor or good years better than a model that essentially works with yields at a similar level. Outliers which represented high or low yield years ensured that models recognize upwelling or downwelling peaks and will therefore better reproduce such years in the future. In applying regression methods, outliers are discarded and extreme values are generally smoothed (Scian, 2004). Especially because outliers and extreme values, i.e. yields that are particularly high or low, are so important for climate impact studies, the inclusion of these extreme yields in the overall model leads to better modelling results.

5.4.2 Average yields and yield variations

The results shown in section 4.2.1 reveal that differences in average yield levels were mainly explained by differences in the median available field water capacity across Bavarian soils, for both wheat and maize. The higher the median available field water capacity, the higher the yield. This observation for example is in contrast to the statement that weather factors are more relevant to mimic crop yield uncertainties than soil variations when considering large areas on the province or district level (Etwire et al., 2013; Hansen and Indeje, 2004; Jones et al., 2000). However, the observed positive relationship between average yields and soil quality in Germany is supported by the study conducted by Lüttger and Feike (2018). It is assumed that adverse weather conditions lead to lower yields in soils with lower median available field water capacity and therefore they showed a lower buffering capacity towards adverse weather conditions than soils with a higher median available field water capacity (Folberth et al., 2016). Nevertheless, the analyses from 4.1.4 reveal that under adverse weather conditions yields were also reduced on soils with a high median available field water capacity. Although adverse weather conditions reduced yields on all soils, a more differentiated pattern was obtained by considering yield stability. For silage maize, yield stability decreased on soils with a low median available field water capacity. Whereas the yield stability of wheat was not significantly reduced on sites with a lower available field water capacity. This observation indicates again that maize was more prone to dry conditions than wheat and is in accordance with findings of other studies (Daryanto et al., 2016; Gottschalk et al., 2018; Webber et al., 2018). Moreover, maize is susceptible to water deficits especially during the phase of flowering (Araus et al., 2012; Rattalino Edreira and Otegui, 2013; Sánchez et al., 2014), while wheat requires most water during the phase from shooting to heading and during the phase from heading to milky ripeness (Zhang et al., 1999). The phenological phases in which wheat is sensitive to water deficits were thus observed earlier in the year than for maize. For the observed period, the available soil water is generally sufficiently filled up until May. For maize, the flowering time was at the end of June, when the available soil water was already decreased and thus reduced yield. Interannuel yield variability was determined by the varying intensity of environmental factors, while average yield differences in Bavaria were mainly explained by the different median available field water capacity. For wheat, the contribution of the median available field water capacity to explain the mean yield level was higher than for maize. Yield volatility was higher for maize on soils with a low median available field water capacity than on soils with a high median available field water capacity. In addition to the available field water capacity, which also determines the buffering capacity of the soil in dry conditions, other factors must have influenced the interannual yield variations. The studies of Etwire et al. (2013), Hansen and Indeje (2004) and Jones et al. (2000) emphasize, that weather factors were more relevant for the differences in yields in between years than the buffer capacity of soils. On the other hand, Porter and Semenov (2005) reported that for winter cereal on heavy soils 12% of the yield variation was due to the variation in temperature, radiation and rainfall and 17% of thev yield variation was due to lighter soils. Accordingly, soil conditions led to differences in yield variability but were not the main factor explaining the variability. In fact, the interannual variability of yield can be influenced by several other factors like weeds, pests and diseases (Gregory et al., 2009) or management decisions regarding fertilizer-use, crop-rotations (Brisson et al., 2010; Calviño et al., 2003) or choice of cultivars (Rezaei et al., 2018). Moreover, interannual variability of yields may also have occurred due to different spatial aggregation and thus may not have been recorded completely.

5.4.3 Aggregation effects

Due to the spatial aggregation of sites, higher explanatory values were achieved in the modelling process (Albers et al., 2017; Gornott and Wechsung, 2016, 2015; Gottschalk et al., 2018). With regard to the spatial aggregation, no improved results were achieved for maize by geographically larger study areas. However, other studies obtained higher explanatory power of the model parameters by spatial aggregation (Albers et al., 2017; Gornott and Wechsung, 2016, 2015; Gottschalk et al., 2018). The model's response variables were spatially autocorrelated since the sites were adjacent to each other (Bakker et al., 2005). As long as response variables are autocorrelated, aggregation leads to a leveling out of outliers and hence the model fits are increased (de Koning et al., 1998; Overmars et al., 2003). For silage maize this observation was not confirmed. The aggregation did not result in a higher explanatory power of the model. One reason could be that differences in yield levels showed similar patterns for Soil-Climate-Areas and counties. It seemed that yield differences between the counties and the Soil-Climate-Areas were comparable. Another reason may be that the yield statistics on the county level in Bavaria were not representative. In some counties only one or two yield data were reported, whereas in other counties more yield data did contribute to the statistics. With winter wheat, however an aggregation effect was clearly observed, which means that yields could be better predicted for Soil-Climate-Areas than for counties. The spatial aggregation used in this thesis was based on Roßberg et al.'s (2007) definition of areas with similar soil and climate conditions. The fact that the spatial aggregation did not provide better results for prediction of maize yields suggested that Roßberg's et al. (2007) classification of areas with similar climatic and soil conditions was possibly more based on site requirements of wheat than of maize. Alexandrov and Hoogenboom (2001) showed also better model results for spatial aggregations based on climatically homogenous areas. However, the aggregation technique is also used to filter out influences like pests and diseases. Other influences like pests and diseases could bias model results at the county level. The fact that no better explanation for maize was obtained by spatial aggregation suggests that maize yields at the county level were primarily influenced by climatic factors. The shorter growing season of maize compared to wheat may reduce the complex influence of several other growth drivers. Furthermore maize has a lower susceptibility to diseases than wheat (Gottschalk et al., 2018). On the other hand, it appears unlikely that management inputs from farmers have the same effect throughout Bavaria. Therefore, it is possibe that the estimated coefficents of maize yields are not fully representative.

5.4.4 Multicollinearity between abiotic factors and statistical tests

Abiotic factors explaining yield differences were collinear. There was a clear effect observed of collinearity on the size, perhaps the sign, and also the standard error of the regression coefficients that were associated with these collinear variables and therefore their interpretation (Johnston et al., 2018). The parameter estimates could be unstable, standard errors on estimates can be inflated and consequemtly the inference statistically biased (Dormann et al., 2013). Collinearities complicate the interpretation of multiple regressions because it is not clear which factor influences the yield to what extent (Jeong et al., 2016; Peng et al., 2004; Sheehy et al., 2006). The relative importance of variables is difficult to assess (Dormann et al., 2013). Moreover they show in many locations low signal-to-noise ratios in yield or weather records (Lobell and Burke, 2010). In some situations the effects of collinearity have limited impact on the modelled results (Dormann et al., 2013). Collinearity has less impact if stationarity is assumed. Stationarity indicates that factors that influence each other will continue to influence each other in the future, thus relationships will remain the same in the future (Lobell and Burke, 2010). For radiation and temperature, this means that the temperature will continue to rise in the future due to an increase in radiation. Because of collinearity, the evaluation of statistical models on a range of different spatial scales was regarded as useful (Lobell and Burke, 2010). However, extrapolation beyond the geographical or environmental range of the data is susceptible to serious errors, as the patterns of collinearity are likely to change (Dormann et al., 2013). In this thesis, different spatial levels were the subject of the analyses. The different spatial observations revealed that similar factors were selected for the model calculation and thus the same collinearities existed for the investigated areas. However, Dormann et al. (2013) reported that collinearity between environmental factors was spatially not constant. Thus, the assumption that factors will have the same relationship with each other in the future or for the whole investigated area entails a number of risks. On the one hand, there was a possibility that some factors react differently than previously assumed, e.g. this could be possible after triggering a certain threshold value which was not observed so far. On the other hand, adaptation strategies by farmers were neglected. This could lead to a change in the relationship between two factors. However, in a discussion of when one can safely ignore collinearity Allison (2012) and O’Brien (2016) identified three situations when collinearity can be ignored. One of the assumption was if one or more of the variables was a power of another variable included in the regression, collinearity can be ignored. Thus the variation inflation factor (vif) is calculated for the simple factors that are included in the models. Their quadratic terms were not taken into account for calculations of the vif. In summary, simple abiotic factors used in the panel models were not collinear to each other and thus can be used in panel models. Since the relative importance of variables is difficult to assess (Dormann et al., 2013), the following section was limited to simple abiotic factors that were included in the panel models and not their quadratic terms.

5.4.5 Factors to parametrize models

Using the panel model to predict yields also enabled the determination of the importance of each variable in the model. Due to collinearities that existed between simple and quadratic factors in the model, only the importance of the simple factors was addressed. Nevertheless, it should be kept in mind that collinearities complicate the interpretation of multiple regressions because it is not clear which factor influences the yield to what extent (Jeong et al., 2016; Peng et al., 2004; Sheehy et al., 2006). The quadratic expressions of abiotic factors indicated in particular that relationships can become negative once a certain threshold value is exceeded. This statement is also consistent with other findings (Butler and Huybers, 2012; Lobell et al., 2011a; Lobell and Burke, 2010; Michel and Makowski, 2013; Schlenker and Roberts, 2009). Too high temperatures for example reduce photosynthesis of wheat due to stomatal closure, thus reducing yield. Tables 23 - 25 show the importance of individual abiotic factors contributing to the predictive ability of the model. The factor that exerted most often the greatest influence on yield levels was the temperature maximum of a month. From findings of other studies it becomes evident, that the inclusion of extreme temperatures like the maximum temperature could improve the performance of models (Butler and Huybers, 2012; Carlson, 1990; Schlenker and Roberts, 2009). However the research from Prost et al. (2008) outlined that the usage of several variables rendered it difficult to select the most relevant variable to explain yield levels. Since maximum temperature was selected in most models, the assumption that it was the most important factor determining yield levels can be supported. Concerning other factors, the inclusion of the available soil water content did not have a large influence on the model results, but nonetheless effects were observed (Table 23 andTable *25*). It was conceivable that the inclusion of a soil water content index would have improved modelling. In the study by Peichl et al. (2018), influences of the soil water content index on the yield of up to 10% were reported. Nevertheless, the inclusion of the soil water content index as a further explanatory variable did not lead to closer relationships than those reported in this thesis. Similar results were reported by Scian (2004) who concluded that models with indices as variables were not more meaningful than models with simple averages of temperature and precipitation. The greatest positive influence on the yield of both crops was due to high temperatures in the months from June to August and radiation in June for winter wheat yields at the county level.

The calculated models explained between 61% and 80% of the variance of wheat and maize yields with an error level of maximum 5% on the aggregation level of Soil-Climate-Areas. For the county level the mean R^2 was 0.62 for wheat and 0.66 for maize. The remaining variance was explained by other parameters not accounted for in these models. This thesis did not account for other factors influencing the variance of yields, such as management or extreme events. Using the mean of the monthly abiotic factors for example did not account for extreme events, which also can be the cause of strong effects on yields. Aside from this the influence of pests and diseases on crop yield levels cannot be included in statistical models.

5.4.6 Challenges in yield predictions using panel models

The models responded to the influence of abiotic factors on yield levels. Furthermore an impact of future changes regarding the factors used in this thesis was assessed which means the model can be used to study possible effects of climate change on crop yields. Farmers can obtain an understanding of how their yield levels will possibly change in the future depending on the changes of the abiotic factors used in this thesis (see section 4.4.3). On the basis of the results, they will be able to consider if the future use of techniques such as irrigation will be necessary or not. Furthermore, there is a possibility to estimate from which moment the use of irrigation will be appropriate. Nevertheless the models share limitations. Climate models on which yield predictions are based, do not sufficiently account for climate extremes like drought because they are not represented directly in climate models (Mearns et al., 2001). But water shortages or dry periods lead to reduced yields (Brouwer et al., 1989; Sarto et al., 2017; Zampieri et al., 2017). Using climate models for yield predictions allows for the assessment of mean yield changes, because the mean changes of the climate parameters are used as basis. Therefore the predicted yield reductions reported in 4.4.3 refer to the predicted mean decrease of yield levels due to mean adverse weather conditions predicted for the future. Thus the yield levels in extreme years can be significantly lower. A further limitation of the model has to be attributed to the geography. The data which were used here for the estimation of parameters did not reflect relationships between abiotic factors and yield levels elsewhere (Jones et al., 2017). Thus the models are limited to Bavaria. However, the relationships underlying yield and abiotic factors could be relevant for other system responses within a similar climate. Another limitation of statistical models is that they cannot estimate adaptions or other changes (Jones et al., 2017; Lobell and Burke, 2010). As the model was intended to assess the influence of climate on yield levels, this limitation was not relevant for the objective of this thesis. For the purpose of completeness, however, this limitation is indicated. Other studies refer to the so-called “out of sample” limitations of statistical models (Boote et al., 1996; Gornott and Wechsung, 2016, 2015; Lobell and Burke, 2010; Roberts et al., 2017) which means the extrapolation of yield levels on the basis of unobserved abiotic factors in the past may lead to misleading conclusions in the future. Since more than 90% of the data on which the climate scenarios are based also existed in the data set of past observations, this factor is probably negligible and only relevant for values outside the measurement range.The models in this thesis allowed for future predictions and performed well in the context of yield variability (see section 4.4.1.2). Ensemble crop models were able to predict mean yields, but regarding yield variability they performed less well (Rötter et al., 2011). Schlenker and Roberts (2009) concluded that the processes behind plant growth and especially yield are very complex and cannot be analyzed by a regression analysis. But Lobell and Burke (2010) concluded that all statistical crop models assume underlying crop processes or mechanisms. This means for example that there is a priori knowledge of the correlation between temperature and yields. Angus et al. (1986) performed a survey of spring wheat development. They concluded that the developmental responses to temperature and photoperiod from emergence to anthesis were non-linear, though for sowing to emergence and for anthesis to crop maturity the response to temperature was linear. In this thesis a good example was the simplified process of the simulated available soil water content for such underlying processes between yield and available soil water content. Nevertheless the model was not able to address all factors that influence yields. Processes which were connected to a lack of fertilizer like initial nitrogen stress cannot be considered. Furthermore yield reductions due to wrong management cannot be addressed. All in all the models can be used to assess possible impacts of climate change on yield levels for different spatial aggregation levels in Bavaria. To assess the models and possible consequences of climate change on future yields more comprehensively, process-based models could be included for further analysis or random forest models. PLSR as a method for crop yield predictions did however not perform better as multiple regression models (Dormann et al., 2013).

6 Conclusions

6.1 Relationships between abiotic factors, phenological phases and yields of silage maize and winter wheat in Bavarian Soil-Climate-Areas

For both investigated crops, wheat and maize, the available field water capacity primarily accounted for the observed differences in yield, while for maize this seemed to be even more important than for wheat. In part the higher water need of maize may account for this. Wheat yields seem to be particularly affected by heat leading to accelerated maturation in the reproductive phase thus shortening the grain-filling phase. Very recent observations not accounted for in this work highlight also the importance of drought spells in the early season. The former observation, however, is in agreement with Semenov and Shewry (2011) who identified heat stress and not drought as a yield limiting factor for wheat in Europe. For maize, on the other hand, weather-related yield limitations might be also due to a lack of precipitation in decisive growth stages. In conclusion and supported by the frequent observation of close positive correlations between maize yield and precipitation in this thesis, water supply can be identified as yield limiting factor for maize. Furthermore, weather conditions seem to play an even more important role in determining maize yields than wheat yields.

6.2 Evaluation of optimal time intervals using statistical models

The evaluation of optimal time intervals for statistical modelling was based on linear relationships. Further investigation of the relationships between abiotic factors and yield might provide different results. For forthcoming statistical modelling relationships between abiotic factors and yield should be examined for all factors individually. As further yield influencing factor the weather variability should be considered, which was not considered by averaging weather data in the modelling of climate predictions. Changes of the variability of temperature for example had the same effect on the development and growth of wheat as changing its mean value (Porter and Semenov, 2005). Nonhebel (1994) concluded that with the usage of daily weather data different simulation results can be obtained as compared to using averaged values. Porter and Semenov (2005) reported that highly resolved weather variables have an even greater relevance in the modelling of extreme events. Since no better model results with high resolution weather variables were achieved in this thesis, it can be concluded that the relationships between environmental factors and yields were not sufficiently well modelled. For future modelling, especially high resolution weather data in the critical phases might be of importance. One possibility might be to combine daily weather data in critical vegetation phases with average values of abiotic factors. It became evident that aggregations on a monthly basis are adequate for the modelling of average yields. However, yields that were influenced by unfavorable weather conditions were better predicted than yields experiencing more favorable weather conditions. This might indicate that higher resolution weather data could improve the modeling results. In this work static time periods were not less suited compared to phenologically based time units for the statistical crop modelling.

6.3 Yield predictions of winter wheat and silage maize in Bavaria

The panel models calculated in this thesis allowed to predict future yields in Bavaria. However, model parameters are only valid for Bavaria and underlying the assumption that the relationships between collinear factors will not change. Overall, yields were well predicted. Results from literature are not so straightforward regarding the evaluation of statistical methods for yield predictions (Lobell and Burke, 2010; Schlenker and Lobell, 2010; Schlenker and Roberts, 2009; Shi et al., 2013). Contrasting findings regarding yield predictions were also achieved when considering other modelling techniques. Machine-learning methods or process-based models used for yield predictions performed often better (Jeong et al., 2016; Lobell and Burke, 2010; Roberts et al., 2017). But they also require more data and are not as convenient as statistical models. Another advantage of statistical models is that they can implicitly consider factors that are difficult to model for example pests and diseases (Gornott and Wechsung, 2015; Porter et al., 1991). The usage of statistical models enables the consideration of factors that are difficult to model due to a lack of knowledge of the underlying modelling processes.

Due to large differences in topography in Bavaria, a precipitation gradient is present that increases from north to south, whereas the temperature behaves in exactly the opposite way. This entails heterogeneous weather conditions in Bavaria. Both different weather conditions as well as different soil characteristics affect yields in Bavaria. The differences become more apparent by spatially aggregating on Soil-Climate-Areas. At county level, variations between yields can be observed, due to the increase of heterogeneous soil properties and the increase of different weather conditions among the individual counties. Interestingly climatically unfavorable years decreased yields throughout Bavaria. The yield statistics for the years 2016 to 2019 were not available at the time when this work was done. Including these more recent years characterized by an even wider range weather conditions and yields might be particularly rewarding in future work. In summary, this thesis allows for a better understanding of main drivers influencing mean yields across Bavaria, particularly highlighting the available field water capacity. Inter-annual variations are influenced particularly by precipitation and heat.

References

Abu-Mostafa, Y.S., Magdon-Ismail, M., Lin, H.T., 2012. Learning from Data: A Short Course. AMLBook.com.

Albers, H., Gornott, C., Hüttel, S., 2017. How do inputs and weather drive wheat yield volatility? The example of Germany. Food Policy 70, 50–61.

Alexandrov, V.A., Hoogenboom, G., 2001. Climate variation and crop production in Georgia, USA, during the twentieth century. Clim. Res. 17, 33–43.

Allison, P., 2012. When you can safely ignore multicollinearity. Stat. Horiz. URL https://statisticalhorizons.com/multicollinearity

Araus, J.L., Serret, M.D., Edmeades, G., 2012. Phenotyping maize for adaptation to drought. Front. Physiol. 3. https://doi.org/10.3389/fphys.2012.00305

Asseng, S., Ewert, F., Rosenzweig, C., Jones, J.W., Hatfield, J.L., Ruane, A.C., Boote, K.J., Thorburn, P.J., Rötter, R.P., Cammarano, D., Brisson, N., Basso, B., Martre, P., Aggarwal, P.K., Angulo, C., Bertuzzi, P., Biernath, C., Challinor, A.J., Doltra, J., Gayler, S., Goldberg, R., Grant, R., Heng, L., Hooker, J., Hunt, L.A., Ingwersen, J., Izaurralde, R.C., Kersebaum, K.C., Müller, C., Naresh Kumar, S., Nendel, C., O'Leary, G., Olesen, J.E., Osborne, T.M., Palosuo, T., Priesack, E., Ripoche, D., Semenov, M.A., Shcherbak, I., Steduto, P., Stöckle, C., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Travasso, M., Waha, K., Wallach, D., White, J.W., Williams, J.R., Wolf, J., 2013. Uncertainty in simulating wheat yields under climate change. Nat. Clim. Change 3, 827–832. https://doi.org/10.1038/nclimate1916

Asseng, S., Foster, I., Turner, N.C., 2011a. The impact of temperature variability on wheat yields. Glob. Change Biol. 17, 997–1012. https://doi.org/10.1111/j.1365-2486.2010.02262.x

Asseng, S., Foster, I., Turner, N.C., 2011b. The impact of temperature variability on wheat yields. Glob. Change Biol. 17, 997–1012. https://doi.org/10.1111/j.1365-2486.2010.02262.x

Bakker, M.M., Govers, G., Ewert, F., Rounsevell, M., Jones, R., 2005. Variability in regional wheat yields as a function of climate, soil and economic variables: Assessing the risk of confounding. Agric. Ecosyst. Environ. 110, 195–209. https://doi.org/10.1016/j.agee.2005.04.016

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

Barrios, S., Ouattara, B., Strobl, E., 2008. The impact of climatic change on agricultural production: Is it different for Africa? Food Policy 33, 287–298. https://doi.org/10.1016/j.foodpol.2008.01.003

Bassu, S., Brisson, N., Durand, J.-L., Boote, K., Lizaso, J., Jones, J.W., Rosenzweig, C., Ruane, A.C., Adam, M., Baron, C., Basso, B., Biernath, C., Boogaard, H., Conijn, S., Corbeels, M., Deryng, D., Sanctis, G.D., Gayler, S., Grassini, P., Hatfield, J., Hoek, S., Izaurralde, C., Jongschaap, R., Kemanian, A.R., Kersebaum, K.C., Kim, S.-H., Kumar, N.S., Makowski, D., Müller, C., Nendel, C., Priesack, E., Pravia, M.V., Sau, F., Shcherbak, I., Tao, F., Teixeira, E., Timlin, D., Waha, K., 2014. How do various maize crop models vary in their responses to climate change factors? Glob. Change Biol. 20, 2301–2320. https://doi.org/10.1111/gcb.12520

Batchelor, W.D., Basso, B., Paz, J.O., 2002. Examples of strategies to analyze spatial and temporal yield variability using crop models. Eur. J. Agron., Process Simulation and Application of Cropping System Models 18, 141–158. https://doi.org/10.1016/S1161-0301(02)00101-6

Bayerisches Landesamt für Statistik, (ed.), 2016a. GENESIS-Online Datenbank Themen. Land- und Forstwirtschaft, Fischerei. Ernte- und Betriebsberichterstattung (EBE); Feldfr. Grünland. Ernte: Kreise, Durchschnittlicher Hektarertrag, Fruchtart (Getreide), Jahre. [WWW Document]. URL https://www.statistikdaten.bayern.de/genesis/online/data?operation=previous&levelindex=3&levelid=1537794656419&levelid=1537794584998&step=2 (accessed 3.23.17).

Bayerisches Landesamt für Statistik, (ed.), 2016b. GENESIS-Online Datenbank Themen. Land-und Forstwirtschaft, Fischerei. Ernte-, Betriebsberichterstattung (EBE): Feldfr. Grünland. Ernte: Kreise, Durchschnittlicher Hektarertrag, Fruchtarten (Hülsen-, Hackfrüchte, Futterpflanzen, Handelsgewächse), Jahre. [WWW Document]. URL https://www.statistikdaten.bayern.de/genesis/online/data?operation=abruftabelleBearbeiten&levelindex=2&levelid=1537795735191&auswahloperation=abruftabelleAuspraegungAuswaeh-len&auswahlverzeichnis=ordnungsstruktur&auswahlziel=werteabruf&selectionname=41241-002z&auswahltext=%23Z-01.01.2015%2C01.01.2014%2C01.01.2013%2C01.01.2012%2C01.01.2011%2C01.01.2010%2C01.01.2009%2C01.01.2008%2C01.01.2007%2C01.01.2006%2C01.01.2005%2C01.01.2004%2C01.01.2003%2C01.01.2002%2C01.01.2001%2C01.01.2000%2C01.01.1999%2C01.01.1998%2C01.01.1997%2C01.01.1996%2C01.01.1995%2C01.01.1994%2C01.01.1993%2C01.01.1992%2C01.01.1991&nummer=3&variable=1&name=KREISE&werteabruf=Werteabruf (accessed 3.23.17).

Bayerisches Landesamt für Umwelt, (ed.), 2020. Mittelwerte des Gebietsniederschlags [WWW Document]. URL https://www.lfu.bayern.de/wasser/klima_wandel/bayern/niederschlag/index.htm (accessed 5.16.20).

BayStUV, (Bayerisches Staatsministerium für Umwelt und Verbraucherschutz), 2018. Bodenkundliche Landesaufnahme; Erwerb von Karten [WWW Document]. Bayernportal. URL http://www.freistaat.bayern/dokumente/leistung/326535653429 (accessed 9.26.18).

Biologische Bundesanstalt für Land- und Forstwirtschaft, Bundessortenamt und CHemische Industrie, 1989. Entwicklungsstadien mono-und dikotyler Pflanzen. BBCH Scale.

Birch, C.J., Hammer, G.L., Rickert, K.G., 1998. Temperature and photoperiod sensitivity of development in five cultivars of maize (Zea mays L.) from emergence to tassel initiation. Field Crops Res. 55, 93–107. https://doi.org/10.1016/S0378-4290(97)00062-2

Blanc, E., Schlenker, W., 2017. The Use of Panel Models in Assessments of Climate Impacts on Agriculture. Rev. Environ. Econ. Policy 11, 258–279. https://doi.org/10.1093/reep/rex016

Bonelli, L.E., Monzon, J.P., Cerrudo, A., Rizzalli, R.H., Andrade, F.H., 2016. Maize grain yield components and source-sink relationship as affected by the delay in sowing date. Field Crops Res. 198, 215–225. https://doi.org/10.1016/j.fcr.2016.09.003

Bonhomme, R., 2000. Bases and limits to using ‘degree.day’ units. Eur. J. Agron. 13, 1–10. https://doi.org/10.1016/S1161-0301(00)00058-7

Bonhomme, R., Derieux, M., Edmeades, G.O., 1994. Flowering of Diverse Maize Cultivars in Relation to Temperature and Photoperiod in Multilocation Field Trials. Crop Sci. 34, cropsci1994.0011183X003400010028x. https://doi.org/10.2135/cropsci1994.0011183X003400010028x

Boote, K.J., Jones, J.W., Pickering, N.B., 1996. Potential Uses and Limitations of Crop Models. Agron. J. 88, 704. https://doi.org/10.2134/agronj1996.00021962008800050005x

Boote, K.J., Jones, J.W., White, J.W., Asseng, S., Lizaso, J.I., 2013. Putting mechanisms into crop production models. Plant Cell Environ. 36, 1658–1672. https://doi.org/10.1111/pce.12119

Bradley, A.V., Gerard, F.F., Barbier, N., Weedon, G.P., Anderson, L.O., Huntingford, C., Aragão, L.E.O.C., Zelazowski, P., Arai, E., 2011. Relationships between phenology, radiation and precipitation in the Amazon region. Glob. Change Biol. 17, 2245–2260. https://doi.org/10.1111/j.1365-2486.2011.02405.x

Brisson, N., Gate, P., Gouache, D., Charmet, G., Oury, F.-X., Huard, F., 2010. Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. Field Crops Res. 119, 201–212. https://doi.org/10.1016/j.fcr.2010.07.012

Brouwer, C., Heibloem, M., 1986. Part II Determination of Irrigation water needs. Chapter 3: Crop water needs. Calculation of the crop water need. Indicative Values of crop water need., in: Irrigation Water Management: Training Manual No.3 Irrigation Water Needs.

Brouwer, C., Prins, K., Heibloem, M., 1989. Irrigation water management: irrigation scheduling. Train. Man. 4.

Bundesanstalt für Landwirtschaft und Ernährung, R. 423 M., Kritische Infrastruktur Landwirtschaf, 2018. Bericht zur Markt- und Versorgungslage Getreide 2018.

Butler, E.E., Huybers, P., 2012. Adaptation of US maize to temperature variations. Nat. Clim. Change 3, 68.

Çakir, R., 2004. Effect of water stress at different development stages on vegetative and reproductive growth of corn. Field Crops Res. 89, 1–16. https://doi.org/10.1016/j.fcr.2004.01.005

Calviño, P.A., Andrade, F.H., Sadras, V.O., 2003. Maize Yield as Affected by Water Availability, Soil Depth, and Crop Management. Agron. J. 95, 275–281. https://doi.org/10.2134/agronj2003.2750

Cannell, R.Q., Belford, R.K., Gales, K., Dennis, C.W., Prew, R.D., 1980. Effects of waterlogging at different stages of development on the growth and yield of winter wheat. J. Sci. Food Agric. 31, 117–132. https://doi.org/10.1002/jsfa.2740310203

Carlson, R.E., 1990. Heat Stress, Plant-Available Soil Moisture, and Corn Yields in Iowa: A Short- and Long-Term View. jpa 3, 293. https://doi.org/10.2134/jpa1990.0293

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

Chaves, M.M., 1991. Effects of Water Deficits on Carbon Assimilation. J. Exp. Bot. 42, 1–16. https://doi.org/10.1093/jxb/42.1.1

Chen, C.-C., McCarl, B.A., Schimmelpfennig, D.E., 2004. Yield Variability as Influenced by Climate: A Statistical Investigation. Clim. Change 66, 239–261. https://doi.org/10.1023/B:CLIM.0000043159.33816.e5

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

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

Choudhury, A., Jones, J., 2014. CROP YIELD PREDICTION USING TIME SERIES MODELS 15, 16.

Ciais, P., Reichstein, M., Viovy, N., Granier, A., Ogee, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., De Noblet, N., Friend, A.D., Friedlingstein, P., Grunwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., Valentini, R., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. Nature 437, 529–533. https://doi.org/10.1038/nature03972

Cirilo, A.G., Andrade, F.H., 1994. Sowing Date and Maize Productivity: II. Kernel Number Determination. Crop Sci. 34, cropsci1994.0011183X003400040038x. https://doi.org/10.2135/cropsci1994.0011183X003400040038x

Cleland, E.E., Chuine, I., Menzel, A., Mooney, H.A., Schwartz, M.D., 2007. Shifting plant phenology in response to global change. Trends Ecol. Evol. 22, 357–365. https://doi.org/10.1016/j.tree.2007.04.003

Cross, H., Zuber, M., 1972. Prediction of Flowering Dates in Maize Based on Different Methods of Estimating Thermal Units 1. Agron. J. 64, 351–355.

Daryanto, S., Wang, L., Jacinthe, P.-A., 2016. Global Synthesis of Drought Effects on Maize and Wheat Production. PLOS ONE 11, e0156362. https://doi.org/10.1371/journal.pone.0156362

de Koning, G.H.J., Veldkamp, A., Fresco, L.O., 1998. Land use in Ecuador: a statistical analysis at different aggregation levels. Agric. Ecosyst. Environ. 70, 231–247. https://doi.org/10.1016/S0167-8809(98)00151-0

de Wit, C.T., Centre for Agricultural Publications and Documentation (Wageningen), 1965. Photosynthesis of leaf canopies. Centre for Agricultural Publications and Documentation, Wageningen.

Decker, W.L., Jones, V.K., Achutuni, R., 1986. Impact of climate change from increased atmospheric carbon dioxide on American Agriculture (No. DOE/NBB-0077). Missouri Univ., Columbia (USA). Dept. of Atmospheric Science.

Deutsche Landwirtschafts-Gesellschaft (Germany : West), 1979. DLG-Mitteilungen. DLG-Verlag.

Deutsches Maiskomitee e. V., (DMK), 2017. Standortansprüche - klimatische Einflussgrößen - Temperatur [WWW Document]. URL https://www.maiskomitee.de/Produktion/Anbau/Standortanspr%C3%BCche (accessed 11.15.18).

Diepenbrock, W., Ellmer, F., Léon, J., 2016. Ackerbau, Pflanzenbau und Pflanzenzüchtung: Grundwissen Bachelor. UTB.

Dixon, B.L., Hollinger, S.E., Garcia, P., Tirupattur, V., 1994. Estimating Corn Yield Response Models To Predict Impacts Of Climate Change. J. Agric. Resour. Econ. 19, 1–11.

Donatelli, M., Srivastava, A.K., Duveiller, G., Niemeyer, S., Fumagalli, D., 2015. Climate change impact and potential adaptation strategies under alternate realizations of climate scenarios for three major crops in Europe. Environ. Res. Lett. 10, 075005. https://doi.org/10.1088/1748-9326/10/7/075005

Dormann, C.F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., Marquéz, J.R.G., Gruber, B., Lafourcade, B., Leitão, P.J., Münkemüller, T., McClean, C., Osborne, P.E., Reineking, B., Schröder, B., Skidmore, A.K., Zurell, D., Lautenbach, S., 2013. Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. Ecography 36, 27–46. https://doi.org/10.1111/j.1600-0587.2012.07348.x

Duveiller, G., Donatelli, M., Fumagalli, D., Zucchini, A., Nelson, R., Baruth, B., 2017. A dataset of future daily weather data for crop modelling over Europe derived from climate change scenarios. Theor. Appl. Climatol. 127, 573–585. https://doi.org/10.1007/s00704-015-1650-4

DWD, 1991. Anleitung für die phänologischen Beobachter des Deutschen Wetterdienstes, Vorschriften und Betriebsunterlagen, 17th ed. Deutscher Wetterdienst Offenbach.

DWD, C.D.C. (CDC), 2018a. Deutscher Wetterdienst Klima und Umwelt [WWW Document]. Offenb. Dtschl. URL ftp://ftp-cdc.dwd.de/pub/CDC/observations_germany/phenology/annual_reporters/crops/historical/ (accessed 7.28.17).

DWD, C.D.C. (CDC), 2018b. Eintrittsdaten verschiedener Entwicklungsstadien landwirtschaftlicher Kulturpflanzen von der Bestellung bis zur Ernte (Jahresmelder, historisch), Version v005 [WWW Document]. URL ftp://ftp-cdc.dwd.de/pub/CDC/observations_germany/phenology/annual_reporters/crops/historical/ BESCHREIBUNG_obsgermany_phenology_annual_reporters_crops_historical_de.pdf (accessed 1.11.18).

EC-JRC-AGRI4CAST, 2012. European Commission Joint Research Centre Interpolated Meteorological Data. Inst. Environ. Sustain. Monit. Agric. Resour. MARS Unit.

Edreira, J.I.R., Guilpart, N., Sadras, V., Cassman, K.G., van Ittersum, M.K., Schils, R.L., Grassini, P., 2018. Water productivity of rainfed maize and wheat: A local to global perspective. Agric. For. Meteorol. 259, 364–373.

Ehlers, W., 1996. Wasser in Boden und Pflanze: Dynamik des Wasserhaushalts als Grundlage von Pflanzenwachstum und Ertrag. Ulmer.

Eitzinger, J., Šťastná, M., Žalud, Z., Dubrovský, M., 2003. A simulation study of the effect of soil water balance and water stress on winter wheat production under different climate change scenarios. Agric. Water Manag. 61, 195–217. https://doi.org/10.1016/S0378-3774(03)00024-6

Erekul, O., Köhn, W., 2006. Effect of Weather and Soil Conditions on Yield Components and Bread-Making Quality of Winter Wheat (Triticum aestivum L.) and Winter Triticale (Triticosecale Wittm.) Varieties in North-East Germany. J. Agron. Crop Sci. 192, 452–464. https://doi.org/10.1111/j.1439-037X.2006.00234.x

Estrella, N., Sparks, T.H., Menzel, A., 2007. Trends and temperature response in the phenology of crops in Germany. Glob. Change Biol. 13, 1737–1747. https://doi.org/10.1111/j.1365-2486.2007.01374.x

Etwire, P.M., Al-Hassan, R.M., Kuwornu, J.K.M., Osei-Owusu, Y., 2013. Application of Livelihood Vulnerability Index in Assessing Vulnerability to Climate Change and Variability in Northern Ghana. J. Environ. Earth Sci. 3, 157-170–170.

European Environment Agency, 1995. CORINE Land Cover.

Eurostat, 2019a. Weizen und Dinkel nach Fläche, Erntemenge und Feuchtigkeitsgehalt [WWW Document]. Landwirtsch. Erzeugnisse Pflanzl. Erzeugnisse.

Eurostat, 2019b. Grünmais/Silomais nach Fläche, Erntemenge und Feuchtigkeitsgehalt [WWW Document]. Landwirtsch. Erzeugnisse Pflanzl. Erzeugnisse.

Eurostat, (ed.), 2015. Regions in the European Union: nomenclature of territorial units for statistics ; NUTS 2013/EU-28, Eurostat manuals and guidelines. Publ. of the Europ. Union, Luxembourg.

Ewert, F., Porter, J., Honermeier, B., 1996. Use of AFRCWHEAT2 to predict the development of main stem and tillers in winter triticale and winter wheat in North East Germany. Eur. J. Agron. 5, 89–103. https://doi.org/10.1016/S1161-0301(96)02012-6

FAO, 1977. Chapter 5 - Introduction to crop evapotranspiration (ETc). FAO Tech. Pap., FAO IRRIGATION AND DRAINAGE PAPERS Crop water requirements.

FAO, F., 2009. How to feed the world in 2050.

Folberth, C., Skalský, R., Moltchanova, E., Balkovič, J., Azevedo, L.B., Obersteiner, M., Velde, M. van der, 2016. Uncertainty in soil data can outweigh climate impact signals in global crop yield simulations. Nat. Commun. 7, 1–13. https://doi.org/10.1038/ncomms11872

FOODSECURITY -MARS4CAST, 2015. Agri4Cast Data [WWW Document]. Dly. Weather Data Crop Model. Eur. Deriv. Clim. Change Scenar. URL http://agri4cast.jrc.ec.europa.eu/DataPortal/RequestDataResource.aspx?idResource=24&o=d (accessed 4.10.19).

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food Security: The Challenge of Feeding 9 Billion People. Science 327, 812–818. https://doi.org/10.1126/science.1185383

Gornott, C., Wechsung, F., 2016. Statistical regression models for assessing climate impacts on crop yields: A validation study for winter wheat and silage maize in Germany. Agric. For. Meteorol. 217, 89–100.

Gornott, C., Wechsung, F., 2015. Niveauneutrale Modellierung der Ertragsvolatilität von Winterweizen und Silomais auf mehreren räumlichen Ebenen in Deutschland. J. Für Kult. 65, 248–254.

Gottschalk, P., Lüttger, A., Huang, S., Leppelt, T., Wechsung, F., 2018. Evaluation of crop yield simulations of an eco-hydrological model at different scales for Germany. Field Crops Res. 228, 48–59. https://doi.org/10.1016/j.fcr.2018.07.013

Grace, J., 1988. Temperature as a determinant of plant productivity. Symp. Soc. Exp. Biol. 42, 91–107.

Gregory, P.J., Johnson, S.N., Newton, A.C., Ingram, J.S.I., 2009. Integrating pests and pathogens into the climate change/food security debate. J. Exp. Bot. 60, 2827–2838. https://doi.org/10.1093/jxb/erp080

Handmer, J., Honda, Y., Kundzewicz, Z.W., Arnell, N., Benito, G., Hatfield, J., Mohamed, I.F., Peduzzi, P., Wu, S., Sherstyukov, B., 2012. Changes in impacts of climate extremes: human systems and ecosystems, in: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (Eds.)]. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge ; New York, pp. 231–290.

Hansen, J.W., Indeje, M., 2004. Linking dynamic seasonal climate forecasts with crop simulation for maize yield prediction in semi-arid Kenya. Agric. For. Meteorol. 125, 143–157. https://doi.org/10.1016/j.agrformet.2004.02.006

Hansen, L.T., 1991. Farmer Response to Changes in Climate: The Case of Corn Production [WWW Document]. J. Agric. Econ. Res. URL https://ageconsearch.umn.edu/record/138230 (accessed 6.20.19).

Hardacre, A.K., Turnbull, H.L., 1986. The Growth and Development of Maize (Zea mays L.) at Five Temperatures. Ann. Bot. 58, 779–787.

Harrell, F., 2015. Regression Modeling Strategies: With Applications to Linear Models, Logistic and Ordinal Regression, and Survival Analysis, 2nd ed, Springer Series in Statistics. Springer International Publishing. https://doi.org/10.1007/978-3-319-19425-7

Heimfarth, L.E., Finger, R., Musshoff, O., 2012. Hedging weather risk on aggregated and individual farm-level: Pitfalls of aggregation biases on the evaluation of weather index-based insurance. Agric. Finance Rev. 72, 471–487. https://doi.org/10.1108/00021461211277295

Heuer, G.R., Heermann, D.F., McKee, T.B., Benci, J.F., 1978. Predicting winter wheat phenology using temperature and photoperiod. Climatol. Rep. 78-2.

Hilden, M., Lehtonen, H., Bärlund, I., Hakala, K., Kaukoranta, T., Tattari, S., 2005. The practice and process of adaptation in Finnish agriculture.

Hoch, I., 1962. Estimation of Production Function Parameters Combining Time-Series and Cross-Section Data. Econometrica 30, 34–53. https://doi.org/10.2307/1911286

Hodges, T., 1990. Predicting Crop Phenology. CRC Press.

Hoffmann, H., Zhao, G., Asseng, S., Bindi, M., Biernath, C., Constantin, J., Coucheney, E., Dechow, R., Doro, L., Eckersten, H., Gaiser, T., Grosz, B., Heinlein, F., Kassie, B.T., Kersebaum, K.-C., Klein, C., Kuhnert, M., Lewan, E., Moriondo, M., Nendel, C., Priesack, E., Raynal, H., Roggero, P.P., Rötter, R.P., Siebert, S., Specka, X., Tao, F., Teixeira, E., Trombi, G., Wallach, D., Weihermüller, L., Yeluripati, J., Ewert, F., 2016. Impact of Spatial Soil and Climate Input Data Aggregation on Regional Yield Simulations. PLOS ONE 11, e0151782. https://doi.org/10.1371/journal.pone.0151782

Holzkämper, A., Calanca, P., Fuhrer, J., 2012. Statistical crop models: predicting the effects of temperature and precipitation changes. Clim. Res. 51, 11–21. https://doi.org/10.3354/cr01057

Holzkämper, A., Fossati, D., Hiltbrunner, J., Fuhrer, J., 2015. Spatial and temporal trends in agro-climatic limitations to production potentials for grain maize and winter wheat in Switzerland. Reg. Environ. Change 15, 109–122.

Holzkämper, A., Fuhrer, J., 2015. Wie sich der Klimawandel auf den Maisanbau in der Schweiz auswirkt. Agrar. Schweiz 6, 440–447.

Hu, W., Si, B., 2013. Soil water content evaluation considering time-invariant spatial pattern and space-variant temporal change. Hydrol. Earth Syst. Sci. Discuss. 10.

Hu, W., Si, B.C., 2016. Estimating spatially distributed soil water content at small watershed scales based on decomposition of temporal anomaly and time stability analysis. Hydrol. Earth Syst. Sci. 20, 571–587. https://doi.org/10.5194/hess-20-571-2016

Ibáñez, I., Primack, R.B., Miller-Rushing, A.J., Ellwood, E., Higuchi, H., Lee, S.D., Kobori, H., Silander, J.A., 2010. Forecasting phenology under global warming. Philos. Trans. R. Soc. B Biol. Sci. 365, 3247–3260. https://doi.org/10.1098/rstb.2010.0120

Iglesias, A., Quiroga, S., 2007. Measuring the risk of climate variability to cereal production at five sites in Spain. Clim. Res. 34, 47–57. https://doi.org/10.3354/cr034047

Iizumi, T., Sakuma, H., Yokozawa, M., Luo, J.-J., Challinor, A.J., Brown, M.E., Sakurai, G., Yamagata, T., 2013. Prediction of seasonal climate-induced variations in global food production. Nat. Clim. Change 3, 904–908. https://doi.org/10.1038/nclimate1945

Isik, M., Devadoss, S., 2006. An analysis of the impact of climate change on crop yields and yield variability. Appl. Econ. 38, 835–844. https://doi.org/10.1080/00036840500193682

Jamieson, P.D., Brooking, I.R., Semenov, M.A., Porter, J.R., 1998. Making sense of wheat development: a critique of methodology. Field Crops Res. 55, 117–127. https://doi.org/10.1016/S0378-4290(97)00072-5

Jasper, C., 2016. Nutzbare Feldkapazität landwirtschaftlicher Böden in Bayern. (Masterarbeit). Technische Universität München.

Jensen, M.E., Burman, R.D., Allen, R.G., American Society of Civil Engineers, Committee on Irrigation Water Requirements, 1990. Evapotranspiration and irrigation water requirements: a manual. The Society, New York, N.Y.

Jeong, J.H., Resop, J.P., Mueller, N.D., Fleisher, D.H., Yun, K., Butler, E.E., Timlin, D.J., Shim, K.-M., Gerber, J.S., Reddy, V.R., Kim, S.-H., 2016. Random Forests for Global and Regional Crop Yield Predictions. PLOS ONE 11, e0156571. https://doi.org/10.1371/journal.pone.0156571

Jin, Z., Zhuang, Q., Tan, Z., Dukes, J.S., Zheng, B., Melillo, J.M., 2016. Do maize models capture the impacts of heat and drought stresses on yield? Using algorithm ensembles to identify successful approaches. Glob. Change Biol. 22, 3112–3126. https://doi.org/10.1111/gcb.13376

Johnston, R., Jones, K., Manley, D., 2018. Confounding and collinearity in regression analysis: a cautionary tale and an alternative procedure, illustrated by studies of British voting behaviour. Qual. Quant. 52, 1957–1976. https://doi.org/10.1007/s11135-017-0584-6

Jones, J.W., Antle, J.M., Basso, B., Boote, K.J., Conant, R.T., Foster, I., Godfray, H.C.J., Herrero, M., Howitt, R.E., Janssen, S., Keating, B.A., Munoz-Carpena, R., Porter, C.H., Rosenzweig, C., Wheeler, T.R., 2017. Brief history of agricultural systems modeling. Agric. Syst. 155, 240–254. https://doi.org/10.1016/j.agsy.2016.05.014

Jones, J.W., Hansen, J.W., Royce, F.S., Messina, C.D., 2000. Potential benefits of climate forecasting to agriculture. Agric. Ecosyst. Environ. 82, 169–184. https://doi.org/10.1016/S0167-8809(00)00225-5

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L., Wilkens, P.W., Singh, U., Gijsman, A.J., Ritchie, J.T., 2003. The DSSAT cropping system model. Eur. J. Agron. 18, 235–265.

Kaylen, M.S., Wade, J.W., Frank, D.B., 1992. Stochastic trend, weather and US corn yield variability. Appl. Econ. 24, 513–518. https://doi.org/10.1080/00036849200000064

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N., Meinke, H., Hochman, Z., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18, 267–288.

Kern, A., Barcza, Z., Marjanović, H., Árendás, T., Fodor, N., Bónis, P., Bognár, P., Lichtenberger, J., 2018. Statistical modelling of crop yield in Central Europe using climate data and remote sensing vegetation indices. Agric. For. Meteorol. 260–261, 300–320. https://doi.org/10.1016/j.agrformet.2018.06.009

Kersebaum, K., Mirschel, W., Wenkel, K., Manderscheid, R., Weige, H., Nendel, C., 2009. Modelling climate change impacts on crop growth and management in Germany. Clim Var Model Tools Agric Decis-Mak Nova Sci Publ NY USA.

Kersebaum, K.C., Nendel, C., 2014. Site-specific impacts of climate change on wheat production across regions of Germany using different CO2 response functions. Eur. J. Agron., Land, Climate and Resources 2020. Decision Support for Agriculture under Climate Change 52, 22–32. https://doi.org/10.1016/j.eja.2013.04.005

Kirby, E.J.M., Porter, J.R., Day, W., Adam, J.S., Appleyard, M., Ayling, S., Baker, C.K., Belford, R.K., Biscoe, P.V., Chapman, A., Fuller, M.P., Hampson, J., Hay, R.K.M., Matthews, S., Thompson, W.J., Weir, A.H., Willington, V.B.A., Wood, D.W., 1987. An analysis of primordium initiation in Avalon winter wheat crops with different sowing dates and at nine sites in England and Scotland. J. Agric. Sci. 109, 123–134. https://doi.org/10.1017/S0021859600081065

Kirtman, B., Power, S.B., Adedoyin, A.J., Boer, G.J., Bojariu, R., Doblas-Reyes, F., Fiore, A.M., Kimoto, M., Meehl, G., Prather, M., Sarr, A., Schär, C., Sutton, R., van Oldenborgh, G.J., Vecchi, G., Wang, H.-J., Bindoff, N.L., Cameron-Smith, P., Clifton, O., Corti, S., Durack, P.J., Fichefet, T., García-Serrano, J., Ginoux, P., Guemas, V., Hawkins, E., Holland, M., Infanti, J., Ishii, M., Jacob, D., John, J., Klimont, Z., Knutson, T., Krinner, G., Lawrence, D., Lu, J., Murphy, D., Naik, V., Robock, A., Rodrigues, L., Sedláček, J., Slater, A., Smith, D., Stevenson, D.S., van Noije, T., Vavrus, S., Voulgarakis, A., Wild, O., Woollings, T., Young, P., Delecluse, P., Palmer, T., Shepherd, T., Zwiers, F., 2013. Projections and Predictability, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (Eds.)]. Cambridge University Press, Cambridge ; New York, pp. 953–1028.

Knapp, S., van der Heijden, M.G.A., 2018. A global meta-analysis of yield stability in organic and conservation agriculture. Nat. Commun. 9. https://doi.org/10.1038/s41467-018-05956-1

Kovats, R.S., Valentini, L.M., Bouwer, E., Georgopoulou, D., Jacob, K., Martin, E., Rounsevell, M., Soussana, J.F., 2014. Europe, in: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects.Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on ClimateChange[Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi,Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White(Eds.)]. Cambridge University Press, Cambridge ; New York, pp. 1267–1305.

Krause, P., Boyle, D.P., Bäse, F., 2005. Comparison of different efficiency criteria for hydrological model assessment. Adv. Geosci. 5, 89–97. https://doi.org/10.5194/adgeo-5-89-2005

Krishna, K.R., 2015. Agricultural Prairies: Natural Resources and Crop Productivity. CRC Press.

Kuhnert, M., Yeluripati, J., Smith, P., Hoffmann, H., van Oijen, M., Constantin, J., Coucheney, E., Dechow, R., Eckersten, H., Gaiser, T., Grosz, B., Haas, E., Kersebaum, K.-C., Kiese, R., Klatt, S., Lewan, E., Nendel, C., Raynal, H., Sosa, C., Specka, X., Teixeira, E., Wang, E., Weihermüller, L., Zhao, G., Zhao, Z., Ogle, S., Ewert, F., 2017. Impact analysis of climate data aggregation at different spatial scales on simulated net primary productivity for croplands. Eur. J. Agron., Uncertainty in crop model predictions 88, 41–52. https://doi.org/10.1016/j.eja.2016.06.005

Langensiepen, M., Hanus, H., Schoop, P., Gräsle, W., 2008. Validating CERES-wheat under North-German environmental conditions. Agric. Syst. 97, 34–47. https://doi.org/10.1016/j.agsy.2007.11.001

Lawes, R.A., Oliver, Y.M., Robertson, M.J., 2009. Integrating the effects of climate and plant available soil water holding capacity on wheat yield. Field Crops Res. 113, 297–305. https://doi.org/10.1016/j.fcr.2009.06.008

Leeper, R.A., Runge, E.C.A., Walker, W.M., 1974. Effect of Plant-Available Stored Soil Moisture on Corn Yields. I. Constant Climatic Conditions1. Agron. J. 66, 723–727. https://doi.org/10.2134/agronj1974.00021962006600060005x

Liu, Y., Wang, E., Yang, X., Wang, J., 2010. Contributions of climatic and crop varietal changes to crop production in the North China Plain, since 1980s. Glob. Change Biol. 16, 2287–2299. https://doi.org/10.1111/j.1365-2486.2009.02077.x

Liu, Z., Hubbard, K.G., Lin, X., Yang, X., 2013. Negative effects of climate warming on maize yield are reversed by the changing of sowing date and cultivar selection in Northeast China. Glob. Change Biol. 19, 3481–3492. https://doi.org/10.1111/gcb.12324

Lobell, D.B., 2010. Crop Responses to Climate: Time-Series Models, in: Climate Change and Food Security: Adapting Agriculture to a Warmer World [Lobell, D.B., Burke, M.B. (Eds.)], Advances in Global Change Research. Springer Netherlands.

Lobell, D.B., 2007. Changes in diurnal temperature range and national cereal yields. Agric. For. Meteorol. 145, 229–238. https://doi.org/10.1016/j.agrformet.2007.05.002

Lobell, D.B., Bänziger, M., Magorokosho, C., Vivek, B., 2011a. Nonlinear heat effects on African maize as evidenced by historical yield trials. Nat. Clim. Change 1, 42–45. https://doi.org/10.1038/nclimate1043

Lobell, D.B., Burke, M.B., 2010. On the use of statistical models to predict crop yield responses to climate change. Agric. For. Meteorol. 150, 1443–1452. https://doi.org/10.1016/j.agrformet.2010.07.008

Lobell, D.B., Field, C.B., 2007. Global scale climate–crop yield relationships and the impacts of recent warming. Environ. Res. Lett. 2, 014002. https://doi.org/10.1088/1748-9326/2/1/014002

Lobell, D.B., Hammer, G.L., McLean, G., Messina, C., Roberts, M.J., Schlenker, W., 2013. The critical role of extreme heat for maize production in the United States. Nat. Clim. Change 3, 497–501. https://doi.org/10.1038/nclimate1832

Lobell, D.B., Ortiz-Monasterio, J.I., 2007. Impacts of day versus night temperatures on spring wheat yields: A comparison of empirical and CERES model predictions in three locations. Agron. J. 99, 469–477. https://doi.org/10.2134/agronj2006.0209

Lobell, D.B., Ortiz-Monasterio, J.I., Asner, G.P., Matson, P.A., Naylor, R.L., Falcon, W.P., 2005. Analysis of wheat yield and climatic trends in Mexico. Field Crops Res. 94, 250–256. https://doi.org/10.1016/j.fcr.2005.01.007

Lobell, D.B., Roberts, M.J., Schlenker, W., Braun, N., Little, B.B., Rejesus, R.M., Hammer, G.L., 2014. Greater Sensitivity to Drought Accompanies Maize Yield Increase in the U.S. Midwest. Science 344, 516–519. https://doi.org/10.1126/science.1251423

Lobell, D.B., Schlenker, W., Costa-Roberts, J., 2011b. Climate Trends and Global Crop Production Since 1980. Science 333, 616–620. https://doi.org/10.1126/science.1204531

Loomis, R.S., Williams, W.A., 1963. Maximum Crop Productivity: An Estimate 1. Crop Sci. 3, 67–72.

Lüttger, A.B., Feike, T., 2018. Development of heat and drought related extreme weather events and their effect on winter wheat yields in Germany. Theor. Appl. Climatol. 132, 15–29. https://doi.org/10.1007/s00704-017-2076-y

Maharjan, G.R., Hoffmann, H., Webber, H., Srivastava, A.K., Weihermüller, L., Villa, A., Coucheney, E., Lewan, E., Trombi, G., Moriondo, M., Bindi, M., Grosz, B., Dechow, R., Kuhnert, M., Doro, L., Kersebaum, K.-C., Stella, T., Specka, X., Nendel, C., Constantin, J., Raynal, H., Ewert, F., Gaiser, T., 2019. Effects of input data aggregation on simulated crop yields in temperate and Mediterranean climates. Eur. J. Agron. 103, 32–46. https://doi.org/10.1016/j.eja.2018.11.001

Mäkinen, H., Kaseva, J., Trnka, M., Balek, J., Kersebaum, K.C., Nendel, C., Gobin, A., Olesen, J.E., Bindi, M., Ferrise, R., Moriondo, M., Rodríguez, A., Ruiz-Ramos, M., Takáč, J., Bezák, P., Ventrella, D., Ruget, F., Capellades, G., Kahiluoto, H., 2018. Sensitivity of European wheat to extreme weather. Field Crops Res. 222, 209–217. https://doi.org/10.1016/j.fcr.2017.11.008

Maraun, D., 2013. When will trends in European mean and heavy daily precipitation emerge? Environ. Res. Lett. 8, 014004. https://doi.org/10.1088/1748-9326/8/1/014004

Maytín, C.E., Acevedo, M.F., Jaimez, R., Andressen, R., Harwell, M.A., Robock, A., Azócar, A., 1995. Potential effects of global climatic change on the phenology and yield of maize in venezuela. Clim. Change 29, 189–211. https://doi.org/10.1007/BF01094016

McCuen, R.H., Knight, Z., Cutter, A.G., 2006. Evaluation of the Nash–Sutcliffe efficiency index. J. Hydrol. Eng. 11, 597–602.

McMaster, G.S., Smika, D.E., 1988. Estimation and evaluation of winter wheat phenology in the central Great Plains. Agric. For. Meteorol. 43, 1–18.

McMaster, G.S., White, J.W., Hunt, L.A., Jamieson, P.D., Dhillon, S.S., Ortiz-Monasterio, J.I., 2008. Simulating the Influence of Vernalization, Photoperiod and Optimum Temperature on Wheat Developmental Rates. Ann. Bot. 102, 561–569. https://doi.org/10.1093/aob/mcn115

McMaster, G.S., Wilhelm, W., 1997. Growing degree-days: one equation, two interpretations. Agric. For. Meteorol. 87, 291–300.

McMaster, G.S., Wilhelm, W.W., 2003. Phenological responses of wheat and barley to water and temperature: improving simulation models. J. Agric. Sci. 141, 129–147. https://doi.org/10.1017/S0021859603003460

Mearns, L.O., Hulme, M., Carter, T.R., Leemans, R., Lal, M., Whetton, P., 2001. Climate Scenario Development, in: Houghton, J.T., Ding, Y., Griggs, D.J., Noguer, M., Linden, P.J. van der, Dai, X., Maskell, K., Johnson, C.A. (Eds.), Climate Change 2001: The Scientific Basis: Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge ; New York.

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

Menzel, A., Vopelius, J. von, Estrella, N., Schleip, C., Dose, V., 2006. Farmers annual activities are not tracking the speed of climate change. https://doi.org/10.3354/cr032201

Michel, L., Makowski, D., 2013. Comparison of Statistical Models for Analyzing Wheat Yield Time Series. PLoS ONE 8, e78615. https://doi.org/10.1371/journal.pone.0078615

Michèle, P., 2018. OECD-FAO AGRICULTURAL OUTLOOK 2018-2027 Chapter 3. Cereals, 109–125.

Miller, P., Lanier, W., Brandt, S., 2001. Using growing degree days to predict plant stages. AgExtension Commun. Coord. Commun. Serv. Mont. State Univ.-Bozeman Bozeman MO.

Mittelbach, H., Seneviratne, S.I., 2012. A new perspective on the spatio-temporal variability of soil moisture: temporal dynamics versus time-invariant contributions. Hydrol. Earth Syst. Sci. 16, 2169–2179. https://doi.org/10.5194/hess-16-2169-2012

Monteith, J.L., 1965a. Light Distribution and Photosynthesis in Field Crops. Ann. Bot. 29, 17–37. https://doi.org/10.1093/oxfordjournals.aob.a083934

Monteith, J.L., 1965b. Evaporation and environment. Symp. Soc. Exp. Biol. 19, 205–234.

Monteith, J.L., Moss C. J., Cooke G. W., Pirie N: W., Bell G. D. H., 1977. Climate and the efficiency of crop production in Britain. Philos. Trans. R. Soc. Lond. B Biol. Sci. 281, 277–294. https://doi.org/10.1098/rstb.1977.0140

Moriasi, D.N., G. Arnold, J., W. Van Liew, M., L. Bingner, R., D. Harmel, R., L. Veith, T., 2007. Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. Trans. ASABE 50, 885–900. https://doi.org/10.13031/2013.23153

Moriondo, M., Giannakopoulos, C., Bindi, M., 2011. Climate change impact assessment: the role of climate extremes in crop yield simulation. Clim. Change 104, 679–701. https://doi.org/10.1007/s10584-010-9871-0

Muchow, R., 1989. Comparative productivity of maize, sorghum and pearl millet in a semi-arid tropical environment II. Effect of water deficits. Field Crops Res. 20, 207–219.

Muchow, R.C., Sinclair, T.R., Bennett, J.M., 1990. Temperature and Solar Radiation Effects on Potential Maize Yield across Locations. Agron. J. 82, 338–343. https://doi.org/10.2134/agronj1990.00021962008200020033x

Mundlak, Y., 1961. Empirical Production Function Free of Management Bias. Am. J. Agric. Econ. 43, 44–56. https://doi.org/10.2307/1235460

Murray, F.W., 1967. On the Computation of Saturation Vapor Pressure. J. Appl. Meteorol. 6, 203–204. https://doi.org/10.1175/1520-0450(1967)006<0203:OTCOSV>2.0.CO;2

Nakićenović, N., Intergovernmental Panel on Climate Change, Swart, R. (Eds.), 2000. Special report on emissions scenarios: a special report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge ; New York.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I—A discussion of principles. J. Hydrol. 10, 282–290.

Nendel, C., Wieland, R., Mirschel, W., Specka, X., Guddat, C., Kersebaum, K.C., 2013. Simulating regional winter wheat yields using input data of different spatial resolution. Field Crops Res. 145, 67–77. https://doi.org/10.1016/j.fcr.2013.02.014

Nickl, U., Gehring, K., Weigand, S., 2014. Getreide und Maisbau. Produktionstechnische Grundlagen., in: Landwirtschaftlicher Pflanzenbau: Grundlagen Des Acker- Und Pflanzenbaus, Der Guten Fachlichen Praxis, Der Verfahrenstechnik Sowie Der Agrarmeteorologie Und Des Klimawandels - Produktions- Und Verfahrenstechnik Der Kulturpflanzen - Dauergrnland - Sonderkulturen - Nachwachsende Rohstoffe - Okologischer Landbau - Naturschutz Und Landschaftspflege - Feldversuchswesen - Waldbewirtschaftung, Die Landwirtschaft. BLV Buchverlag, pp. 373–404.

Nonhebel, S., 1994. The effects of use of average instead of daily weather data in crop growth simulation models. Agric. Syst. 44, 377–396. https://doi.org/10.1016/0308-521X(94)90194-K

O'Brien, R.M., 2016. Dropping Highly Collinear Variables from a Model: Why it Typically is Not a Good Idea*. Soc. Sci. Q. 98, 360–375. https://doi.org/10.1111/ssqu.12273

Olesen, J.E., Bøcher, P.K., Jensen, T., 2000. Comparison of scales of climate and soil data for aggregating simulated yields of winter wheat in Denmark. Agric. Ecosyst. Environ. 82, 213–228. https://doi.org/10.1016/S0167-8809(00)00227-9

Ort, D.R., Oxborough, K., Wise, R.R., 1994. Depressions of photosynthesis in crops with water deficits., in: Photoinhibition of Photosynthesis: From Molecular Nechanisms to the Field, Environmental Plant Biology Series. Bios Scientific Publ., Oxford, pp. 315–329.

Ortiz-Bobea, A., Just, R.E., 2013. Modeling the Structure of Adaptation in Climate Change Impact Assessment. Am. J. Agric. Econ. 95, 244–251. https://doi.org/10.1093/ajae/aas035

Oury, B., 1965. Allowing for Weather in Crop Production Model Building. Am. J. Agric. Econ. 47, 270–283. https://doi.org/10.2307/1236574

Overmars, K.P., de Koning, G.H.J., Veldkamp, A., 2003. Spatial autocorrelation in multi-scale land use models. Ecol. Model. 164, 257–270. https://doi.org/10.1016/S0304-3800(03)00070-X

Peichl, M., Thober, S., Meyer, V., Samaniego, L., 2018. The effect of soil moisture anomalies on maize yield in Germany. Nat. Hazards Earth Syst. Sci. 18, 889–906. https://doi.org/10.5194/nhess-18-889-2018

Peng, S., Huang, J., Sheehy, J.E., Laza, R.C., Visperas, R.M., Zhong, X., Centeno, G.S., Khush, G.S., Cassman, K.G., 2004. Rice yields decline with higher night temperature from global warming. Proc. Natl. Acad. Sci. 101, 9971–9975. https://doi.org/10.1073/pnas.0403720101

Porter, J.H., Parry, M.L., Carter, T.R., 1991. The potential effects of climatic change on agricultural insect pests. Agric. For. Meteorol. 57, 221–240. https://doi.org/10.1016/0168-1923(91)90088-8

Porter, J.R., Gawith, M., 1999. Temperatures and the growth and development of wheat: a review. Eur. J. Agron. 10, 23–36.

Porter, J.R., Kirby, E.J.M., Day, W., Adam, J.S., Appleyard, M., Ayling, S., Baker, C.K., Beale, P., Belford, R.K., Biscoe, P.V., Chapman, A., Fuller, M.P., Hampson, J., Hay, R.K.M., Hough, M.N., Matthews, S., Thompson, W.J., Weir, A.H., Willington, V.B.A., Wood, D.W., 1987. An analysis of morphological development stages in avalon winter wheat crops with different sowing dates and at ten sites in England and Scotland. J. Agric. Sci. 109, 107–121. https://doi.org/10.1017/S0021859600081053

Porter, J.R., Semenov, M.A., 2005. Crop responses to climatic variation. Philos. Trans. R. Soc. B Biol. Sci. 360, 2021–2035.

Porter, J.R., Xie, L., Challinor, A.J., Cochrane, K., Howden, S.M., Iqbal, M.M., Lobell, D.B., Travasso, M.I., 2014. Food security and food production systems.

Porwollik, V., Müller, C., Elliott, J., Chryssanthacopoulos, J., Iizumi, T., Ray, D.K., Ruane, A.C., Arneth, A., Balkovič, J., Ciais, P., Deryng, D., Folberth, C., Izaurralde, R.C., Jones, C.D., Khabarov, N., Lawrence, P.J., Liu, W., Pugh, T.A.M., Reddy, A., Sakurai, G., Schmid, E., Wang, X., de Wit, A., Wu, X., 2017. Spatial and temporal uncertainty of crop yield aggregations. Eur. J. Agron., Uncertainty in crop model predictions 88, 10–21. https://doi.org/10.1016/j.eja.2016.08.006

Prasad, P.V.V., Staggenborg, S.A., Ristic, Z., 2008. Impacts of Drought and/or Heat Stress on Physiological, Developmental, Growth, and Yield Processes of Crop Plants. Response Crops Ltd. Water Underst. Model. Water Stress Eff. Plant Growth Process. advancesinagric, 301–355. https://doi.org/10.2134/advagricsystmodel1.c11

Priesack, E., Berkenkamp, A., Gayler, S., Hartmann, H.P., Loos, C., 2008. Chapter 4.1 - Development and Application of Agro-Ecosystem Models, in: Schröder, P., Pfadenhauer, J., Munch, J.C. (Eds.), Perspectives for Agroecosystem Management. Balancing Environmental and Socio-Economic Demands [Schröder, P., Pfadenhauer, J., Munch J.C. (Eds.)]. Elsevier, San Diego, pp. 329–349. https://doi.org/10.1016/B978-044451905-4.50014-3

Priesack, E., Gayler, S., Rötzer, T., Seifert, T., Pretzsch, H., 2012. Mechanistic Modelling of Soil–Plant–Atmosphere Systems, in: Matyssek, R., Schnyder, H., Oßwald, W., Ernst, D., Munch, J.C., Pretzsch, Hans (Eds.), Growth and Defence in Plants [Matyssek R., Schnyder H., Oßwald W., Ernst D., Munch J., Pretzsch H. (Eds.)], Ecological Studies (Analysis and Sythesis). Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 335–353. https://doi.org/10.1007/978-3-642-30645-7_15

Prost, L., Makowski, D., Jeuffroy, M.-H., 2008. Comparison of stepwise selection and Bayesian model averaging for yield gap analysis. Ecol. Model. 219, 66–76. https://doi.org/10.1016/j.ecolmodel.2008.07.026

Rattalino Edreira, J.I., Guilpart, N., Sadras, V., Cassman, K.G., van Ittersum, M.K., Schils, R.L.M., Grassini, P., 2018. Water productivity of rainfed maize and wheat: A local to global perspective. Agric. For. Meteorol. 259, 364–373. https://doi.org/10.1016/j.agrformet.2018.05.019

Rattalino Edreira, J.I., Otegui, M.E., 2013. Heat stress in temperate and tropical maize hybrids: A novel approach for assessing sources of kernel loss in field conditions. Field Crops Res. 142, 58–67. https://doi.org/10.1016/j.fcr.2012.11.009

Ray, D.K., Gerber, J.S., MacDonald, G.K., West, P.C., 2015. Climate variation explains a third of global crop yield variability. Nat. Commun. 6, 5989. https://doi.org/10.1038/ncomms6989

Reid, J.F., Zur, B., Hesketh, J.D., 1990. THE DYNAMICS OF A MAIZE CANOPY DEVELOPMENT 2. LEAF AREA GROWTH 10.

Reidsma, P., Ewert, F., Oude Lansink, A., 2007. Analysis of farm performance in Europe under different climatic and management conditions to improve understanding of adaptive capacity. Clim. Change 84, 403–422. https://doi.org/10.1007/s10584-007-9242-7

Reiner, L., 1992. Weizen aktuell. DLG Verlag.

Rezaei, E.E., Siebert, S., Hüging, H., Ewert, F., 2018. Climate change effect on wheat phenology depends on cultivar change. Sci. Rep. 8, 4891. https://doi.org/10.1038/s41598-018-23101-2

Richardson, A.D., Keenan, T.F., Migliavacca, M., Ryu, Y., Sonnentag, O., Toomey, M., 2013. Climate change, phenology, and phenological control of vegetation feedbacks to the climate system. Agric. For. Meteorol. 169, 156–173. https://doi.org/10.1016/j.agrformet.2012.09.012

Rigby, J.R., Porporato, A., 2008. Spring frost risk in a changing climate. Geophys. Res. Lett. 35. https://doi.org/10.1029/2008GL033955

Rippel, R., Brandhuber, R., Beck, R., Walter, R., Müller, C., 2014. Bodenkundliche Grundlagen. Humus, Bodenleben, Austauschvorrgänge., in: Alsing, W. (ed.), Maxant, H. (ed.) (Eds.), Landwirtschaftlicher Pflanzenbau: Grundlagen Des Acker- Und Pflanzenbaus, Der Guten

Fachlichen Praxis, Der Verfahrenstechnik Sowie Der Agrarmeteorologie Und Des Klimawandels - Produktions- Und Verfahrenstechnik Der Kulturpflanzen - Dauergrnland - Sonderkulturen - Nachwachsende Rohstoffe - Okologischer Landbau - Naturschutz Und Land-Landschaftspflege - Feldversuchswesen - Waldbewirtschaftung, Die Landwirtschaft. BLV Buchverlag, pp. 25–71.

Roberts, M.J., Braun, N.O., Sinclair, T.R., Lobell, D.B., Schlenker, W., 2017. Comparing and combining process-based crop models and statistical models with some implications for climate change. Environ. Res. Lett. 12, 095010. https://doi.org/10.1088/1748-9326/aa7f33

Rosenzweig, C., Parry, M.L., 1994. Potential impact of climate change on world food supply. Nature 367, 133. https://doi.org/10.1038/367133a0

Roßberg, D., Michel, V., Graf, R., Neukampf, R., 2007. Definition von Boden-Klima-Räumen für die Bundesrepublik Deutschland. Nachrichtenblatt Dtsch. Pflanzenschutzdienstes 59, 155–161.

Rötter, R.P., Carter, T.R., Olesen, J.E., Porter, J.R., 2011. Crop–climate models need an overhaul. Nat. Clim. Change 1, 175–177. https://doi.org/10.1038/nclimate1152

Rötzer, T., Chmielewski, F., 2001. Phenological maps of Europe. Clim. Res. 18, 249–257. https://doi.org/10.3354/cr018249

Runge, E., 1968. Effects of Rainfall and Temperature Interactions During the Growing Season on Corn Yield 1. Agron. J. 60, 503–507.

Russell, G., Wilson, G.W., 1994. An agro-pedo-climatological knowledge-base of wheat in Europe.

Sacks, W.J., Kucharik, C.J., 2011. Crop management and phenology trends in the U.S. Corn Belt: Impacts on yields, evapotranspiration and energy balance. Agric. For. Meteorol. 151, 882–894. https://doi.org/10.1016/j.agrformet.2011.02.010

Sánchez, B., Rasmussen, A., Porter, J.R., 2014. Temperatures and the growth and development of maize and rice: a review. Glob. Change Biol. 20, 408–417. https://doi.org/10.1111/gcb.12389

Sarto, M., V.,.M., Sarto, J., R.,.W., Rampim, L., Rosset, J., S., Bassegio, D., da Costa, P., F., Inagaki, A., M., 2017. Wheat phenology and yield under drought: A review. Aust. J. Crop Sci. 11, 941.

Schauberger, B., Rolinski, S., Müller, C., 2016. A network-based approach for semi-quantitative knowledge mining and its application to yield variability. Environ. Res. Lett. 11, 123001. https://doi.org/10.1088/1748-9326/11/12/123001

Schlenker, W., Lobell, D.B., 2010. Robust negative impacts of climate change on African agriculture. Environ. Res. Lett. 5, 014010. https://doi.org/10.1088/1748-9326/5/1/014010

Schlenker, W., Roberts, M.J., 2009. Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. Proc. Natl. Acad. Sci. 106, 15594–15598. https://doi.org/10.1073/pnas.0906865106

Schönwiese, C.-D., Staeger, T., Trömel, S., 2005. Klimawandel und Extremereignisse in Deutschland. Klimastatusbericht 7–17.

Scian, B.V., 2004. Environmental variables for modeling wheat yields in the southwest pampa region of Argentina. Int. J. Biometeorol. 48, 206–212. https://doi.org/10.1007/s00484-004-0198-2

Semenov, M.A., Porter, J.R., 1995. Climatic variability and the modelling of crop yields. Agric. For. Meteorol. 73, 265–283. https://doi.org/10.1016/0168-1923(94)05078-K

Semenov, M.A., Shewry, P.R., 2011. Modelling predicts that heat stress, not drought, will increase vulnerability of wheat in Europe. Sci. Rep. 1, 66. https://doi.org/10.1038/srep00066

Setter, T.L., Waters, I., 2003. Review of prospects for germplasm improvement for waterlogging tolerance in wheat, barley and oats. Plant Soil 253, 1–34. https://doi.org/10.1023/A:1024573305997

Shao, G.C., Lan, J.J., Yu, S.E., Liu, N., Guo, R.Q., She, D.L., 2013. Photosynthesis and growth of winter wheat in response to waterlogging at different growth stages. Photosynthetica 51, 429–437. https://doi.org/10.1007/s11099-013-0039-9

Sheehy, J.E., Mitchell, P.L., Ferrer, A.B., 2006. Decline in rice grain yields with temperature: Models and correlations can give different estimates. Field Crops Res. 98, 151–156. https://doi.org/10.1016/j.fcr.2006.01.001

Shi, W., Tao, F., Zhang, Z., 2013. A review on statistical models for identifying climate contributions to crop yields. J. Geogr. Sci. 23, 567–576. https://doi.org/10.1007/s11442-013-1029-3

Shim, D., Lee, K.-J., Lee, B.-W., 2017. Response of phenology- and yield-related traits of maize to elevated temperature in a temperate region. Crop J. 5, 305–316. https://doi.org/10.1016/j.cj.2017.01.004

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

Siebert, S., Webber, H., Rezaei, E.E., 2017. Weather impacts on crop yields - searching for simple answers to a complex problem. Environ. Res. Lett. 12, 081001. https://doi.org/10.1088/1748-9326/aa7f15

Singh, S.D., 1981. Moisture-Sensitive Growth Stages of Dwarf Wheat and Optimal Sequencing of Evapotranspiration Deficits 1. Agron. J. 73, 387–391. https://doi.org/10.2134/agronj1981.00021962007300030001x

Slafer, G.A., Rawson, H.M., 1995. Base and optimum temperatures vary with genotype and stage of development in wheat. Plant Cell Environ. 18, 671–679. https://doi.org/10.1111/j.1365-3040.1995.tb00568.x

Soja, A., Soja, G., 2003. Dokumentation von Auswirkungen extremer Wetterereignisse auf die landwirtschaftliche Produktion. Startprojekt Klimaschutz StartClim 3b-Erste Anal. Extrem. Wetterereignisse Ihrer Auswirkungen Österr. ARC Seibersdorf Reserach Seibersdorf.

Spinoni, J., Vogt, J., Barbosa, P., 2015. European degree-day climatologies and trends for the period 1951–2011. Int. J. Climatol. 35, 25–36. https://doi.org/10.1002/joc.3959

Stahr, K., Kandeler, E., Herrmann, L., Streck, T., 2020. Bodenkunde und Standortlehre. UTB GmbH.

Statistisches Bundesamt, 2018. DESTATIS. Land-und Forstwirtschaft, Fischerei. Wachstum und Ernte -Feldfrüchte -Fachserie: 3, Reihe 3. 2.1. Kohlhammer, Wiesbaden.

Statistisches Bundesamt, 2015. DESTATIS. Land-und Forstwirtschaft, Fischerei. Wachstum und Ernte -Feldfrüchte -Fachserie: 3, Reihe 3. 2.1. Qualitätsbericht. Kohlhammer, Wiesbaden.

Statistisches Bundesamt, 1982b. DESTATIS. Land-und Forstwirtschaft, Fischerei. Wachstum und Ernte -Feldfrüchte -Fachserie: 3, Reihe 3. 2.1. Anlage: Ernte- und Betriebsberichterstattung (EBE): Feld-früchte und Grünland. Kohlhammer, Wiesbaden.

Statistisches Bundesamt, 1982c. DESTATIS. Land-und Forstwirtschaft, Fischerei. Wachstum und Ernte -Feldfrüchte -Fachserie: 3, Reihe 3. 2.1. Anleitung für die Ernte- und Betriebsberichterstattung der landwirtschaftlichen Feldfrüchte und Grünlandes. Kohlhammer, Wiesbaden.

Statistisches Bundesamt, 1982a. DESTATIS. Land-und Forstwirtschaft, Fischerei. Wachstum und Ernte -Feldfrüchte -Fachserie: 3, Reihe 3. 2.1. Kohlhammer, Wiesbaden.

Stone, P.J., Nicolas, M.E., 1995. Effect of Timing of Heat Stress During Grain Filling on Two Wheat Varieties Differing in Heat Tolerance. I. Grain Growth. Funct. Plant Biol. 22, 927–934. https://doi.org/10.1071/pp9950927

Stone, P.J., Sorensen, I.B., Jamieson, P.D., 1999. Effect of soil temperature on phenology, canopy development, biomass and yield of maize in a cool-temperate climate. Field Crops Res. 63, 169–178. https://doi.org/10.1016/S0378-4290(99)00033-7

Stratonovitch, P., Semenov, M.A., 2015. Heat tolerance around flowering in wheat identified as a key trait for increased yield potential in Europe under climate change. J. Exp. Bot. 66, 3599–3609. https://doi.org/10.1093/jxb/erv070

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

Tao, F., Yokozawa, M., Xu, Y., Hayashi, Y., Zhang, Z., 2006. Climate changes and trends in phenology and yields of field crops in China, 1981–2000. Agric. For. Meteorol. 138, 82–92. https://doi.org/10.1016/j.agrformet.2006.03.014

Thomas, B., Vince-Prue, D., 1996. Photoperiodism in Plants. Elsevier.

van Bussel, L.G.J., Ewert, F., Leffelaar, P.A., 2011a. Effects of data aggregation on simulations of crop phenology. Agric. Ecosyst. Environ., Scaling methods in integrated assessment of agricultural systems 142, 75–84. https://doi.org/10.1016/j.agee.2010.03.019

van Bussel, L.G.J., Müller, C., van Keulen, H., Ewert, F., Leffelaar, P.A., 2011b. The effect of temporal aggregation of weather input data on crop growth models' results. Agric. For. Meteorol. 151, 607–619. https://doi.org/10.1016/j.agrformet.2011.01.007

van Bussel, L.G.J., Stehfest, E., Siebert, S., Müller, C., Ewert, F., 2015. Simulation of the phenological development of wheat and maize at the global scale. Glob. Ecol. Biogeogr. 24, 1018–1029. https://doi.org/10.1111/geb.12351

van Keulen, H., Wolf, J., 1986. Modelling of agricultural production: weather, soils and crops, Simulation monographs. Pudoc.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview. Clim. Change 109, 5. https://doi.org/10.1007/s10584-011-0148-z

Wallach, D., 2011. Crop Model Calibration: A Statistical Perspective. Agron. J. 103, 1144–1151. https://doi.org/10.2134/agronj2010.0432

Wardlaw, I.F., 1974. Temperature control of translocation.

Webber, H., Ewert, F., Olesen, J.E., Müller, C., Fronzek, S., Ruane, A.C., Bourgault, M., Martre, P., Ababaei, B., Bindi, M., Ferrise, R., Finger, R., Fodor, N., Gabaldón-Leal, C., Gaiser, T., Jabloun, M., Kersebaum, K.-C., Lizaso, J.I., Lorite, I.J., Manceau, L., Moriondo, M., Nendel, C., Rodríguez, A., Ruiz-Ramos, M., Semenov, M.A., Siebert, S., Stella, T., Stratonovitch, P., Trombi, G., Wallach, D., 2018. Diverging importance of drought stress for maize and winter wheat in Europe. Nat. Commun. 9. https://doi.org/10.1038/s41467-018-06525-2

Wheeler, T.R., Batts, G.R., Ellis, R.H., Hadley, P., Morison, J.I.L., 1996. Growth and yield of winter wheat (Triticum aestivum) crops in response to CO2 and temperature. J. Agric. Sci. 127, 37–48. https://doi.org/10.1017/S0021859600077352

Wheeler, T.R., Craufurd, P.Q., Ellis, R.H., Porter, J.R., Vara Prasad, P.V., 2000. Temperature variability and the yield of annual crops. Agric. Ecosyst. Environ. 82, 159–167. https://doi.org/10.1016/S0167-8809(00)00224-3

Wilson, D.R., Muchow, R.C., Murgatroyd, C.J., 1995. Model analysis of temperature and solar radiation limitations to maize potential productivity in a cool climate. Field Crops Res. 43, 1–18. https://doi.org/10.1016/0378-4290(95)00037-Q

Wu, R., Lawes, R., Oliver, Y., Fletcher, A., Chen, C., 2019. How well do we need to estimate plant-available water capacity to simulate water-limited yield potential? Agric. Water Manag. 212, 441–447. https://doi.org/10.1016/j.agwat.2018.09.029

Xiao, D., Qi, Y., Shen, Y., Tao, F., Moiwo, J.P., Liu, J., Wang, R., Zhang, H., Liu, F., 2016. Impact of warming climate and cultivar change on maize phenology in the last three decades in North China Plain. Theor. Appl. Climatol. 124, 653–661. https://doi.org/10.1007/s00704-015-1450-x

Yan, W., Wallace, D.H., 1998. Simulation and Prediction of Plant Phenology for Five Crops Based on Photoperiod×Temperature Interaction. Ann. Bot. 81, 705–716. https://doi.org/10.1006/anbo.1998.0625

Yang, S.-R., Koo, W.W., Wilson, W.W., 1992. Heteroskedasticity in Crop Yield Models. J. Agric. Resour. Econ. 17, 103–109.

Ye, T., Nie, J., Wang, J., Shi, P., Wang, Z., 2015. Performance of detrending models of crop yield risk assessment: evaluation on real and hypothetical yield data. Stoch. Environ. Res. Risk Assess. 29, 109–117. https://doi.org/10.1007/s00477-014-0871-x

Zampieri, M., Ceglar, A., Dentener, F., Toreti, A., 2017. Wheat yield loss attributable to heat waves, drought and water excess at the global, national and subnational scales. Environ. Res. Lett. 12, 064008. https://doi.org/10.1088/1748-9326/aa723b

Zhang, H., Wang, X., You, M., Liu, C., 1999. Water-yield relations and water-use efficiency of winter wheat in the North China Plain. Irrig. Sci. 19, 37–45. https://doi.org/10.1007/s002710050069

Zhao, G., Hoffmann, H., Yeluripati, J., Xenia, S., Nendel, C., Coucheney, E., Kuhnert, M., Tao, F., Constantin, J., Raynal, H., Teixeira, E., Grosz, B., Doro, L., Kiese, R., Eckersten, H., Haas, E., Cammarano, D., Kassie, B., Moriondo, M., Trombi, G., Bindi, M., Biernath, C., Heinlein, F., Klein, C., Priesack, E., Lewan, E., Kersebaum, K.-C., Rötter, R., Roggero, P.P., Wallach, D., Asseng, S., Siebert, S., Gaiser, T., Ewert, F., 2016. Evaluating the precision of eight spatial sampling schemes in estimating regional means of simulated yield for two crops. Environ. Model. Softw. 80, 100–112. https://doi.org/10.1016/j.envsoft.2016.02.022

Zhao, J., Yang, X., 2018. Distribution of high-yield and high-yield-stability zones for maize yield potential in the main growing regions in China. Agric. For. Meteorol. 248, 511–517. https://doi.org/10.1016/j.agrformet.2017.10.016

A. Supplemental Tables: Counties and Soil-Climate-Areas

No.	County	Soil-Climate-Area	Abbreviation of Soil-Climate-Area
1	Aichach-Friedberg	Tertiärhügelland Donau Süd	THD
2	Altoetting	Moränen Hügelland Voralpenland	MHV
3	Amberg-Sulzbach	Albflächen Ostbayerisches Hügelland	AOH
4	Ansbach	Albflächen Ostbayerisches Hügelland	
5	Aschaffenburg	Odenwald Spessart	OWS
6	Augsburg	Tertiärhügelland Donau Süd	
7	Bad Kissingen	Nordwestbayern Franken	NWF
8	Bamberg	Nordwestbayern Franken	
9	Bayreuth	Verwitterungsböden in den Höhenlagen	VIH
10	Cham	Verwitterungsböden in den Höhenlagen	
11	Coburg	Verwitterungsböden in den Übergangslagen	VIU
12	Dachau	Tertiärhügelland Donau Süd	
13	Deggendorf	Gäu Donau Inntal	GDI
14	Dillingen_Donau	Tertiärhügelland Donau Süd	
15	Dingolfing-Landau	Gäu Donau Inntal	
16	Donau-Ries	Albflächen Ostbayerisches Hügelland	
17	Ebersberg	Tertiärhügelland Donau Süd	
18	Eichstaett	Albflächen Ostbayerisches Hügelland	
19	Erding	Tertiärhügelland Donau Süd	
20	Erlangen-Hoechstadt	Nordwestbayern Franken	
21	Forchheim	Albflächen Ostbayerisches Hügelland	
22	Freising	Tertiärhügelland Donau Süd	
23	Fuerstenfeldbruck	Tertiärhügelland Donau Süd	
24	Fuerth	Nordwestbayern Franken	
25	Guenzburg	Tertiärhügelland Donau Süd	
26	Hassberge	Nordwestbayern Franken	
27	Hof	Verwitterungsböden in den Höhenlagen	
28	Kehlheim	Tertiärhügelland Donau Süd	
29	Kitzingen	Nordwestbayern Franken	
30	Kronach	Verwitterungsböden in den Höhenlagen	
31	Kulmbach	Verwitterungsböden in den Höhenlagen	
32	Landsberg Lech	Moränen Hügelland Voralpenland	
33	Landshut	Gäu Donau Inntal	
34	Lichtenfels	Albflächen Ostbayerisches Hügelland	
35	Main-Spessart	Nordwestbayern Franken	
36	Miltenberg	Odenwald Spessart	
37	Muehldorf	Moränen Hügelland Voralpenland	
38	Muenchen	Tertiärhügelland Donau Süd	
39	Neuburg-Schrobenhausen	Tertiärhügelland Donau Süd	
40	Neumarkt_Oberp.	Albflächen Ostbayerisches Hügelland	
41	Neustadt_Aisch	Nordwestbayern Franken	
42	Neustadt_Waldnaab	Verwitterungsböden in den Höhenlagen	
43	Neu-Ulm	Tertiärhügelland Donau Süd	
44	Nuernberger Land	Albflächen Ostbayerisches Hügelland	
45	Passau(LKR)	Gäu Donau Inntal	
46	Pfaffenhofen	Tertiärhügelland Donau Süd	
47	Regensburg(LKR)	Albflächen Ostbayerisches Hügelland	
48	Rhoen-Grabfeld	Verwitterungsböden in den Übergangslagen	
49	Roth	Nordwestbayern Franken	
50	Rottal-Inn	Gäu Donau Inntal	
51	Schwandorf	Verwitterungsböden in den Höhenlagen	
52	Schweinfurt	Nordwestbayern Franken	
53	Starnberg	Moränen Hügelland Voralpenland	
54	Straubing-Bogen	Gäu Donau Inntal	
55	Tirschenreuth	Verwitterungsböden in den Höhenlagen	
56	Traunstein	Moränen Hügelland Voralpenland	
57	Unterallgaeu	Moränen Hügelland Voralpenland	
58	Weissenburg-Gunzenhausen	Albflächen Ostbayerisches Hügelland	
59	Wuerzburg	Nordwestbayern Franken	
60	Wunsiedel	Verwitterungsböden in den Höhenlagen	

B. Supplemental Figures: Yield data of Bavarian Soil-Climate-Areas

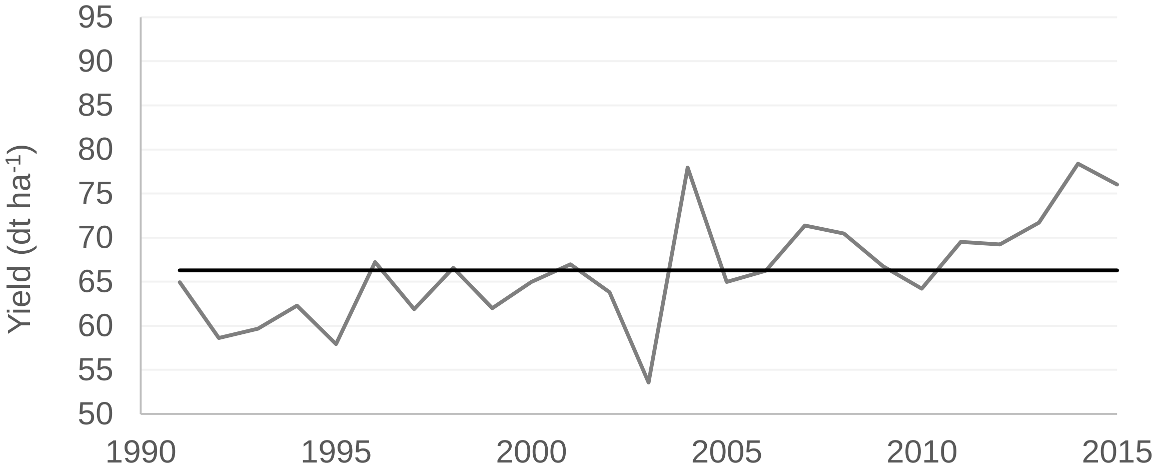


Figure B. 1: Wheat yield development in *Albflächen Ostbayerisches Hügelland* (AOH) from 1991-2015. The black horizontal line indicates AOH’s mean yield from 1991-2015.

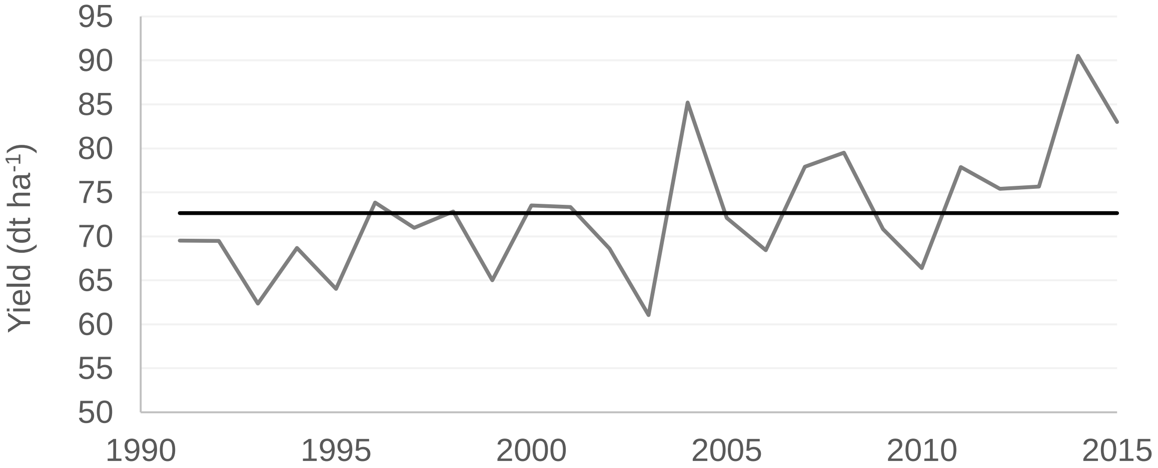


Figure B. 2: Wheat yield development in *Gäu Donau Inntal* (GDI) from 1991-2015. The black horizontal line indicates GDI’s mean yield from 1991-2015.

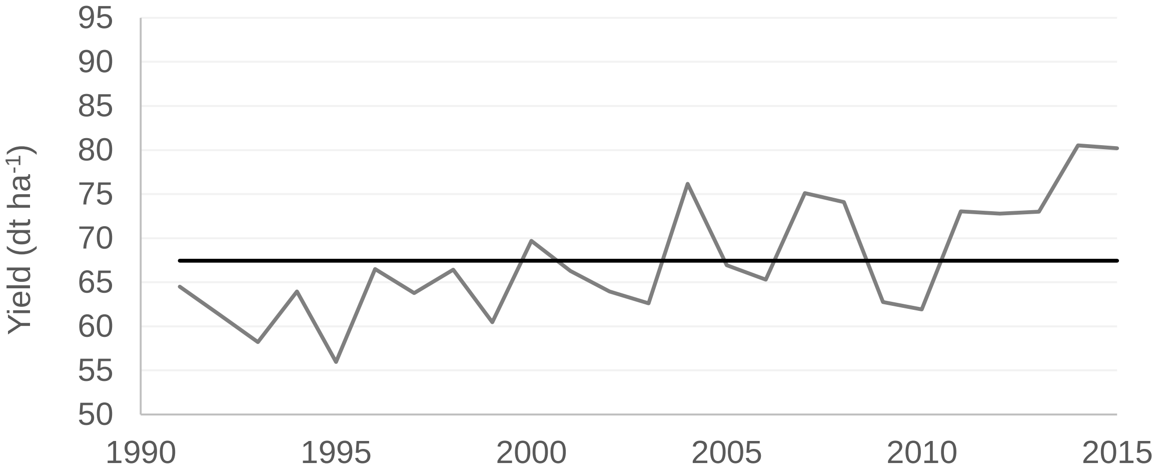


Figure B. 3: Wheat yield development in *Moränen Hügelland Voralpenland* (MHV) from 1991-2015. The black horizontal line indicates MHV's mean yield from 1991-2015.

Figure B. 4: Wheat yield development in *Nordwestbayern Franken* (NWF) from 1991-2015. The black horizontal line indicates NWF's mean yield from 1991-2015.

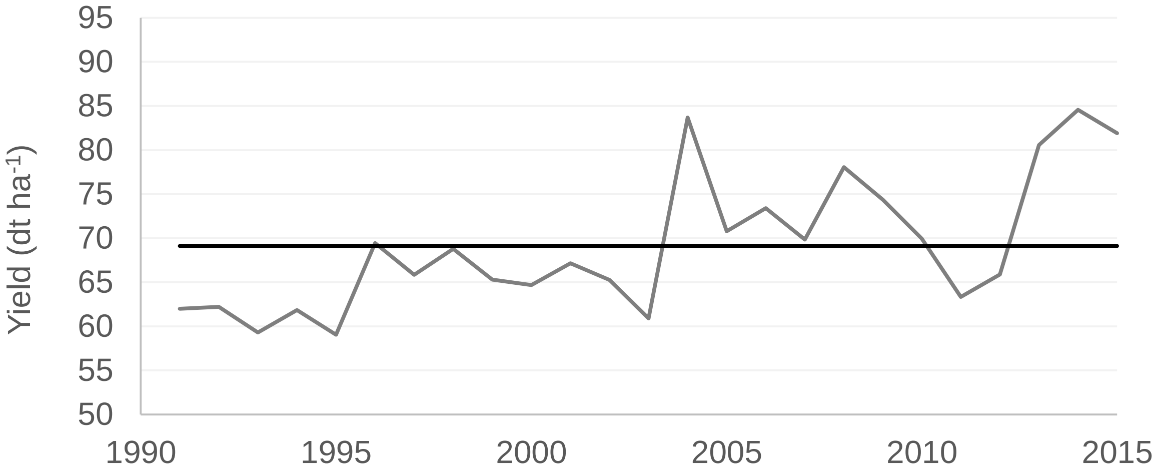


Figure B. 5 Wheat yield development in *Odenwald Spessart* (OWS) from 1991-2015. The black horizontal line indicates OWS's mean yield from 1991-2015.

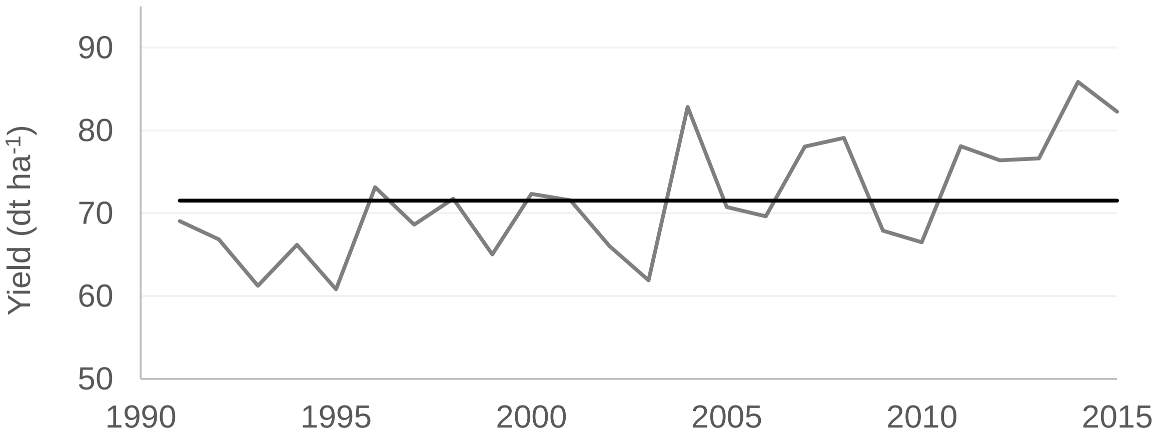


Figure B. 6: Wheat yield development in *Tertiärhügelland Donau Süd* (THD) from 1991-2015. The black horizontal line indicates THD's mean yield from 1991-2015.

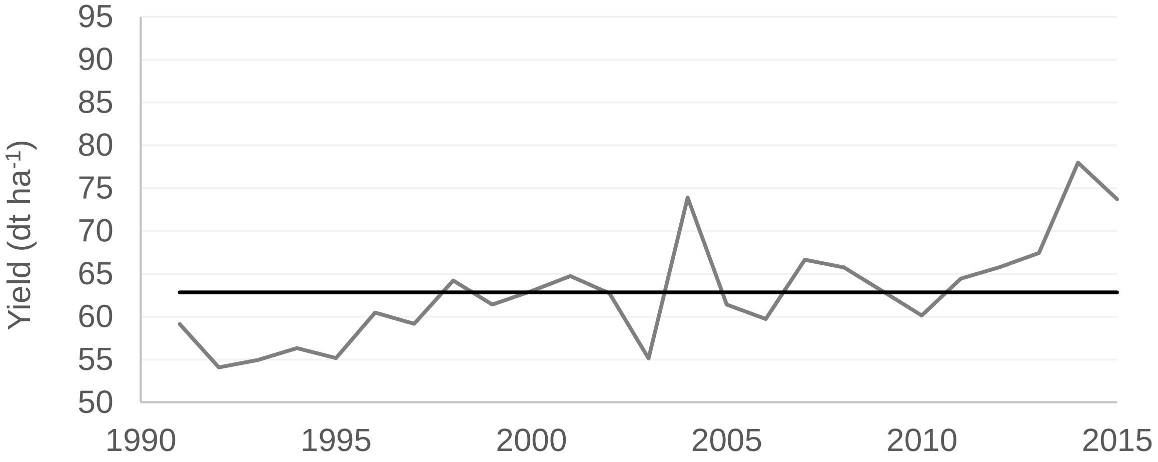


Figure B. 7: Wheat yield development in *Verwitterungsböden in den Höhenlagen* (VIH) from 1991-2015. The black horizontal line indicates VIH's mean yield from 1991-2015.

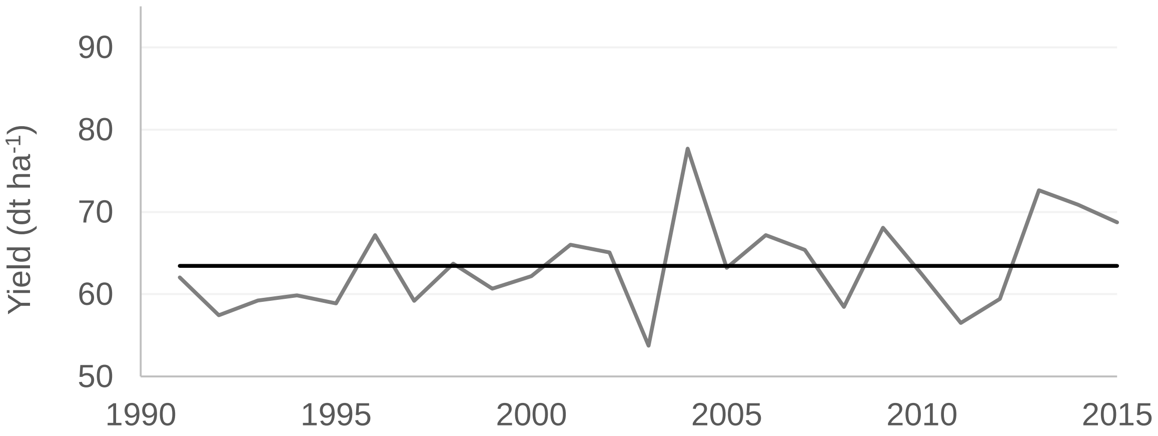


Figure B. 8: Wheat yield development in *Verwitterungsböden in den Übergangslagen* (VIU) from 1991-2015. The black horizontal line indicates VIU's mean yield from 1991-2015.

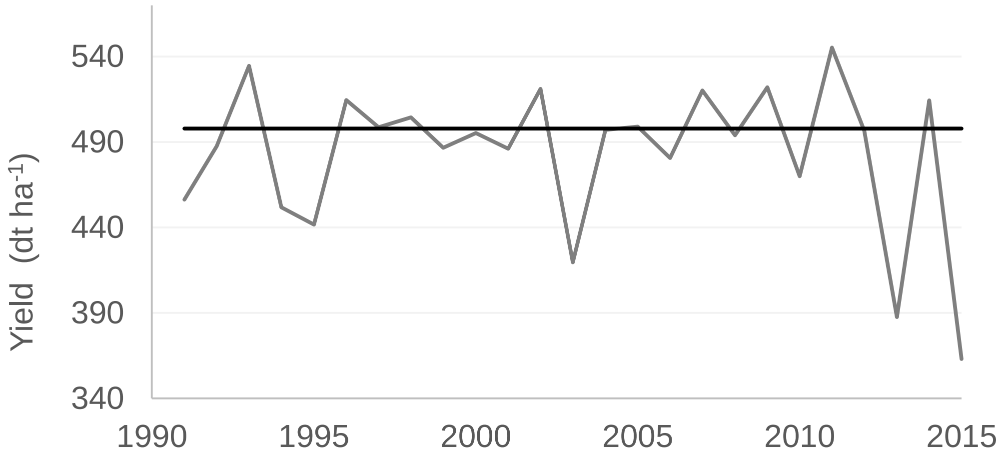


Figure B. 9: Maize yield development in *Albflächen Ostbayerisches Hügelland* (AOH) from 1991-2015. The black horizontal line indicates AOH's mean yield from 1991-2015.

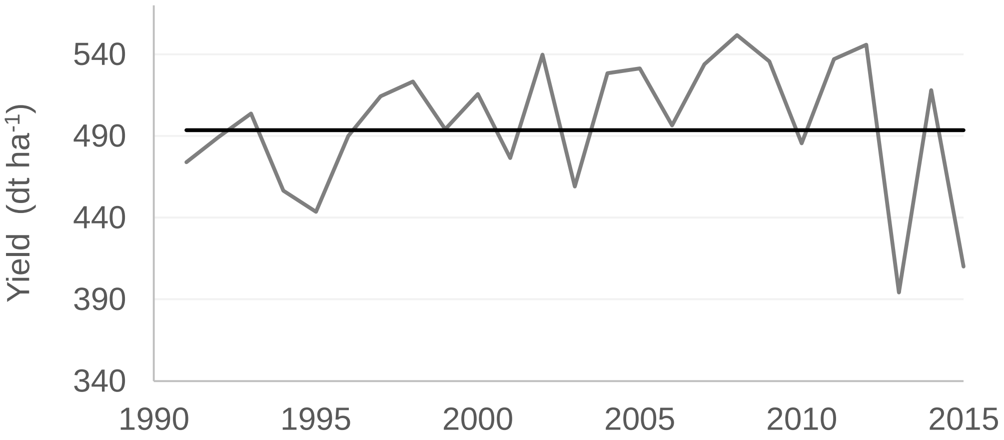


Figure B. 10: Maize yield development in *Gäu Donau Inntal* (GDI) from 1991-2015. The black horizontal line indicates GDI's mean yield from 1991-2015.

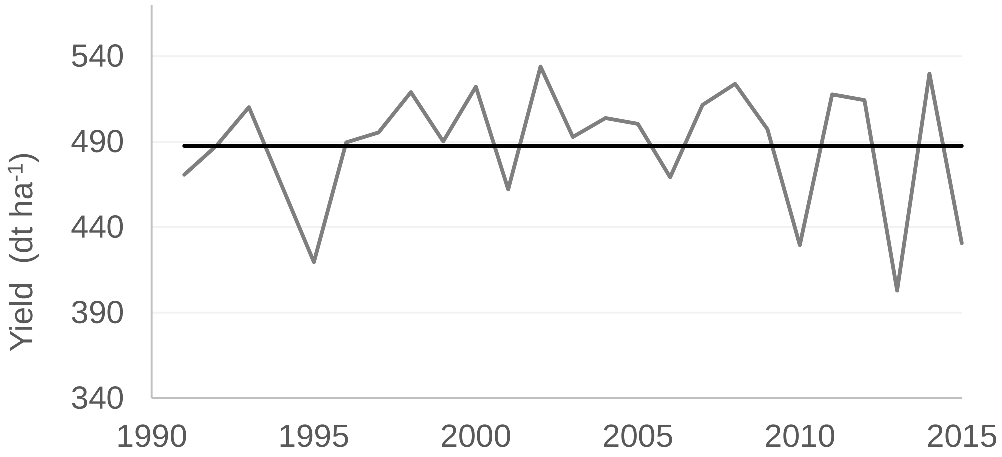


Figure B. 11: Maize yield development in *Moränen Hügelland Voralpenland* (MHV) from 1991-2015. The black horizontal line indicates MHV's mean yield from 1991-2015.

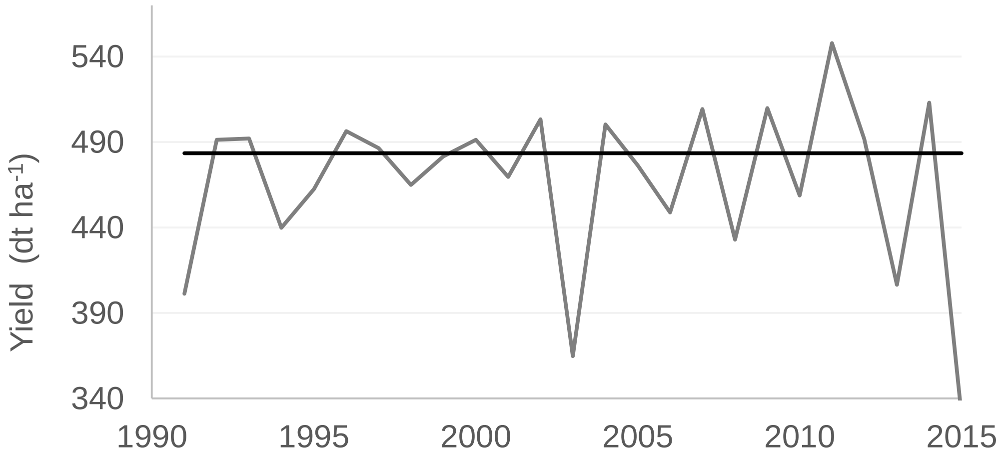


Figure B. 12: Maize yield development in *Nordwestbayern Franken* (NWF) from 1991-2015. The black horizontal line indicates NWF's mean yield from 1991-2015.

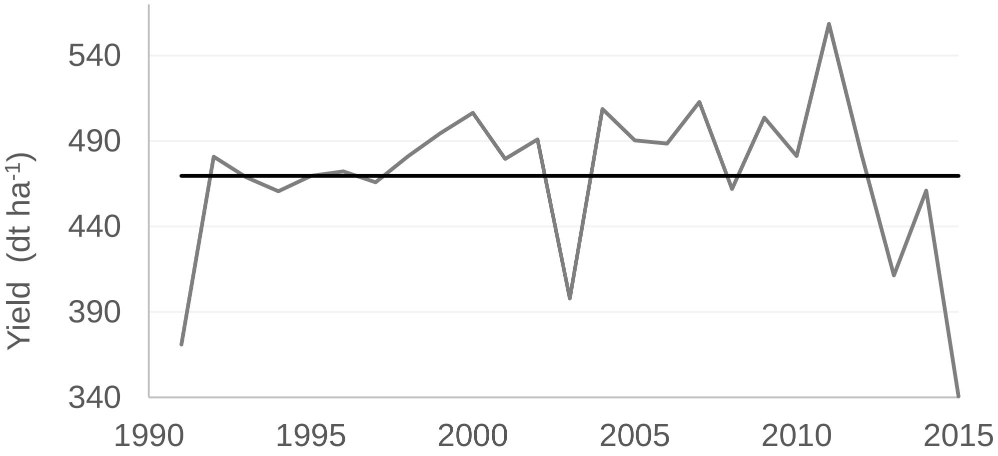


Figure B. 13: Maize yield development in *Odenwald Spessart* (OWS) from 1991-2015. The black horizontal line indicates OWS's mean yield from 1991-2015.

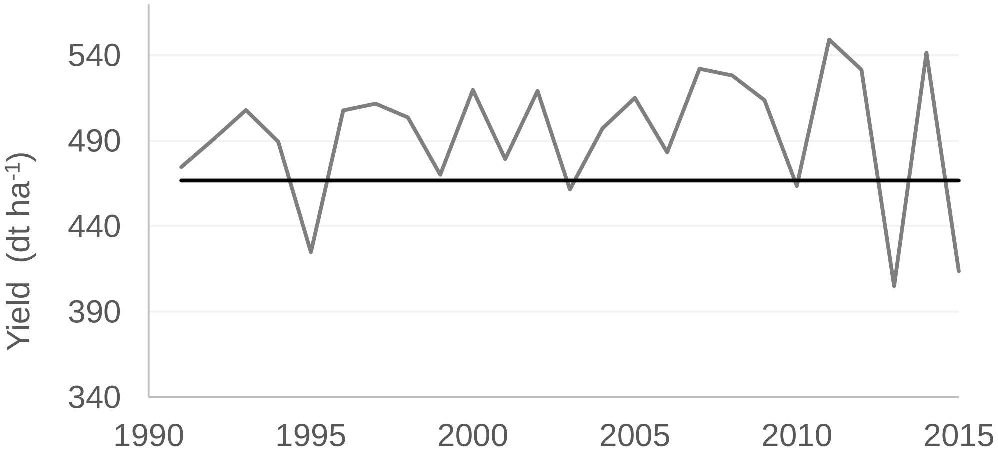


Figure B. 14: Maize yield development in *Tertiärhügelland Donau Süd* (THD) from 1991-2015. The black horizontal line indicates THD's mean yield from 1991-2015.

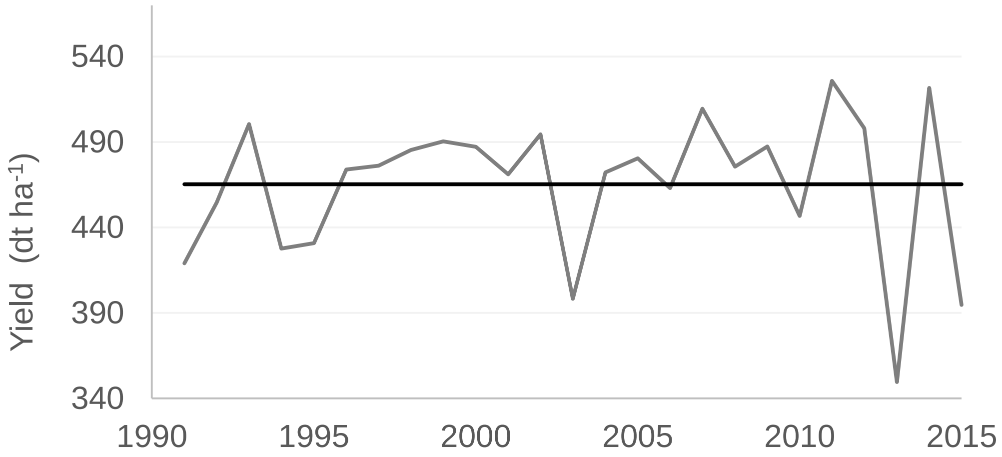


Figure B. 15: Maize yield development in *Verwitterungsböden in den Höhenlagen* (VIH) from 1991-2015. The black horizontal line indicates VIH’s mean yield from 1991-2015.

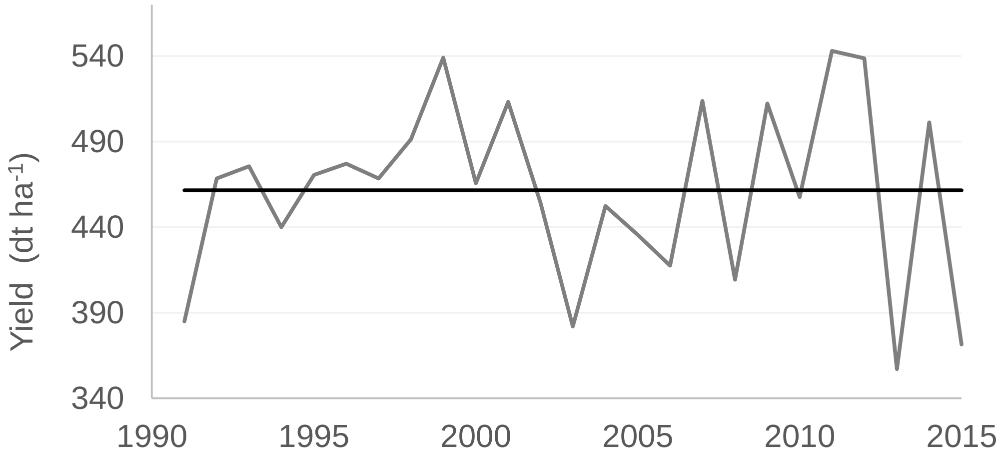


Figure B. 16: Maize yield development in *Verwitterungsböden in den Übergangslagen* (VIU) from 1991-2015. The black horizontal line indicates VIU’s mean yield from 1991-2015.

C. Supplemental Tables Section 4.2

C 1: Correlation coefficients of abiotic factors with the duration of the phenological phase one to three for wheat. The level of significance is indicated with ns: not significant, *p < 0.05, **p < 0.01, ***p < 0.001.

Sowing to emergence

Soil-Climate-Area	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Albflächen	0.66***	0ns	0.54***	0.63***	0.58***	0.22*	0ns	0.01ns	0ns	0.29**	0ns	0.28**
Gäu	0.46***	0.04ns	0.36**	0.42***	0.47***	0.51***	0.02ns	0.03ns	0ns	0.05ns	0.06ns	0.44***
Moränenhügelland	0.48***	0.03ns	0.55***	0.3**	0.48***	0.33**	0.38**	0.28**	0.21*	0ns	0ns	0.29**
Nordwestbayern Franken	0.58***	0.05ns	0.45***	0.54***	0.55***	0.47***	0.01ns	0.01ns	0ns	0.08ns	0.07ns	0.46***
Odenwald	0.07ns	0.03ns	0.07ns	0.06ns	0.07ns	0.51***	0.01ns	0.12ns	0.02ns	0.28**	0.14ns	0.36**
Tertiärhügelland	0.7***	0.03ns	0.68***	0.51***	0.7***	0.2*	0.1ns	0.14ns	0.1ns	0.3**	0.01ns	0.12ns
Höhenlagen	0.21*	0.08ns	0.14ns	0.21*	0.23*	0.33**	0ns	0ns	0.03ns	0ns	0.06ns	0.23*
Übergangslagen	0.12ns	0.01ns	0.06ns	0.16*	0.15ns	0.24*	0.07ns	0ns	0.04ns	0.02ns	0.02ns	0.38***

Emergence - Stem elongation

Soil-Climate-Area	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Albflächen	0.38**	0ns	0.38**	0.3**	0.34**	0.03ns	0.03ns	0.03ns	0.02ns	0.21*	0.01ns	0.32**
Gäu	0.33**	0.02ns	0.35**	0.26**	0.3**	0.07ns	0.07ns	0.06ns	0.02ns	0.06ns	0.01ns	0.46***
Moränenhügelland	0.14ns	0.01ns	0.15ns	0.11ns	0.06ns	0.15ns	0.12ns	0.1ns	0.04ns	0ns	0ns	0.51***
Nordwestbayern Franken	0.27**	0.03ns	0.31**	0.21*	0.27**	0.23*	0.26**	0.02ns	0ns	0.03ns	0.02ns	0.61***
Odenwald	0ns	0.09ns	0ns	0.01ns	0ns	0.51***	0.23*	0.03ns	0.07ns	0.13ns	0.18*	0.62***
Tertiärhügelland	0.27**	0.14ns	0.3**	0.19*	0.12ns	0.02ns	0.04ns	0.19*	0.13ns	0.02ns	0.07ns	0.4***
Höhenlagen	0.36**	0.03ns	0.38**	0.3**	0.25*	0.07ns	0.12ns	0.02ns	0.01ns	0.16*	0ns	0.48***
Übergangslagen	0.12ns	0.17*	0.09ns	0.14ns	0.19*	0.4***	0.36**	0ns	0.08ns	0.01ns	0.03ns	0.68***

Stem elongation - Heading

Soil-Climate-Area	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Albflächen	0.57***	0.08ns	0.51***	0.38**	0.11ns	0.03ns	0.18*	0.22*	0.09ns	0.08ns	0.05ns	0.24*
Gäu	0.53***	0.31**	0.62***	0.16*	0ns	0.12ns	0.38***	0.4***	0.23*	0.07ns	0.32**	0.4***
Moränenhügelland	0.33**	0.14ns	0.4***	0.1ns	0.01ns	0.25*	0.28**	0.51***	0.27**	0.08ns	0.15ns	0.46***
Nordwestbayern Franken	0.6***	0.06ns	0.56***	0.37**	0.08ns	0.17*	0.29**	0.29**	0.05ns	0.01ns	0.03ns	0.44***
Odenwald	0ns	0.16*	0ns	0ns	0ns	0.64***	0.02ns	0.1ns	0.21*	0.09ns	0.02ns	0.83***
Tertiärhügelland	0.71***	0.08ns	0.63***	0.46***	0.18*	0.15ns	0.23*	0.28**	0.1ns	0.01ns	0.05ns	0.4***
Höhenlagen	0.62***	0.08ns	0.59***	0.41***	0.12ns	0.15ns	0.21*	0.23*	0.07ns	0.03ns	0.06ns	0.41***
Übergangslagen	0.51***	0.08ns	0.51***	0.34**	0.11ns	0.42***	0.5***	0.33**	0.05ns	0.01ns	0.02ns	0.61***

Table C 2: Correlation coefficients of abiotic factors with the duration of the phenological phase four and five for wheat. The level of significance is indicated with ns: not significant, *p < 0.05, **p < 0.01, ***p < 0.001.

Heading - Beginning of milk ripening												
Soil-Climate-Area	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Albflächen	0.5***	0.01ns	0.54***	0.37**	0.25*	0.23*	0.38**	0.23*	0.05ns	0.01ns	0.01ns	0.43***
Gäu	0.11ns	0.04ns	0.1ns	0.11ns	0.15ns	0.55***	0.08ns	0.18*	0ns	0.18*	0.1ns	0.65***
Moränenhügelland	0.2*	0.06ns	0.21*	0.15ns	0.22*	0.67***	0.18*	0.34**	0.01ns	0.1ns	0.13ns	0.78***
Nordwestbayern Franken	0.35**	0ns	0.37**	0.25*	0.15ns	0.14ns	0.3**	0.38**	0.16*	0.17*	0ns	0.26**
Odenwald	0.11ns	0ns	0.14ns	0.05ns	0.02ns	0.81***	0.08ns	0.49***	0.01ns	0.47***	0ns	0.82***
Tertiärhügelland	0.39***	0ns	0.38**	0.34**	0.29**	0.06ns	0.26**	0.17*	0.09ns	0ns	0ns	0.26**
Höhenlagen	0.37**	0.21*	0.38***	0.28**	0.16*	0.06ns	0.31**	0.46***	0.26**	0.01ns	0.19*	0.21*
Übergangslagen	0.35**	0.06ns	0.45***	0.16ns	0.06ns	0.47***	0.35**	0.4***	0.06ns	0.23*	0ns	0.56***

Beginning of milk ripening - Beginning of yellow ripening												
Soil-Climate-Area	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Albflächen	0.31**	0.42***	0.33**	0.2*	0.13ns	0.19*	0.22*	0.56***	0.14ns	0.03ns	0ns	0.32**
Gäu	0.09ns	0ns	0.06ns	0.13ns	0.08ns	0.54***	0ns	0.06ns	0.09ns	0.01ns	0ns	0.6***
Moränenhügelland	0.17*	0ns	0.13ns	0.18*	0.14ns	0.58***	0.02ns	0.34**	0.05ns	0.04ns	0.01ns	0.66***
Nordwestbayern Franken	0.36**	0.08ns	0.25*	0.46***	0.3**	0.15ns	0.09ns	0.16*	0ns	0.02ns	0ns	0.29**
Odenwald	0ns	0.01ns	0ns	0.01ns	0.01ns	0.83***	0ns	0.25*	0.33**	0.04ns	0ns	0.87***
Tertiärhügelland	0.37**	0ns	0.34**	0.3**	0.14ns	0.1ns	0.2*	0.14ns	0.04ns	0.01ns	0ns	0.22*
Höhenlagen	0.28**	0.17*	0.27**	0.24*	0.03ns	0.1ns	0.24*	0.35**	0.11ns	0.01ns	0ns	0.28**
Übergangslagen	0.16*	0.01ns	0.14ns	0.17*	0.01ns	0.39***	0.2*	0.3**	0ns	0.02ns	0ns	0.45***

Table C 3: Correlation coefficients of abiotic factors with the duration of the phenological phase one to three for maize. The level of significance is indicated with ns: not significant, *p < 0.05, **p < 0.01, ***p < 0.001.

Sowing to emergence

Soil-Climate-Area	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Albflächen	0.73***	0.21*	0.67***	0.5***	0.13ns	0.21*	0.22*	0.44***	0.1ns	0.03ns	0.09ns	0.47***
Gäu	0.59***	0.26**	0.59***	0.37**	0.15ns	0.45***	0.24*	0.65***	0.21*	0ns	0.05ns	0.71***
Moränenhügelland	0.5***	0.02ns	0.39***	0.4***	0.21*	0.34**	0.04ns	0.36**	0.1ns	0ns	0.02ns	0.58***
Nordwestbayern Franken	0.58***	0.08ns	0.49***	0.43***	0.13ns	0.14ns	0.13ns	0.31**	0.01ns	0.01ns	0.01ns	0.42***
Odenwald	0.37**	0ns	0.35**	0.26**	0.07ns	0.25*	0.07ns	0.24*	0.01ns	0.03ns	0ns	0.46***
Tertiärhügelland	0.68***	0.22*	0.66***	0.39***	0.22*	0.43***	0.11ns	0.63***	0.29**	0ns	0.02ns	0.6***
Höhenlagen	0.63***	0.01ns	0.7***	0.34**	0.14ns	0.43***	0.34**	0.31**	0.01ns	0.02ns	0ns	0.64***
Übergangslagen	0.25*	0.02ns	0.2*	0.21*	0.03ns	0.33**	0.04ns	0.07ns	0ns	0.07ns	0.01ns	0.64***

Emergence - Stem elongation

Soil-Climate-Area	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Albflächen	0.45***	0.13ns	0.51***	0.12ns	0ns	0.74***	0.34**	0.51***	0.01ns	0.46***	0.02ns	0.85***
Gäu	0.17*	0.26**	0.35**	0ns	0.08ns	0.69***	0.43***	0.59***	0.19*	0.37**	0.2*	0.82***
Moränenhügelland	0.23*	0.09ns	0.26**	0.11ns	0ns	0.61***	0.19*	0.56***	0.17*	0.26**	0.12ns	0.73***
Nordwestbayern Franken	0.69***	0.15ns	0.61***	0.47***	0.08ns	0.31**	0.37**	0.47***	0.11ns	0.03ns	0.11ns	0.57***
Odenwald	0ns	0.05ns	0ns	0.01ns	0ns	0.84***	0ns	0.36**	0.25*	0.66***	0.22*	0.91***
Tertiärhügelland	0.45***	0.18*	0.55***	0.13ns	0ns	0.62***	0.52***	0.42***	0.1ns	0.26**	0.12ns	0.75***
Höhenlagen	0.12ns	0.03ns	0.15ns	0.05ns	0ns	0.69***	0.13ns	0.43***	0.06ns	0.41***	0.01ns	0.78***
Übergangslagen	0.39***	0.11ns	0.35**	0.27**	0.02ns	0.74***	0.14ns	0.18*	0.02ns	0.28**	0.02ns	0.82***

Stem elongation - Tassel emergence

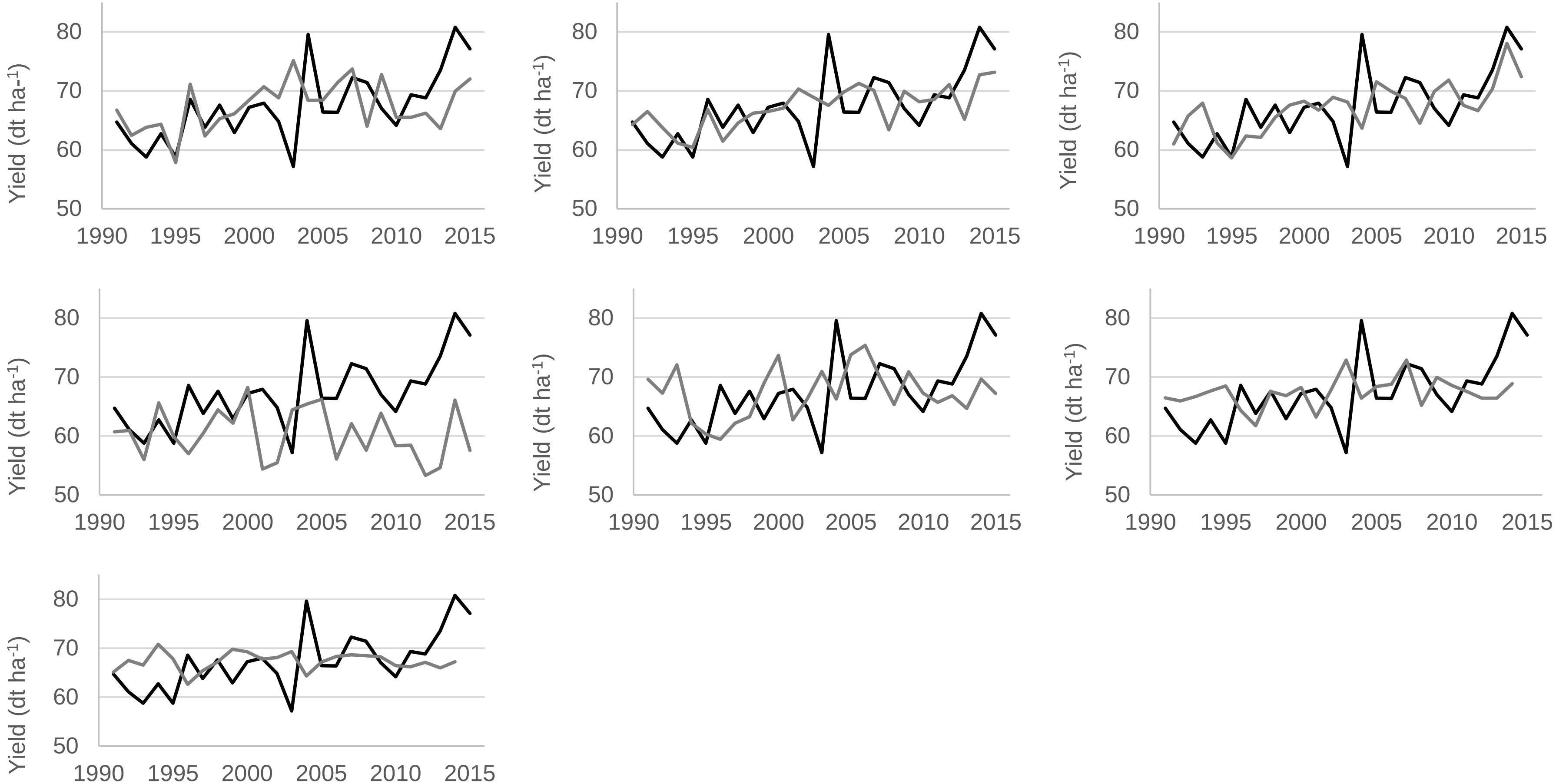
Soil-Climate-Area	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Albflächen	0.54***	0.04ns	0.44***	0.59***	0.44***	0.03ns	0.21*	0.23*	0.1ns	0.22*	0.03ns	0.29**
Gäu	0.61***	0.01ns	0.59***	0.57***	0.56***	0.59***	0.3**	0.34**	0.01ns	0.1ns	0ns	0.7***
Moränenhügelland	0.38**	0.03ns	0.32**	0.43***	0.43***	0.59***	0.13ns	0.3**	0.01ns	0ns	0.01ns	0.71***
Nordwestbayern Franken	0.35**	0.01ns	0.25*	0.44***	0.31**	0.25*	0.06ns	0.15ns	0ns	0ns	0ns	0.33**
Odenwald	0.12ns	0.12ns	0.13ns	0.08ns	0.01ns	0.64***	0.06ns	0.22*	0.04ns	0.03ns	0.22*	0.74***
Tertiärhügelland	0.66***	0ns	0.64***	0.64***	0.54***	0.19*	0.34**	0.39***	0.18*	0.16*	0ns	0.37**
Höhenlagen	0.47***	0.05ns	0.48***	0.36**	0.27**	0.11ns	0.28**	0.59***	0.28**	0.06ns	0.24*	0.29**
Übergangslagen	0.17*	0ns	0.12ns	0.22*	0.16*	0.42***	0.12ns	0.41***	0ns	0.11ns	0ns	0.46***

Table C 4: Correlation coefficients of abiotic factors with the duration of the phenological phase four to six for maize. The level of significance is indicated with ns: not significant, *p < 0.05, **p < 0.01, ***p < 0.001.

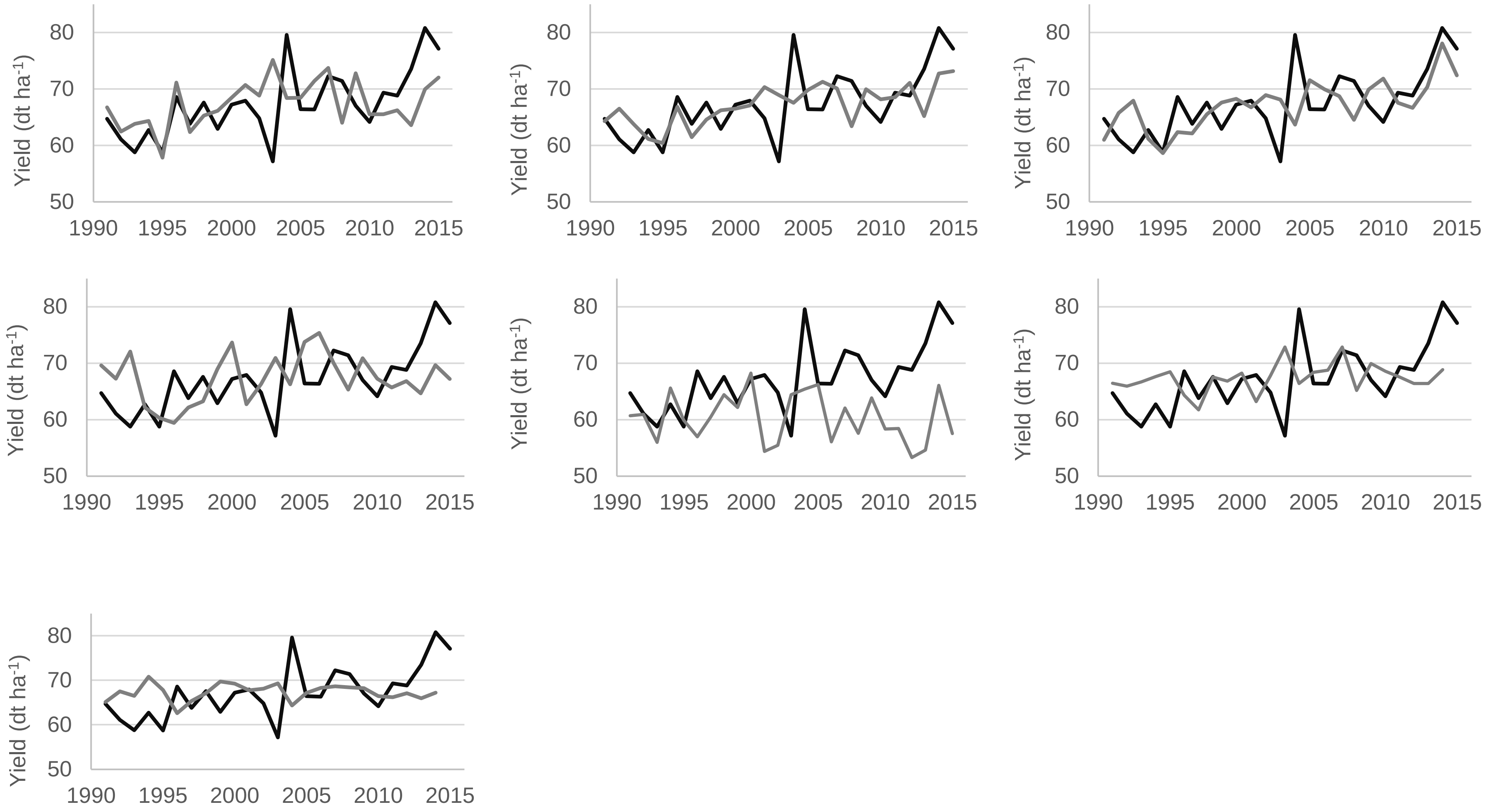
Tassel emerg. - Flowering												
Soil-Climate-Area	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Albflächen	0.44***	0.05ns	0.45***	0.29**	0.21*	0.28**	0.31**	0.35**	0.15ns	0.24*	0ns	0.41***
Gäu	0.29**	0.09ns	0.26**	0.17*	0.09ns	0.44***	0.2*	0.48***	0.24*	0.02ns	0.08ns	0.46***
Moränenhügelland	0.02ns	0.01ns	0.02ns	0.01ns	0.04ns	0.67***	0.04ns	0.18*	0.01ns	0.07ns	0.02ns	0.76***
Nordwestbayern Franken	0.21*	0.07ns	0.16*	0.18*	0.05ns	0.47***	0.06ns	0.3**	0.02ns	0ns	0.01ns	0.58***
Odenwald	0.03ns	0ns	0.01ns	0.05ns	0.07ns	0.91***	0.03ns	0.64***	0.18*	0.3**	0.03ns	0.93***
Tertiärhügelland	0.47***	0.32**	0.54***	0.16*	0.03ns	0.17*	0.46***	0.28**	0.16*	0.25*	0.23*	0.3**
Höhenlagen	0.38**	0.09ns	0.36**	0.36**	0.23*	0.16*	0.28**	0.23*	0.03ns	0.1ns	0.08ns	0.34**
Übergangslagen	0.57***	0.14ns	0.55***	0.49***	0.28**	0.81***	0.21*	0.37**	0ns	0.09ns	0ns	0.85***
Flowering - Milk ripening												
Soil-Climate-Area	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Albflächen	0.47***	0.08ns	0.51***	0.24*	0.01ns	0.04ns	0.37**	0.55***	0.32**	0ns	0.08ns	0.21*
Gäu	0.3**	0.05ns	0.29**	0.25*	0.34**	0.2*	0.13ns	0.29**	0.09ns	0ns	0.01ns	0.45***
Moränenhügelland	0.2*	0.3**	0.21*	0.13ns	0.06ns	0.55***	0.15ns	0.56***	0.15ns	0.24*	0.26**	0.69***
Nordwestbayern Franken	0.26**	0.02ns	0.29**	0.16*	0ns	0.18*	0.24*	0.44***	0.08ns	0.05ns	0ns	0.47***
Odenwald	0.12ns	0.11ns	0.11ns	0.11ns	0ns	0.83***	0.08ns	0.25*	0.42***	0.13ns	0.21*	0.91***
Tertiärhügelland	0.15ns	0.02ns	0.14ns	0.14ns	0.04ns	0.29**	0.02ns	0.31**	0.06ns	0.07ns	0.01ns	0.53***
Höhenlagen	0.11ns	0.07ns	0.11ns	0.06ns	0.01ns	0.13ns	0.06ns	0.21*	0.03ns	0.01ns	0.01ns	0.34**
Übergangslagen	0.13ns	0.04ns	0.17*	0.05ns	0ns	0.4***	0.24*	0.3**	0ns	0.24*	0.04ns	0.5***
Milk ripening - Dough ripening												
Soil-Climate-Area	t_avg	SW	t_max	t_min	VPD	Etc	Rad_avg	prec	WB	GDD	SW_min	Rad_sum
Albflächen	0.43***	0.09ns	0.44***	0.31**	0.13ns	0.08ns	0.36**	0.39***	0.16*	0.01ns	0.02ns	0.3**
Gäu	0.42***	0.16*	0.45***	0.28**	0.1ns	0.4***	0.51***	0.57***	0.29**	0ns	0.05ns	0.63***
Moränenhügelland	0ns	0.01ns	0ns	0.01ns	0ns	0.56***	0ns	0.28**	0ns	0.03ns	0.01ns	0.71***
Nordwestbayern Franken	0.52***	0.1ns	0.49***	0.42***	0.17*	0.18*	0.25*	0.45***	0.16*	0ns	0.03ns	0.44***
Odenwald	0.03ns	0.21*	0.06ns	0ns	0.05ns	0.85***	0.16*	0.4***	0.14ns	0.04ns	0.05ns	0.93***
Tertiärhügelland	0.42***	0ns	0.49***	0.24*	0.09ns	0.31**	0.56***	0.5***	0.18*	0.03ns	0.01ns	0.57***
Höhenlagen	0.31**	0ns	0.26**	0.36**	0.13ns	0.06ns	0.23*	0.08ns	0.01ns	0.17*	0.03ns	0.31**
Übergangslagen	0.13ns	0ns	0.15ns	0.08ns	0.07ns	0.26**	0.13ns	0.14ns	0ns	0.01ns	0ns	0.38***

D. Supplemental Figures Section 4.3

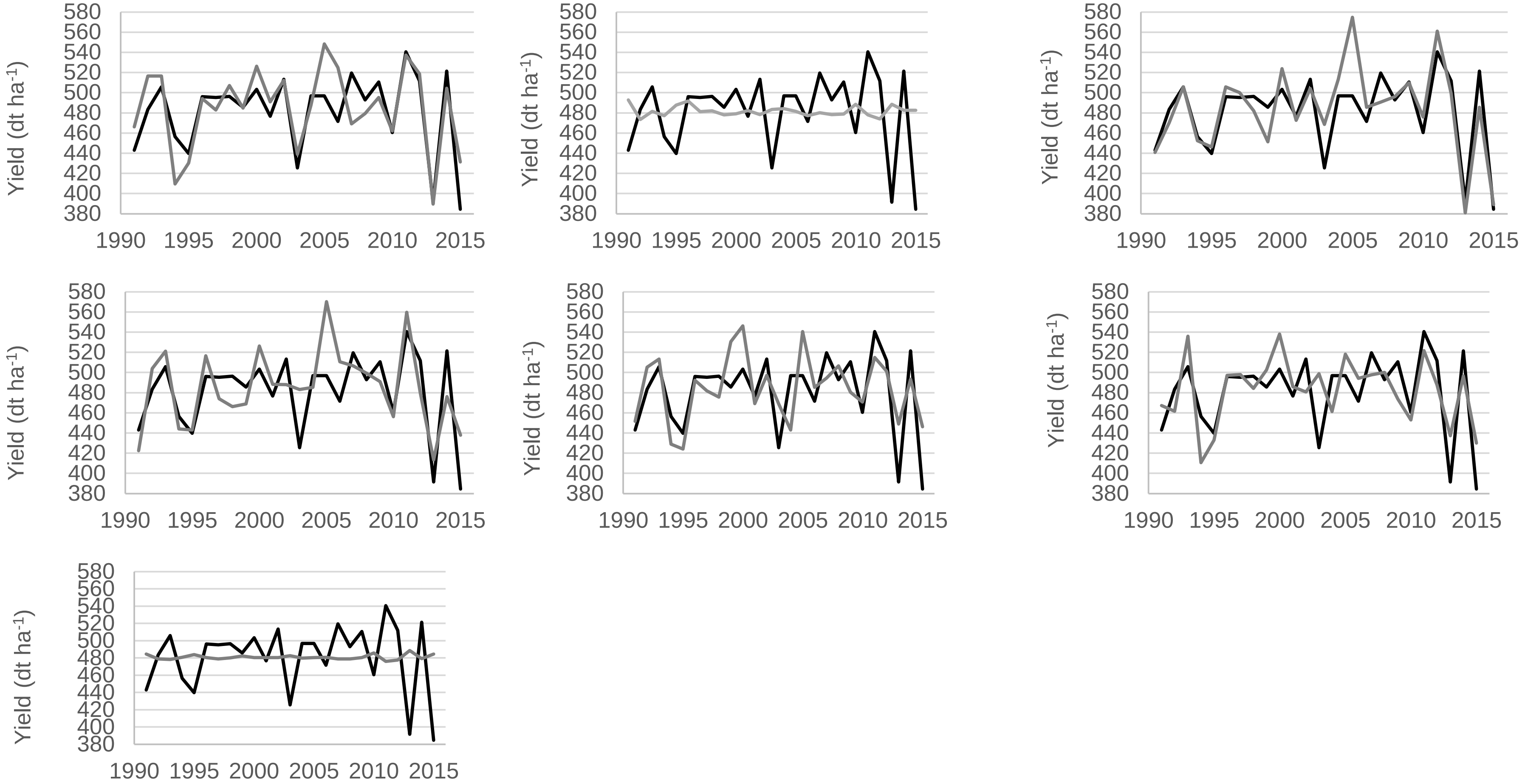
Figures D 1: Average actual **wheat yields** (black line) and predicted yields (grey line) for the **calendar methodology**. Time intervals ordered from upper left to lower right: 1 day, 2 days, 5 days, 10 days, 15 days, 1 month and the whole calender vegetation period.



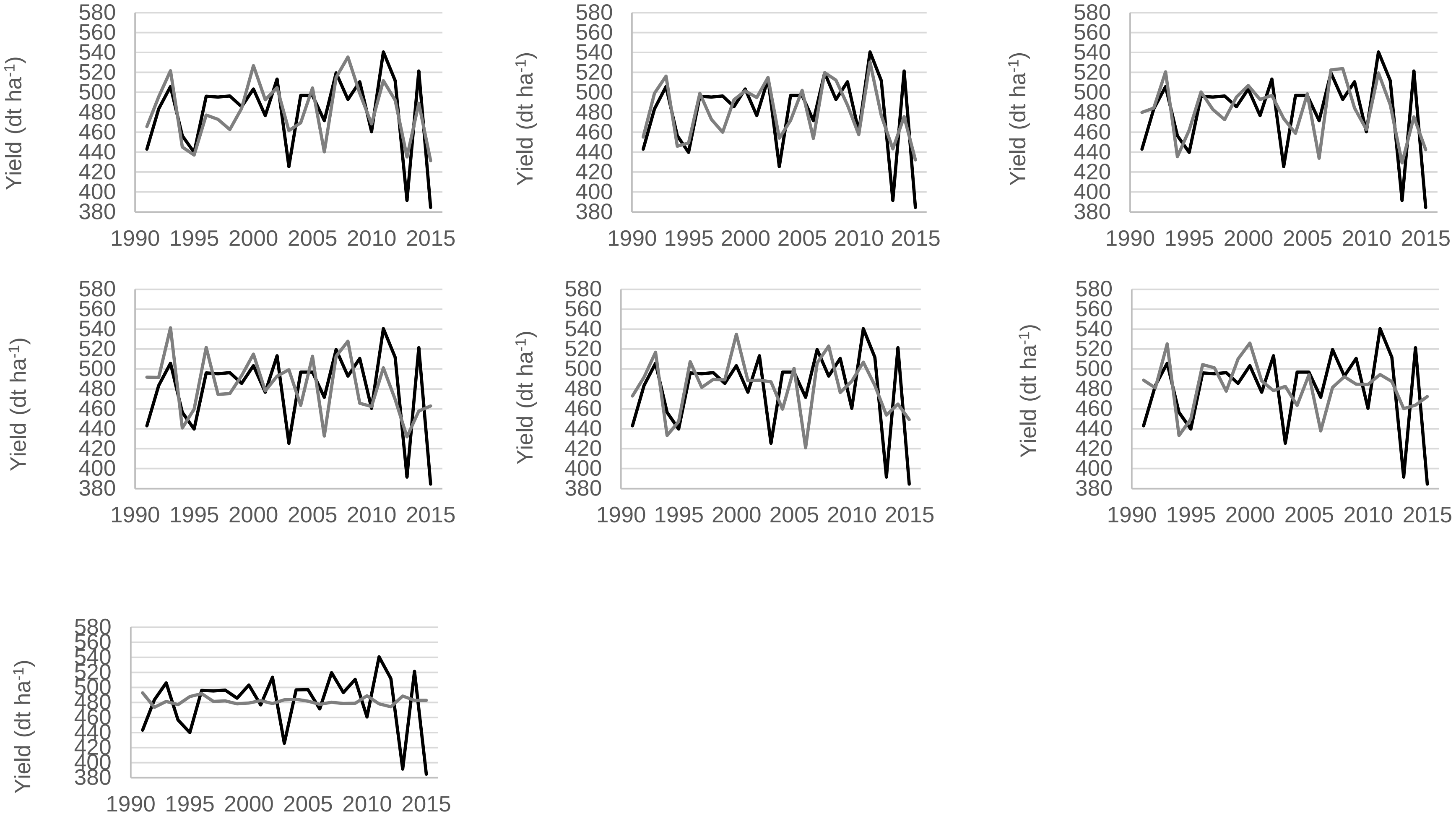
Figures D 2: Average actual **wheat yield** (black line) and predicted yield (grey line) for the **phenology methodology**. Time intervals ordered from upper left to lower right: 153 units, 75 units, 30 units, 15 units, 10 units, each phenological phase and the whole vegetation period.



Figures D 3: Average actual **maize yields** (black line) and predicted yields (grey line) for the **calendar methodology**. Time intervals ordered from upper left to lower right: 1 day, 2 days, 5 days, 10 days, 15 days, 1 month and the whole calender vegetation period.



Figures D 4: Average actual **maize yield** (black line) and predicted yield (grey line) for the **phenology methodology**. Time intervals ordered from upper left to lower right: 118 units, 89 units, 35 units, 17 units, 11 units, each phenological phase and the whole vegetation period.



E. Supplemental Tables Section 4.4

Table E 1: Observed and predicted maize and wheat yields in dt ha^{-1} for Bavarian counties from 1991 to 2015 with a 95% confidence interval given for both cultures observed yields see (upper and lower confidence interval in table).

County	Year	Maize observed yield	Maize predicted yield	Lower Confidence Intervall	Upper Confidence Intervall	Wheat obs. detrendet yield	Wheat predicted yields	Lower Confidence Intervall	Upper Confidence Intervall
Aichach-Friedberg	1991	509.70	469.75	455.89	483.60	65.30	61.12	59.15	63.08
Aichach-Friedberg	1992	476.70	481.72	472.79	490.64	66.16	65.32	64.11	66.52
Aichach-Friedberg	1993	512.40	532.18	523.05	541.30	67.02	65.93	64.68	67.18
Aichach-Friedberg	1994	497.30	483.08	472.99	493.16	67.88	65.76	64.15	67.38
Aichach-Friedberg	1995	418.00	454.38	443.18	465.59	68.74	65.85	64.59	67.11
Aichach-Friedberg	1996	499.50	495.64	487.45	503.82	69.60	68.66	67.56	69.76
Aichach-Friedberg	1997	493.20	509.38	498.61	520.16	70.46	64.13	62.86	65.41
Aichach-Friedberg	1998	475.50	504.89	496.97	512.82	71.32	67.75	66.50	69.01
Aichach-Friedberg	1999	454.40	484.66	475.68	493.63	72.18	66.35	64.93	67.77
Aichach-Friedberg	2000	537.50	513.38	502.41	524.34	73.04	67.21	65.53	68.90
Aichach-Friedberg	2001	501.30	478.46	469.30	487.61	73.90	66.52	65.06	67.98
Aichach-Friedberg	2002	529.50	530.29	520.38	540.20	74.76	71.20	69.95	72.45
Aichach-Friedberg	2003	446.20	468.22	458.22	478.21	75.62	68.18	66.73	69.62
Aichach-Friedberg	2004	491.90	502.23	494.66	509.80	76.48	66.64	65.41	67.87
Aichach-Friedberg	2005	517.40	507.90	499.23	516.58	77.35	66.21	64.77	67.66
Aichach-Friedberg	2006	497.40	473.48	464.73	482.24	78.21	71.56	70.29	72.83
Aichach-Friedberg	2007	515.10	512.57	504.35	520.79	79.07	72.43	71.13	73.73
Aichach-Friedberg	2008	522.80	507.00	498.24	515.76	79.93	67.18	66.01	68.35
Aichach-Friedberg	2009	554.70	500.33	492.52	508.14	80.79	70.10	68.74	71.46
Aichach-Friedberg	2010	452.50	435.01	426.55	443.46	81.65	73.06	71.65	74.47
Aichach-Friedberg	2011	611.70	531.57	521.67	541.47	82.51	72.42	71.11	73.73
Aichach-Friedberg	2012	557.60	528.61	523.27	533.95	83.37	69.97	68.75	71.19
Aichach-Friedberg	2013	409.90	390.84	379.90	401.78	84.23	74.16	72.74	75.59
Aichach-Friedberg	2014	536.00	550.03	540.60	559.46	85.09	73.19	71.57	74.82
Aichach-Friedberg	2015	398.90	414.02	406.70	421.34	85.95	74.70	73.31	76.09
Altoetting	1991	527.10	475.85	460.79	490.90	61.48	65.18	63.44	66.93
Altoetting	1992	509.20	485.55	474.34	496.76	62.04	67.79	66.29	69.29
Altoetting	1993	538.10	540.10	501.60	578.59	62.60	68.73	66.65	70.81
Altoetting	1994	500.20	461.89	454.46	469.32	63.16	68.99	67.29	70.68

Altoetting	1995	449.00	458.96	448.74	469.17	63.73	66.07	64.56	67.58
Altoetting	1996	501.70	495.20	486.23	504.18	64.29	69.76	68.47	71.05
Altoetting	1997	527.20	532.82	521.90	543.74	64.85	64.75	63.18	66.32
Altoetting	1998	549.90	509.31	497.41	521.20	65.41	67.13	65.46	68.81
Altoetting	1999	515.80	488.84	475.17	502.51	65.97	66.63	64.20	69.06
Altoetting	2000	535.10	531.26	515.99	546.53	66.54	67.90	66.52	69.28
Altoetting	2001	472.30	458.77	445.03	472.51	67.10	66.42	64.69	68.16
Altoetting	2002	551.60	512.56	483.87	541.25	67.66	75.35	74.02	76.68
Altoetting	2003	487.10	479.88	464.73	495.03	68.22	73.17	71.45	74.89
Altoetting	2004	546.50	505.22	497.63	512.81	68.79	69.52	68.12	70.93
Altoetting	2005	477.80	514.71	503.70	525.73	69.35	68.03	65.85	70.21
Altoetting	2006	469.40	465.89	454.07	477.71	69.91	71.44	69.89	73.00
Altoetting	2007	516.10	516.95	505.73	528.17	70.47	76.60	74.83	78.36
Altoetting	2008	497.20	555.70	544.44	566.97	71.04	71.72	70.31	73.13
Altoetting	2009	505.50	512.10	493.12	531.09	71.60	68.51	65.79	71.22
Altoetting	2010	422.00	491.22	470.87	511.57	72.16	74.10	72.16	76.03
Altoetting	2011	542.20	562.92	549.51	576.33	72.72	74.45	72.87	76.03
Altoetting	2012	484.20	546.74	535.97	557.51	73.28	73.19	71.40	74.98
Altoetting	2013	403.30	429.49	417.32	441.66	73.85	82.26	79.96	84.56
Altoetting	2014	509.30	504.02	490.30	517.74	74.41	82.05	79.51	84.58
Altoetting	2015	491.00	429.48	419.07	439.89	74.97	76.57	74.98	78.15
Amberg-Sulzbach	1991	437.20	458.43	448.19	468.67	56.58	59.24	57.93	60.54
Amberg-Sulzbach	1992	499.60	374.95	316.01	433.90	57.11	50.51	41.84	59.17
Amberg-Sulzbach	1993	529.00	510.95	502.35	519.55	57.64	61.25	59.83	62.68
Amberg-Sulzbach	1994	446.10	404.15	394.54	413.76	58.17	64.63	63.30	65.95
Amberg-Sulzbach	1995	451.90	443.59	435.65	451.54	58.71	64.16	62.98	65.34
Amberg-Sulzbach	1996	507.00	494.29	483.89	504.70	59.24	61.28	59.70	62.86
Amberg-Sulzbach	1997	493.50	469.91	461.29	478.53	59.77	60.29	58.72	61.86
Amberg-Sulzbach	1998	519.80	490.61	480.66	500.56	60.30	64.08	62.96	65.20
Amberg-Sulzbach	1999	465.30	486.70	478.25	495.15	60.83	65.14	63.92	66.35
Amberg-Sulzbach	2000	481.40	507.51	498.34	516.68	61.36	62.98	61.40	64.56
Amberg-Sulzbach	2001	458.90	483.55	474.89	492.22	61.90	63.19	61.94	64.44
Amberg-Sulzbach	2002	530.90	500.74	492.18	509.30	62.43	65.56	64.37	66.74
Amberg-Sulzbach	2003	398.40	388.96	378.70	399.22	62.96	64.42	62.98	65.86
Amberg-Sulzbach	2004	495.40	488.65	480.45	496.84	63.49	64.10	63.00	65.19
Amberg-Sulzbach	2005	534.90	514.15	505.60	522.69	64.02	64.85	63.56	66.14

Amberg-Sulzbach	2006	478.60	461.50	451.72	471.28	64.56	63.90	62.47	65.34
Amberg-Sulzbach	2007	551.30	512.54	506.03	519.06	65.09	69.76	68.54	70.97
Amberg-Sulzbach	2008	480.30	493.24	485.15	501.33	65.62	66.49	65.38	67.60
Amberg-Sulzbach	2009	529.50	494.75	488.57	500.93	66.15	68.18	66.79	69.58
Amberg-Sulzbach	2010	471.30	450.22	439.67	460.76	66.68	68.49	67.26	69.71
Amberg-Sulzbach	2011	569.60	538.36	529.23	547.48	67.21	68.54	67.27	69.81
Amberg-Sulzbach	2012	519.90	501.68	495.67	507.70	67.75	66.14	64.96	67.31
Amberg-Sulzbach	2013	369.90	368.00	359.28	376.72	68.28	67.87	66.57	69.18
Amberg-Sulzbach	2014	571.30	503.32	493.42	513.22	68.81	70.10	68.61	71.58
Amberg-Sulzbach	2015	384.20	365.01	355.72	374.30	69.34	66.32	65.28	67.36
Ansbach	1991	424.80	449.35	437.71	461.00	58.06	59.67	58.04	61.30
Ansbach	1992	482.00	487.20	479.03	495.37	58.55	62.73	61.38	64.08
Ansbach	1993	571.60	497.88	489.07	506.69	59.03	62.03	60.85	63.20
Ansbach	1994	453.20	446.47	438.22	454.72	59.52	61.43	59.89	62.97
Ansbach	1995	457.80	459.99	450.28	469.71	60.00	63.55	62.20	64.90
Ansbach	1996	519.30	496.25	488.68	503.82	60.48	64.93	63.81	66.05
Ansbach	1997	491.80	481.99	474.61	489.37	60.97	60.94	59.70	62.18
Ansbach	1998	490.10	480.21	472.42	488.00	61.45	63.84	62.77	64.91
Ansbach	1999	507.50	489.42	478.51	500.34	61.94	67.43	66.25	68.62
Ansbach	2000	506.70	511.80	501.99	521.60	62.42	61.97	60.19	63.74
Ansbach	2001	457.50	448.62	435.90	461.34	62.91	67.02	65.64	68.41
Ansbach	2002	520.00	501.94	495.27	508.62	63.39	66.99	65.82	68.16
Ansbach	2003	377.70	369.92	356.07	383.77	63.88	65.03	62.67	67.39
Ansbach	2004	481.40	490.00	481.89	498.12	64.36	66.07	64.94	67.19
Ansbach	2005	497.80	505.34	497.28	513.41	64.84	66.30	65.20	67.39
Ansbach	2006	483.20	457.15	446.33	467.98	65.33	66.33	64.89	67.78
Ansbach	2007	505.50	508.48	500.95	516.01	65.81	68.17	66.85	69.50
Ansbach	2008	493.80	479.16	471.25	487.06	66.30	66.28	65.01	67.55
Ansbach	2009	520.90	488.02	481.09	494.96	66.78	69.02	67.75	70.28
Ansbach	2010	471.80	458.66	448.78	468.53	67.27	68.77	67.41	70.13
Ansbach	2011	549.40	543.87	534.19	553.55	67.75	70.79	69.15	72.44
Ansbach	2012	455.80	500.87	493.15	508.60	68.24	69.83	68.35	71.31
Ansbach	2013	405.30	398.03	389.35	406.70	68.72	69.70	68.48	70.92
Ansbach	2014	520.80	521.49	512.20	530.78	69.21	69.16	67.60	70.72
Ansbach	2015	377.30	389.97	382.54	397.40	69.69	67.62	66.37	68.87
Aschaffenburg	1991	339.40	438.79	426.10	451.48	59.82	62.36	60.63	64.08

Aschaffenburg	1992	488.40	507.55	497.82	517.29	60.29	64.45	63.08	65.82
Aschaffenburg	1993	430.10	470.15	456.94	483.37	60.77	65.25	63.71	66.78
Aschaffenburg	1994	433.30	429.29	416.30	442.27	61.25	59.99	57.76	62.23
Aschaffenburg	1995	486.90	462.90	452.31	473.49	61.72	65.58	64.24	66.92
Aschaffenburg	1996	479.20	492.55	484.67	500.43	62.20	67.62	66.38	68.86
Aschaffenburg	1997	449.90	485.36	476.50	494.21	62.67	62.43	60.57	64.29
Aschaffenburg	1998	506.90	470.29	459.25	481.33	63.15	61.49	59.88	63.11
Aschaffenburg	1999	492.80	496.41	486.72	506.10	63.62	65.26	63.77	66.75
Aschaffenburg	2000	524.60	507.69	494.62	520.76	64.10	61.23	59.01	63.45
Aschaffenburg	2001	484.30	453.60	443.54	463.66	64.58	63.77	61.71	65.82
Aschaffenburg	2002	503.40	509.76	498.81	520.72	65.05	67.02	65.32	68.73
Aschaffenburg	2003	381.90	383.03	370.16	395.90	65.53	64.28	61.97	66.59
Aschaffenburg	2004	493.80	483.95	473.89	494.02	66.00	64.49	63.30	65.67
Aschaffenburg	2005	506.00	502.90	493.44	512.36	66.48	66.37	64.91	67.83
Aschaffenburg	2006	500.60	467.31	452.21	482.40	66.96	64.05	62.18	65.91
Aschaffenburg	2007	504.50	514.63	503.92	525.35	67.43	67.88	65.77	69.98
Aschaffenburg	2008	481.40	454.42	441.99	466.84	67.91	61.83	60.28	63.38
Aschaffenburg	2009	504.90	481.48	474.14	488.81	68.38	66.50	65.13	67.88
Aschaffenburg	2010	489.20	474.79	463.58	486.00	68.86	68.66	67.17	70.15
Aschaffenburg	2011	563.30	538.24	525.52	550.97	69.33	71.66	69.65	73.67
Aschaffenburg	2012	499.40	485.53	475.47	495.58	69.81	66.75	64.81	68.70
Aschaffenburg	2013	398.60	432.85	423.87	441.83	70.29	71.08	69.89	72.27
Aschaffenburg	2014	490.30	519.67	509.81	529.53	70.76	70.26	68.33	72.19
Aschaffenburg	2015	349.20	383.94	372.79	395.09	71.24	65.39	63.79	66.99
Augsburg	1991	469.50	467.24	453.36	481.12	65.50	58.01	55.00	61.02
Augsburg	1992	474.60	494.59	486.25	502.93	66.19	65.43	64.21	66.65
Augsburg	1993	503.70	531.90	522.89	540.90	66.88	65.17	63.93	66.40
Augsburg	1994	502.40	491.81	481.60	502.02	67.57	66.29	64.77	67.81
Augsburg	1995	437.40	448.51	436.53	460.48	68.25	65.01	63.73	66.28
Augsburg	1996	507.70	491.43	482.58	500.27	68.94	67.99	66.84	69.15
Augsburg	1997	524.50	504.01	493.26	514.75	69.63	62.91	61.59	64.23
Augsburg	1998	500.10	503.09	495.41	510.77	70.32	66.92	65.69	68.16
Augsburg	1999	465.10	484.95	475.73	494.18	71.00	64.71	63.33	66.08
Augsburg	2000	539.20	512.72	501.17	524.26	71.69	66.77	65.11	68.42
Augsburg	2001	535.30	481.54	472.48	490.61	72.38	65.82	64.25	67.39
Augsburg	2002	527.40	527.51	517.96	537.07	73.07	71.45	70.19	72.72

Augsburg	2003	477.70	474.33	463.71	484.95	73.76	68.44	67.00	69.87
Augsburg	2004	514.00	504.56	496.71	512.42	74.44	66.47	65.28	67.65
Augsburg	2005	523.80	510.20	501.65	518.75	75.13	66.81	65.39	68.23
Augsburg	2006	505.90	474.78	465.22	484.35	75.82	70.34	68.99	71.68
Augsburg	2007	553.20	505.90	497.68	514.11	76.51	72.19	70.80	73.58
Augsburg	2008	551.80	506.40	498.21	514.59	77.19	66.49	65.35	67.63
Augsburg	2009	531.80	497.02	489.80	504.24	77.88	70.80	69.43	72.17
Augsburg	2010	480.70	442.95	434.35	451.56	78.57	72.68	71.36	74.00
Augsburg	2011	572.00	531.17	520.93	541.40	79.26	71.77	70.44	73.10
Augsburg	2012	549.40	527.09	521.68	532.50	79.95	70.29	69.12	71.46
Augsburg	2013	417.60	395.28	384.55	406.02	80.63	73.62	72.26	74.99
Augsburg	2014	561.60	560.49	551.41	569.57	81.32	72.02	70.38	73.66
Augsburg	2015	424.30	424.91	417.67	432.14	82.01	74.70	73.33	76.07
Bad Kissingen	1991	344.50	402.14	389.97	414.32	56.79	55.01	53.35	56.66
Bad Kissingen	1992	469.80	497.11	489.87	504.34	57.19	63.50	62.24	64.76
Bad Kissingen	1993	441.50	479.16	469.10	489.21	57.59	61.08	59.74	62.41
Bad Kissingen	1994	416.80	439.32	429.90	448.73	57.99	59.39	57.85	60.93
Bad Kissingen	1995	446.60	472.92	463.27	482.58	58.39	64.14	62.73	65.56
Bad Kissingen	1996	451.80	495.59	487.23	503.96	58.78	62.77	61.70	63.84
Bad Kissingen	1997	458.20	450.56	439.12	462.01	59.18	59.92	58.39	61.46
Bad Kissingen	1998	463.40	467.62	457.81	477.42	59.58	60.83	59.47	62.20
Bad Kissingen	1999	496.00	492.40	483.89	500.90	59.98	63.55	62.49	64.61
Bad Kissingen	2000	490.00	500.07	488.77	511.37	60.38	61.00	59.12	62.87
Bad Kissingen	2001	471.60	467.80	457.93	477.67	60.78	65.26	63.41	67.11
Bad Kissingen	2002	474.30	494.22	484.22	504.21	61.18	65.13	63.57	66.69
Bad Kissingen	2003	346.70	421.96	413.11	430.80	61.58	66.11	64.61	67.62
Bad Kissingen	2004	532.00	470.39	459.32	481.45	61.97	62.02	60.73	63.31
Bad Kissingen	2005	414.80	470.43	461.77	479.10	62.37	63.49	62.39	64.60
Bad Kissingen	2006	431.80	443.85	433.25	454.45	62.77	64.31	62.97	65.65
Bad Kissingen	2007	495.00	528.67	518.78	538.56	63.17	65.36	63.97	66.75
Bad Kissingen	2008	379.60	461.26	452.40	470.12	63.57	61.31	60.02	62.61
Bad Kissingen	2009	462.10	482.74	475.95	489.52	63.97	64.18	62.96	65.40
Bad Kissingen	2010	417.30	473.48	462.65	484.32	64.37	67.55	65.91	69.18
Bad Kissingen	2011	496.50	522.98	513.05	532.90	64.77	67.94	66.14	69.74
Bad Kissingen	2012	489.60	499.11	491.50	506.72	65.16	62.19	60.66	63.73
Bad Kissingen	2013	369.90	431.96	423.49	440.42	65.56	67.01	65.67	68.35

Bad Kissingen	2014	497.30	511.88	501.39	522.37	65.96	68.85	67.19	70.51
Bad Kissingen	2015	294.10	401.96	393.19	410.73	66.36	64.94	63.54	66.35
Bamberg	1991	400.10	431.47	422.22	440.72	54.16	59.69	58.37	61.01
Bamberg	1992	478.30	475.95	468.26	483.65	54.63	62.16	60.88	63.44
Bamberg	1993	499.20	486.88	476.52	497.24	55.10	61.68	60.42	62.94
Bamberg	1994	430.00	414.70	404.96	424.43	55.56	59.85	58.16	61.54
Bamberg	1995	444.70	444.40	434.70	454.09	56.03	60.78	59.35	62.21
Bamberg	1996	486.40	510.72	502.30	519.14	56.50	61.86	60.76	62.97
Bamberg	1997	487.90	477.85	469.17	486.52	56.96	61.36	59.98	62.74
Bamberg	1998	493.90	473.67	465.27	482.07	57.43	61.86	60.63	63.09
Bamberg	1999	477.80	487.46	479.02	495.90	57.90	64.44	63.35	65.54
Bamberg	2000	475.00	502.76	492.25	513.27	58.36	61.87	60.40	63.35
Bamberg	2001	484.80	462.92	453.21	472.64	58.83	64.59	63.13	66.05
Bamberg	2002	480.60	497.92	489.24	506.60	59.30	65.32	64.04	66.60
Bamberg	2003	397.80	404.98	395.10	414.85	59.76	65.45	63.95	66.95
Bamberg	2004	467.40	500.13	492.13	508.12	60.23	63.45	62.45	64.46
Bamberg	2005	471.70	508.53	501.40	515.66	60.70	63.64	62.34	64.94
Bamberg	2006	440.30	465.55	453.10	478.00	61.16	62.14	60.60	63.67
Bamberg	2007	502.50	539.93	531.12	548.75	61.63	66.44	64.91	67.97
Bamberg	2008	402.80	477.99	468.29	487.68	62.10	63.58	62.09	65.07
Bamberg	2009	511.90	475.86	468.51	483.22	62.56	66.66	65.12	68.20
Bamberg	2010	448.00	455.37	443.75	466.99	63.03	68.47	67.06	69.88
Bamberg	2011	523.10	540.72	532.43	549.02	63.50	70.23	68.56	71.89
Bamberg	2012	476.20	497.20	487.48	506.91	63.96	65.23	63.45	67.02
Bamberg	2013	409.30	416.25	408.02	424.49	64.43	66.97	65.73	68.22
Bamberg	2014	469.60	513.23	503.48	522.97	64.90	69.05	67.10	71.00
Bamberg	2015	355.80	397.39	389.14	405.65	65.36	66.26	64.89	67.64
Bayreuth	1991	422.60	416.31	405.17	427.44	52.35	56.66	55.11	58.21
Bayreuth	1992	466.70	472.72	465.75	479.69	52.96	62.90	61.79	64.00
Bayreuth	1993	528.60	494.51	485.70	503.32	53.56	58.88	57.72	60.03
Bayreuth	1994	425.10	405.67	396.39	414.95	54.17	62.25	61.19	63.32
Bayreuth	1995	440.10	439.16	430.85	447.46	54.78	60.66	59.47	61.85
Bayreuth	1996	479.20	486.22	476.00	496.44	55.39	59.87	58.36	61.39
Bayreuth	1997	471.00	458.48	448.93	468.03	55.99	57.71	56.43	58.99
Bayreuth	1998	489.10	482.02	471.37	492.67	56.60	62.02	60.86	63.17
Bayreuth	1999	465.50	482.94	473.86	492.01	57.21	62.77	61.94	63.60

Bayreuth	2000	494.50	506.95	496.59	517.31	57.81	62.62	60.88	64.36
Bayreuth	2001	447.80	468.28	456.78	479.79	58.42	61.29	59.80	62.78
Bayreuth	2002	485.90	485.70	477.17	494.22	59.03	63.35	62.43	64.28
Bayreuth	2003	423.60	420.42	409.73	431.11	59.64	62.08	60.78	63.38
Bayreuth	2004	479.10	486.90	478.83	494.97	60.24	62.44	61.49	63.40
Bayreuth	2005	491.30	499.89	491.88	507.89	60.85	61.67	60.51	62.82
Bayreuth	2006	480.20	458.37	449.35	467.38	61.46	66.33	65.12	67.53
Bayreuth	2007	492.90	500.36	493.73	506.99	62.06	65.93	64.90	66.97
Bayreuth	2008	458.20	479.71	471.88	487.55	62.67	65.24	64.06	66.42
Bayreuth	2009	474.90	492.17	484.96	499.38	63.28	67.01	65.44	68.59
Bayreuth	2010	415.20	444.93	432.83	457.03	63.89	65.46	64.17	66.75
Bayreuth	2011	527.50	527.19	518.64	535.74	64.49	65.13	63.77	66.50
Bayreuth	2012	493.30	492.25	485.17	499.32	65.10	64.21	63.34	65.08
Bayreuth	2013	343.00	381.55	372.69	390.41	65.71	67.27	65.83	68.70
Bayreuth	2014	534.90	496.06	486.75	505.37	66.32	68.13	66.97	69.29
Bayreuth	2015	403.30	395.08	387.72	402.44	66.92	65.71	64.77	66.64
Cham	1991	482.40	442.71	432.43	453.00	55.46	59.10	57.92	60.27
Cham	1992	460.80	465.00	456.88	473.12	56.14	62.90	61.73	64.08
Cham	1993	494.40	508.80	499.42	518.18	56.83	59.96	58.37	61.56
Cham	1994	414.40	399.16	389.45	408.87	57.51	61.58	60.27	62.89
Cham	1995	416.60	446.10	437.46	454.75	58.20	59.73	58.13	61.33
Cham	1996	477.50	485.68	475.75	495.61	58.88	60.68	59.03	62.33
Cham	1997	480.40	487.56	477.78	497.35	59.57	59.47	58.20	60.75
Cham	1998	497.00	495.23	485.79	504.67	60.25	63.54	62.34	64.74
Cham	1999	489.30	486.98	478.81	495.16	60.94	64.62	63.58	65.67
Cham	2000	492.80	498.00	488.00	508.00	61.62	62.25	60.81	63.70
Cham	2001	503.60	464.92	455.26	474.58	62.31	62.15	60.93	63.36
Cham	2002	542.10	506.07	495.87	516.28	62.99	65.12	64.02	66.23
Cham	2003	442.50	417.69	407.50	427.88	63.68	62.87	61.27	64.47
Cham	2004	525.40	483.00	475.53	490.46	64.36	62.79	61.64	63.94
Cham	2005	515.10	511.78	503.14	520.43	65.05	62.42	60.95	63.90
Cham	2006	488.40	480.69	470.14	491.23	65.73	67.26	65.83	68.69
Cham	2007	548.20	509.84	502.56	517.12	66.41	68.68	67.25	70.12
Cham	2008	509.60	484.85	477.52	492.18	67.10	65.76	64.67	66.85
Cham	2009	504.60	508.34	500.10	516.59	67.78	67.89	66.54	69.24
Cham	2010	492.20	467.55	456.90	478.20	68.47	67.92	66.34	69.49

Cham	2011	519.80	541.52	531.87	551.18	69.15	69.35	67.68	71.01
Cham	2012	538.50	521.74	512.95	530.54	69.84	69.50	68.13	70.87
Cham	2013	333.30	389.79	380.26	399.31	70.52	68.72	67.46	69.99
Cham	2014	512.70	495.97	487.15	504.80	71.21	69.12	67.61	70.62
Cham	2015	420.70	377.42	368.40	386.43	71.89	64.50	63.17	65.83
Coburg	1991	398.80	409.54	397.98	421.11	58.83	56.31	54.94	57.68
Coburg	1992	465.40	462.70	455.62	469.78	59.12	62.79	61.67	63.91
Coburg	1993	475.00	491.51	481.25	501.77	59.40	60.54	59.44	61.64
Coburg	1994	428.90	426.84	418.33	435.36	59.69	60.59	59.23	61.96
Coburg	1995	473.10	442.17	433.02	451.32	59.98	60.93	59.55	62.31
Coburg	1996	494.40	497.07	487.53	506.61	60.26	61.86	60.70	63.02
Coburg	1997	483.00	465.38	455.45	475.31	60.55	61.78	60.29	63.26
Coburg	1998	488.20	469.52	459.38	479.67	60.84	61.97	60.76	63.18
Coburg	1999	510.00	484.54	476.39	492.70	61.12	63.40	62.67	64.12
Coburg	2000	491.50	487.19	476.19	498.19	61.41	62.29	60.60	63.99
Coburg	2001	491.80	465.65	455.55	475.75	61.70	64.01	62.26	65.75
Coburg	2002	467.40	479.57	469.39	489.75	61.99	64.07	62.70	65.44
Coburg	2003	387.70	434.47	425.24	443.70	62.27	67.49	65.76	69.23
Coburg	2004	481.10	494.49	486.89	502.10	62.56	63.25	62.06	64.43
Coburg	2005	463.20	485.76	477.85	493.66	62.85	61.79	60.61	62.97
Coburg	2006	396.60	448.53	437.16	459.90	63.13	63.07	61.81	64.33
Coburg	2007	500.70	511.26	495.05	527.46	63.42	64.37	61.84	66.90
Coburg	2008	432.40	462.98	453.34	472.63	63.71	65.70	63.11	68.30
Coburg	2009	506.00	466.29	458.21	474.36	63.99	66.09	64.25	67.93
Coburg	2010	462.70	447.60	431.82	463.38	64.28	66.62	65.30	67.94
Coburg	2011	519.80	531.37	523.03	539.71	64.57	64.15	62.35	65.95
Coburg	2012	530.10	503.13	494.26	512.00	64.85	63.07	61.79	64.35
Coburg	2013	349.70	400.29	391.33	409.26	65.14	69.08	67.70	70.46
Coburg	2014	484.80	482.79	472.45	493.13	65.43	70.66	69.42	71.91
Coburg	2015	398.10	414.84	406.57	423.11	65.71	66.73	65.57	67.88
Dachau	1991	414.00	478.26	464.16	492.35	63.39	63.55	61.95	65.16
Dachau	1992	462.50	473.82	465.55	482.09	64.21	65.83	64.65	67.02
Dachau	1993	423.90	541.89	532.74	551.05	65.02	65.92	64.82	67.02
Dachau	1994	435.10	480.00	471.46	488.54	65.84	66.18	64.81	67.56
Dachau	1995	405.20	435.96	424.55	447.38	66.65	66.90	65.59	68.21
Dachau	1996	424.50	474.02	463.33	484.72	67.47	71.25	70.07	72.44

Dachau	1997	488.90	528.07	516.71	539.43	68.28	65.05	64.01	66.10
Dachau	1998	422.90	478.71	468.47	488.95	69.09	67.87	66.77	68.97
Dachau	1999	403.30	486.99	477.61	496.37	69.91	67.85	66.58	69.11
Dachau	2000	440.70	533.06	511.63	554.49	70.72	67.48	66.08	68.87
Dachau	2001	375.70	460.34	449.55	471.12	71.54	67.21	66.02	68.40
Dachau	2002	455.00	533.83	522.84	544.82	72.35	73.96	72.82	75.10
Dachau	2003	429.60	447.88	439.20	456.56	73.17	69.22	67.79	70.66
Dachau	2004	445.80	502.41	495.08	509.73	73.98	68.05	66.86	69.25
Dachau	2005	498.80	516.43	508.65	524.21	74.80	69.07	67.84	70.30
Dachau	2006	472.60	483.17	474.49	491.85	75.61	72.42	71.22	73.61
Dachau	2007	549.40	505.78	495.98	515.58	76.43	72.23	71.05	73.41
Dachau	2008	541.20	508.93	499.09	518.77	77.24	66.78	65.64	67.93
Dachau	2009	419.80	507.12	498.27	515.97	78.06	69.69	68.44	70.93
Dachau	2010	421.90	444.35	433.40	455.30	78.87	73.94	72.53	75.35
Dachau	2011	531.30	546.74	537.73	555.76	79.69	73.18	71.95	74.41
Dachau	2012	523.20	527.16	520.81	533.52	80.50	71.24	70.16	72.31
Dachau	2013	407.70	385.59	376.05	395.13	81.31	74.44	73.10	75.79
Dachau	2014	549.40	549.73	539.95	559.52	82.13	76.29	74.87	77.71
Dachau	2015	407.90	414.81	406.18	423.44	82.94	77.24	75.89	78.60
Deggendorf	1991	493.10	479.62	467.98	491.26	69.22	69.66	68.38	70.95
Deggendorf	1992	473.90	483.57	473.33	493.82	69.77	70.34	69.16	71.53
Deggendorf	1993	483.80	550.50	540.23	560.77	70.31	68.68	67.25	70.10
Deggendorf	1994	496.20	429.72	420.13	439.32	70.86	70.19	69.01	71.37
Deggendorf	1995	449.20	460.60	451.18	470.02	71.41	72.62	71.34	73.91
Deggendorf	1996	461.50	505.66	496.67	514.66	71.96	71.70	70.37	73.04
Deggendorf	1997	512.10	534.97	524.99	544.94	72.50	67.93	66.85	69.01
Deggendorf	1998	535.70	535.56	526.81	544.31	73.05	71.96	70.59	73.34
Deggendorf	1999	481.50	512.13	501.23	523.03	73.60	72.64	71.63	73.64
Deggendorf	2000	514.30	511.38	500.33	522.43	74.15	69.07	67.57	70.58
Deggendorf	2001	472.90	492.32	481.69	502.95	74.69	69.37	67.83	70.91
Deggendorf	2002	542.60	539.24	529.66	548.81	75.24	74.65	73.69	75.60
Deggendorf	2003	518.60	457.55	443.05	472.05	75.79	71.76	70.16	73.35
Deggendorf	2004	563.80	492.62	485.98	499.25	76.34	71.31	70.31	72.30
Deggendorf	2005	591.20	541.43	532.25	550.61	76.88	72.01	70.42	73.61
Deggendorf	2006	509.30	489.60	479.45	499.75	77.43	73.24	71.81	74.68
Deggendorf	2007	551.20	535.21	526.70	543.72	77.98	78.50	76.88	80.12

Deggendorf	2008	577.20	537.72	527.75	547.69	78.53	74.78	73.66	75.90
Deggendorf	2009	535.60	534.22	524.19	544.24	79.07	76.53	74.98	78.08
Deggendorf	2010	469.30	495.07	483.92	506.22	79.62	79.69	78.42	80.96
Deggendorf	2011	519.00	562.71	553.53	571.89	80.17	77.54	76.13	78.95
Deggendorf	2012	514.10	559.96	550.49	569.42	80.72	77.17	75.90	78.45
Deggendorf	2013	370.30	407.92	397.45	418.40	81.26	77.25	76.21	78.30
Deggendorf	2014	471.40	519.08	509.91	528.25	81.81	79.84	78.02	81.65
Deggendorf	2015	410.40	411.11	401.28	420.94	82.36	76.40	75.31	77.50
Dillingen_Donau	1991	483.00	473.80	454.87	492.72	63.15	67.34	65.81	68.86
Dillingen_Donau	1992	504.20	504.79	494.19	515.38	63.81	68.88	67.50	70.26
Dillingen_Donau	1993	539.90	537.17	527.48	546.85	64.47	69.93	68.70	71.15
Dillingen_Donau	1994	466.90	487.38	478.24	496.52	65.13	67.71	66.09	69.32
Dillingen_Donau	1995	438.30	440.88	426.57	455.19	65.79	67.83	66.45	69.22
Dillingen_Donau	1996	519.40	501.42	492.79	510.05	66.45	71.93	70.90	72.97
Dillingen_Donau	1997	501.70	526.66	514.40	538.93	67.10	67.18	65.80	68.56
Dillingen_Donau	1998	515.80	525.79	517.67	533.90	67.76	71.46	70.35	72.56
Dillingen_Donau	1999	506.20	485.03	474.84	495.22	68.42	70.33	68.84	71.82
Dillingen_Donau	2000	548.10	526.98	517.38	536.59	69.08	70.34	68.71	71.97
Dillingen_Donau	2001	530.50	476.33	466.82	485.84	69.74	70.12	68.65	71.59
Dillingen_Donau	2002	539.60	529.58	520.60	538.56	70.40	74.79	73.79	75.79
Dillingen_Donau	2003	474.70	477.49	467.11	487.86	71.06	73.68	71.91	75.46
Dillingen_Donau	2004	505.00	506.38	498.12	514.65	71.72	70.05	68.91	71.20
Dillingen_Donau	2005	528.30	521.26	512.36	530.15	72.38	69.75	68.20	71.30
Dillingen_Donau	2006	519.20	484.01	474.59	493.42	73.04	72.05	70.63	73.48
Dillingen_Donau	2007	541.30	518.79	509.21	528.37	73.70	75.82	74.40	77.24
Dillingen_Donau	2008	554.80	516.13	507.97	524.30	74.36	68.63	67.37	69.89
Dillingen_Donau	2009	529.20	493.58	484.55	502.62	75.02	75.61	74.06	77.15
Dillingen_Donau	2010	466.70	463.46	453.66	473.26	75.68	76.51	75.12	77.91
Dillingen_Donau	2011	513.80	553.43	542.74	564.12	76.34	75.07	73.87	76.27
Dillingen_Donau	2012	510.40	536.02	529.79	542.25	77.00	73.62	72.50	74.74
Dillingen_Donau	2013	483.00	385.02	373.11	396.93	77.66	77.52	76.22	78.82
Dillingen_Donau	2014	496.80	542.19	531.15	553.23	78.32	77.91	76.37	79.44
Dillingen_Donau	2015	387.20	410.03	401.46	418.60	78.98	75.55	74.48	76.62
Dingolfing-Landau	1991	470.50	480.39	466.79	493.99	65.16	69.17	67.90	70.45
Dingolfing-Landau	1992	481.50	479.77	469.03	490.52	65.80	70.38	69.06	71.70
Dingolfing-Landau	1993	487.10	545.21	533.79	556.63	66.45	70.44	68.94	71.93

Dingolfing-Landau	1994	439.20	453.70	445.25	462.14	67.09	70.26	68.92	71.60
Dingolfing-Landau	1995	425.70	445.53	435.59	455.47	67.73	70.54	69.29	71.80
Dingolfing-Landau	1996	494.90	504.86	495.56	514.16	68.37	72.68	71.41	73.95
Dingolfing-Landau	1997	538.40	536.46	525.13	547.78	69.01	68.55	67.34	69.76
Dingolfing-Landau	1998	527.30	523.65	514.96	532.35	69.66	70.98	69.67	72.28
Dingolfing-Landau	1999	497.40	511.97	501.15	522.79	70.30	72.93	71.90	73.95
Dingolfing-Landau	2000	528.00	513.29	503.42	523.15	70.94	69.18	67.73	70.63
Dingolfing-Landau	2001	479.90	490.37	480.06	500.67	71.58	70.15	68.62	71.68
Dingolfing-Landau	2002	545.80	539.59	530.13	549.06	72.22	75.64	74.60	76.67
Dingolfing-Landau	2003	439.50	462.38	448.79	475.97	72.86	72.64	71.10	74.18
Dingolfing-Landau	2004	509.10	495.09	487.85	502.32	73.51	70.48	69.42	71.54
Dingolfing-Landau	2005	518.10	535.05	525.88	544.21	74.15	71.82	70.06	73.57
Dingolfing-Landau	2006	473.20	495.34	485.00	505.68	74.79	75.30	73.75	76.85
Dingolfing-Landau	2007	520.00	533.53	524.64	542.41	75.43	80.01	78.28	81.73
Dingolfing-Landau	2008	562.40	551.66	541.83	561.48	76.07	75.28	73.96	76.59
Dingolfing-Landau	2009	575.80	548.56	538.80	558.31	76.71	76.05	74.53	77.57
Dingolfing-Landau	2010	483.30	463.49	450.99	475.98	77.36	81.27	79.90	82.64
Dingolfing-Landau	2011	582.00	563.87	554.67	573.06	78.00	77.89	76.41	79.38
Dingolfing-Landau	2012	556.80	554.76	544.77	564.74	78.64	76.68	75.44	77.92
Dingolfing-Landau	2013	383.50	402.83	392.40	413.27	79.28	78.48	77.24	79.72
Dingolfing-Landau	2014	530.40	515.65	506.43	524.86	79.92	79.91	78.08	81.74
Dingolfing-Landau	2015	394.70	402.57	391.96	413.18	80.57	76.98	75.76	78.19
Donau-Ries	1991	492.50	468.25	454.74	481.76	64.78	64.14	62.54	65.74
Donau-Ries	1992	521.70	491.10	478.31	503.88	65.45	64.49	62.76	66.23
Donau-Ries	1993	585.50	515.25	506.51	523.99	66.12	64.25	63.17	65.33
Donau-Ries	1994	491.00	480.47	471.64	489.30	66.80	64.51	63.13	65.90
Donau-Ries	1995	476.20	454.01	445.31	462.70	67.47	65.07	63.86	66.29
Donau-Ries	1996	530.80	503.33	495.61	511.04	68.14	66.87	65.86	67.87
Donau-Ries	1997	513.50	508.16	497.34	518.99	68.82	62.61	61.39	63.84
Donau-Ries	1998	537.90	501.24	493.11	509.37	69.49	67.57	66.60	68.54
Donau-Ries	1999	483.90	484.36	475.44	493.28	70.16	69.24	68.10	70.39
Donau-Ries	2000	503.70	514.91	506.40	523.43	70.84	67.16	65.48	68.84
Donau-Ries	2001	494.40	472.57	462.92	482.22	71.51	68.54	67.26	69.82
Donau-Ries	2002	567.40	514.66	507.45	521.87	72.18	69.47	68.60	70.34
Donau-Ries	2003	440.70	424.00	413.94	434.06	72.86	67.86	66.31	69.41
Donau-Ries	2004	508.50	494.82	487.00	502.64	73.53	65.88	64.79	66.97

Donau-Ries	2005	542.60	507.77	499.32	516.23	74.20	66.52	65.30	67.75
Donau-Ries	2006	476.40	467.19	457.47	476.90	74.88	67.92	66.58	69.26
Donau-Ries	2007	537.80	522.72	514.31	531.13	75.55	70.53	69.29	71.77
Donau-Ries	2008	540.80	504.32	496.69	511.95	76.22	66.67	65.61	67.73
Donau-Ries	2009	545.50	493.28	485.70	500.86	76.90	71.68	70.27	73.10
Donau-Ries	2010	467.50	462.80	453.22	472.38	77.57	71.57	70.26	72.88
Donau-Ries	2011	500.60	546.47	535.69	557.25	78.24	71.19	69.83	72.56
Donau-Ries	2012	510.30	518.12	512.46	523.78	78.92	69.76	68.74	70.79
Donau-Ries	2013	441.70	391.13	380.97	401.29	79.59	72.47	71.27	73.67
Donau-Ries	2014	496.20	520.66	508.80	532.53	80.26	71.64	70.09	73.19
Donau-Ries	2015	360.70	401.21	392.22	410.20	80.94	70.36	69.40	71.32
Ebersberg	1991	425.00	470.06	456.97	483.14	62.59	61.51	59.64	63.38
Ebersberg	1992	473.40	452.85	444.43	461.27	63.11	63.01	61.87	64.16
Ebersberg	1993	511.60	507.08	494.67	519.49	63.63	65.35	63.35	67.35
Ebersberg	1994	480.40	498.63	488.44	508.83	64.15	67.29	66.01	68.58
Ebersberg	1995	408.80	444.31	432.84	455.78	64.67	60.48	58.61	62.34
Ebersberg	1996	495.20	458.72	446.06	471.39	65.19	67.88	66.24	69.52
Ebersberg	1997	509.90	501.55	489.86	513.25	65.70	59.03	57.53	60.53
Ebersberg	1998	530.90	477.66	469.21	486.11	66.22	64.67	63.36	65.99
Ebersberg	1999	471.30	486.20	477.12	495.28	66.74	68.04	66.60	69.49
Ebersberg	2000	504.90	518.62	503.84	533.40	67.26	65.76	64.29	67.23
Ebersberg	2001	446.00	465.57	453.35	477.79	67.78	64.01	62.42	65.60
Ebersberg	2002	517.80	524.31	514.76	533.85	68.30	70.81	69.46	72.16
Ebersberg	2003	437.00	407.52	397.03	418.01	68.82	64.68	62.65	66.71
Ebersberg	2004	532.60	505.09	497.05	513.12	69.34	65.24	64.01	66.47
Ebersberg	2005	538.00	509.30	499.54	519.06	69.86	68.57	67.15	69.99
Ebersberg	2006	458.00	484.47	474.46	494.47	70.38	69.91	68.68	71.15
Ebersberg	2007	528.70	499.16	489.59	508.73	70.90	69.31	68.09	70.53
Ebersberg	2008	513.40	514.32	506.04	522.59	71.42	66.42	65.24	67.61
Ebersberg	2009	515.30	508.91	500.19	517.62	71.94	63.51	62.03	65.00
Ebersberg	2010	414.10	469.27	459.06	479.48	72.45	68.62	67.30	69.94
Ebersberg	2011	539.60	531.86	522.85	540.86	72.97	69.32	68.03	70.60
Ebersberg	2012	546.30	536.68	527.37	545.99	73.49	69.77	68.67	70.87
Ebersberg	2013	456.20	395.89	387.10	404.68	74.01	71.13	69.82	72.45
Ebersberg	2014	548.30	528.04	518.71	537.37	74.53	72.59	71.17	74.00
Ebersberg	2015	440.50	414.04	405.34	422.73	75.05	73.62	72.20	75.04

Eichstaett	1991	470.40	456.28	446.68	465.88	64.92	65.03	63.84	66.22
Eichstaett	1992	472.70	450.51	436.20	464.81	65.53	63.75	61.94	65.55
Eichstaett	1993	516.60	530.14	521.44	538.84	66.15	65.63	64.47	66.80
Eichstaett	1994	452.40	451.79	442.95	460.62	66.77	66.77	65.59	67.95
Eichstaett	1995	437.70	450.69	441.78	459.60	67.38	66.26	65.11	67.42
Eichstaett	1996	499.30	510.05	500.80	519.31	68.00	67.92	66.73	69.11
Eichstaett	1997	506.20	508.47	499.65	517.30	68.62	67.67	66.47	68.88
Eichstaett	1998	518.20	504.93	495.94	513.92	69.23	69.01	67.91	70.12
Eichstaett	1999	487.40	478.67	469.16	488.17	69.85	70.24	69.01	71.47
Eichstaett	2000	512.10	511.79	502.25	521.33	70.47	66.49	64.97	68.02
Eichstaett	2001	490.40	477.53	468.40	486.67	71.08	69.44	68.18	70.70
Eichstaett	2002	547.70	511.33	504.14	518.53	71.70	70.74	69.84	71.64
Eichstaett	2003	467.10	416.21	405.47	426.95	72.32	69.03	67.51	70.55
Eichstaett	2004	514.20	480.35	472.25	488.45	72.93	68.64	67.68	69.59
Eichstaett	2005	524.20	503.49	495.37	511.62	73.55	68.28	67.22	69.34
Eichstaett	2006	509.50	478.06	469.16	486.96	74.17	70.98	69.80	72.17
Eichstaett	2007	545.90	524.15	516.74	531.56	74.78	74.66	73.42	75.89
Eichstaett	2008	519.90	508.46	500.73	516.19	75.40	68.74	67.77	69.71
Eichstaett	2009	544.80	498.75	491.19	506.31	76.02	72.81	71.54	74.08
Eichstaett	2010	475.90	464.43	456.49	472.37	76.63	74.41	73.31	75.51
Eichstaett	2011	548.80	562.48	553.47	571.49	77.25	72.99	71.88	74.09
Eichstaett	2012	528.90	513.15	507.51	518.79	77.87	71.13	70.08	72.17
Eichstaett	2013	412.40	379.06	369.69	388.43	78.48	73.29	72.28	74.31
Eichstaett	2014	545.40	530.62	522.05	539.19	79.10	75.91	74.42	77.39
Eichstaett	2015	368.40	380.73	370.66	390.81	79.72	70.88	69.82	71.94
Erding	1991	506.70	480.18	464.15	496.21	65.83	64.93	63.27	66.60
Erding	1992	517.50	476.35	466.91	485.79	66.39	67.09	65.80	68.38
Erding	1993	478.80	517.34	494.53	540.15	66.96	69.06	67.65	70.47
Erding	1994	555.10	480.02	471.98	488.07	67.53	68.29	66.93	69.65
Erding	1995	437.10	422.12	409.39	434.84	68.10	64.47	62.84	66.11
Erding	1996	528.50	489.71	480.27	499.15	68.66	70.42	69.23	71.62
Erding	1997	553.80	529.78	518.47	541.09	69.23	65.45	64.27	66.63
Erding	1998	544.80	498.98	488.43	509.53	69.80	69.74	68.62	70.86
Erding	1999	496.60	493.51	484.13	502.89	70.37	69.06	67.71	70.41
Erding	2000	547.80	533.59	509.96	557.22	70.93	68.78	67.23	70.33
Erding	2001	467.90	472.58	461.59	483.56	71.50	68.03	66.73	69.33

Erding	2002	535.20	541.11	526.66	555.56	72.07	76.32	75.09	77.54
Erding	2003	460.70	467.54	456.79	478.29	72.64	71.61	70.24	72.98
Erding	2004	538.10	513.32	505.69	520.95	73.20	69.14	68.08	70.20
Erding	2005	515.70	522.06	514.24	529.88	73.77	69.19	67.56	70.82
Erding	2006	496.60	490.29	480.49	500.09	74.34	73.88	72.44	75.31
Erding	2007	546.00	523.85	515.82	531.89	74.91	75.85	74.56	77.13
Erding	2008	546.50	546.20	537.75	554.66	75.47	72.29	71.18	73.39
Erding	2009	530.00	522.39	512.77	532.02	76.04	72.64	71.27	74.01
Erding	2010	470.90	465.81	454.87	476.74	76.61	77.77	76.55	78.99
Erding	2011	562.20	549.87	541.53	558.21	77.18	75.34	73.98	76.69
Erding	2012	567.50	559.90	551.41	568.40	77.74	73.48	72.31	74.64
Erding	2013	429.20	401.24	391.53	410.95	78.31	76.06	74.63	77.49
Erding	2014	561.30	527.45	518.51	536.38	78.88	77.58	75.96	79.21
Erding	2015	464.90	393.17	382.28	404.06	79.44	75.87	74.33	77.41
Erlangen-Hoechstadt	1991	405.30	433.61	424.68	442.53	52.02	61.92	60.86	62.99
Erlangen-Hoechstadt	1992	454.30	465.12	455.65	474.60	52.58	62.92	61.78	64.06
Erlangen-Hoechstadt	1993	505.50	485.69	473.87	497.51	53.14	62.85	61.47	64.22
Erlangen-Hoechstadt	1994	438.90	389.38	376.86	401.90	53.70	58.29	56.31	60.26
Erlangen-Hoechstadt	1995	443.70	430.87	420.57	441.16	54.26	62.85	61.44	64.26
Erlangen-Hoechstadt	1996	475.60	510.21	501.52	518.91	54.82	62.15	61.07	63.23
Erlangen-Hoechstadt	1997	458.00	484.84	477.08	492.61	55.38	62.13	61.03	63.24
Erlangen-Hoechstadt	1998	443.10	483.86	474.98	492.74	55.94	63.47	61.91	65.02
Erlangen-Hoechstadt	1999	417.40	481.30	471.84	490.75	56.50	65.46	64.41	66.51
Erlangen-Hoechstadt	2000	516.70	509.92	500.11	519.73	57.06	63.75	62.19	65.32
Erlangen-Hoechstadt	2001	477.00	466.97	457.19	476.74	57.62	66.86	65.50	68.22
Erlangen-Hoechstadt	2002	515.10	499.10	490.56	507.65	58.18	66.45	65.29	67.62
Erlangen-Hoechstadt	2003	344.50	398.96	388.63	409.28	58.74	66.86	65.30	68.41
Erlangen-Hoechstadt	2004	454.50	495.92	487.89	503.95	59.30	63.93	62.96	64.89
Erlangen-Hoechstadt	2005	487.90	522.91	515.40	530.43	59.86	66.18	64.92	67.44
Erlangen-Hoechstadt	2006	438.00	466.54	454.54	478.55	60.42	64.64	63.16	66.13
Erlangen-Hoechstadt	2007	487.80	536.22	527.95	544.48	60.98	67.93	66.47	69.38
Erlangen-Hoechstadt	2008	420.80	482.70	471.88	493.53	61.54	64.75	63.52	65.99
Erlangen-Hoechstadt	2009	463.90	491.45	483.80	499.10	62.10	68.29	66.95	69.62
Erlangen-Hoechstadt	2010	430.40	470.81	462.11	479.50	62.66	69.85	68.55	71.14
Erlangen-Hoechstadt	2011	518.80	557.90	547.80	567.99	63.22	72.73	71.12	74.34
Erlangen-Hoechstadt	2012	463.30	502.12	492.43	511.82	63.78	69.05	67.43	70.67

Erlangen-Hoechstadt	2013	369.90	408.51	399.09	417.92	64.34	69.19	67.99	70.38
Erlangen-Hoechstadt	2014	409.60	513.41	502.56	524.27	64.90	71.39	69.63	73.15
Erlangen-Hoechstadt	2015	347.00	387.62	378.09	397.14	65.46	67.88	66.58	69.19
Forchheim	1991	387.60	437.98	428.47	447.50	54.13	60.35	59.18	61.52
Forchheim	1992	468.40	474.77	467.69	481.85	54.74	63.15	62.08	64.23
Forchheim	1993	502.70	500.55	491.35	509.75	55.35	60.77	59.63	61.90
Forchheim	1994	417.50	392.39	382.71	402.06	55.96	62.12	60.79	63.44
Forchheim	1995	442.30	438.29	429.51	447.07	56.57	62.17	61.02	63.33
Forchheim	1996	501.40	496.62	488.08	505.15	57.18	61.41	60.14	62.67
Forchheim	1997	479.40	468.41	460.04	476.78	57.79	61.18	60.12	62.23
Forchheim	1998	483.80	478.56	468.93	488.19	58.40	62.70	61.53	63.88
Forchheim	1999	498.30	486.15	477.90	494.40	59.01	64.06	63.24	64.88
Forchheim	2000	493.50	508.82	499.23	518.41	59.62	63.29	61.88	64.71
Forchheim	2001	500.50	463.19	453.71	472.66	60.23	64.59	63.34	65.84
Forchheim	2002	489.20	495.75	487.48	504.02	60.84	64.78	63.86	65.71
Forchheim	2003	407.40	408.92	399.11	418.74	61.45	64.91	63.57	66.26
Forchheim	2004	472.30	480.85	473.01	488.69	62.06	63.11	62.09	64.13
Forchheim	2005	469.10	509.09	500.74	517.45	62.67	63.11	61.86	64.36
Forchheim	2006	451.90	458.92	447.80	470.05	63.28	64.35	62.94	65.76
Forchheim	2007	508.20	507.40	499.46	515.34	63.89	66.50	65.24	67.76
Forchheim	2008	444.20	480.80	472.12	489.49	64.50	65.93	64.64	67.22
Forchheim	2009	520.90	484.04	477.62	490.46	65.11	67.16	65.85	68.46
Forchheim	2010	500.90	459.20	449.62	468.78	65.72	66.78	65.58	67.97
Forchheim	2011	560.70	541.50	533.21	549.78	66.33	67.05	65.57	68.53
Forchheim	2012	491.10	492.88	485.39	500.37	66.94	66.93	65.85	68.02
Forchheim	2013	396.50	392.71	384.17	401.25	67.55	67.25	66.13	68.37
Forchheim	2014	493.50	509.21	500.40	518.01	68.16	69.32	67.95	70.69
Forchheim	2015	389.10	392.59	384.76	400.42	68.77	66.43	65.38	67.47
Freising	1991	460.00	477.15	461.56	492.74	62.37	66.08	64.57	67.59
Freising	1992	469.00	472.19	462.53	481.86	62.99	65.94	64.75	67.13
Freising	1993	481.60	549.24	540.17	558.30	63.62	69.24	67.99	70.49
Freising	1994	502.00	471.06	462.22	479.90	64.24	67.18	65.69	68.67
Freising	1995	412.70	425.37	413.00	437.73	64.86	66.73	65.34	68.12
Freising	1996	493.70	497.34	487.77	506.91	65.48	71.12	69.92	72.31
Freising	1997	510.20	534.46	523.37	545.56	66.10	66.55	65.41	67.70
Freising	1998	504.00	493.65	484.65	502.65	66.73	70.55	69.41	71.70

Freising	1999	457.50	487.49	477.93	497.05	67.35	68.56	67.24	69.88
Freising	2000	470.50	535.40	516.84	553.96	67.97	68.71	67.35	70.06
Freising	2001	448.10	478.36	468.84	487.87	68.59	68.93	67.72	70.14
Freising	2002	496.60	532.27	521.26	543.27	69.21	75.19	74.13	76.25
Freising	2003	425.80	448.37	438.89	457.86	69.84	70.35	68.91	71.78
Freising	2004	449.80	511.69	504.21	519.16	70.46	69.39	68.31	70.46
Freising	2005	451.80	519.74	512.00	527.48	71.08	69.43	68.06	70.81
Freising	2006	457.20	487.05	477.85	496.26	71.70	74.31	72.98	75.65
Freising	2007	493.40	523.46	516.06	530.86	72.32	75.18	74.00	76.36
Freising	2008	479.50	538.86	531.23	546.48	72.95	71.01	69.96	72.07
Freising	2009	460.30	522.04	513.17	530.91	73.57	73.62	72.31	74.93
Freising	2010	446.00	463.36	453.19	473.54	74.19	76.78	75.58	77.97
Freising	2011	543.90	551.84	543.05	560.62	74.81	75.30	74.09	76.51
Freising	2012	503.70	554.40	546.52	562.28	75.43	74.03	73.01	75.04
Freising	2013	383.20	391.17	381.49	400.86	76.06	74.30	73.10	75.51
Freising	2014	526.50	538.60	529.26	547.94	76.68	75.86	74.32	77.41
Freising	2015	379.70	412.71	403.40	422.01	77.30	77.26	75.83	78.68
Fuerstenfeldbruck	1991	445.80	457.72	444.47	470.97	63.87	63.11	60.64	65.58
Fuerstenfeldbruck	1992	486.20	457.55	448.67	466.43	64.47	63.75	62.22	65.29
Fuerstenfeldbruck	1993	491.00	537.44	528.11	546.77	65.06	67.15	65.83	68.47
Fuerstenfeldbruck	1994	474.00	486.03	476.87	495.20	65.65	70.16	68.82	71.50
Fuerstenfeldbruck	1995	429.40	441.86	430.19	453.54	66.24	67.07	65.90	68.23
Fuerstenfeldbruck	1996	462.00	476.55	467.21	485.88	66.84	69.01	67.93	70.10
Fuerstenfeldbruck	1997	475.10	510.27	498.98	521.57	67.43	64.70	63.68	65.73
Fuerstenfeldbruck	1998	485.80	476.87	466.68	487.05	68.02	68.21	66.97	69.45
Fuerstenfeldbruck	1999	438.80	486.08	476.46	495.70	68.62	68.21	67.00	69.42
Fuerstenfeldbruck	2000	520.80	541.76	519.08	564.44	69.21	67.49	66.18	68.81
Fuerstenfeldbruck	2001	468.80	469.72	458.18	481.26	69.80	65.89	64.48	67.30
Fuerstenfeldbruck	2002	505.60	523.91	513.49	534.33	70.40	74.83	73.49	76.17
Fuerstenfeldbruck	2003	488.60	424.34	415.11	433.56	70.99	69.17	67.36	70.97
Fuerstenfeldbruck	2004	493.60	497.20	488.82	505.58	71.58	68.12	67.05	69.18
Fuerstenfeldbruck	2005	505.60	514.13	505.97	522.29	72.17	69.80	68.71	70.88
Fuerstenfeldbruck	2006	494.90	470.18	459.93	480.43	72.77	70.37	69.08	71.65
Fuerstenfeldbruck	2007	527.00	495.71	484.90	506.52	73.36	74.04	72.48	75.59
Fuerstenfeldbruck	2008	510.40	501.48	492.22	510.75	73.95	68.93	67.70	70.16
Fuerstenfeldbruck	2009	509.70	499.36	491.55	507.17	74.55	70.34	69.15	71.53

Fuerstenfeldbruck	2010	466.90	434.12	424.65	443.59	75.14	74.08	72.79	75.38
Fuerstenfeldbruck	2011	508.70	522.76	513.79	531.73	75.73	73.65	72.48	74.82
Fuerstenfeldbruck	2012	514.30	504.59	496.43	512.74	76.33	72.76	71.32	74.20
Fuerstenfeldbruck	2013	433.20	374.22	365.01	383.43	76.92	73.83	72.43	75.23
Fuerstenfeldbruck	2014	565.40	560.10	550.32	569.88	77.51	74.46	73.04	75.87
Fuerstenfeldbruck	2015	453.20	390.18	381.00	399.37	78.10	75.77	74.28	77.26
Fuerth	1991	380.60	438.21	429.29	447.14	50.59	64.88	63.82	65.95
Fuerth	1992	449.30	465.54	455.95	475.12	51.25	63.80	62.65	64.95
Fuerth	1993	480.40	500.07	488.39	511.74	51.90	62.93	61.59	64.28
Fuerth	1994	420.00	393.79	381.43	406.14	52.56	60.13	58.28	61.98
Fuerth	1995	456.10	429.44	419.14	439.73	53.22	63.83	62.44	65.22
Fuerth	1996	489.90	501.80	493.62	509.98	53.88	62.68	61.55	63.82
Fuerth	1997	457.70	491.17	483.15	499.19	54.54	61.18	60.07	62.29
Fuerth	1998	437.10	486.97	478.29	495.65	55.20	64.70	63.20	66.20
Fuerth	1999	471.40	480.91	472.20	489.62	55.85	66.47	65.47	67.47
Fuerth	2000	445.40	514.86	505.00	524.73	56.51	65.00	63.45	66.55
Fuerth	2001	381.30	479.11	469.78	488.43	57.17	67.18	65.88	68.48
Fuerth	2002	496.40	498.51	490.24	506.77	57.83	67.61	66.46	68.76
Fuerth	2003	312.50	404.51	394.40	414.62	58.49	66.79	65.36	68.22
Fuerth	2004	445.90	489.81	481.36	498.27	59.15	66.15	65.07	67.23
Fuerth	2005	448.20	526.38	517.67	535.08	59.80	67.18	65.91	68.44
Fuerth	2006	438.10	478.23	467.17	489.28	60.46	66.35	64.90	67.80
Fuerth	2007	461.90	529.74	521.82	537.65	61.12	69.52	68.08	70.97
Fuerth	2008	440.80	482.85	472.23	493.47	61.78	65.77	64.63	66.91
Fuerth	2009	463.10	506.21	497.89	514.53	62.44	69.07	67.72	70.41
Fuerth	2010	426.80	468.42	459.76	477.07	63.10	70.36	69.14	71.57
Fuerth	2011	591.90	569.66	556.60	582.71	63.76	74.10	72.56	75.63
Fuerth	2012	499.80	506.84	497.64	516.03	64.41	70.96	69.40	72.53
Fuerth	2013	416.00	402.12	392.74	411.51	65.07	71.84	70.59	73.09
Fuerth	2014	564.20	526.00	515.17	536.82	65.73	72.83	71.19	74.46
Fuerth	2015	304.90	375.79	365.62	385.97	66.39	68.90	67.64	70.16
Guenzburg	1991	505.90	460.05	446.45	473.65	66.18	62.00	59.98	64.03
Guenzburg	1992	548.00	499.57	490.49	508.65	66.69	67.86	66.72	69.00
Guenzburg	1993	531.90	531.13	522.46	539.80	67.21	67.43	66.24	68.62
Guenzburg	1994	534.20	486.85	478.00	495.70	67.72	67.95	66.53	69.37
Guenzburg	1995	459.30	450.02	436.64	463.40	68.23	68.37	66.97	69.78

Guenzburg	1996	525.90	497.95	488.58	507.31	68.75	71.82	70.64	72.99
Guenzburg	1997	509.80	504.86	492.89	516.83	69.26	64.09	62.84	65.34
Guenzburg	1998	536.30	518.93	510.97	526.89	69.77	68.92	67.81	70.03
Guenzburg	1999	518.60	486.68	476.85	496.51	70.28	67.04	65.62	68.46
Guenzburg	2000	539.30	521.71	511.60	531.82	70.80	68.55	66.95	70.15
Guenzburg	2001	529.50	478.79	469.18	488.40	71.31	67.82	66.41	69.22
Guenzburg	2002	560.50	525.24	516.09	534.39	71.82	73.29	72.27	74.32
Guenzburg	2003	526.10	482.70	472.08	493.32	72.34	71.65	70.18	73.13
Guenzburg	2004	550.10	502.45	494.18	510.72	72.85	69.36	68.31	70.40
Guenzburg	2005	572.00	507.34	497.97	516.72	73.36	69.09	67.82	70.36
Guenzburg	2006	562.00	471.06	461.29	480.82	73.87	72.44	71.15	73.74
Guenzburg	2007	592.90	501.25	491.72	510.77	74.39	75.56	74.18	76.95
Guenzburg	2008	585.70	512.16	504.32	519.99	74.90	68.27	67.17	69.37
Guenzburg	2009	539.60	497.88	490.23	505.52	75.41	73.89	72.50	75.28
Guenzburg	2010	512.30	436.96	427.12	446.80	75.93	75.56	74.27	76.84
Guenzburg	2011	551.50	545.69	536.39	554.99	76.44	74.68	73.60	75.77
Guenzburg	2012	514.80	533.89	527.87	539.90	76.95	74.91	73.90	75.91
Guenzburg	2013	324.50	400.28	389.20	411.35	77.47	75.61	74.41	76.80
Guenzburg	2014	543.90	559.28	549.72	568.84	77.98	75.37	74.00	76.75
Guenzburg	2015	386.20	418.80	411.43	426.18	78.49	77.23	75.82	78.64
Hassberge	1991	387.50	427.36	417.80	436.93	58.93	59.68	58.51	60.85
Hassberge	1992	486.90	479.53	472.53	486.53	59.09	62.82	61.61	64.03
Hassberge	1993	484.50	484.55	473.87	495.24	59.25	61.93	60.80	63.07
Hassberge	1994	439.80	421.57	411.92	431.22	59.42	59.88	58.32	61.44
Hassberge	1995	458.30	450.35	441.00	459.70	59.58	62.21	60.83	63.59
Hassberge	1996	509.10	504.23	495.41	513.04	59.74	63.23	62.24	64.23
Hassberge	1997	482.80	473.09	463.06	483.11	59.90	63.12	61.77	64.46
Hassberge	1998	458.80	475.67	465.70	485.64	60.07	62.19	60.97	63.42
Hassberge	1999	502.20	488.10	479.43	496.77	60.23	64.48	63.64	65.31
Hassberge	2000	510.80	501.79	489.96	513.61	60.39	63.22	61.71	64.73
Hassberge	2001	496.30	470.63	461.27	479.98	60.55	66.09	64.53	67.65
Hassberge	2002	486.60	496.45	487.01	505.89	60.72	66.33	65.05	67.61
Hassberge	2003	357.40	419.31	409.60	429.02	60.88	66.69	65.21	68.17
Hassberge	2004	502.00	483.64	475.36	491.91	61.04	64.29	63.33	65.24
Hassberge	2005	509.80	490.81	483.45	498.17	61.21	63.39	62.32	64.46
Hassberge	2006	429.90	449.88	438.51	461.25	61.37	64.40	63.04	65.75

Hassberge	2007	497.30	531.46	522.25	540.67	61.53	65.86	64.48	67.24
Hassberge	2008	397.50	466.60	456.39	476.81	61.69	62.73	61.31	64.14
Hassberge	2009	503.30	471.93	465.16	478.70	61.86	66.76	65.47	68.05
Hassberge	2010	438.40	453.84	442.26	465.41	62.02	68.57	67.29	69.85
Hassberge	2011	536.90	535.22	526.24	544.21	62.18	69.58	68.15	71.02
Hassberge	2012	493.50	498.58	489.79	507.37	62.34	66.40	65.05	67.74
Hassberge	2013	353.50	416.78	408.67	424.88	62.51	68.88	67.73	70.02
Hassberge	2014	464.80	501.73	492.76	510.69	62.67	71.83	70.31	73.35
Hassberge	2015	364.50	392.51	383.86	401.15	62.83	66.38	65.11	67.65
Hof	1991	382.30	401.61	383.84	419.38	57.98	53.52	51.70	55.35
Hof	1992	398.20	484.57	476.38	492.77	58.49	62.21	60.67	63.75
Hof	1993	456.20	499.46	486.83	512.10	58.99	57.77	56.19	59.34
Hof	1994	430.90	434.16	421.25	447.06	59.50	60.19	58.77	61.60
Hof	1995	421.20	426.85	414.27	439.43	60.01	56.19	53.96	58.41
Hof	1996	426.70	462.80	441.76	483.85	60.51	56.12	53.15	59.09
Hof	1997	456.90	448.53	433.38	463.67	61.02	50.73	48.15	53.30
Hof	1998	477.50	490.25	475.22	505.29	61.53	60.24	58.63	61.85
Hof	1999	510.10	459.54	447.02	472.06	62.04	60.54	59.33	61.76
Hof	2000	488.60	485.34	469.65	501.03	62.54	60.91	58.47	63.35
Hof	2001	460.00	454.96	439.81	470.11	63.05	56.88	54.53	59.24
Hof	2002	450.30	481.06	468.61	493.51	63.56	58.35	56.62	60.09
Hof	2003	409.70	444.08	433.58	454.58	64.06	61.40	59.74	63.06
Hof	2004	444.40	462.68	447.93	477.42	64.57	60.57	58.50	62.65
Hof	2005	455.70	456.67	440.72	472.63	65.08	60.93	59.90	61.96
Hof	2006	443.20	446.95	430.45	463.45	65.59	67.41	65.22	69.59
Hof	2007	509.40	505.28	494.02	516.53	66.09	65.80	64.45	67.15
Hof	2008	465.10	477.80	468.76	486.85	66.60	62.72	61.11	64.34
Hof	2009	460.40	460.18	449.72	470.64	67.11	64.03	61.38	66.69
Hof	2010	394.50	414.36	387.00	441.71	67.61	63.55	60.58	66.52
Hof	2011	536.30	513.13	500.50	525.75	68.12	57.65	55.48	59.81
Hof	2012	456.90	489.55	477.99	501.11	68.63	59.37	57.89	60.84
Hof	2013	371.60	372.35	360.47	384.23	69.13	64.01	60.79	67.22
Hof	2014	497.40	496.59	480.70	512.48	69.64	65.10	63.74	66.45
Hof	2015	372.70	449.12	437.70	460.54	70.15	65.47	64.15	66.79
Kehlheim	1991	483.10	470.96	459.70	482.23	64.70	67.25	66.03	68.48
Kehlheim	1992	470.60	449.28	437.34	461.21	65.40	64.63	63.30	65.96

Kehlheim	1993	546.20	529.35	520.24	538.46	66.10	65.75	64.50	67.00
Kehlheim	1994	501.20	449.79	441.28	458.31	66.80	66.89	65.62	68.17
Kehlheim	1995	443.00	435.77	426.58	444.96	67.50	66.92	65.75	68.08
Kehlheim	1996	564.80	512.21	503.13	521.28	68.19	68.71	67.54	69.88
Kehlheim	1997	524.30	525.72	516.68	534.76	68.89	67.65	66.52	68.77
Kehlheim	1998	478.20	508.11	498.90	517.33	69.59	68.11	66.96	69.26
Kehlheim	1999	454.20	499.19	490.75	507.63	70.29	71.19	70.06	72.33
Kehlheim	2000	490.50	506.64	496.94	516.34	70.99	66.55	65.15	67.95
Kehlheim	2001	506.30	484.65	475.61	493.69	71.69	69.12	67.93	70.31
Kehlheim	2002	509.80	527.11	519.44	534.79	72.39	71.75	70.96	72.54
Kehlheim	2003	432.30	414.50	403.85	425.15	73.09	68.48	67.06	69.91
Kehlheim	2004	491.10	496.94	489.74	504.14	73.79	68.97	68.13	69.81
Kehlheim	2005	508.50	521.86	514.62	529.11	74.49	68.40	67.14	69.66
Kehlheim	2006	480.70	486.71	477.35	496.07	75.19	72.62	71.46	73.78
Kehlheim	2007	546.10	526.75	518.92	534.58	75.89	75.01	73.73	76.29
Kehlheim	2008	534.70	518.87	511.58	526.17	76.59	70.01	69.07	70.94
Kehlheim	2009	520.30	511.26	503.33	519.18	77.29	71.34	70.08	72.61
Kehlheim	2010	495.70	468.09	459.43	476.74	77.99	74.91	73.66	76.15
Kehlheim	2011	549.40	554.82	546.22	563.43	78.69	72.78	71.64	73.93
Kehlheim	2012	532.30	529.09	522.72	535.46	79.39	72.57	71.40	73.74
Kehlheim	2013	400.60	380.63	371.25	390.01	80.09	72.92	71.87	73.98
Kehlheim	2014	500.20	535.06	526.65	543.48	80.79	75.47	74.04	76.89
Kehlheim	2015	489.80	378.68	368.13	389.23	81.49	72.18	70.90	73.45
Kitzingen	1991	380.90	426.74	416.47	437.00	64.11	59.80	58.54	61.06
Kitzingen	1992	513.30	505.26	495.32	515.20	64.41	61.51	60.05	62.96
Kitzingen	1993	482.10	453.45	441.38	465.52	64.71	63.93	62.41	65.46
Kitzingen	1994	424.80	447.25	434.24	460.26	65.01	58.90	56.98	60.83
Kitzingen	1995	482.00	456.20	443.91	468.50	65.31	63.23	61.85	64.61
Kitzingen	1996	505.00	496.62	487.77	505.47	65.62	64.85	63.62	66.09
Kitzingen	1997	480.90	473.50	463.73	483.26	65.92	59.94	58.38	61.51
Kitzingen	1998	451.00	460.40	449.59	471.21	66.22	61.64	60.45	62.83
Kitzingen	1999	434.60	487.12	476.72	497.52	66.52	63.80	62.67	64.93
Kitzingen	2000	448.40	492.60	477.32	507.88	66.82	59.85	57.81	61.88
Kitzingen	2001	457.50	448.06	437.38	458.74	67.12	64.72	62.92	66.52
Kitzingen	2002	502.20	505.58	495.64	515.52	67.42	66.19	64.78	67.61
Kitzingen	2003	338.30	381.35	369.15	393.55	67.72	66.69	64.86	68.51

Kitzingen	2004	521.30	490.71	481.82	499.60	68.03	64.60	63.50	65.70
Kitzingen	2005	463.10	477.63	468.45	486.81	68.33	64.91	63.70	66.12
Kitzingen	2006	395.80	463.60	449.03	478.17	68.63	64.91	63.12	66.69
Kitzingen	2007	530.60	530.23	520.20	540.27	68.93	66.61	64.90	68.32
Kitzingen	2008	405.00	448.22	435.58	460.85	69.23	63.86	62.30	65.43
Kitzingen	2009	527.50	471.61	463.33	479.88	69.53	65.33	64.09	66.58
Kitzingen	2010	460.90	451.53	439.75	463.31	69.83	68.40	66.82	69.98
Kitzingen	2011	579.40	545.60	533.45	557.76	70.13	73.84	71.50	76.18
Kitzingen	2012	503.70	483.99	472.64	495.33	70.44	66.11	63.89	68.34
Kitzingen	2013	432.90	430.83	420.88	440.77	70.74	68.84	67.65	70.03
Kitzingen	2014	537.30	513.95	503.67	524.23	71.04	70.66	68.84	72.49
Kitzingen	2015	294.20	378.08	366.45	389.71	71.34	65.68	64.12	67.25
Kronach	1991	374.40	405.41	394.17	416.65	53.70	56.60	55.31	57.89
Kronach	1992	431.70	455.12	447.98	462.25	54.16	62.54	61.47	63.62
Kronach	1993	487.50	496.19	485.53	506.85	54.62	59.39	58.26	60.51
Kronach	1994	431.30	417.59	408.56	426.63	55.09	61.12	59.98	62.27
Kronach	1995	420.90	439.90	430.63	449.18	55.55	60.46	59.01	61.91
Kronach	1996	467.80	490.40	479.88	500.93	56.02	60.73	59.42	62.03
Kronach	1997	453.80	457.46	446.23	468.68	56.48	59.18	57.70	60.66
Kronach	1998	460.40	473.22	463.77	482.68	56.95	61.54	60.43	62.65
Kronach	1999	455.90	470.98	462.08	479.88	57.41	61.82	61.06	62.57
Kronach	2000	408.20	490.10	477.94	502.27	57.87	62.76	60.93	64.58
Kronach	2001	426.90	467.32	456.13	478.51	58.34	62.01	60.58	63.45
Kronach	2002	431.70	470.08	459.62	480.53	58.80	60.95	59.52	62.38
Kronach	2003	340.20	417.07	407.89	426.24	59.27	63.39	62.13	64.64
Kronach	2004	449.80	488.05	480.33	495.77	59.73	61.83	60.61	63.05
Kronach	2005	435.00	471.95	463.82	480.08	60.20	60.88	59.77	61.98
Kronach	2006	412.30	447.91	436.44	459.37	60.66	64.55	63.22	65.88
Kronach	2007	450.00	502.68	487.47	517.90	61.13	63.87	61.39	66.36
Kronach	2008	462.20	457.67	448.92	466.41	61.59	65.19	62.70	67.68
Kronach	2009	460.30	464.03	455.53	472.54	62.05	64.81	62.82	66.79
Kronach	2010	445.40	441.91	421.78	462.05	62.52	64.55	62.89	66.20
Kronach	2011	479.00	522.69	514.45	530.93	62.98	61.92	59.81	64.03
Kronach	2012	484.90	497.50	488.66	506.35	63.45	61.61	60.43	62.79
Kronach	2013	321.50	390.80	381.65	399.95	63.91	68.53	66.92	70.13
Kronach	2014	483.30	472.94	462.79	483.09	64.38	68.48	67.34	69.61

Kronach	2015	308.10	422.91	414.35	431.47	64.84	66.01	64.87	67.16
Kulmbach	1991	370.00	410.54	398.68	422.40	56.95	55.03	53.58	56.48
Kulmbach	1992	473.30	470.51	463.03	477.99	57.32	63.13	62.01	64.25
Kulmbach	1993	508.50	493.65	483.95	503.36	57.69	59.31	58.09	60.52
Kulmbach	1994	410.00	415.13	405.96	424.29	58.06	61.65	60.58	62.73
Kulmbach	1995	444.90	447.49	438.54	456.44	58.44	59.43	57.96	60.90
Kulmbach	1996	528.30	475.58	463.88	487.27	58.81	58.82	57.07	60.56
Kulmbach	1997	525.10	454.98	444.16	465.80	59.18	56.06	54.54	57.58
Kulmbach	1998	515.20	482.78	472.96	492.61	59.55	61.68	60.53	62.83
Kulmbach	1999	552.30	478.36	469.36	487.35	59.92	62.18	61.37	63.00
Kulmbach	2000	553.90	485.96	475.09	496.82	60.29	62.69	60.92	64.46
Kulmbach	2001	547.30	458.70	447.21	470.18	60.66	60.01	58.41	61.61
Kulmbach	2002	531.40	476.50	467.52	485.47	61.03	61.68	60.49	62.87
Kulmbach	2003	376.90	427.77	418.11	437.43	61.40	62.79	61.52	64.07
Kulmbach	2004	518.60	479.59	470.88	488.29	61.78	62.13	60.86	63.41
Kulmbach	2005	521.00	483.26	474.59	491.92	62.15	61.57	60.64	62.51
Kulmbach	2006	497.80	450.67	438.72	462.62	62.52	65.71	64.32	67.10
Kulmbach	2007	547.30	501.51	493.57	509.44	62.89	64.07	62.61	65.53
Kulmbach	2008	464.40	465.70	458.19	473.22	63.26	63.38	61.95	64.81
Kulmbach	2009	536.30	470.20	462.01	478.38	63.63	64.60	62.63	66.56
Kulmbach	2010	498.40	433.80	417.68	449.92	64.00	63.80	62.12	65.49
Kulmbach	2011	594.50	511.72	502.31	521.12	64.37	62.44	60.97	63.91
Kulmbach	2012	539.90	488.63	479.49	497.77	64.74	61.27	60.13	62.40
Kulmbach	2013	376.00	385.88	376.43	395.33	65.11	66.84	64.70	68.97
Kulmbach	2014	595.30	488.99	478.41	499.58	65.49	66.66	65.61	67.70
Kulmbach	2015	395.80	419.66	411.32	428.01	65.86	64.48	63.37	65.58
Landsberg Lech	1991	447.30	447.91	434.83	460.99	61.24	56.94	54.58	59.30
Landsberg Lech	1992	476.60	484.22	476.59	491.86	62.07	64.75	63.60	65.90
Landsberg Lech	1993	505.00	523.31	513.67	532.96	62.91	65.91	64.55	67.26
Landsberg Lech	1994	440.60	488.31	478.75	497.88	63.74	67.64	66.37	68.91
Landsberg Lech	1995	410.00	450.76	439.34	462.17	64.57	62.61	61.25	63.97
Landsberg Lech	1996	483.60	474.75	465.57	483.93	65.41	64.40	63.14	65.66
Landsberg Lech	1997	459.30	480.29	467.77	492.82	66.24	62.74	61.58	63.90
Landsberg Lech	1998	495.10	491.46	483.47	499.46	67.08	64.90	63.95	65.85
Landsberg Lech	1999	475.20	477.84	468.76	486.92	67.91	64.66	63.27	66.05
Landsberg Lech	2000	510.80	505.47	492.64	518.29	68.74	65.18	63.70	66.67

Landsberg Lech	2001	449.30	464.15	452.45	475.86	69.58	63.92	62.56	65.28
Landsberg Lech	2002	503.50	482.45	467.76	497.13	70.41	72.19	70.96	73.41
Landsberg Lech	2003	498.70	472.87	464.85	480.89	71.24	69.99	68.58	71.41
Landsberg Lech	2004	481.40	490.82	479.71	501.93	72.08	64.28	62.99	65.57
Landsberg Lech	2005	500.50	501.30	491.93	510.68	72.91	66.27	65.03	67.52
Landsberg Lech	2006	461.70	469.68	459.45	479.91	73.75	68.33	66.99	69.68
Landsberg Lech	2007	496.60	492.98	482.58	503.38	74.58	73.70	72.33	75.06
Landsberg Lech	2008	520.20	501.65	491.50	511.80	75.41	68.16	67.05	69.27
Landsberg Lech	2009	498.60	493.01	485.98	500.03	76.25	69.04	67.84	70.25
Landsberg Lech	2010	427.00	428.76	416.80	440.72	77.08	70.28	69.18	71.38
Landsberg Lech	2011	518.00	517.71	507.18	528.23	77.91	69.53	68.28	70.78
Landsberg Lech	2012	505.80	506.39	497.28	515.50	78.75	73.35	71.80	74.90
Landsberg Lech	2013	389.60	387.97	378.31	397.63	79.58	70.47	69.09	71.85
Landsberg Lech	2014	546.00	548.51	538.89	558.13	80.41	69.10	67.61	70.59
Landsberg Lech	2015	371.10	419.58	412.00	427.15	81.25	73.14	71.81	74.46
Landshut	1991	495.90	476.62	461.20	492.03	67.31	66.12	64.72	67.53
Landshut	1992	495.00	478.61	468.38	488.83	67.87	66.28	65.08	67.49
Landshut	1993	503.90	542.75	532.58	552.92	68.43	69.37	68.19	70.55
Landshut	1994	443.20	473.11	464.91	481.30	68.99	69.29	68.09	70.49
Landshut	1995	427.70	431.91	419.82	444.00	69.54	66.45	64.98	67.92
Landshut	1996	506.00	501.35	492.52	510.18	70.10	70.36	69.16	71.56
Landshut	1997	537.20	528.69	517.45	539.93	70.66	66.29	65.11	67.47
Landshut	1998	526.90	519.74	511.51	527.97	71.22	70.40	69.27	71.52
Landshut	1999	502.70	500.66	490.55	510.78	71.77	70.12	69.08	71.16
Landshut	2000	547.70	522.66	513.27	532.04	72.33	68.48	67.03	69.93
Landshut	2001	479.80	483.87	473.68	494.07	72.89	68.59	67.28	69.90
Landshut	2002	573.40	527.88	518.73	537.03	73.45	74.77	73.73	75.81
Landshut	2003	464.00	464.65	452.27	477.04	74.00	71.31	69.98	72.64
Landshut	2004	539.80	500.33	493.32	507.34	74.56	68.93	67.89	69.97
Landshut	2005	534.00	519.56	511.50	527.63	75.12	68.97	67.30	70.65
Landshut	2006	510.50	489.18	479.58	498.78	75.68	73.92	72.46	75.38
Landshut	2007	573.80	533.91	525.87	541.94	76.23	76.17	74.78	77.55
Landshut	2008	553.70	545.03	536.60	553.45	76.79	73.44	72.37	74.50
Landshut	2009	529.00	528.14	519.45	536.82	77.35	73.72	72.52	74.92
Landshut	2010	461.90	470.58	460.09	481.07	77.91	79.78	78.53	81.03
Landshut	2011	544.00	555.92	547.64	564.21	78.46	75.29	73.89	76.70

Landshut	2012	575.20	550.49	542.48	558.50	79.02	73.17	71.90	74.44
Landshut	2013	398.30	405.07	394.92	415.22	79.58	77.90	76.32	79.47
Landshut	2014	552.40	529.95	521.33	538.57	80.14	78.17	76.23	80.11
Landshut	2015	386.40	407.29	398.05	416.54	80.70	76.61	75.24	77.97
Lichtenfels	1991	444.70	419.66	409.42	429.90	57.45	60.69	59.50	61.88
Lichtenfels	1992	463.80	463.71	456.46	470.96	57.90	63.15	62.05	64.25
Lichtenfels	1993	514.70	497.90	488.15	507.65	58.36	62.55	61.41	63.70
Lichtenfels	1994	459.80	422.88	413.50	432.25	58.82	61.03	59.53	62.52
Lichtenfels	1995	472.30	436.97	427.29	446.65	59.27	61.82	60.44	63.20
Lichtenfels	1996	528.10	501.34	491.85	510.82	59.73	63.44	62.35	64.52
Lichtenfels	1997	484.50	466.45	456.61	476.29	60.18	62.78	61.31	64.24
Lichtenfels	1998	486.50	476.23	467.09	485.36	60.64	63.18	62.01	64.34
Lichtenfels	1999	529.60	482.29	474.07	490.51	61.10	65.28	64.47	66.09
Lichtenfels	2000	496.80	487.11	476.70	497.51	61.55	64.51	63.10	65.92
Lichtenfels	2001	502.90	469.60	459.98	479.22	62.01	66.18	64.93	67.43
Lichtenfels	2002	475.80	485.63	476.12	495.13	62.46	64.36	63.09	65.63
Lichtenfels	2003	378.40	412.35	403.46	421.24	62.92	65.68	64.40	66.95
Lichtenfels	2004	502.60	494.78	487.07	502.48	63.38	64.37	63.23	65.51
Lichtenfels	2005	491.50	492.04	484.30	499.78	63.83	63.24	62.10	64.38
Lichtenfels	2006	453.70	448.45	436.84	460.06	64.29	64.50	63.21	65.80
Lichtenfels	2007	497.00	508.32	493.13	523.50	64.74	65.22	62.89	67.55
Lichtenfels	2008	467.10	465.17	455.46	474.89	65.20	65.26	62.76	67.76
Lichtenfels	2009	502.90	471.53	463.60	479.45	65.66	66.87	65.07	68.66
Lichtenfels	2010	487.30	451.65	436.47	466.84	66.11	67.71	66.39	69.02
Lichtenfels	2011	555.10	534.80	526.50	543.10	66.57	64.96	63.30	66.62
Lichtenfels	2012	497.70	504.74	495.92	513.56	67.02	65.18	63.94	66.42
Lichtenfels	2013	341.60	399.46	390.37	408.55	67.48	69.19	67.84	70.54
Lichtenfels	2014	467.70	491.75	481.82	501.67	67.94	70.82	69.42	72.22
Lichtenfels	2015	371.60	416.76	408.42	425.10	68.39	67.38	66.24	68.53
Main-Spessart	1991	406.60	416.03	403.38	428.68	64.53	62.50	61.13	63.86
Main-Spessart	1992	551.90	522.86	514.92	530.80	64.84	66.48	65.28	67.69
Main-Spessart	1993	504.90	475.15	463.51	486.79	65.16	65.41	64.16	66.66
Main-Spessart	1994	469.90	446.09	434.73	457.44	65.47	62.66	61.00	64.31
Main-Spessart	1995	497.00	466.15	456.09	476.21	65.79	66.45	65.14	67.76
Main-Spessart	1996	490.90	504.78	496.96	512.61	66.11	66.52	65.53	67.51
Main-Spessart	1997	501.40	470.15	460.38	479.92	66.42	61.46	60.00	62.93

Main-Spessart	1998	450.50	476.08	464.77	487.39	66.74	63.83	62.62	65.04
Main-Spessart	1999	479.60	492.33	483.01	501.65	67.05	67.50	66.47	68.54
Main-Spessart	2000	478.90	499.18	486.46	511.89	67.37	63.34	61.62	65.05
Main-Spessart	2001	485.20	463.23	453.12	473.33	67.68	68.24	66.48	69.99
Main-Spessart	2002	474.40	508.92	499.13	518.71	68.00	69.55	68.15	70.94
Main-Spessart	2003	349.60	407.21	396.55	417.88	68.32	69.46	67.87	71.05
Main-Spessart	2004	546.30	477.15	467.87	486.42	68.63	65.97	65.02	66.92
Main-Spessart	2005	450.70	481.89	472.68	491.11	68.95	67.54	66.54	68.54
Main-Spessart	2006	429.30	472.88	461.34	484.42	69.26	67.37	65.95	68.79
Main-Spessart	2007	507.80	539.38	530.20	548.57	69.58	68.53	67.16	69.91
Main-Spessart	2008	463.50	476.69	467.60	485.79	69.89	64.83	63.68	65.97
Main-Spessart	2009	532.80	493.41	487.02	499.80	70.21	69.06	68.03	70.08
Main-Spessart	2010	490.10	468.77	457.58	479.95	70.53	71.75	70.24	73.26
Main-Spessart	2011	555.00	541.23	531.00	551.45	70.84	73.67	72.17	75.18
Main-Spessart	2012	515.20	511.78	503.44	520.12	71.16	67.69	66.31	69.07
Main-Spessart	2013	455.80	434.91	427.04	442.78	71.47	71.40	70.29	72.52
Main-Spessart	2014	543.20	514.98	505.81	524.15	71.79	73.60	72.14	75.06
Main-Spessart	2015	364.90	408.88	400.21	417.55	72.10	67.16	65.85	68.48
Miltenberg	1991	402.70	422.11	409.42	434.79	61.10	68.20	66.52	69.89
Miltenberg	1992	473.30	519.26	510.25	528.28	62.07	71.83	70.59	73.07
Miltenberg	1993	507.70	496.58	484.49	508.67	63.04	69.79	68.46	71.13
Miltenberg	1994	488.10	444.22	431.97	456.46	64.01	66.80	64.77	68.83
Miltenberg	1995	452.50	446.96	436.47	457.45	64.98	70.36	68.82	71.90
Miltenberg	1996	465.30	492.71	483.05	502.37	65.94	72.94	71.47	74.40
Miltenberg	1997	481.80	486.11	477.19	495.03	66.91	66.75	64.92	68.59
Miltenberg	1998	455.20	482.79	472.40	493.18	67.88	68.64	67.23	70.06
Miltenberg	1999	496.10	499.86	490.04	509.68	68.85	72.06	70.84	73.27
Miltenberg	2000	488.50	520.42	509.19	531.65	69.82	68.00	66.37	69.63
Miltenberg	2001	475.00	476.77	466.88	486.66	70.79	70.71	69.00	72.43
Miltenberg	2002	478.50	504.82	495.42	514.22	71.76	74.28	73.00	75.55
Miltenberg	2003	413.90	398.96	386.93	410.98	72.72	72.00	69.89	74.11
Miltenberg	2004	523.90	500.74	491.41	510.06	73.69	71.37	70.03	72.70
Miltenberg	2005	474.90	515.77	505.16	526.38	74.66	72.59	71.25	73.93
Miltenberg	2006	476.60	487.84	474.27	501.41	75.63	74.72	72.92	76.53
Miltenberg	2007	521.10	519.90	508.99	530.80	76.60	74.02	71.98	76.06
Miltenberg	2008	442.40	500.53	490.50	510.56	77.57	67.23	65.45	69.01

Miltenberg	2009	502.60	493.36	485.57	501.16	78.53	74.59	73.05	76.13
Miltenberg	2010	473.30	460.73	448.38	473.08	79.50	76.49	74.71	78.28
Miltenberg	2011	553.70	553.89	543.08	564.71	80.47	76.18	74.68	77.69
Miltenberg	2012	465.90	504.87	496.33	513.41	81.44	71.53	69.80	73.25
Miltenberg	2013	424.40	421.55	409.93	433.17	82.41	77.44	76.06	78.81
Miltenberg	2014	431.70	534.33	524.97	543.69	83.38	79.03	77.38	80.67
Miltenberg	2015	332.10	420.34	410.65	430.03	84.35	72.57	71.24	73.90
Muehldorf	1991	482.20	481.65	466.22	497.08	61.75	64.88	63.22	66.54
Muehldorf	1992	466.40	485.84	474.69	497.00	62.25	67.54	66.09	68.98
Muehldorf	1993	467.60	534.06	495.92	572.19	62.76	67.95	65.44	70.46
Muehldorf	1994	460.30	462.91	455.52	470.29	63.27	69.16	67.70	70.63
Muehldorf	1995	435.90	454.18	442.06	466.30	63.78	66.32	64.93	67.71
Muehldorf	1996	482.00	496.02	487.30	504.74	64.29	70.90	69.72	72.09
Muehldorf	1997	530.30	536.15	525.09	547.21	64.79	65.64	64.40	66.89
Muehldorf	1998	564.50	507.13	498.67	515.58	65.30	69.09	67.84	70.33
Muehldorf	1999	539.30	486.20	475.56	496.85	65.81	69.03	67.10	70.97
Muehldorf	2000	545.90	539.67	520.04	559.31	66.32	69.02	67.82	70.22
Muehldorf	2001	486.10	466.11	453.72	478.50	66.82	67.77	66.36	69.18
Muehldorf	2002	545.00	531.32	507.09	555.54	67.33	76.35	75.31	77.38
Muehldorf	2003	482.10	473.32	459.97	486.66	67.84	73.26	71.79	74.73
Muehldorf	2004	526.90	505.95	498.95	512.95	68.35	68.99	67.72	70.26
Muehldorf	2005	544.60	520.74	512.05	529.43	68.86	70.14	68.41	71.87
Muehldorf	2006	507.60	484.70	475.47	493.92	69.36	71.53	69.98	73.09
Muehldorf	2007	554.60	521.72	512.80	530.65	69.87	75.15	73.71	76.60
Muehldorf	2008	535.60	555.47	546.09	564.86	70.38	73.17	72.06	74.29
Muehldorf	2009	516.70	511.34	498.62	524.05	70.89	70.00	68.19	71.80
Muehldorf	2010	431.10	476.16	464.05	488.26	71.39	76.79	75.55	78.03
Muehldorf	2011	524.10	552.75	543.73	561.78	71.90	74.76	73.26	76.26
Muehldorf	2012	556.40	551.61	542.83	560.39	72.41	72.65	70.96	74.33
Muehldorf	2013	417.00	419.11	407.05	431.16	72.92	82.58	80.20	84.97
Muehldorf	2014	553.80	531.52	522.26	540.78	73.43	82.41	79.97	84.86
Muehldorf	2015	471.90	432.71	422.77	442.66	73.93	78.35	76.93	79.78
Muenchen	1991	450.30	464.88	453.01	476.76	65.35	60.98	59.15	62.80
Muenchen	1992	463.80	454.67	446.69	462.66	65.41	62.58	61.28	63.88
Muenchen	1993	477.00	516.56	506.20	526.92	65.47	64.92	63.64	66.20
Muenchen	1994	417.90	484.59	475.03	494.16	65.53	66.78	65.41	68.16

Muenchen	1995	418.80	443.75	432.71	454.79	65.59	60.51	58.85	62.16
Muenchen	1996	464.00	461.06	450.71	471.42	65.65	66.45	65.06	67.85
Muenchen	1997	483.00	493.78	482.09	505.48	65.71	59.42	58.15	60.69
Muenchen	1998	496.30	484.71	476.31	493.11	65.76	64.19	63.08	65.29
Muenchen	1999	457.20	493.77	485.00	502.54	65.82	67.98	66.57	69.39
Muenchen	2000	501.90	525.01	511.90	538.12	65.88	66.15	64.73	67.57
Muenchen	2001	381.80	471.30	459.77	482.84	65.94	64.28	62.81	65.75
Muenchen	2002	508.40	532.21	523.01	541.42	66.00	70.56	69.34	71.78
Muenchen	2003	433.00	419.86	410.13	429.59	66.06	65.88	64.05	67.72
Muenchen	2004	460.80	500.66	492.83	508.49	66.11	65.76	64.47	67.04
Muenchen	2005	488.70	516.93	509.32	524.54	66.17	68.64	67.25	70.03
Muenchen	2006	400.00	479.72	470.26	489.18	66.23	69.10	67.88	70.31
Muenchen	2007	501.10	495.57	486.20	504.94	66.29	69.92	68.36	71.49
Muenchen	2008	472.20	500.29	490.70	509.89	66.35	66.83	65.59	68.08
Muenchen	2009	488.10	495.17	486.68	503.65	66.41	64.94	63.59	66.29
Muenchen	2010	427.30	455.36	445.42	465.31	66.47	68.10	66.65	69.55
Muenchen	2011	521.70	517.46	508.63	526.29	66.52	70.43	69.01	71.86
Muenchen	2012	527.80	513.93	505.77	522.09	66.58	69.51	68.23	70.78
Muenchen	2013	367.30	382.37	373.44	391.30	66.64	70.59	69.24	71.95
Muenchen	2014	537.00	541.61	530.52	552.70	66.70	71.78	70.19	73.37
Muenchen	2015	370.00	386.42	377.16	395.68	66.76	71.16	69.69	72.63
Neuburg-Schrobenhausen	1991	478.80	481.36	467.40	495.32	64.94	66.45	65.02	67.87
Neuburg-Schrobenhausen	1992	505.90	471.91	460.27	483.56	65.74	64.95	63.71	66.18
Neuburg-Schrobenhausen	1993	564.50	539.78	530.32	549.24	66.54	66.15	65.07	67.23
Neuburg-Schrobenhausen	1994	504.00	479.33	470.58	488.07	67.35	65.61	64.17	67.05
Neuburg-Schrobenhausen	1995	415.60	445.31	435.45	455.17	68.15	67.27	66.21	68.33
Neuburg-Schrobenhausen	1996	537.70	509.93	500.89	518.96	68.95	69.44	68.37	70.51
Neuburg-Schrobenhausen	1997	519.70	510.27	500.11	520.43	69.76	67.53	66.38	68.67
Neuburg-Schrobenhausen	1998	519.00	504.06	494.95	513.17	70.56	69.03	67.87	70.18
Neuburg-Schrobenhausen	1999	480.80	476.01	466.72	485.30	71.36	70.71	69.35	72.08
Neuburg-Schrobenhausen	2000	533.80	511.96	501.85	522.07	72.17	68.48	66.81	70.16

Neuburg-Schrobenhausen	2001	531.40	482.07	472.90	491.23	72.97	70.02	68.76	71.29
Neuburg-Schrobenhausen	2002	559.10	524.19	516.96	531.42	73.77	70.50	69.58	71.42
Neuburg-Schrobenhausen	2003	427.50	443.71	433.35	454.08	74.58	70.21	68.65	71.78
Neuburg-Schrobenhausen	2004	503.00	498.65	490.99	506.30	75.38	68.46	67.47	69.45
Neuburg-Schrobenhausen	2005	523.20	513.80	506.14	521.46	76.18	68.18	66.76	69.60
Neuburg-Schrobenhausen	2006	473.00	478.34	468.70	487.98	76.99	71.00	69.82	72.17
Neuburg-Schrobenhausen	2007	534.50	519.00	511.14	526.86	77.79	73.75	72.57	74.94
Neuburg-Schrobenhausen	2008	511.10	518.21	511.30	525.12	78.59	68.38	67.46	69.29
Neuburg-Schrobenhausen	2009	522.80	506.21	499.10	513.31	79.39	72.73	71.60	73.86
Neuburg-Schrobenhausen	2010	474.10	468.17	460.71	475.63	80.20	73.87	72.73	75.01
Neuburg-Schrobenhausen	2011	538.50	552.05	542.85	561.25	81.00	74.02	72.79	75.24
Neuburg-Schrobenhausen	2012	531.40	526.59	520.75	532.43	81.80	72.91	71.89	73.93
Neuburg-Schrobenhausen	2013	372.90	388.02	378.39	397.65	82.61	72.95	71.87	74.03
Neuburg-Schrobenhausen	2014	568.50	544.44	534.85	554.03	83.41	76.40	74.91	77.90
Neuburg-Schrobenhausen	2015	380.40	398.96	390.09	407.82	84.21	73.21	72.11	74.32
Neumarkt_Oberp.	1991	523.20	440.38	430.74	450.03	63.48	59.84	58.63	61.04
Neumarkt_Oberp.	1992	509.40	433.49	417.43	449.54	64.02	62.06	59.61	64.51
Neumarkt_Oberp.	1993	533.90	513.90	505.36	522.43	64.57	61.86	60.67	63.05
Neumarkt_Oberp.	1994	467.30	435.85	426.90	444.79	65.11	64.21	63.18	65.24
Neumarkt_Oberp.	1995	442.90	448.17	440.06	456.28	65.65	62.81	61.60	64.02
Neumarkt_Oberp.	1996	564.20	498.31	489.67	506.95	66.19	61.77	60.39	63.16
Neumarkt_Oberp.	1997	483.70	479.30	470.38	488.22	66.73	61.00	59.77	62.24
Neumarkt_Oberp.	1998	474.10	496.02	487.94	504.09	67.27	63.88	62.92	64.84
Neumarkt_Oberp.	1999	471.90	492.18	483.30	501.05	67.81	67.85	66.64	69.05
Neumarkt_Oberp.	2000	456.00	506.20	496.43	515.97	68.35	63.24	61.75	64.73
Neumarkt_Oberp.	2001	488.70	461.56	450.74	472.37	68.89	65.97	64.75	67.20
Neumarkt_Oberp.	2002	493.50	502.60	495.50	509.69	69.43	65.69	64.66	66.72
Neumarkt_Oberp.	2003	431.80	400.22	388.41	412.03	69.97	64.29	62.65	65.94
Neumarkt_Oberp.	2004	486.90	481.10	473.15	489.06	70.51	65.13	64.18	66.08

Neumarkt_Oberp.	2005	516.50	508.47	500.34	516.61	71.05	64.80	63.72	65.89
Neumarkt_Oberp.	2006	477.30	459.97	450.58	469.36	71.59	67.04	65.91	68.17
Neumarkt_Oberp.	2007	517.20	516.44	509.51	523.38	72.13	69.93	68.86	71.00
Neumarkt_Oberp.	2008	500.40	478.61	471.31	485.90	72.68	67.17	66.19	68.14
Neumarkt_Oberp.	2009	520.40	495.41	488.52	502.29	73.22	68.95	67.54	70.36
Neumarkt_Oberp.	2010	414.60	459.89	450.72	469.05	73.76	69.65	68.58	70.73
Neumarkt_Oberp.	2011	542.60	550.45	541.08	559.81	74.30	68.45	67.22	69.68
Neumarkt_Oberp.	2012	476.90	501.91	496.49	507.32	74.84	67.95	66.94	68.96
Neumarkt_Oberp.	2013	390.40	378.07	368.91	387.23	75.38	68.94	67.79	70.09
Neumarkt_Oberp.	2014	495.70	512.14	503.84	520.44	75.92	70.35	68.94	71.76
Neumarkt_Oberp.	2015	359.70	368.37	358.88	377.86	76.46	66.88	65.92	67.85
Neustadt_Aisch	1991	402.40	441.66	431.22	452.09	60.54	62.19	61.03	63.36
Neustadt_Aisch	1992	491.90	493.38	485.34	501.42	60.99	62.94	61.80	64.08
Neustadt_Aisch	1993	510.40	481.71	471.04	492.37	61.45	63.69	62.47	64.92
Neustadt_Aisch	1994	448.30	422.78	412.37	433.20	61.90	60.02	58.50	61.55
Neustadt_Aisch	1995	455.30	441.92	432.28	451.55	62.35	64.40	63.23	65.57
Neustadt_Aisch	1996	529.30	503.12	494.89	511.35	62.80	64.32	63.36	65.27
Neustadt_Aisch	1997	520.10	481.09	473.23	488.95	63.25	62.76	61.72	63.80
Neustadt_Aisch	1998	468.10	475.44	467.05	483.82	63.70	63.46	62.51	64.41
Neustadt_Aisch	1999	487.70	489.13	479.85	498.42	64.15	66.68	65.75	67.61
Neustadt_Aisch	2000	518.40	503.81	493.11	514.52	64.60	62.18	60.58	63.79
Neustadt_Aisch	2001	473.80	452.36	442.69	462.02	65.05	67.36	66.10	68.62
Neustadt_Aisch	2002	506.00	498.83	491.06	506.60	65.50	67.42	66.41	68.42
Neustadt_Aisch	2003	382.80	380.22	368.14	392.29	65.96	65.65	63.93	67.37
Neustadt_Aisch	2004	465.20	493.11	485.52	500.70	66.41	66.52	65.58	67.46
Neustadt_Aisch	2005	496.70	508.86	500.93	516.78	66.86	66.52	65.46	67.58
Neustadt_Aisch	2006	473.20	455.28	443.26	467.29	67.31	66.17	64.67	67.68
Neustadt_Aisch	2007	497.90	523.53	516.00	531.06	67.76	68.56	67.15	69.97
Neustadt_Aisch	2008	429.70	470.85	460.91	480.78	68.21	65.63	64.45	66.82
Neustadt_Aisch	2009	536.50	490.50	483.87	497.13	68.66	67.85	66.70	69.00
Neustadt_Aisch	2010	477.00	465.76	457.30	474.21	69.11	69.04	67.81	70.28
Neustadt_Aisch	2011	565.30	547.61	538.11	557.11	69.56	71.88	70.32	73.45
Neustadt_Aisch	2012	484.50	497.86	489.47	506.25	70.02	68.07	66.53	69.60
Neustadt_Aisch	2013	409.80	411.96	403.44	420.48	70.47	69.82	68.84	70.80
Neustadt_Aisch	2014	510.20	519.49	509.97	529.02	70.92	70.06	68.58	71.54
Neustadt_Aisch	2015	279.40	384.69	376.47	392.92	71.37	67.23	66.07	68.38

Neustadt_Waldnaab	1991	433.70	421.19	410.31	432.07	62.70	57.51	56.10	58.92
Neustadt_Waldnaab	1992	473.00	488.77	479.80	497.73	63.09	61.15	59.66	62.64
Neustadt_Waldnaab	1993	500.20	498.90	490.01	507.79	63.49	57.04	55.55	58.52
Neustadt_Waldnaab	1994	416.60	402.61	392.23	412.99	63.88	62.65	61.41	63.89
Neustadt_Waldnaab	1995	431.10	441.25	432.45	450.05	64.27	58.04	56.49	59.60
Neustadt_Waldnaab	1996	469.10	486.64	475.59	497.69	64.66	59.56	57.75	61.38
Neustadt_Waldnaab	1997	477.70	449.50	438.35	460.65	65.05	55.84	54.34	57.34
Neustadt_Waldnaab	1998	470.00	483.46	472.28	494.64	65.45	60.25	59.13	61.38
Neustadt_Waldnaab	1999	480.90	469.08	460.15	478.02	65.84	60.82	59.77	61.87
Neustadt_Waldnaab	2000	491.40	499.39	488.86	509.91	66.23	61.50	59.75	63.25
Neustadt_Waldnaab	2001	443.30	458.46	447.76	469.16	66.62	59.15	57.63	60.67
Neustadt_Waldnaab	2002	491.90	490.47	479.94	501.01	67.02	61.51	60.34	62.68
Neustadt_Waldnaab	2003	389.10	399.61	388.28	410.95	67.41	60.88	59.30	62.47
Neustadt_Waldnaab	2004	465.90	487.82	478.37	497.27	67.80	61.18	59.86	62.51
Neustadt_Waldnaab	2005	482.90	502.79	492.96	512.63	68.19	58.69	57.18	60.20
Neustadt_Waldnaab	2006	476.40	469.21	458.75	479.67	68.58	65.29	63.77	66.81
Neustadt_Waldnaab	2007	493.30	499.60	491.88	507.31	68.98	66.80	65.54	68.06
Neustadt_Waldnaab	2008	467.00	469.31	461.16	477.47	69.37	64.36	63.12	65.61
Neustadt_Waldnaab	2009	483.80	502.22	493.07	511.38	69.76	67.59	65.89	69.29
Neustadt_Waldnaab	2010	432.90	435.08	423.83	446.34	70.15	65.11	63.70	66.53
Neustadt_Waldnaab	2011	491.40	533.65	523.79	543.51	70.55	65.13	63.42	66.85
Neustadt_Waldnaab	2012	497.60	486.47	479.40	493.53	70.94	64.34	63.11	65.56
Neustadt_Waldnaab	2013	360.00	381.25	371.79	390.71	71.33	66.46	64.76	68.15
Neustadt_Waldnaab	2014	509.80	493.38	482.79	503.96	71.72	66.18	64.73	67.63
Neustadt_Waldnaab	2015	415.90	373.74	365.49	382.00	72.11	63.22	61.97	64.47
Neu-Ulm	1991	526.50	449.12	435.40	462.83	54.28	63.18	61.60	64.76
Neu-Ulm	1992	505.10	507.06	497.61	516.52	54.99	66.93	65.77	68.09
Neu-Ulm	1993	481.50	515.71	507.26	524.15	55.69	65.53	64.25	66.80
Neu-Ulm	1994	478.60	492.48	482.76	502.19	56.40	64.84	63.28	66.41
Neu-Ulm	1995	408.20	460.75	448.90	472.61	57.10	68.75	67.10	70.40
Neu-Ulm	1996	539.00	496.10	486.00	506.20	57.81	70.63	69.33	71.94
Neu-Ulm	1997	533.80	508.00	496.47	519.52	58.51	62.47	61.22	63.73
Neu-Ulm	1998	547.40	525.45	517.53	533.38	59.22	66.78	65.66	67.91
Neu-Ulm	1999	501.40	491.89	482.57	501.21	59.93	66.28	65.03	67.53
Neu-Ulm	2000	561.10	528.64	519.28	537.99	60.63	67.45	65.84	69.06
Neu-Ulm	2001	516.50	477.07	467.30	486.83	61.34	65.39	64.01	66.76

Neu-Ulm	2002	492.70	530.90	521.74	540.06	62.04	71.01	69.93	72.09
Neu-Ulm	2003	548.70	487.25	475.99	498.51	62.75	71.08	69.47	72.70
Neu-Ulm	2004	492.50	501.87	492.80	510.94	63.45	69.05	68.02	70.08
Neu-Ulm	2005	520.80	507.35	497.64	517.06	64.16	68.54	67.46	69.61
Neu-Ulm	2006	491.10	473.26	463.61	482.91	64.86	71.35	70.16	72.54
Neu-Ulm	2007	519.00	493.31	483.28	503.35	65.57	73.04	71.76	74.32
Neu-Ulm	2008	543.60	507.16	499.95	514.38	66.28	66.86	65.81	67.90
Neu-Ulm	2009	556.20	501.82	493.82	509.81	66.98	72.05	70.72	73.39
Neu-Ulm	2010	517.40	442.72	432.59	452.86	67.69	73.68	72.34	75.03
Neu-Ulm	2011	595.60	549.53	540.18	558.87	68.39	73.00	71.88	74.12
Neu-Ulm	2012	523.50	532.96	526.61	539.31	69.10	74.87	73.70	76.04
Neu-Ulm	2013	395.20	402.63	393.32	411.94	69.80	74.33	73.07	75.59
Neu-Ulm	2014	543.80	543.62	532.78	554.47	70.51	73.52	72.21	74.83
Neu-Ulm	2015	413.80	411.78	404.17	419.40	71.21	76.29	74.51	78.06
Nuernberger Land	1991	407.70	435.97	426.60	445.35	56.20	60.46	59.33	61.59
Nuernberger Land	1992	477.40	460.38	452.22	468.55	56.50	62.20	61.19	63.20
Nuernberger Land	1993	521.40	500.30	490.79	509.80	56.81	61.51	60.38	62.65
Nuernberger Land	1994	439.00	403.54	393.29	413.79	57.11	60.92	59.49	62.34
Nuernberger Land	1995	402.60	433.73	424.66	442.80	57.42	62.04	60.84	63.24
Nuernberger Land	1996	486.60	493.97	485.30	502.65	57.72	60.26	59.01	61.51
Nuernberger Land	1997	509.50	472.24	463.26	481.23	58.02	59.06	57.92	60.20
Nuernberger Land	1998	500.00	478.20	469.48	486.93	58.33	62.53	61.27	63.79
Nuernberger Land	1999	480.60	482.17	473.65	490.68	58.63	64.66	63.73	65.59
Nuernberger Land	2000	483.20	506.60	496.93	516.28	58.94	62.59	61.22	63.96
Nuernberger Land	2001	486.60	459.58	449.27	469.88	59.24	64.72	63.54	65.91
Nuernberger Land	2002	520.50	489.35	481.17	497.53	59.54	64.53	63.54	65.52
Nuernberger Land	2003	450.30	398.04	387.00	409.08	59.85	64.14	62.62	65.66
Nuernberger Land	2004	491.20	480.29	472.21	488.37	60.15	63.29	62.27	64.32
Nuernberger Land	2005	425.00	513.21	504.84	521.58	60.46	64.09	62.89	65.30
Nuernberger Land	2006	449.40	465.98	456.06	475.89	60.76	64.73	63.38	66.08
Nuernberger Land	2007	494.70	516.62	509.31	523.93	61.06	67.61	66.46	68.76
Nuernberger Land	2008	461.50	480.69	472.05	489.34	61.37	64.88	63.86	65.90
Nuernberger Land	2009	487.80	499.75	492.39	507.10	61.67	67.49	66.30	68.69
Nuernberger Land	2010	457.10	459.13	450.30	467.97	61.98	67.33	66.18	68.49
Nuernberger Land	2011	523.50	553.27	543.81	562.73	62.28	69.06	67.60	70.53
Nuernberger Land	2012	469.90	498.72	490.91	506.54	62.58	67.58	66.38	68.78

Nuernberger Land	2013	356.30	391.77	382.54	401.00	62.89	68.11	66.99	69.23
Nuernberger Land	2014	520.00	512.46	502.94	521.97	63.19	69.41	67.88	70.94
Nuernberger Land	2015	337.40	375.31	367.05	383.57	63.50	66.54	65.42	67.67
Passau(LKR)	1991	468.70	506.43	494.76	518.10	63.04	69.35	67.94	70.77
Passau(LKR)	1992	531.40	488.05	477.44	498.65	63.51	72.69	71.17	74.21
Passau(LKR)	1993	510.90	542.24	530.03	554.45	63.99	70.18	68.66	71.70
Passau(LKR)	1994	437.80	435.75	425.39	446.10	64.46	72.74	71.36	74.13
Passau(LKR)	1995	469.00	462.72	449.97	475.47	64.93	72.69	71.45	73.93
Passau(LKR)	1996	493.70	499.71	490.20	509.23	65.40	71.74	70.33	73.15
Passau(LKR)	1997	480.80	542.58	531.39	553.78	65.87	65.85	64.78	66.92
Passau(LKR)	1998	514.00	535.39	526.73	544.05	66.34	69.32	68.27	70.37
Passau(LKR)	1999	496.00	513.87	504.70	523.05	66.81	70.65	69.75	71.54
Passau(LKR)	2000	490.70	525.78	515.91	535.65	67.29	69.08	67.56	70.61
Passau(LKR)	2001	458.60	488.40	476.88	499.92	67.76	67.57	66.14	69.01
Passau(LKR)	2002	541.00	532.75	520.90	544.59	68.23	74.06	73.10	75.02
Passau(LKR)	2003	483.00	483.86	470.55	497.17	68.70	70.63	69.20	72.05
Passau(LKR)	2004	510.90	503.59	496.30	510.89	69.17	71.54	70.27	72.81
Passau(LKR)	2005	502.80	531.20	520.90	541.51	69.64	71.50	69.88	73.12
Passau(LKR)	2006	493.30	487.30	475.66	498.93	70.11	72.72	71.40	74.03
Passau(LKR)	2007	515.40	516.36	504.86	527.85	70.59	76.81	75.32	78.30
Passau(LKR)	2008	490.00	540.50	530.51	550.48	71.06	72.02	70.93	73.10
Passau(LKR)	2009	502.30	534.65	517.47	551.82	71.53	72.92	70.93	74.91
Passau(LKR)	2010	498.30	503.91	473.60	534.22	72.00	75.65	74.31	76.98
Passau(LKR)	2011	517.90	571.48	561.96	581.00	72.47	78.17	76.81	79.54
Passau(LKR)	2012	529.60	559.76	549.06	570.45	72.94	77.03	75.70	78.36
Passau(LKR)	2013	413.50	420.23	409.88	430.57	73.41	75.84	74.79	76.89
Passau(LKR)	2014	469.90	522.33	511.92	532.73	73.89	80.44	78.83	82.05
Passau(LKR)	2015	437.80	385.30	373.66	396.94	74.36	75.95	74.66	77.24
Pfaffenhofen	1991	487.40	482.43	468.30	496.56	62.00	66.61	65.28	67.93
Pfaffenhofen	1992	516.20	465.56	455.37	475.75	62.63	65.50	64.48	66.52
Pfaffenhofen	1993	567.00	530.60	521.29	539.91	63.27	66.64	65.44	67.85
Pfaffenhofen	1994	504.10	480.39	471.56	489.21	63.91	66.74	65.44	68.04
Pfaffenhofen	1995	415.90	418.21	407.97	428.44	64.55	67.25	66.09	68.41
Pfaffenhofen	1996	548.40	507.37	498.21	516.53	65.19	70.44	69.27	71.61
Pfaffenhofen	1997	538.00	529.39	518.97	539.81	65.82	67.82	66.67	68.98
Pfaffenhofen	1998	495.00	504.95	496.32	513.58	66.46	68.73	67.64	69.82

Pfaffenhofen	1999	477.50	486.75	477.87	495.62	67.10	69.63	68.46	70.81
Pfaffenhofen	2000	541.50	513.39	504.39	522.40	67.74	66.92	65.59	68.24
Pfaffenhofen	2001	472.70	484.78	475.78	493.77	68.38	68.28	67.13	69.44
Pfaffenhofen	2002	532.70	529.41	521.53	537.29	69.01	72.19	71.36	73.03
Pfaffenhofen	2003	453.00	422.65	412.71	432.59	69.65	68.33	66.85	69.81
Pfaffenhofen	2004	494.00	499.28	491.96	506.60	70.29	68.34	67.43	69.25
Pfaffenhofen	2005	518.50	515.35	508.25	522.46	70.93	68.15	66.95	69.36
Pfaffenhofen	2006	458.70	485.38	476.55	494.21	71.57	71.39	70.26	72.52
Pfaffenhofen	2007	501.50	526.98	519.75	534.21	72.20	73.49	72.32	74.66
Pfaffenhofen	2008	527.30	522.42	515.53	529.31	72.84	69.69	68.69	70.68
Pfaffenhofen	2009	514.80	506.55	499.05	514.05	73.48	71.99	70.86	73.12
Pfaffenhofen	2010	445.50	456.62	448.14	465.09	74.12	73.70	72.66	74.75
Pfaffenhofen	2011	549.00	561.84	553.17	570.51	74.76	73.29	72.13	74.45
Pfaffenhofen	2012	540.10	532.05	526.69	537.42	75.39	72.58	71.65	73.52
Pfaffenhofen	2013	389.10	389.48	380.87	398.08	76.03	72.16	71.08	73.24
Pfaffenhofen	2014	543.60	554.52	545.53	563.51	76.67	76.05	74.55	77.55
Pfaffenhofen	2015	396.60	405.14	396.39	413.89	77.31	74.55	73.28	75.83
Regensburg(LKR)	1991	486.10	453.33	442.79	463.87	66.73	66.84	65.76	67.93
Regensburg(LKR)	1992	497.40	453.02	441.80	464.24	67.26	65.40	64.27	66.52
Regensburg(LKR)	1993	532.80	530.33	519.49	541.17	67.79	64.60	63.05	66.14
Regensburg(LKR)	1994	444.40	424.66	414.88	434.44	68.32	66.46	65.16	67.76
Regensburg(LKR)	1995	425.60	441.86	433.28	450.44	68.84	66.70	65.57	67.83
Regensburg(LKR)	1996	507.70	513.86	505.41	522.31	69.37	67.34	66.15	68.53
Regensburg(LKR)	1997	501.20	513.02	504.50	521.53	69.90	65.75	64.74	66.77
Regensburg(LKR)	1998	527.20	506.41	497.06	515.76	70.43	67.67	66.44	68.89
Regensburg(LKR)	1999	452.70	516.70	506.43	526.97	70.96	70.23	69.17	71.30
Regensburg(LKR)	2000	502.70	502.84	491.71	513.97	71.48	63.66	62.13	65.19
Regensburg(LKR)	2001	491.70	482.67	473.17	492.17	72.01	67.96	66.78	69.13
Regensburg(LKR)	2002	527.80	528.85	520.26	537.44	72.54	70.50	69.67	71.33
Regensburg(LKR)	2003	412.50	399.80	386.93	412.67	73.07	65.94	64.46	67.42
Regensburg(LKR)	2004	482.00	490.85	483.83	497.86	73.60	67.79	66.88	68.69
Regensburg(LKR)	2005	494.50	529.50	521.85	537.16	74.12	66.99	65.72	68.26
Regensburg(LKR)	2006	504.00	498.22	487.43	509.01	74.65	70.56	69.35	71.77
Regensburg(LKR)	2007	514.70	532.36	524.59	540.13	75.18	73.34	71.91	74.77
Regensburg(LKR)	2008	490.60	512.36	503.93	520.78	75.71	68.81	67.75	69.88
Regensburg(LKR)	2009	512.00	509.79	501.53	518.05	76.24	70.06	68.83	71.29

Regensburg(LKR)	2010	456.60	478.41	469.63	487.18	76.76	76.07	74.75	77.38
Regensburg(LKR)	2011	526.50	553.46	544.37	562.54	77.29	72.93	71.71	74.15
Regensburg(LKR)	2012	527.50	522.53	515.82	529.24	77.82	71.10	69.80	72.41
Regensburg(LKR)	2013	384.00	385.44	376.18	394.71	78.35	73.01	71.97	74.05
Regensburg(LKR)	2014	514.00	520.21	510.86	529.57	78.88	75.06	73.38	76.74
Regensburg(LKR)	2015	341.00	379.96	369.16	390.77	79.40	69.37	68.08	70.66
Rhoen-Grabfeld	1991	371.10	393.20	379.07	407.32	61.15	53.98	52.40	55.55
Rhoen-Grabfeld	1992	471.70	475.06	467.71	482.40	61.44	62.24	60.98	63.49
Rhoen-Grabfeld	1993	476.10	475.28	464.81	485.75	61.73	60.56	59.32	61.79
Rhoen-Grabfeld	1994	451.30	433.49	424.67	442.32	62.02	60.24	58.87	61.62
Rhoen-Grabfeld	1995	468.20	466.02	457.10	474.93	62.30	62.95	61.76	64.14
Rhoen-Grabfeld	1996	459.80	492.71	483.71	501.71	62.59	61.99	60.87	63.10
Rhoen-Grabfeld	1997	454.00	464.54	453.96	475.13	62.88	58.98	57.81	60.14
Rhoen-Grabfeld	1998	494.40	466.70	455.43	477.96	63.17	61.25	59.97	62.54
Rhoen-Grabfeld	1999	568.30	484.33	475.33	493.33	63.46	62.64	61.75	63.53
Rhoen-Grabfeld	2000	440.00	495.50	481.88	509.11	63.75	60.56	58.54	62.58
Rhoen-Grabfeld	2001	534.80	464.68	453.85	475.52	64.04	63.57	61.56	65.58
Rhoen-Grabfeld	2002	441.00	485.49	474.90	496.09	64.33	63.29	61.76	64.82
Rhoen-Grabfeld	2003	376.30	438.48	428.61	448.34	64.62	65.63	63.66	67.59
Rhoen-Grabfeld	2004	423.90	482.41	474.21	490.61	64.91	61.91	60.93	62.89
Rhoen-Grabfeld	2005	407.90	479.52	472.05	486.98	65.19	63.27	62.37	64.17
Rhoen-Grabfeld	2006	438.70	444.27	432.52	456.02	65.48	63.66	62.45	64.87
Rhoen-Grabfeld	2007	526.90	514.22	504.31	524.12	65.77	64.70	63.25	66.15
Rhoen-Grabfeld	2008	386.40	457.86	448.54	467.17	66.06	62.03	60.43	63.64
Rhoen-Grabfeld	2009	518.80	474.15	467.39	480.91	66.35	64.44	63.16	65.71
Rhoen-Grabfeld	2010	452.70	466.89	455.23	478.55	66.64	66.90	65.34	68.46
Rhoen-Grabfeld	2011	566.10	519.53	510.98	528.09	66.93	66.84	65.33	68.34
Rhoen-Grabfeld	2012	547.20	499.69	491.52	507.87	67.22	61.73	60.46	62.99
Rhoen-Grabfeld	2013	364.60	415.67	407.54	423.80	67.51	68.06	66.76	69.35
Rhoen-Grabfeld	2014	517.70	497.42	486.98	507.87	67.80	68.00	66.64	69.35
Rhoen-Grabfeld	2015	344.80	417.03	408.29	425.77	68.08	65.81	64.58	67.05
Roth	1991	400.20	453.76	444.99	462.53	56.64	61.14	59.79	62.50
Roth	1992	455.90	449.73	438.63	460.83	56.99	61.43	59.89	62.97
Roth	1993	501.90	505.17	496.68	513.66	57.34	60.97	59.88	62.06
Roth	1994	420.50	429.65	420.79	438.51	57.69	62.62	61.34	63.90
Roth	1995	416.50	445.60	436.77	454.43	58.04	62.22	61.04	63.39

Roth	1996	461.90	505.06	496.40	513.73	58.39	62.04	60.55	63.53
Roth	1997	484.50	480.21	471.52	488.90	58.74	62.94	61.69	64.20
Roth	1998	483.90	479.49	470.70	488.28	59.09	64.29	63.09	65.49
Roth	1999	473.90	499.70	489.63	509.76	59.44	68.13	66.65	69.60
Roth	2000	432.00	489.69	477.63	501.75	59.79	61.75	59.78	63.73
Roth	2001	440.50	454.73	439.40	470.06	60.14	66.90	65.30	68.51
Roth	2002	521.10	498.35	490.69	506.00	60.49	65.43	64.00	66.86
Roth	2003	408.90	365.57	350.93	380.20	60.84	63.11	60.64	65.58
Roth	2004	502.00	469.84	459.87	479.81	61.19	64.60	63.64	65.57
Roth	2005	502.40	508.56	498.91	518.20	61.53	64.13	62.91	65.36
Roth	2006	464.90	449.70	437.84	461.55	61.88	64.38	62.97	65.79
Roth	2007	526.00	511.69	503.55	519.83	62.23	68.23	66.94	69.51
Roth	2008	508.20	465.78	457.60	473.97	62.58	66.28	65.21	67.34
Roth	2009	517.20	493.12	486.28	499.96	62.93	68.61	67.35	69.88
Roth	2010	464.50	448.15	439.03	457.27	63.28	68.28	67.11	69.45
Roth	2011	567.00	535.22	526.56	543.89	63.63	69.37	68.11	70.63
Roth	2012	447.60	480.14	473.40	486.87	63.98	69.16	68.14	70.18
Roth	2013	375.00	383.33	374.11	392.55	64.33	69.70	68.59	70.80
Roth	2014	526.20	519.68	510.27	529.09	64.68	70.83	69.56	72.09
Roth	2015	362.10	364.71	354.97	374.45	65.03	64.62	63.50	65.74
Rottal-Inn	1991	497.70	494.79	480.50	509.07	61.51	66.72	65.41	68.04
Rottal-Inn	1992	502.80	489.80	479.03	500.57	62.02	68.51	67.23	69.80
Rottal-Inn	1993	513.40	515.74	503.00	528.49	62.53	68.61	67.14	70.08
Rottal-Inn	1994	462.70	435.55	427.65	443.45	63.04	68.94	67.58	70.30
Rottal-Inn	1995	455.80	459.24	449.21	469.28	63.54	68.41	67.26	69.55
Rottal-Inn	1996	503.50	498.62	490.51	506.72	64.05	70.27	69.04	71.49
Rottal-Inn	1997	532.50	536.11	525.96	546.25	64.56	64.96	63.96	65.97
Rottal-Inn	1998	555.30	527.80	520.07	535.53	65.07	68.77	67.83	69.71
Rottal-Inn	1999	482.20	496.41	487.27	505.56	65.57	68.66	67.27	70.05
Rottal-Inn	2000	524.60	521.20	512.44	529.95	66.08	67.87	66.60	69.14
Rottal-Inn	2001	496.00	481.88	470.23	493.53	66.59	67.24	65.87	68.61
Rottal-Inn	2002	540.80	541.38	528.56	554.21	67.10	73.81	72.86	74.76
Rottal-Inn	2003	453.00	472.92	459.73	486.11	67.60	70.90	69.62	72.17
Rottal-Inn	2004	531.70	512.32	505.49	519.16	68.11	68.80	67.68	69.92
Rottal-Inn	2005	534.20	521.79	511.90	531.67	68.62	71.05	69.41	72.70
Rottal-Inn	2006	506.70	479.45	469.73	489.18	69.13	72.50	71.26	73.74

Rottal-Inn	2007	540.60	521.44	510.44	532.44	69.63	75.85	74.38	77.33
Rottal-Inn	2008	560.80	546.09	535.78	556.40	70.14	71.56	70.40	72.72
Rottal-Inn	2009	533.20	527.48	513.43	541.53	70.65	69.20	67.10	71.30
Rottal-Inn	2010	519.60	471.97	457.13	486.81	71.16	75.10	73.97	76.23
Rottal-Inn	2011	575.40	556.98	547.02	566.94	71.66	76.17	74.88	77.46
Rottal-Inn	2012	560.30	556.25	545.80	566.70	72.17	74.24	72.92	75.57
Rottal-Inn	2013	426.40	424.74	413.67	435.81	72.68	78.12	76.62	79.61
Rottal-Inn	2014	529.20	508.98	498.05	519.91	73.19	80.29	78.41	82.18
Rottal-Inn	2015	425.20	395.97	384.47	407.47	73.70	75.88	74.51	77.25
Schwandorf	1991	466.20	432.83	422.72	442.94	55.37	58.34	57.09	59.60
Schwandorf	1992	471.90	465.37	457.37	473.37	56.11	63.16	62.04	64.29
Schwandorf	1993	524.00	507.26	498.46	516.05	56.84	60.10	58.54	61.66
Schwandorf	1994	415.00	399.52	390.07	408.96	57.57	64.51	63.23	65.79
Schwandorf	1995	423.70	443.94	435.06	452.82	58.30	61.74	60.43	63.05
Schwandorf	1996	539.40	485.68	475.17	496.20	59.03	61.22	59.55	62.89
Schwandorf	1997	504.70	463.71	453.48	473.94	59.76	59.29	58.02	60.55
Schwandorf	1998	489.40	487.38	476.80	497.96	60.49	62.76	61.60	63.92
Schwandorf	1999	505.10	487.78	480.33	495.22	61.23	63.65	62.66	64.65
Schwandorf	2000	494.20	499.60	489.62	509.57	61.96	62.05	60.49	63.62
Schwandorf	2001	493.00	461.43	451.58	471.27	62.69	61.77	60.51	63.03
Schwandorf	2002	528.60	494.31	484.51	504.11	63.42	63.69	62.70	64.69
Schwandorf	2003	422.40	391.09	380.39	401.79	64.15	61.60	60.03	63.16
Schwandorf	2004	477.80	485.50	477.79	493.20	64.88	63.44	62.15	64.74
Schwandorf	2005	504.40	509.86	501.26	518.46	65.61	60.58	59.02	62.14
Schwandorf	2006	465.40	478.29	468.00	488.58	66.35	65.89	64.35	67.42
Schwandorf	2007	522.40	501.09	493.54	508.63	67.08	68.06	66.79	69.32
Schwandorf	2008	486.80	484.78	476.44	493.12	67.81	66.50	65.29	67.72
Schwandorf	2009	492.10	502.66	495.43	509.90	68.54	67.26	65.90	68.62
Schwandorf	2010	438.40	451.43	441.53	461.33	69.27	66.59	65.25	67.93
Schwandorf	2011	546.30	543.84	533.72	553.95	70.00	68.25	66.53	69.96
Schwandorf	2012	463.70	507.68	500.65	514.72	70.74	67.31	66.07	68.56
Schwandorf	2013	320.60	384.64	375.16	394.11	71.47	66.69	65.32	68.07
Schwandorf	2014	499.90	498.36	488.95	507.76	72.20	68.95	67.39	70.51
Schwandorf	2015	334.10	366.66	358.00	375.32	72.93	64.71	63.37	66.05
Schweinfurt	1991	458.10	431.77	422.10	441.45	61.44	61.87	60.69	63.06
Schweinfurt	1992	518.80	502.55	494.73	510.36	61.71	63.92	62.71	65.14

Schweinfurt	1993	451.00	475.84	464.53	487.15	61.97	62.68	61.44	63.92
Schweinfurt	1994	433.10	448.92	437.90	459.94	62.23	60.88	59.20	62.57
Schweinfurt	1995	461.50	455.45	445.26	465.65	62.49	64.63	63.19	66.08
Schweinfurt	1996	516.30	506.82	498.12	515.51	62.75	64.23	63.14	65.32
Schweinfurt	1997	489.60	465.53	454.15	476.92	63.02	61.95	60.51	63.40
Schweinfurt	1998	466.20	478.44	467.79	489.10	63.28	62.36	61.16	63.55
Schweinfurt	1999	515.30	499.96	490.68	509.23	63.54	65.02	64.00	66.05
Schweinfurt	2000	519.20	491.63	479.69	503.57	63.80	62.46	60.80	64.11
Schweinfurt	2001	504.20	464.45	454.41	474.49	64.06	66.66	64.86	68.46
Schweinfurt	2002	544.40	506.14	496.61	515.68	64.33	68.94	67.60	70.29
Schweinfurt	2003	345.60	408.84	398.72	418.95	64.59	66.88	65.45	68.32
Schweinfurt	2004	503.10	479.99	469.94	490.04	64.85	64.36	63.30	65.42
Schweinfurt	2005	454.80	477.74	468.68	486.79	65.11	65.19	64.16	66.21
Schweinfurt	2006	420.50	451.24	439.09	463.40	65.37	65.05	63.62	66.48
Schweinfurt	2007	534.20	545.31	535.24	555.38	65.64	67.25	65.88	68.61
Schweinfurt	2008	422.70	462.23	451.49	472.97	65.90	63.12	61.85	64.38
Schweinfurt	2009	532.10	473.17	466.39	479.94	66.16	66.31	65.16	67.47
Schweinfurt	2010	457.10	458.50	448.28	468.72	66.42	68.95	67.53	70.37
Schweinfurt	2011	513.70	533.54	523.40	543.67	66.68	72.06	70.47	73.65
Schweinfurt	2012	504.80	493.49	484.96	502.02	66.95	66.54	65.11	67.96
Schweinfurt	2013	433.60	429.35	421.47	437.22	67.21	68.61	67.54	69.68
Schweinfurt	2014	510.60	518.04	508.30	527.77	67.47	70.81	69.21	72.41
Schweinfurt	2015	336.10	391.18	381.37	400.99	67.73	66.01	64.71	67.32
Starnberg	1991	428.10	431.63	420.37	442.89	55.24	58.05	55.87	60.24
Starnberg	1992	465.70	449.17	441.17	457.17	55.86	60.36	58.85	61.88
Starnberg	1993	507.40	512.88	500.97	524.79	56.47	62.55	61.02	64.09
Starnberg	1994	439.40	478.29	467.86	488.73	57.09	67.60	65.74	69.46
Starnberg	1995	411.50	449.15	436.74	461.57	57.70	59.36	57.72	61.01
Starnberg	1996	473.40	466.31	456.16	476.46	58.31	62.54	60.97	64.10
Starnberg	1997	447.30	467.71	455.77	479.65	58.93	57.92	56.39	59.45
Starnberg	1998	466.60	479.11	470.20	488.01	59.54	62.54	61.33	63.75
Starnberg	1999	438.40	482.63	473.14	492.12	60.16	63.96	62.24	65.67
Starnberg	2000	491.60	509.71	498.64	520.78	60.77	63.99	62.41	65.58
Starnberg	2001	437.10	463.27	452.29	474.26	61.38	60.51	58.93	62.08
Starnberg	2002	548.50	511.06	502.22	519.90	62.00	68.29	66.90	69.68
Starnberg	2003	463.80	430.49	421.27	439.70	62.61	66.11	64.34	67.88

Starnberg	2004	478.10	484.78	475.02	494.55	63.23	61.76	60.32	63.19
Starnberg	2005	484.40	491.13	482.02	500.24	63.84	65.03	63.45	66.61
Starnberg	2006	438.50	463.44	453.58	473.30	64.45	67.56	66.07	69.06
Starnberg	2007	485.20	495.75	487.32	504.18	65.07	70.57	68.92	72.22
Starnberg	2008	514.40	480.97	471.10	490.84	65.68	64.93	63.36	66.50
Starnberg	2009	498.30	487.58	480.55	494.61	66.30	64.67	63.30	66.04
Starnberg	2010	393.90	439.63	428.50	450.76	66.91	65.26	63.87	66.64
Starnberg	2011	484.30	507.24	496.94	517.53	67.52	67.59	65.98	69.20
Starnberg	2012	510.60	494.19	485.26	503.12	68.14	68.34	66.61	70.07
Starnberg	2013	359.20	385.49	376.64	394.34	68.75	67.99	66.13	69.84
Starnberg	2014	512.50	536.33	524.52	548.13	69.37	67.97	66.04	69.90
Starnberg	2015	316.30	401.94	395.22	408.65	69.98	69.98	68.31	71.65
Straubing-Bogen	1991	418.00	467.90	456.88	478.92	69.27	69.14	67.93	70.35
Straubing-Bogen	1992	452.10	467.03	455.19	478.87	69.90	69.03	67.73	70.33
Straubing-Bogen	1993	523.00	537.52	526.64	548.40	70.54	69.08	67.51	70.64
Straubing-Bogen	1994	459.90	427.19	417.41	436.96	71.18	69.71	68.33	71.09
Straubing-Bogen	1995	433.90	441.02	431.86	450.17	71.81	69.25	67.89	70.62
Straubing-Bogen	1996	480.20	509.79	501.16	518.42	72.45	70.75	69.50	72.01
Straubing-Bogen	1997	485.50	537.36	526.81	547.90	73.09	68.51	67.31	69.71
Straubing-Bogen	1998	481.20	531.46	521.75	541.17	73.72	71.48	69.93	73.03
Straubing-Bogen	1999	505.10	520.88	507.15	534.61	74.36	73.59	72.52	74.65
Straubing-Bogen	2000	488.70	497.72	486.18	509.26	74.99	69.23	67.65	70.80
Straubing-Bogen	2001	472.00	502.01	491.77	512.25	75.63	70.53	69.05	72.02
Straubing-Bogen	2002	494.90	539.83	529.85	549.81	76.27	75.98	74.77	77.19
Straubing-Bogen	2003	396.20	443.74	427.42	460.05	76.90	72.17	70.51	73.82
Straubing-Bogen	2004	515.80	478.65	470.82	486.47	77.54	70.29	69.26	71.31
Straubing-Bogen	2005	508.30	536.57	527.22	545.92	78.18	70.56	68.80	72.32
Straubing-Bogen	2006	485.80	490.35	479.28	501.42	78.81	75.06	73.60	76.52
Straubing-Bogen	2007	502.90	543.40	534.15	552.66	79.45	79.71	77.94	81.49
Straubing-Bogen	2008	566.20	533.03	522.16	543.91	80.09	75.80	74.40	77.21
Straubing-Bogen	2009	537.80	533.86	523.19	544.53	80.72	77.54	75.80	79.29
Straubing-Bogen	2010	480.20	489.97	477.69	502.26	81.36	83.89	82.16	85.63
Straubing-Bogen	2011	484.00	556.59	546.82	566.35	82.00	78.12	76.55	79.69
Straubing-Bogen	2012	539.70	549.48	540.59	558.36	82.63	77.08	75.71	78.45
Straubing-Bogen	2013	373.10	396.78	385.78	407.79	83.27	79.27	78.04	80.50
Straubing-Bogen	2014	554.50	506.36	496.46	516.25	83.91	80.39	77.91	82.87

Straubing-Bogen	2015	406.30	422.42	413.66	431.17	84.54	77.97	76.78	79.16
Tirschenreuth	1991	444.80	410.26	395.71	424.81	60.09	54.34	52.62	56.06
Tirschenreuth	1992	466.00	494.95	486.73	503.16	60.70	63.66	62.37	64.95
Tirschenreuth	1993	507.30	497.81	488.98	506.65	61.32	58.22	56.76	59.68
Tirschenreuth	1994	442.80	434.77	424.35	445.20	61.93	63.16	62.12	64.21
Tirschenreuth	1995	458.10	460.88	452.34	469.42	62.55	58.70	57.10	60.31
Tirschenreuth	1996	447.90	488.27	477.64	498.90	63.16	60.82	58.96	62.68
Tirschenreuth	1997	461.90	459.59	448.52	470.65	63.77	56.13	54.38	57.87
Tirschenreuth	1998	494.30	489.13	478.76	499.50	64.39	62.19	61.01	63.37
Tirschenreuth	1999	485.00	469.98	460.51	479.45	65.00	61.15	60.14	62.15
Tirschenreuth	2000	497.20	507.69	496.90	518.49	65.62	63.00	61.09	64.90
Tirschenreuth	2001	493.60	458.32	444.23	472.41	66.23	56.92	54.97	58.86
Tirschenreuth	2002	537.00	478.93	469.07	488.79	66.85	61.49	60.36	62.63
Tirschenreuth	2003	388.80	435.17	424.10	446.24	67.46	61.38	60.09	62.67
Tirschenreuth	2004	450.40	484.55	475.18	493.93	68.07	60.58	59.36	61.81
Tirschenreuth	2005	484.20	508.38	499.26	517.51	68.69	60.00	58.58	61.42
Tirschenreuth	2006	479.00	470.04	459.56	480.52	69.30	66.11	64.72	67.49
Tirschenreuth	2007	529.40	514.55	507.54	521.55	69.92	67.22	66.05	68.38
Tirschenreuth	2008	516.80	478.67	470.98	486.35	70.53	65.20	64.04	66.35
Tirschenreuth	2009	512.40	492.77	484.42	501.13	71.15	67.80	66.05	69.55
Tirschenreuth	2010	481.30	436.73	422.90	450.57	71.76	66.47	64.82	68.12
Tirschenreuth	2011	552.30	513.27	503.94	522.61	72.37	62.40	60.99	63.82
Tirschenreuth	2012	517.30	502.45	495.09	509.81	72.99	64.31	63.36	65.26
Tirschenreuth	2013	364.80	366.62	356.86	376.38	73.60	66.96	64.76	69.16
Tirschenreuth	2014	561.30	503.92	493.42	514.42	74.22	66.33	65.07	67.59
Tirschenreuth	2015	434.60	405.95	397.77	414.14	74.83	64.49	63.50	65.48
Traunstein	1991	444.10	463.42	447.84	479.00	57.86	63.48	61.72	65.24
Traunstein	1992	508.10	469.78	461.33	478.23	58.49	65.23	63.95	66.51
Traunstein	1993	503.80	530.87	506.08	555.65	59.12	65.58	63.38	67.78
Traunstein	1994	456.50	482.91	474.95	490.87	59.75	70.31	68.98	71.64
Traunstein	1995	416.40	395.01	376.87	413.15	60.38	62.63	60.93	64.32
Traunstein	1996	478.70	449.51	433.08	465.94	61.01	65.45	63.63	67.26
Traunstein	1997	520.90	506.77	492.71	520.82	61.64	58.04	55.81	60.28
Traunstein	1998	504.00	507.03	497.45	516.61	62.27	65.51	64.14	66.89
Traunstein	1999	500.50	504.83	491.00	518.65	62.90	66.94	65.32	68.55
Traunstein	2000	524.80	529.68	512.92	546.44	63.53	67.45	66.30	68.60

Traunstein	2001	423.30	458.22	444.37	472.07	64.16	65.38	63.95	66.81
Traunstein	2002	538.70	496.88	481.06	512.70	64.79	72.32	71.32	73.32
Traunstein	2003	518.80	494.99	478.99	511.00	65.42	70.95	69.28	72.61
Traunstein	2004	484.50	491.63	480.89	502.36	66.05	62.68	60.61	64.75
Traunstein	2005	462.00	536.17	520.45	551.89	66.67	64.46	62.54	66.39
Traunstein	2006	461.90	467.10	453.55	480.66	67.30	69.80	68.59	71.02
Traunstein	2007	486.90	477.17	462.01	492.33	67.93	73.07	71.96	74.19
Traunstein	2008	535.70	520.16	511.05	529.27	68.56	66.08	64.84	67.32
Traunstein	2009	450.90	474.03	450.36	497.69	69.19	61.84	58.84	64.85
Traunstein	2010	424.00	451.89	430.78	473.00	69.82	71.40	70.02	72.77
Traunstein	2011	493.30	549.11	535.56	562.66	70.45	71.65	70.35	72.94
Traunstein	2012	501.50	526.38	512.17	540.60	71.08	70.58	69.50	71.66
Traunstein	2013	404.10	428.49	418.91	438.08	71.71	73.73	72.45	75.02
Traunstein	2014	511.20	504.37	487.03	521.71	72.34	78.53	76.95	80.10
Traunstein	2015	498.50	439.61	430.83	448.40	72.97	73.76	72.40	75.13
Unterallgaeu	1991	495.30	450.15	436.50	463.80	61.46	59.64	56.90	62.38
Unterallgaeu	1992	501.30	504.47	495.68	513.26	62.11	66.98	65.86	68.10
Unterallgaeu	1993	539.60	530.01	521.17	538.86	62.76	69.03	67.68	70.38
Unterallgaeu	1994	494.40	491.49	481.96	501.02	63.41	67.93	66.41	69.45
Unterallgaeu	1995	394.60	459.65	447.71	471.59	64.06	68.11	66.59	69.64
Unterallgaeu	1996	519.00	485.63	473.94	497.32	64.71	67.85	66.57	69.12
Unterallgaeu	1997	487.60	489.95	477.97	501.92	65.35	64.14	62.85	65.42
Unterallgaeu	1998	534.80	505.31	496.70	513.91	66.00	66.20	65.28	67.12
Unterallgaeu	1999	472.60	486.32	475.09	497.55	66.65	63.79	62.06	65.52
Unterallgaeu	2000	525.00	525.32	505.60	545.04	67.30	65.92	64.18	67.65
Unterallgaeu	2001	505.20	469.66	457.91	481.40	67.95	63.60	62.12	65.09
Unterallgaeu	2002	517.10	496.46	475.03	517.89	68.60	72.59	71.35	73.83
Unterallgaeu	2003	507.10	498.76	488.05	509.47	69.25	73.08	71.51	74.65
Unterallgaeu	2004	505.60	495.55	483.66	507.43	69.90	67.17	65.98	68.36
Unterallgaeu	2005	533.70	506.57	497.51	515.62	70.55	68.38	67.25	69.50
Unterallgaeu	2006	476.80	463.25	452.47	474.03	71.20	69.93	68.58	71.29
Unterallgaeu	2007	530.10	483.15	471.30	495.00	71.84	75.30	73.87	76.73
Unterallgaeu	2008	540.30	503.06	494.79	511.33	72.49	69.90	68.70	71.10
Unterallgaeu	2009	514.00	494.66	487.21	502.11	73.14	71.50	70.35	72.64
Unterallgaeu	2010	479.50	432.18	419.43	444.93	73.79	72.10	70.91	73.29
Unterallgaeu	2011	544.70	530.42	519.80	541.04	74.44	73.27	72.00	74.53

Unterallgaeu	2012	527.50	528.46	521.82	535.11	75.09	74.28	72.84	75.72
Unterallgaeu	2013	445.00	396.90	387.15	406.66	75.74	72.49	71.20	73.78
Unterallgaeu	2014	546.50	554.24	545.18	563.29	76.39	72.58	71.24	73.92
Unterallgaeu	2015	435.40	426.18	417.35	435.01	77.04	76.51	75.10	77.93
Weissenburg-Gunzenhausen	1991	489.90	459.50	449.27	469.73	58.46	62.52	61.20	63.85
Weissenburg-Gunzenhausen	1992	483.20	475.81	463.18	488.44	59.23	63.30	61.53	65.06
Weissenburg-Gunzenhausen	1993	537.10	506.93	498.26	515.61	60.00	62.45	61.37	63.54
Weissenburg-Gunzenhausen	1994	447.50	445.94	436.91	454.98	60.77	63.10	61.91	64.29
Weissenburg-Gunzenhausen	1995	408.60	455.14	446.47	463.81	61.54	62.54	61.28	63.80
Weissenburg-Gunzenhausen	1996	502.10	501.52	493.03	510.02	62.30	64.14	63.06	65.21
Weissenburg-Gunzenhausen	1997	523.40	489.12	480.89	497.34	63.07	61.59	60.59	62.58
Weissenburg-Gunzenhausen	1998	506.20	493.94	486.10	501.79	63.84	65.48	64.53	66.43
Weissenburg-Gunzenhausen	1999	489.90	492.75	483.33	502.17	64.61	67.86	66.78	68.94
Weissenburg-Gunzenhausen	2000	517.00	508.22	499.28	517.17	65.37	64.17	62.53	65.81
Weissenburg-Gunzenhausen	2001	489.60	466.42	455.47	477.36	66.14	67.49	66.17	68.80
Weissenburg-Gunzenhausen	2002	537.80	507.85	501.16	514.55	66.91	67.44	66.54	68.33
Weissenburg-Gunzenhausen	2003	432.50	392.01	380.23	403.79	67.68	65.82	64.05	67.58
Weissenburg-Gunzenhausen	2004	537.80	479.39	471.34	487.45	68.44	65.99	65.02	66.97
Weissenburg-Gunzenhausen	2005	494.20	491.27	482.51	500.03	69.21	65.97	64.81	67.14
Weissenburg-Gunzenhausen	2006	522.20	461.39	451.20	471.58	69.98	65.70	64.46	66.94
Weissenburg-Gunzenhausen	2007	529.90	519.25	511.77	526.72	70.75	68.58	67.38	69.79
Weissenburg-Gunzenhausen	2008	540.60	474.31	465.80	482.82	71.51	67.07	65.91	68.24
Weissenburg-Gunzenhausen	2009	535.90	493.89	486.32	501.47	72.28	70.91	69.58	72.24
Weissenburg-Gunzenhausen	2010	497.20	458.62	449.48	467.76	73.05	71.48	70.13	72.83
Weissenburg-Gunzenhausen	2011	576.60	532.77	524.37	541.17	73.82	71.93	70.48	73.38
Weissenburg-	2012	487.50	499.10	492.22	505.97	74.58	71.41	70.20	72.61

Gunzenhausen									
Weissenburg-Gunzenhausen	2013	377.60	386.45	376.68	396.22	75.35	71.60	70.38	72.81
Weissenburg-Gunzenhausen	2014	519.90	516.54	505.38	527.71	76.12	72.56	71.01	74.11
Weissenburg-Gunzenhausen	2015	341.90	374.92	364.72	385.12	76.89	67.12	66.16	68.08
Wuerzburg	1991	448.00	421.01	410.04	431.98	70.62	59.18	57.89	60.47
Wuerzburg	1992	534.60	508.43	499.11	517.76	70.91	61.79	60.44	63.15
Wuerzburg	1993	551.70	457.41	445.98	468.85	71.20	62.86	61.51	64.22
Wuerzburg	1994	497.00	437.92	425.71	450.13	71.49	59.54	57.76	61.31
Wuerzburg	1995	525.70	463.36	451.35	475.38	71.78	63.69	62.41	64.97
Wuerzburg	1996	543.70	493.58	485.29	501.88	72.07	64.73	63.53	65.92
Wuerzburg	1997	530.50	468.43	458.42	478.44	72.37	59.56	58.06	61.07
Wuerzburg	1998	497.60	455.58	444.73	466.43	72.66	61.38	60.25	62.50
Wuerzburg	1999	542.90	487.39	477.25	497.53	72.95	64.20	63.17	65.24
Wuerzburg	2000	570.20	489.63	475.43	503.83	73.24	60.25	58.22	62.29
Wuerzburg	2001	494.50	447.73	437.46	458.01	73.53	64.95	63.18	66.72
Wuerzburg	2002	535.20	499.99	490.35	509.63	73.82	66.70	65.33	68.07
Wuerzburg	2003	427.90	379.28	366.76	391.79	74.12	66.12	64.41	67.83
Wuerzburg	2004	563.80	475.89	467.34	484.43	74.41	64.27	63.22	65.31
Wuerzburg	2005	540.80	474.41	465.09	483.73	74.70	64.81	63.68	65.94
Wuerzburg	2006	576.60	451.09	438.12	464.07	74.99	65.70	63.99	67.42
Wuerzburg	2007	561.50	526.07	516.72	535.42	75.28	66.49	64.87	68.10
Wuerzburg	2008	491.00	450.26	438.49	462.02	75.57	64.01	62.57	65.44
Wuerzburg	2009	559.20	476.52	468.80	484.25	75.87	65.50	64.35	66.66
Wuerzburg	2010	535.50	446.64	435.72	457.55	76.16	68.27	66.71	69.83
Wuerzburg	2011	578.20	540.71	529.22	552.20	76.45	72.51	70.44	74.58
Wuerzburg	2012	530.40	488.42	478.22	498.62	76.74	66.11	64.08	68.15
Wuerzburg	2013	447.00	432.01	422.65	441.38	77.03	69.42	68.30	70.54
Wuerzburg	2014	611.40	512.47	503.23	521.72	77.32	70.62	68.86	72.38
Wuerzburg	2015	327.90	381.47	370.79	392.15	77.62	66.13	64.73	67.53
Wunsiedel	1991	394.60	413.20	394.53	431.87	55.60	60.90	58.92	62.88
Wunsiedel	1992	450.30	494.14	485.08	503.21	56.22	70.76	69.09	72.43
Wunsiedel	1993	497.90	509.41	497.53	521.30	56.83	65.86	64.05	67.67
Wunsiedel	1994	463.60	413.21	397.37	429.06	57.45	66.26	64.39	68.13
Wunsiedel	1995	422.20	422.08	409.93	434.22	58.06	60.53	58.13	62.92
Wunsiedel	1996	429.30	459.77	441.04	478.50	58.68	61.55	58.82	64.29

Wunsiedel	1997	453.80	463.00	448.21	477.78	59.30	58.82	56.31	61.32
Wunsiedel	1998	475.40	497.27	484.75	509.79	59.91	68.76	66.92	70.61
Wunsiedel	1999	469.40	457.50	446.04	468.96	60.53	66.98	65.50	68.47
Wunsiedel	2000	464.50	520.61	505.81	535.40	61.15	68.89	66.60	71.18
Wunsiedel	2001	424.00	477.92	461.92	493.92	61.76	61.63	59.09	64.17
Wunsiedel	2002	451.40	478.66	466.10	491.22	62.38	66.06	64.19	67.93
Wunsiedel	2003	392.30	460.34	448.78	471.90	63.00	68.92	67.25	70.59
Wunsiedel	2004	438.80	465.43	451.28	479.59	63.61	67.73	66.02	69.45
Wunsiedel	2005	435.10	467.85	454.47	481.22	64.23	68.47	66.96	69.98
Wunsiedel	2006	425.30	453.25	439.91	466.60	64.85	72.00	69.94	74.07
Wunsiedel	2007	492.20	489.57	479.19	499.96	65.46	74.09	72.44	75.75
Wunsiedel	2008	450.90	481.50	472.02	490.97	66.08	69.16	67.17	71.14
Wunsiedel	2009	462.70	472.60	462.22	482.99	66.69	73.78	71.32	76.25
Wunsiedel	2010	423.00	418.45	398.14	438.76	67.31	71.56	69.37	73.75
Wunsiedel	2011	484.70	510.20	497.88	522.52	67.93	67.04	65.06	69.02
Wunsiedel	2012	491.40	499.55	488.82	510.29	68.54	68.02	66.42	69.61
Wunsiedel	2013	355.80	350.38	334.25	366.52	69.16	69.84	66.91	72.77
Wunsiedel	2014	499.80	498.05	484.80	511.30	69.78	73.49	72.04	74.94
Wunsiedel	2015	467.10	440.74	430.19	451.28	70.39	70.66	69.42	71.89

Table E 2: Observed and predicted maize and wheat yields in dt ha^{-1} for Bavarian Soil-Climate-Areas from 1991 to 2015 with a 95% confidence interval given for both cultures observed yields (upper and lower confidence interval).

Soil-Climate-Area	Year	Maize observed yield	Maize predicted yield	Lower Confidence Intervall	Upper Confidence Intervall	Wheat obs. detrendet yield	Wheat predicted yields	Lower Confidence Intervall	Upper Confidence Intervall
Albfleachen_Ostbayerisches_Huegelland	1991	437.20	424.10	403.17	445.04	64.39	64.81	62.92	66.71
Albfleachen_Ostbayerisches_Huegelland	1992	499.60	469.73	457.25	482.21	57.53	55.45	53.20	57.70
Albfleachen_Ostbayerisches_Huegelland	1993	529.00	494.15	476.40	511.89	58.03	55.34	53.54	57.14
Albfleachen_Ostbayerisches_Huegelland	1994	446.10	451.97	437.67	466.28	60.11	60.21	58.21	62.21
Albfleachen_Ostbayerisches_Huegelland	1995	451.90	450.32	430.72	469.92	55.23	60.18	58.01	62.34
Albfleachen_Ostbayerisches_Huegelland	1996	507.00	494.68	479.77	509.59	63.97	64.29	62.08	66.50
Albfleachen_Ostbayerisches_Huegelland	1997	493.50	468.41	454.77	482.06	58.10	57.89	55.81	59.97
Albfleachen_Ostbayerisches_Huegelland	1998	519.80	493.13	474.94	511.33	62.24	63.92	62.05	65.80
Albfleachen_Ostbayerisches_Huegelland	1999	465.30	494.82	483.16	506.48	57.11	60.94	59.20	62.69
Albfleachen_Ostbayerisches_Huegelland	2000	481.40	505.14	491.71	518.58	59.57	59.87	57.23	62.52
Albfleachen_Ostbayerisches_Huegelland	2001	458.90	450.08	435.16	464.99	61.00	60.67	58.34	63.00
Albfleachen_Ostbayerisches_Huegelland	2002	530.90	493.75	483.18	504.33	57.32	60.74	59.11	62.37
Albfleachen_Ostbayerisches_Huegelland	2003	398.40	410.07	392.47	427.66	46.52	50.45	47.40	53.51
Albfleachen_Ostbayerisches_Huegelland	2004	495.40	496.92	488.08	505.75	70.37	69.49	67.75	71.22
Albfleachen_Ostbayerisches_Huegelland	2005	534.90	512.84	497.48	528.19	56.85	59.94	57.82	62.06
Albfleachen_Ostbayerisches_Huegelland	2006	478.60	458.80	438.67	478.93	57.56	60.73	58.43	63.03
Albfleachen_Ostbayerisches_Huegelland	2007	551.30	515.35	501.57	529.14	62.16	61.55	59.51	63.59
Albfleachen_Ostbayerisches_Huegelland	2008	480.30	473.72	460.01	487.44	60.72	62.00	60.37	63.63
Albfleachen_Ostbayerisches_Huegelland	2009	529.50	499.54	486.65	512.43	56.46	61.42	59.19	63.65
Albfleachen_Ostbayerisches_Huegelland	2010	471.30	443.95	427.12	460.78	53.37	54.75	52.52	56.98
Albfleachen_Ostbayerisches_Huegelland	2011	569.60	542.72	524.86	560.59	58.12	57.50	55.34	59.67
Albfleachen_Ostbayerisches_Huegelland	2012	519.90	504.48	492.49	516.47	57.28	54.84	52.93	56.75
Albfleachen_Ostbayerisches_Huegelland	2013	369.90	372.20	353.51	390.90	59.23	59.59	57.49	61.68
Albfleachen_Ostbayerisches_Huegelland	2014	571.30	480.10	466.10	494.11	65.35	66.15	64.01	68.29
Albfleachen_Ostbayerisches_Huegelland	2015	384.20	395.18	379.47	410.90	62.47	62.49	59.70	65.27
Gaeu_Donau_u_Inntal	1991	493.10	501.87	476.93	526.82	68.97	72.51	69.98	75.04
Gaeu_Donau_u_Inntal	1992	473.90	504.85	487.04	522.67	68.36	64.37	61.34	67.39
Gaeu_Donau_u_Inntal	1993	483.80	527.53	503.46	551.60	60.67	59.64	57.66	61.63
Gaeu_Donau_u_Inntal	1994	496.20	470.59	453.08	488.09	66.46	70.57	67.96	73.17
Gaeu_Donau_u_Inntal	1995	449.20	465.38	441.30	489.47	61.21	61.13	58.55	63.70

Gaeu_Donau_u_Inntal	1996	461.50	538.21	523.51	552.91	70.49	66.82	64.65	69.00
Gaeu_Donau_u_Inntal	1997	512.10	514.85	497.00	532.70	67.04	64.29	61.82	66.75
Gaeu_Donau_u_Inntal	1998	535.70	534.19	516.49	551.90	68.35	69.16	66.58	71.73
Gaeu_Donau_u_Inntal	1999	481.50	519.38	496.04	542.72	59.96	60.21	57.75	62.67
Gaeu_Donau_u_Inntal	2000	514.30	548.11	529.70	566.53	67.90	68.40	65.43	71.38
Gaeu_Donau_u_Inntal	2001	472.90	515.52	494.17	536.87	67.17	63.69	61.20	66.19
Gaeu_Donau_u_Inntal	2002	542.60	539.05	520.61	557.48	61.89	63.04	61.21	64.88
Gaeu_Donau_u_Inntal	2003	518.60	458.28	437.93	478.64	53.77	55.98	53.08	58.87
Gaeu_Donau_u_Inntal	2004	563.80	533.63	518.79	548.48	77.37	77.32	75.08	79.57
Gaeu_Donau_u_Inntal	2005	591.20	569.76	552.44	587.07	63.69	60.75	58.13	63.38
Gaeu_Donau_u_Inntal	2006	509.30	505.86	487.10	524.62	59.45	64.40	61.55	67.24
Gaeu_Donau_u_Inntal	2007	551.20	525.04	508.94	541.14	68.39	65.31	62.29	68.34
Gaeu_Donau_u_Inntal	2008	577.20	529.04	511.28	546.80	69.43	67.01	64.64	69.38
Gaeu_Donau_u_Inntal	2009	535.60	543.50	526.71	560.29	60.19	60.77	57.64	63.89
Gaeu_Donau_u_Inntal	2010	469.30	446.94	417.70	476.18	55.18	61.71	58.62	64.79
Gaeu_Donau_u_Inntal	2011	519.00	583.23	564.22	602.24	66.10	67.23	65.16	69.30
Gaeu_Donau_u_Inntal	2012	514.10	552.15	536.62	567.68	63.09	62.11	59.56	64.67
Gaeu_Donau_u_Inntal	2013	370.30	408.25	383.74	432.77	62.76	59.68	56.54	62.81
Gaeu_Donau_u_Inntal	2014	471.40	533.88	518.56	549.20	77.08	69.85	65.53	74.17
Gaeu_Donau_u_Inntal	2015	410.40	415.27	395.08	435.47	69.01	65.02	62.28	67.77
Moraenen_Huegelland_Voralpenland	1991	527.10	496.85	457.91	535.80	63.87	67.15	63.76	70.54
Moraenen_Huegelland_Voralpenland	1992	509.20	489.97	476.58	503.35	60.12	59.65	57.00	62.31
Moraenen_Huegelland_Voralpenland	1993	538.10	530.67	485.08	576.25	56.30	56.57	53.95	59.19
Moraenen_Huegelland_Voralpenland	1994	500.20	490.49	477.12	503.86	61.44	62.88	60.36	65.39
Moraenen_Huegelland_Voralpenland	1995	449.00	434.17	404.88	463.46	52.79	51.84	49.00	54.68
Moraenen_Huegelland_Voralpenland	1996	501.70	486.35	468.20	504.49	62.72	65.95	64.06	67.84
Moraenen_Huegelland_Voralpenland	1997	527.20	495.71	479.01	512.41	59.35	61.31	59.28	63.34
Moraenen_Huegelland_Voralpenland	1998	549.90	515.02	499.33	530.72	61.37	62.04	59.88	64.20
Moraenen_Huegelland_Voralpenland	1999	515.80	506.38	490.18	522.58	54.79	56.96	54.11	59.82
Moraenen_Huegelland_Voralpenland	2000	535.10	516.78	485.30	548.25	63.39	58.91	56.52	61.31
Moraenen_Huegelland_Voralpenland	2001	472.30	465.94	437.24	494.64	59.34	56.93	54.78	59.08
Moraenen_Huegelland_Voralpenland	2002	551.60	515.22	475.63	554.81	56.37	56.31	54.45	58.17
Moraenen_Huegelland_Voralpenland	2003	487.10	446.95	425.50	468.41	54.39	53.11	50.50	55.71
Moraenen_Huegelland_Voralpenland	2004	546.50	498.31	481.11	515.51	67.33	68.28	66.33	70.23
Moraenen_Huegelland_Voralpenland	2005	477.80	541.66	525.39	557.93	57.46	57.31	54.91	59.71
Moraenen_Huegelland_Voralpenland	2006	469.40	485.85	468.42	503.27	55.19	63.44	61.11	65.78

Moraenen_Huegelland_Voralpenland	2007	516.10	482.59	462.44	502.74	64.36	64.78	62.68	66.89
Moraenen_Huegelland_Voralpenland	2008	497.20	524.37	513.55	535.19	62.69	61.36	59.14	63.58
Moraenen_Huegelland_Voralpenland	2009	505.50	503.29	477.04	529.55	50.75	50.62	46.97	54.28
Moraenen_Huegelland_Voralpenland	2010	422.00	513.66	468.40	558.93	49.28	58.50	56.06	60.93
Moraenen_Huegelland_Voralpenland	2011	542.20	576.91	555.52	598.30	59.75	61.05	59.26	62.84
Moraenen_Huegelland_Voralpenland	2012	484.20	512.34	497.01	527.68	58.88	57.49	55.25	59.73
Moraenen_Huegelland_Voralpenland	2013	403.30	389.82	366.80	412.84	58.46	59.71	57.35	62.08
Moraenen_Huegelland_Voralpenland	2014	509.30	528.73	510.84	546.61	65.35	69.10	66.85	71.36
Moraenen_Huegelland_Voralpenland	2015	491.00	387.22	370.17	404.27	64.40	57.45	54.80	60.11
Nordwestbayern_Franken	1991	344.50	422.95	402.26	443.65	61.46	61.74	59.43	64.04
Nordwestbayern_Franken	1992	469.80	482.88	469.98	495.79	56.63	54.75	52.35	57.14
Nordwestbayern_Franken	1993	441.50	436.09	410.98	461.20	54.91	55.93	53.48	58.39
Nordwestbayern_Franken	1994	416.80	438.86	424.21	453.50	59.02	57.31	55.11	59.51
Nordwestbayern_Franken	1995	446.60	441.79	428.27	455.31	56.37	54.75	52.40	57.10
Nordwestbayern_Franken	1996	451.80	491.38	476.96	505.81	66.59	61.34	59.56	63.11
Nordwestbayern_Franken	1997	458.20	463.96	449.29	478.63	57.02	53.74	51.47	56.02
Nordwestbayern_Franken	1998	463.40	485.54	469.46	501.63	61.15	62.60	60.51	64.69
Nordwestbayern_Franken	1999	496.00	485.66	472.58	498.73	58.95	57.15	55.19	59.12
Nordwestbayern_Franken	2000	490.00	507.48	493.61	521.35	58.83	55.23	52.19	58.26
Nordwestbayern_Franken	2001	471.60	445.61	430.38	460.83	61.00	60.54	58.20	62.88
Nordwestbayern_Franken	2002	474.30	488.97	478.80	499.15	59.49	60.98	59.02	62.94
Nordwestbayern_Franken	2003	346.70	396.82	378.38	415.26	45.99	46.36	43.27	49.45
Nordwestbayern_Franken	2004	532.00	479.51	468.12	490.90	74.51	66.95	65.15	68.75
Nordwestbayern_Franken	2005	414.80	487.02	475.00	499.04	56.97	55.55	53.16	57.95
Nordwestbayern_Franken	2006	431.80	449.49	427.72	471.26	59.58	55.00	52.32	57.68
Nordwestbayern_Franken	2007	495.00	509.18	492.06	526.30	60.83	58.65	56.50	60.81
Nordwestbayern_Franken	2008	379.60	456.60	439.44	473.76	55.48	58.43	56.30	60.56
Nordwestbayern_Franken	2009	462.10	477.61	467.17	488.06	61.04	59.53	57.27	61.80
Nordwestbayern_Franken	2010	417.30	440.80	422.33	459.26	56.06	56.52	54.24	58.79
Nordwestbayern_Franken	2011	496.50	534.07	518.67	549.46	50.67	52.03	48.18	55.87
Nordwestbayern_Franken	2012	489.60	506.65	493.90	519.40	49.40	53.58	51.32	55.84
Nordwestbayern_Franken	2013	369.90	388.69	373.96	403.41	65.42	59.27	57.32	61.21
Nordwestbayern_Franken	2014	497.30	479.67	464.71	494.63	65.74	63.64	61.20	66.09
Nordwestbayern_Franken	2015	294.10	395.76	378.62	412.90	60.47	61.32	58.59	64.06
Odenwald_Spessart	1991	339.40	427.63	400.02	455.24	61.28	62.95	60.16	65.75
Odenwald_Spessart	1992	488.40	492.73	478.99	506.47	60.76	55.51	53.17	57.86

Odenwald_Spessart	1993	430.10	436.75	408.93	464.57	57.13	59.94	57.82	62.06
Odenwald_Spessart	1994	433.30	439.66	426.24	453.08	58.96	58.29	56.06	60.52
Odenwald_Spessart	1995	486.90	441.40	426.81	455.99	55.44	58.21	55.54	60.87
Odenwald_Spessart	1996	479.20	494.12	479.15	509.09	65.12	65.12	62.62	67.62
Odenwald_Spessart	1997	449.90	462.47	449.54	475.39	60.79	57.85	55.50	60.20
Odenwald_Spessart	1998	506.90	485.32	473.33	497.32	63.02	65.52	62.88	68.16
Odenwald_Spessart	1999	492.80	477.16	466.84	487.48	58.80	56.71	54.55	58.86
Odenwald_Spessart	2000	524.60	519.72	507.79	531.65	57.48	57.87	54.78	60.96
Odenwald_Spessart	2001	484.30	430.92	416.37	445.47	59.21	61.03	58.30	63.76
Odenwald_Spessart	2002	503.40	489.06	476.89	501.22	56.58	61.22	59.34	63.10
Odenwald_Spessart	2003	381.90	379.95	359.93	399.97	51.51	50.05	46.66	53.44
Odenwald_Spessart	2004	493.80	486.51	478.03	494.99	73.59	69.19	66.81	71.57
Odenwald_Spessart	2005	506.00	506.29	494.44	518.13	59.97	57.17	54.70	59.65
Odenwald_Spessart	2006	500.60	454.44	430.31	478.56	61.85	51.81	48.74	54.89
Odenwald_Spessart	2007	504.50	509.42	492.10	526.73	57.57	64.16	61.45	66.87
Odenwald_Spessart	2008	481.40	458.49	441.24	475.74	65.05	61.90	59.60	64.20
Odenwald_Spessart	2009	504.90	477.00	466.69	487.31	60.63	63.83	61.73	65.93
Odenwald_Spessart	2010	489.20	428.94	412.30	445.57	55.51	60.24	57.87	62.60
Odenwald_Spessart	2011	563.30	524.21	507.90	540.52	48.18	51.87	46.34	57.40
Odenwald_Spessart	2012	499.40	511.10	501.29	520.91	50.01	57.28	54.96	59.61
Odenwald_Spessart	2013	398.60	393.24	378.60	407.88	63.94	62.21	60.03	64.40
Odenwald_Spessart	2014	490.30	501.89	490.42	513.36	67.22	61.14	58.52	63.77
Odenwald_Spessart	2015	349.20	389.16	370.93	407.39	63.85	60.70	57.59	63.81
TertiaerHuegelland_DonauSued	1991	509.70	483.28	450.47	516.08	68.45	65.45	62.21	68.70
TertiaerHuegelland_DonauSued	1992	476.70	496.71	482.98	510.43	65.62	63.90	61.41	66.40
TertiaerHuegelland_DonauSued	1993	512.40	535.07	516.31	553.82	59.41	62.14	60.14	64.14
TertiaerHuegelland_DonauSued	1994	497.30	494.32	482.47	506.16	63.75	63.52	61.10	65.95
TertiaerHuegelland_DonauSued	1995	418.00	435.22	407.71	462.74	57.75	57.21	54.74	59.69
TertiaerHuegelland_DonauSued	1996	499.50	505.28	491.41	519.15	69.46	67.57	65.52	69.63
TertiaerHuegelland_DonauSued	1997	493.20	497.17	480.64	513.69	64.33	63.84	62.27	65.42
TertiaerHuegelland_DonauSued	1998	475.50	517.50	501.22	533.77	66.86	65.50	63.25	67.75
TertiaerHuegelland_DonauSued	1999	454.40	503.44	489.47	517.41	59.51	58.30	55.82	60.77
TertiaerHuegelland_DonauSued	2000	537.50	520.11	493.49	546.73	66.20	63.18	60.78	65.58
TertiaerHuegelland_DonauSued	2001	501.30	473.65	454.26	493.05	64.83	65.06	62.66	67.47
TertiaerHuegelland_DonauSued	2002	529.50	525.23	508.38	542.08	58.68	63.56	61.62	65.50
TertiaerHuegelland_DonauSued	2003	446.20	441.82	419.48	464.15	53.91	56.41	53.58	59.24

TertiaerHuegelland_DonauSued	2004	491.90	514.67	504.44	524.90	74.29	72.42	70.54	74.30
TertiaerHuegelland_DonauSued	2005	517.40	532.84	519.36	546.32	61.57	65.34	63.15	67.52
TertiaerHuegelland_DonauSued	2006	497.40	487.83	468.38	507.27	59.82	64.93	62.46	67.40
TertiaerHuegelland_DonauSued	2007	515.10	511.56	493.98	529.15	67.64	65.88	63.50	68.26
TertiaerHuegelland_DonauSued	2008	522.80	525.39	513.30	537.48	68.06	65.01	63.19	66.82
TertiaerHuegelland_DonauSued	2009	554.70	494.40	481.96	506.84	56.24	61.90	59.57	64.22
TertiaerHuegelland_DonauSued	2010	452.50	433.33	413.37	453.29	54.23	62.52	60.04	65.01
TertiaerHuegelland_DonauSued	2011	611.70	554.64	537.35	571.94	65.25	61.87	59.84	63.90
TertiaerHuegelland_DonauSued	2012	557.60	530.32	519.19	541.46	62.90	61.05	59.38	62.72
TertiaerHuegelland_DonauSued	2013	409.90	375.57	352.49	398.64	62.52	63.34	60.95	65.72
TertiaerHuegelland_DonauSued	2014	536.00	527.30	510.96	543.63	71.17	68.02	65.57	70.47
TertiaerHuegelland_DonauSued	2015	398.90	406.19	390.91	421.47	66.96	63.50	61.25	65.74
Verwitterungsboeden_id_Hoehenlagen	1991	422.60	411.05	390.00	432.10	58.53	62.99	60.98	64.99
Verwitterungsboeden_id_Hoehenlagen	1992	466.70	473.04	458.38	487.70	52.91	56.12	53.88	58.36
Verwitterungsboeden_id_Hoehenlagen	1993	528.60	494.34	477.08	511.60	53.19	55.27	53.25	57.29
Verwitterungsboeden_id_Hoehenlagen	1994	425.10	430.79	410.63	450.94	53.98	61.11	58.67	63.56
Verwitterungsboeden_id_Hoehenlagen	1995	440.10	457.03	438.18	475.88	52.24	53.44	50.67	56.20
Verwitterungsboeden_id_Hoehenlagen	1996	479.20	495.36	480.31	510.41	56.94	58.92	56.56	61.28
Verwitterungsboeden_id_Hoehenlagen	1997	471.00	449.68	431.04	468.32	55.05	56.63	54.75	58.51
Verwitterungsboeden_id_Hoehenlagen	1998	489.10	494.25	470.91	517.58	59.50	60.00	58.24	61.77
Verwitterungsboeden_id_Hoehenlagen	1999	465.50	498.33	484.00	512.66	56.11	54.22	52.27	56.17
Verwitterungsboeden_id_Hoehenlagen	2000	494.50	502.93	486.55	519.31	57.11	57.56	54.90	60.23
Verwitterungsboeden_id_Hoehenlagen	2001	447.80	455.89	436.23	475.54	58.28	55.62	53.25	57.98
Verwitterungsboeden_id_Hoehenlagen	2002	485.90	472.93	460.94	484.92	55.68	54.92	53.35	56.48
Verwitterungsboeden_id_Hoehenlagen	2003	423.60	409.81	392.85	426.76	47.46	48.33	45.77	50.89
Verwitterungsboeden_id_Hoehenlagen	2004	479.10	504.30	484.59	524.00	65.66	64.71	62.83	66.59
Verwitterungsboeden_id_Hoehenlagen	2005	491.30	510.75	493.39	528.11	52.60	53.43	51.10	55.76
Verwitterungsboeden_id_Hoehenlagen	2006	480.20	455.15	433.81	476.49	50.31	55.07	52.50	57.65
Verwitterungsboeden_id_Hoehenlagen	2007	492.90	489.22	474.12	504.31	56.64	56.21	54.08	58.33
Verwitterungsboeden_id_Hoehenlagen	2008	458.20	459.84	445.64	474.04	55.16	57.10	55.27	58.93
Verwitterungsboeden_id_Hoehenlagen	2009	474.90	495.09	479.24	510.94	51.75	56.50	54.03	58.98
Verwitterungsboeden_id_Hoehenlagen	2010	415.20	434.35	414.64	454.05	48.35	52.71	49.98	55.45
Verwitterungsboeden_id_Hoehenlagen	2011	527.50	525.54	506.15	544.94	52.08	55.91	53.81	58.01
Verwitterungsboeden_id_Hoehenlagen	2012	493.30	511.34	496.86	525.83	52.85	50.19	48.02	52.35
Verwitterungsboeden_id_Hoehenlagen	2013	343.00	389.53	370.81	408.25	53.88	53.25	50.82	55.68
Verwitterungsboeden_id_Hoehenlagen	2014	534.90	472.05	458.47	485.64	63.84	63.09	60.82	65.36

Verwitterungsboeden_id_Hoehenlagen	2015	403.30	396.06	381.52	410.60	58.99	55.26	53.26	57.26
Verwitterungsboeden_id_Uebergangslagen	1991	398.80	384.47	359.43	409.50	61.76	60.63	58.61	62.65
Verwitterungsboeden_id_Uebergangslagen	1992	465.40	475.06	461.90	488.21	56.87	58.11	56.13	60.08
Verwitterungsboeden_id_Uebergangslagen	1993	475.00	463.70	440.04	487.36	58.39	57.85	55.17	60.53
Verwitterungsboeden_id_Uebergangslagen	1994	428.90	432.81	420.13	445.49	58.70	59.12	56.89	61.35
Verwitterungsboeden_id_Uebergangslagen	1995	473.10	447.86	433.28	462.44	57.46	56.42	53.78	59.06
Verwitterungsboeden_id_Uebergangslagen	1996	494.40	493.00	476.19	509.80	65.47	63.36	60.75	65.96
Verwitterungsboeden_id_Uebergangslagen	1997	483.00	440.68	424.80	456.56	57.18	54.74	52.12	57.36
Verwitterungsboeden_id_Uebergangslagen	1998	488.20	498.05	474.85	521.25	61.40	62.59	60.50	64.68
Verwitterungsboeden_id_Uebergangslagen	1999	510.00	493.09	478.73	507.45	58.11	58.14	56.19	60.08
Verwitterungsboeden_id_Uebergangslagen	2000	491.50	519.15	504.87	533.42	59.32	62.63	58.85	66.41
Verwitterungsboeden_id_Uebergangslagen	2001	491.80	455.99	441.05	470.94	62.83	60.63	58.49	62.77
Verwitterungsboeden_id_Uebergangslagen	2002	467.40	472.92	460.84	485.00	61.65	60.45	57.85	63.05
Verwitterungsboeden_id_Uebergangslagen	2003	387.70	424.51	410.34	438.68	50.01	52.62	49.54	55.70
Verwitterungsboeden_id_Uebergangslagen	2004	481.10	487.85	472.08	503.63	73.67	66.53	64.78	68.28
Verwitterungsboeden_id_Uebergangslagen	2005	463.20	478.27	464.26	492.28	58.88	60.55	58.80	62.30
Verwitterungsboeden_id_Uebergangslagen	2006	396.60	457.00	431.71	482.30	62.59	58.55	56.02	61.07
Verwitterungsboeden_id_Uebergangslagen	2007	500.70	505.42	492.89	517.96	60.51	53.30	49.70	56.89
Verwitterungsboeden_id_Uebergangslagen	2008	432.40	432.86	416.29	449.43	53.27	65.18	62.73	67.63
Verwitterungsboeden_id_Uebergangslagen	2009	506.00	469.34	457.11	481.57	62.63	61.61	58.95	64.27
Verwitterungsboeden_id_Uebergangslagen	2010	462.70	420.38	399.80	440.97	56.69	56.24	53.70	58.78
Verwitterungsboeden_id_Uebergangslagen	2011	519.80	524.02	510.22	537.83	50.45	54.66	51.50	57.81
Verwitterungsboeden_id_Uebergangslagen	2012	530.10	519.42	506.68	532.16	53.12	53.40	51.24	55.57
Verwitterungsboeden_id_Uebergangslagen	2013	349.70	394.69	378.75	410.63	66.03	54.31	52.24	56.38
Verwitterungsboeden_id_Uebergangslagen	2014	484.80	489.60	477.08	502.13	63.99	68.87	66.04	71.71
Verwitterungsboeden_id_Uebergangslagen	2015	398.10	403.42	390.40	416.44	61.55	58.00	55.83	60.17

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