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The Role of Recent Climate Change in Explaining the Statistical Yield Increase of Maize in Northern Bavaria—A Model Study

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Abstract: Maize yields in many regions of the world have increased significantly since the 1960s. The increase is mainly attributed to technological improvements and climate change. On a regional scale and in recent decades, climate change has altered growth conditions of maize and this, in turn, has influenced changes in yield. In order to analyze the contribution of different factors to yield changes, and to obtain a model setup that could be used for further analyses of yield development, this study systematically investigated the effects of recent climate change, irrigation, cultivar selection and nutrient availability on historical yields in Northern Bavaria. Four sets of simulations were conducted with the mechanistic plant growth model PROMET, during the time period between 1997 and 2020, and the resulting yields were compared to county statistics. In addition, three scenarios were simulated in order to determine yield increase potentials for the highly mechanized agricultural region of Northern Bavaria. The results showed a good agreement with the observed yields (R^2 = 0.76), when considering altered nutrient availability, suggesting that an increase in nutrient uptake by plants plays a key role in reproducing yield statistics and has a main contribution to the observed increasing yield trends. Moreover, other factors considered individually, such as recent climate change, irrigation and cultivar selection, could not explain the yield levels and trends shown by the statistics. The scenario simulations demonstrated potential increases in yield due to irrigation and cultivar adaptation. The yield response to irrigation shows a trend, with recent climate change progressing, of 0–25% when irrigating currently grown cultivars and 10–50% when irrigating an adapted cultivar; rainfed cultivar adaptation consistently increased the level of yields by approximately 10%. This study highlights the importance of a dynamic consideration of growth conditions in the course of climate change, rather than static assumptions of model parameters, and emphasizes the importance of the second-order effects of climate change.

Keywords: crop yield modeling; climate change effects; nutrient availability; cultivar adaptation; supplemental irrigation; Northern Bavaria

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1. Introduction

The yield formation of crops is dependent on environmental factors—such as sufficient water supply, optimal temperature and soil—and agricultural management practices. These factors result in different yield levels of the same crop over time and space in the regions of the world. On a global as well as European average, yields of several crops have increased significantly since the 1960s as a result of technological improvements and changes in the climate [1,2]. Advancements in breeding technologies have enabled the cultivation of maize in many regions of the globe [3]. The development of maize yields in Germany follows the global and European trend showing a tripling since the 1960s. Nevertheless, in the last decade, maize yields in Germany have shown stagnation and a greater interannual variability than in the decades before [4–7]. This may have multiple reasons, which could range from a plateau in fertilization to a leveling off of breeding successes, or could be caused by the already ongoing changes in climate.

In recent decades, the observed temperature increase in Central Europe was larger than the global average of 1.1 °C, and rainfall patterns also show dryer summers and wetter winters [8–10]. In addition, hot and dry summer seasons have become more frequent in Germany [11]. The irrigation of staple crops, such as maize, currently plays a minor role in Germany. However, it may gain in importance in the further course of climate change [12,13]. Thus, important questions for regional water resources planning and management arise as to whether: (a) the rising temperatures and changing precipitation patterns due to ongoing climate change are already affecting yields in Central Europe; (b) to what extent climate change will lead to an expansion of the supplemental irrigation of staple crops, such as maize, in temperate Central Europe; and (c) how such an expansion could impact water distribution conflicts in the region.

Besides water stress, warmer temperatures result in a shorter growing season for maize and, thus, an earlier harvest and lower yield [14,15]. Maize is a C_4-plant and, therefore, is hardly affected by increasing CO_2 levels in the atmosphere, but is strongly dependent on temperature [16]. Earlier harvests in hot years indicate that the cultivars which are used today in this region might no longer be suitable because of the changes in climate that have already occurred in the recent past [17,18]. They may also move out of the climate suitability window as climate change progresses [19].

The influence of recent climate change on the suitability of the cultivars selected by local farmers is not the only factor which may have changed the growing conditions for maize in temperate regions over the last few decades. Increasing temperatures and changing precipitation patterns also affect the availability of fertilizers, specifically nitrogen [20,21], and moisture in the soil, thereby altering the growth conditions for maize. Agricultural management practices, such as fertilization, can be adapted to account for the shifting potentials that a warming climate offers. Especially for maize, irrigation could be introduced to account for possible water deficits in the soil. Nevertheless, under field conditions it is usually difficult to empirically attribute the role of different factors to measured changes in recent maize yields. Schauberger et al. [22] analyzed the statistical yield data of France and found a high correlation between fertilizer application, especially nitrogen, and yield trends, suggesting, that fertilizer input is an important factor affecting observed trends in yield. The effect of increased temperatures and decreased precipitation on yield development in the Czech Republic was investigated by Maitah et al. [23], also by using statistical data. Using process-based models, Medina and Tian [24] found an interdependent effect of climate and management on maize yield trends in the USA.

Many studies generally use experimental plots, where the influence of farm management decisions, such as the selection of seeding date and the level of fertilization and pest control, can be chosen by the investigator. Knowledge of the above-mentioned management factors has a strong influence on the simulation of plant growth and the resulting simulated yield and eventually make up for a large part of the differences observed in growth and yield between controlled field plots and agricultural practice [25,26]. These studies usually do not exceed one or a few cropping cycles and, therefore, do not reflect slow changes in growth conditions, that are, e.g., created through already ongoing changes in climate. Under field conditions the decisions of individual farmers on how to manage their fields are usually unknown. The only data that are available are the agricultural yield statistics, which are aggregated spatially on a national, state or county level (e.g., [27,28]). These statistics are usually available for the longer time period of decades and reflect, in an aggregated way, the influence of changes in growing conditions as well as the adaptation of farming decisions on the resulting yields.

The question arises as to whether, and to what extent, mechanistic plant growth models, which are based on first-order physical and physiological principles and therefore do not rely on regressions of model parameters with observed yield statistics, can also be applied under field conditions to reproduce multi-decadal changes in growing conditions and yields. If so, the results of these mechanistic model simulations could be used to systematically study the possible contribution of different factors, e.g., recent climate change, possible supplemental irrigation, variety changes or fertilizer availability, on the observed changes in yield with time. Could they be used in such a way that small trends in statistical yields can be isolated from the noise of annual variations in climate drivers and, if they exist, be reconstructed and explained through a variation in cultivar or fertilizer availability in mechanistic crop growth simulations? Being able to reconstruct multi-decadal trends in statistical yields with a mechanistic crop growth model is also a prerequisite for further future-oriented simulation-based studies on changes in regional, practical growth conditions and yields. Having proven its capability with past data, a mechanistic crop growth model could then be used to study the impact of climate change on growth conditions and yields for the decades to come, assuming different emission pathways, and to systematically explore the potential of integrated adaptation strategies of cultivar selection, increased supplement irrigation, etc.

The summer of 2022 was remarkable in Central Europe, and particularly in Germany, with temperatures strongly above average and very low precipitation amounts, leading to droughts in many regions and thus affecting agricultural productivity. Since weather conditions similar to 2022 are expected to be more frequent and have a higher intensity in future periods [11], a further question arises as to how yield losses and strong decreases in yield could be prevented. In 2022, maize in Germany had a strong reduction in yield of about 21% compared to the average from 2016 to 2021, as a consequence of these extreme climate conditions [29].

Here, we present an approach for reconstructing statistical yields with an uncalibrated mechanistical crop growth model and to analyze the influence of different factors, such as fertilizer availability or cultivar selection, on the temporal course of observed yields. We selected the study region of Northern Bavaria, which under today's climate can be considered marginal for the cultivation of summer crops because of its warm and dry climate. Based on the results of the analysis, we simulated scenarios based on different measures to prevent yield losses and to further increase yield levels in a region with sophisticated mechanized agriculture. The aim of this study, therefore, is firstly to show, exemplary for maize and in the selected temperate climate geographical region of Northern Bavaria, that the observed average and multi-decadal trend in county yield can be reproduced with a mechanistical crop growth model. Secondly, to determine the contribution of recent climate change, irrigation, fertilizer availability and cultivar on historical yield development and, thirdly, to investigate systematically yield response to irrigation and cultivar choice and explore yield increase potentials in a region with sophisticated mechanized agriculture.

2. Materials and Methods

2.1. Study Site

The study region consists of several counties in Franconia/Germany. It roughly coincides with the catchment area of the Main River with the outlet gauge in Kleinheubach, located in Northern Bavaria. The study region covers an approximate area of 21,519 km^2 (Figure 1 [30]). Agriculturally used areas in the region are characterized by low precipitation of approximately 325.3 mm and high temperatures of approximately 16.2 °C during the growing season between May and September. Compared to other regions in the European moderate climate zone, like Southern Bavaria, the study region is relatively dry due to cyclonic weather patterns that bring more precipitation to the foothills of the Alps than to the low mountain ranges [31]. Most precipitation falls in the winter months. The main agricultural staple crops are cereals, maize and potatoes. Drought events, that have occurred more frequently in the last few decades, have had an increasingly large impact on water-consuming sectors in the region, such as agriculture, industry, drinking water supply and ecology. Restrictions in water availability have led to water-use conflicts in the past among these sectors [32]. The use of irrigation is expanding in the study area for cash crops, such as vine and vegetables. Potatoes are occasionally irrigated for quality purposes during the late growing stage. Staple crops, such as maize and wheat, are not yet irrigated, although pressure is rising on water authorities from the agricultural sector to allocate water quotas for this purpose.

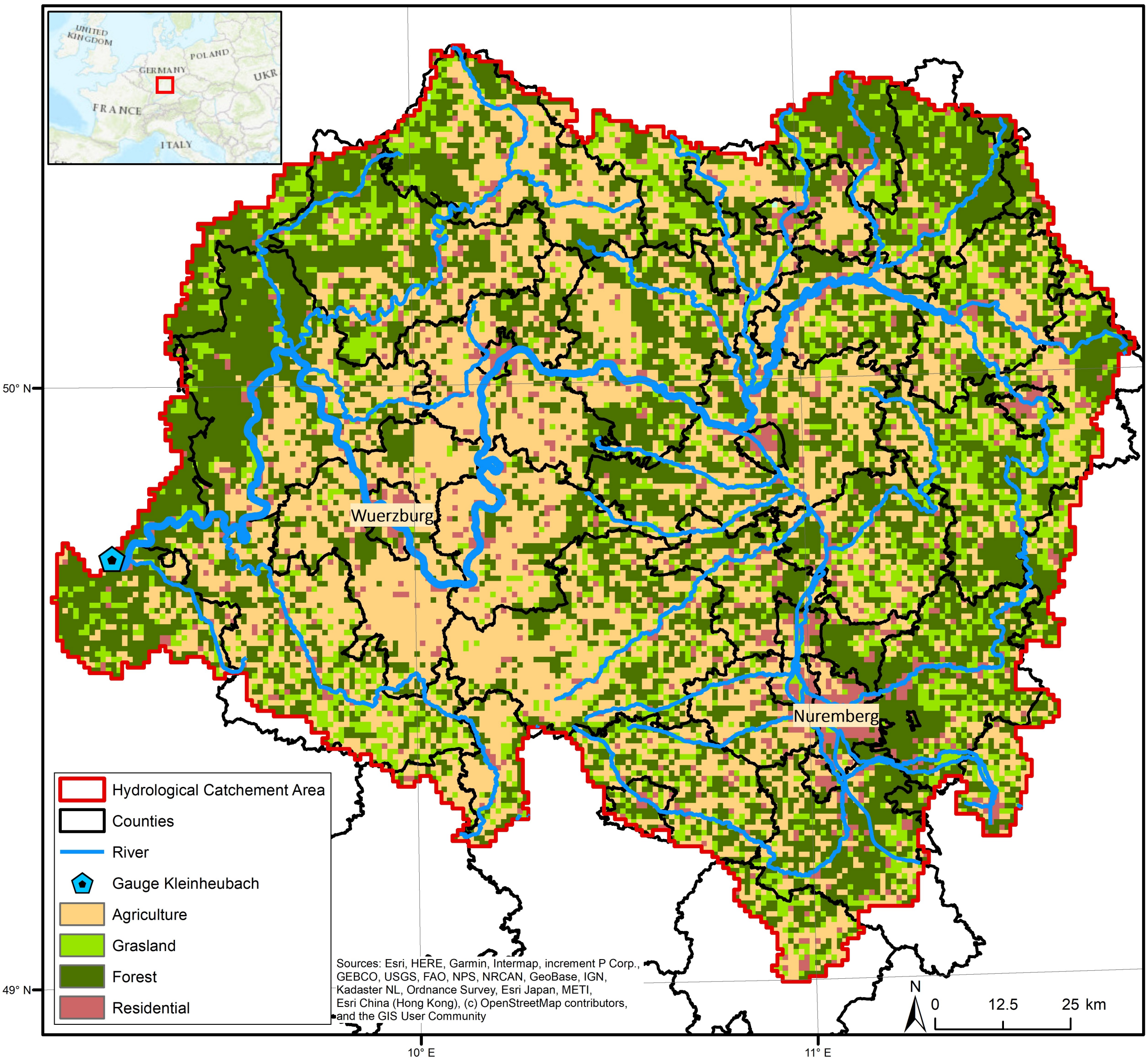

Figure 1. Map of the study area in Northern Bavaria. Data sources: [30,33–37].

The considered period of 24 years between 1997 and 2020, for which high-quality yield data are available on the county level, covers a variety of annual weather conditions and a considerable part of the already ongoing climate change in the region [10,38]. Very dry as well as wet years are included in the meteorological dataset, as can be seen in Figure 2. Regarding a possible change in regional climate (precipitation sum and mean temperature during the growing season from May to September) as a result of global climate change, a decreasing trend in precipitation and an increasing trend in temperature can be identified (Figure 2 [39,40]). Extreme years with low precipitation amounts and high temperatures, such as in 2003, 2015 and 2018, seem to occur with increasing frequency and intensity over the course of the time period from 1997 to 2020 [12,38]. In addition, years with higher precipitation amounts and lower temperatures, such as 2007, 2010 and 2017, can also be found in this period. During the selected time period, these climate parameters have also shown an increase in variation with time. These findings are strong indicators of ongoing climate change.

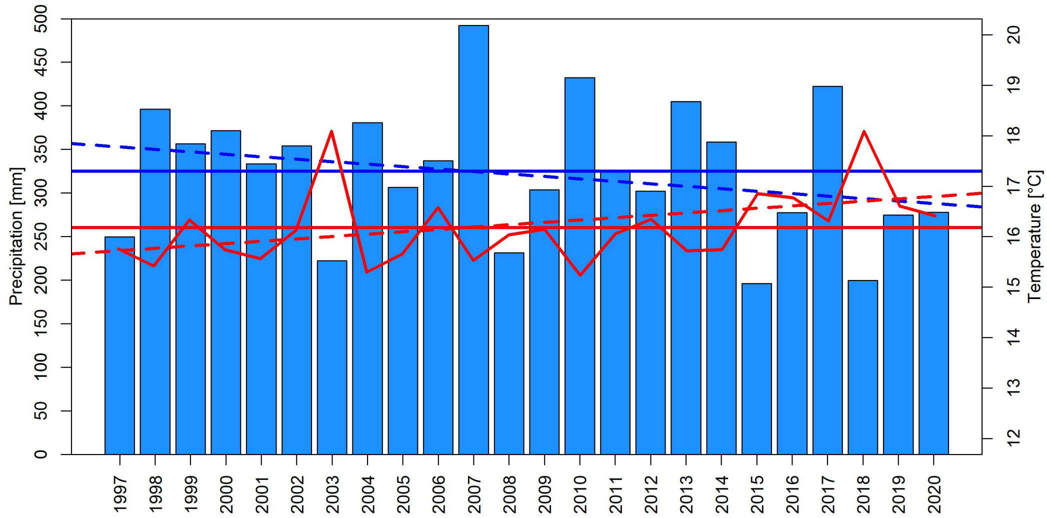

Figure 2. Precipitation sum and mean temperature for the growing season of maize (May to September) in the considered Central European study area of Northern Bavaria. The blue horizontal line shows the mean precipitation sum during the growing season over the time period and the red horizontal line shows the mean temperature over the time period. The dashed lines show the linear trend in precipitation and temperature (trends calculated following [39,40]). Data source: [41].

2.2. The Hydro-Agroecological Model PROMET

The hydro-agroecological simulation model PROMET (Process of Radiation, Mass and Energy Transfer [42–44]) was used in this study. It simulates the energy and matter (water, nitrogen) balance of the land surface and uses a mechanistic crop growth model component based on the Farquhar et al. [45] and Ball–Berry approach [46]. PROMET can simulate plant growth depending on current local weather and environmental conditions [47], as well as take into account agricultural management practices, such as sowing date and irrigation [42]. Since PROMET is an integrated, physically- and physiology-based model with a comprehensive parametrization of crops differentiating between the C_3 and C_4 metabolism of plants [42,48–51], calibration with observed yield data was not conducted. More details about the implementation of the Farquhar et al. [45] approach for C_3 photosynthesis, the Chen et al. [52] approach for C_4 plants and the extrapolation from leaf scale to canopy level within the PROMET model are described by Hank [49]. PROMET has successfully been used in many studies, from a field to a global scale, and has parameterizations for 16 different crop types, with and without the assimilation of remote-sensing-derived parameters, as well as taking into account both recent and future climate change [42,47,53–55].

2.2.1. Determination of Irrigation Requirement

PROMET allows for the demand-driven irrigation of crops. Crop water demand is simulated as the result of photosynthesis and the related CO_2 uptake, which determines the stomatal conductance. Photosynthesis in turn is connected to the plant's water uptake through the Ball–Berry formulation of Rubisco activity [46,49]. Plant water stress is expressed through a soil-suction-dependent water stress factor (0–1), which modifies the Ball–Berry coefficient [49,56]. Irrigation is initiated when a plant's water stress induced by increasing soil suction falls below a threshold value [46]. The reaction of the plant to water stress is simulated by a decrease in stomatal conductivity as a result of increasing soil suction. It is described by the factor GFAC, which can have values from zero to one. Stomatal conductivity not limited by soil suction (GFAC = 1) is reached when soil moisture is close to field capacity; GFAC = 0 describes stomatal conductivity at the wilting point [49]. Demand-driven irrigation is initiated in our approach at a GFAC value of 0.95. When this value is reached, the soil water extraction for that day is determined, and compensated at rates which can be chosen from 10 to 300%, which practically means a threefold overcompensation. Overcompensation allows for the realistic mimicking of sprinkler irrigation practice, which aims to minimize irrigation water losses through the unproductive canopy interception of irrigation water. This is achieved through minimizing the number of irrigation events and, at the same time, not saturating the soil, which would lead to irrigation water waste through percolation. PROMET thereby offers a comprehensive approach to determine plant water demand and does not simply compensate for the water deficit by restoring field capacity. We assumed sprinkler irrigation for all the irrigated scenarios within this study at an overcompensation rate of 300%. Since farmers usually do not know about the soil water deficit or the actual water demand, they can only make educated assumptions about the amount of water that has to be applied to the field. Therefore, this approach corresponds well to the irrigation practices of farmers in Bavaria [57].

2.2.2. The PROMET Concepts of Phenology Cultivar Factor and Nutrient Factor

Crop growth and yield formation are controlled by environmental factors. Maize is a C_4 plant and, therefore, its growth hardly depends on CO_2 concentration in the atmosphere, but is particularly dependent on temperature and water supply. Warmer temperatures have an accelerating effect on the development of maize hybrids, especially when they are adapted to temperate climates [14,15,25,58,59]. In PROMET, the duration of phenology is controlled by the phenology cultivar factor (PCF), which has a value between 0.5 and 1.5. The cultivar factor in essence decelerates or accelerates the phenological development with a progressing temperature sum. Although different cultivars of the same crop differ in many factors, in this paper we limit to the rate at which phenological development takes place. This is the major factor that distinguishes maize cultivars and which has enabled the adaption of maize cultivars to almost all climate zones. A PCF of 1.0 means that phenological development and biomass accumulation are timed in such a way that the plant can utilize the full available growing period to maximize yield in a given climate. Values of the factor lower than 1.0 result in a slower development, which may prevent a chosen cultivar from reaching maturity and harvest. Conversely, values higher than 1.0 lead to an acceleration of development, which may lead to early maturity and reduced yield through a waste of energy capture towards the end of the growing season. Four separate values of PCF can be chosen in PROMET for different growth periods. They can specifically be applied to fine-tune the acceleration or deceleration of plant development during different phenological stages. Table 1 shows which phenological phase each factor refers to. By setting these factors, PROMET also enables the systematic simulation of different hypothetical varieties that might be better adapted to changing climate conditions.

Table 1. Phenological phases according to the German BBCH scale [60] to code the phenological growth stages of maize, to which the four phenology cultivar factors (PCF) and nutrient factors (NF) refer.

PCF/NF	Phenological Phase
1	Emergence to leaf development (BBCH 0–1)
2	Sideshoot development to harvestable vegetative parts (BBCH 3)
3	Inflorescence to fruit development (BBCH 5–7)
4	Maturity (BBCH 8)

A second main aspect for controlling plant growth within PROMET is the nutrient factor (NF), which determines nutrient availability to the plant. We assume that the nutrient availability for the plant is mainly determined by the amount and type of fertilizer applied and by the provision of plant-available fertilizer, which is mobilized from the N-pools in the soil. This mainly depends, for a given soil, on soil temperature and moisture, which in turn depend on climate variables. The ratio between the available fertilizer in the soil and the time-dependent demand of the plant for fertilizer determines, in PROMET, the nitrogen concentration in the plant's leaves, which in turn controls the establishment of RUBISCO and chlorophyll, which in turn determines, to a large extent, plant photosynthesis. Here again, four values for the different phenological phases can be set (Table 1). The NF has a value range from zero to one, where zero means a very low nutrient availability and one means a nutrient availability that satisfies the plant's nutrient demand at any time and, thereby, no nutrient limitation to photosynthesis and development exists. We set the same value of nutrient availability for all phenological stages and varied NF over the years, depending on the scenario (for more details see Section 2.3).

2.3. Conceptual Framework of the Study

All the PROMET simulations were carried out in a spatially distributed way, covering the study region with a spatial resolution of one kilometer. Since maize, because of crop rotation, is not grown on the same fields every year, the maize fields in the study region were statistically distributed with a random generator, which was fed with the local, village-based areal statistics for maize in the study region. This distributed the simulated maize pixels on a 1 × 1 km grid to the locations in the study region, where maize is actually grown and, hence, where the environmental conditions for growing maize are representative for the statistical yield data [27,28]. The PROMET simulations were driven by interpolated meteorological data from the German Weather Service station network and conducted hourly to realistically cover stress factors, such as temperature, water shortage or frost, which can vary strongly both geographically and during the course of the day, and at the same time can have a major impact on crop growth. We considered a 24-year time period from 1997 to 2020 for which high quality yield statistics are available. The conceptual approach is shown in Figure 3. In order to reconstruct, in the best possible way, the temporal evolution of the observed yields in the 24-year record of the county statistics, we assumed that recent climate change, nutrients availability, irrigation and cultivar selection are the main, temporally variable factors influencing plant growth and yield formation. Therefore, systematic simulation runs regarding these factors were conducted. The spatially distributed input parameters for the simulations with PROMET are shown in Table 2.

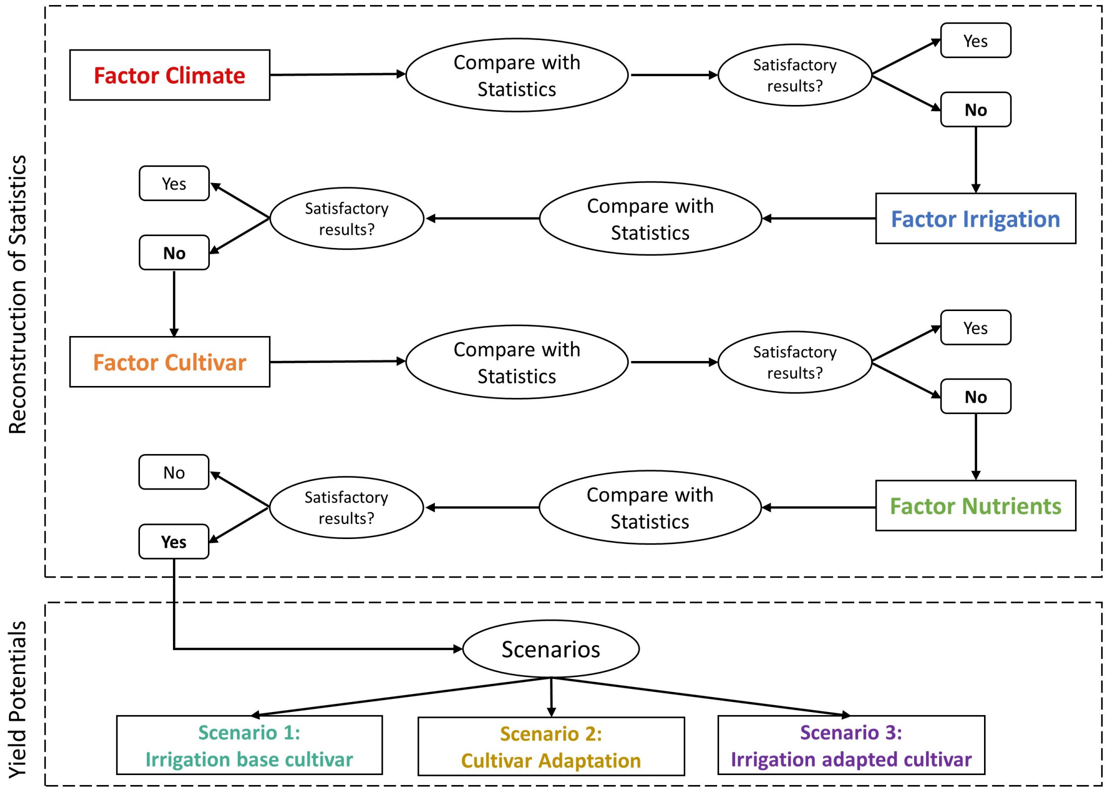

Figure 3. Flow chart depicting the conceptual framework of the model study.

Table 2. Spatially distributed input parameters for the simulation runs with PROMET.

Data	Description	Data Sources
DWD Climate Data	Hourly meteorological station data	Deutscher Wetterdienst (DWD [41])
Digital Elevation Model (DEM)	Spatial resolution of 1000 m	Bundesamt für Kartographie und Geodäsie (BKG [61])
SoilGrids	Global data set at 250 m spatial resolution	Hengl et al. [62]
Land Use	- CORINE land use information at 100 m spatial resolution - EUROSTAT farm land use NUTS-3 regions	- European Union (EU), Copernicus Land Monitoring Service 2018, European Environment Agency (EEA [35]) - European Union (EU), EUROSTAT [63]

First, we considered the factor of recent climate change and assumed no change over the years in management options, such as nutrient availability (NF = 0.5), cultivar choice (PCF = 1.0) and irrigation (no irrigation). This enabled a simulation of yields that only depends on the actual climate and its change over time, without the influence of possible changes in management practices (irrigation), nutrient availability or cultivar change. This allows us to answer the question of whether recent climate change alone can explain the observed increase in maize yield in the region.

In the second set of simulations, we investigated whether the gradual introduction of the irrigation of maize in the region (there are currently no statistics on the irrigation of maize available for the region) could explain the historical development of the yield statistics in the study region. Therefore, we simulated the impact of hypothetical supplemental irrigation on yields in situations when and where plants suffered from moderate to extreme water stress. In this simulation run, we kept nutrient availability and cultivar choice constant over time (NF = 0.5 and PCF = 1.0). The assumption behind the introduction of irrigation into the simulations was based on the decreasing trend in the precipitation amount during the growing season, the increasing interannual variability in precipitation amounts and the question of whether non-controlled irrigation activities carried out by farmers to compensate for water deficits, which are not documented in the statistics, could explain the temporal evolution in yield statistics. Since maize growth is strongly dependent on a sufficient water supply, supplemental irrigation was the first management practice considered in our approach.

In the third set of simulations we considered, in addition to the recent climate change signals, the influence of a possible annual trend in cultivar selection on yield. The rationale behind this assumption was that an increase in air temperature, as can be seen in the annual course of mean temperature during the growing season (Figure 2), would lead to an increase in the phenological development rate which would lead, in turn for a given cultivar, to a reduced time between sowing and harvest. For a given cultivar, this may lead to the sub-optimal use of temperature and radiation for growth and yield formation. By choosing a slower cultivar, this misalignment between increasing temperatures due to climate development and a given cultivar could be compensated for. Therefore, the PCF value was continuously decreased in the simulations for the time period between 1997 and 2020, from 1.1 to 0.9. The NF value was kept constant at 0.5 and no irrigation was assumed. The annual decrease in the PCF value was intended to mimic farmers' possible decisions as an adaptation to their perception of recent climate change in the region; therefore, cultivar selection was the second management practice considered in our approach in order to explain the observed yield increase.

In the fourth set of simulations we considered, in addition to the recent climate change signals, the influence of a possible annual trend in nutrient availability on yield. Fertilizer sales in the region have stagnated over the past 25 years with a clear tendency of a decrease recently due to EU regulations [64]. Therefore, a change in nutrient availability may not be caused by an increase in the amount of fertilizer applied over the past 24 years. We rather hypothesized that increased mineralization rates of the existing soil nitrogen pools, due to increasing soil temperature, led to increasing plant nutrient availability. To consider this in the simulations, we continuously increased NF from 0.45 in 1997 to 0.6 in 2020 and, at the same time, kept PCF constant over time with a value of 1.0. The selection for the value range of NF was based on the findings of previous simulation results. In the simulation run regarding the factor of climate, we could reproduce the mean yield of the time period with an NF value of 0.5. Since the results obtained with the observed climate data and with this time-invariant parametrization had a poor correlation with observed yields, but could reproduce the average yields over the selected time period (see results section), we introduced a trend in NF by continuously increasing its value from 0.45 to 0.6. These values were determined through a sensitivity analysis around the value of 0.5. In addition, we assumed rainfed agriculture because the large-scale irrigation of maize is currently not the common practice in Bavarian agriculture. With this approach we could identify the combined influence of recent climate change and nutrient availability on recent maize yields and account for the yield potentials arising from increasing temperatures.

In order to investigate the potentials of a hypothetical increase in actual yield levels during the last 24 years, we simulated three scenarios based on the model setup of factor nutrients. We assumed the maize parametrization in this model setup as the base cultivar and calculated percent changes in yield due to the three scenarios. The three scenarios were (1) irrigation of the base cultivar, (2) cultivar adaptation and (3) irrigation of the adapted cultivar (Figure 3). The first scenario allowed us to determine the degree at which supplemental irrigation could have already in the past increased yields and whether this showed an increasing temporal trend towards the recent past. For the second scenario, we assumed a cultivar that has a prolonged duration of the reproductive phenological stages (PCF values 3 and 4 set to 0.8) and thus can make better use of the energy that is increasingly available in the course of past warming (adapted cultivar). In order to additionally account for changes in precipitation patterns in the course of recent climate change, we simulated as a third scenario irrigation of the adapted cultivar.

3. Results

3.1. Reconstruction of Yield Statistics

The aggregated yield statistics for the counties in the study area show an increasing trend with time, with a linear increase in yield of 16.1% (1.26 t/ha) in the period between 1997 and 2020 (Figure 4). The interannual yield variability is mainly determined by the annual course of the weather. Statistics show lower yields in years with low precipitation and high temperatures, such as in 2003, 2015 and 2018 (climate conditions in Figure 2 and course of statistical yield in Figure 4). Besides a rising trend, the course of the yield statistics also shows an increasing interannual variability during the last ten years of the considered time period (Figure 4).

Regarding the factor climate (see Figure 3) in the simulation runs (red line in Figure 4), yields at the beginning of the timeline are simulated too high and they decrease over time with a linear trend of 15.9% (1.52 t/ha). The comparison with yield statistics shows an R^2 value of 0.24 and, therefore, the agreement between the simulated yields and the statistical yields is low (Figure 4). The plant growth simulation dependent on climate conditions only is not able to reconstruct the multi-decadal increase or the actual yield levels in each year. The change in temperature and precipitation patterns in the last 24 years does not lead to an increase in the simulated yields as would be expected in the course of warming and the opportunity to accumulate more energy for plant growth. Our results suggest that the given climate conditions, as well as their recent changes over time, are not responsible for the observed yield development in Northern Bavaria and, therefore, the factor climate does not enable the reconstruction of yield statistics.

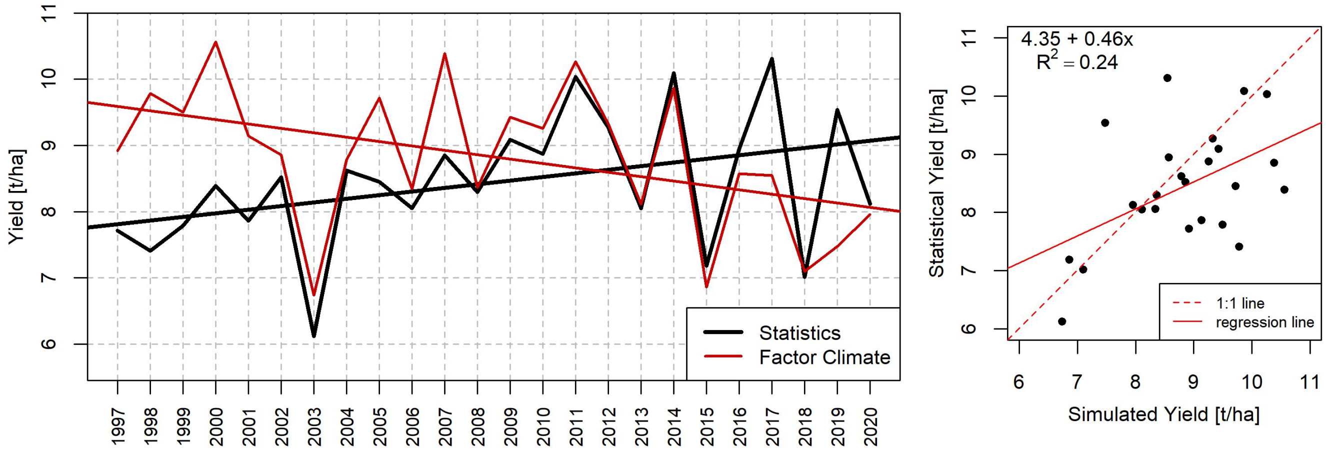

Figure 4. The timeline on the left side shows statistical yields (black line) and simulated yields depending on climate and its change over time (factor climate in Figure 3, red line). Linear trend lines have the same colors as underlying course of yields. On the right side, the linear regression between statistical yields and simulated yields is shown with slope, intercept and coefficient of determination (R^2).

Under the assumption of fully irrigated current maize cultivars in Northern Bavaria (factor irrigation in Figure 3), the annual course of yields follows the blue line in Figure 5. Similar to the rainfed simulation of plant growth dependent on climate conditions (Figure 4), yields in the beginning of the time period are overestimated by the simulation results and they decrease over time with a linear trend of 10.6% (1.02 t/ha). In contrast to the rainfed simulation, irrigation in dry years prevents the strong yield decreases that are seen both in the rainfed simulation and the statistics (e.g., 2015 and 2018, Figure 4). Nevertheless, the agreement between the statistics and this simulation is still low, with an R^2 value of 0.21 (Figure 5). This suggests that irrigation played a minor role in the past years, as already expected, and had no contribution to the observed upward trend in yield.

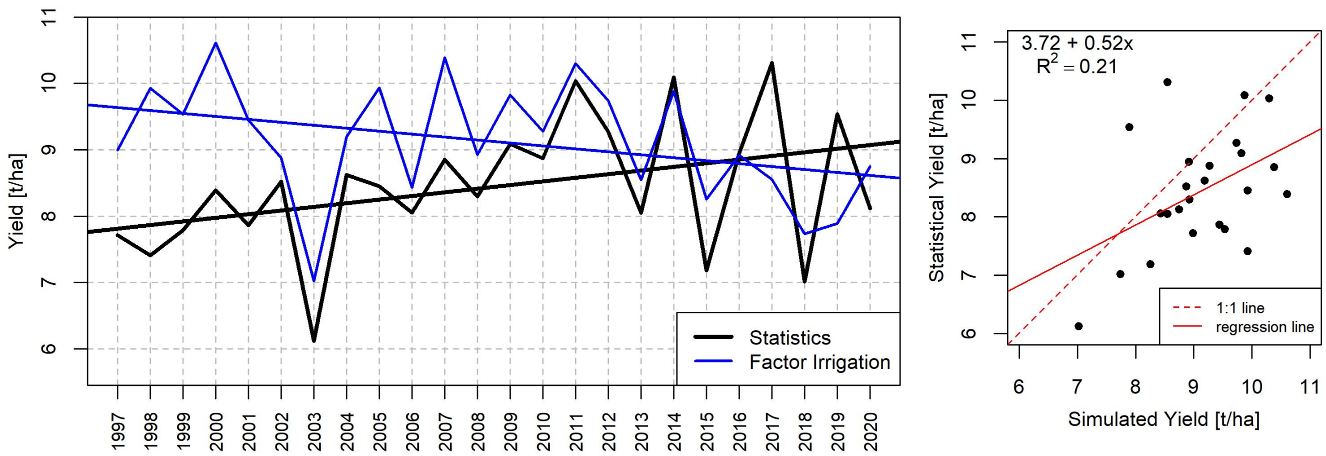

Figure 5. The timeline on the left side shows statistical yields (black line) and simulated yields depending on the assumption of supplemental irrigation in the region (factor irrigation in Figure 3, blue line). Linear trend lines have the same colors as underlying course of yields. On the right side, the linear regression between statistical yields and simulated yields is shown with slope, intercept and coefficient of determination (R^2).

The yield simulation with varying cultivars each year (factor cultivar in Figure 3) leads to a slight but marked improvement in the correlation with the statistics. The R^2 value increases to 0.57, but the simulated yields are still overestimated in the beginning of the time period and they decrease with time with a linear trend of 3.3% (0.3 t/ha, Figure 6). Decelerating phenological development in the course of warming would mean a longer growing period and accumulation of energy and, therefore, an increase in yields. However, the decreasing trend in the simulation results (Figure 6) shows that this aspect alone only partially explains the observed rising trend in yields.

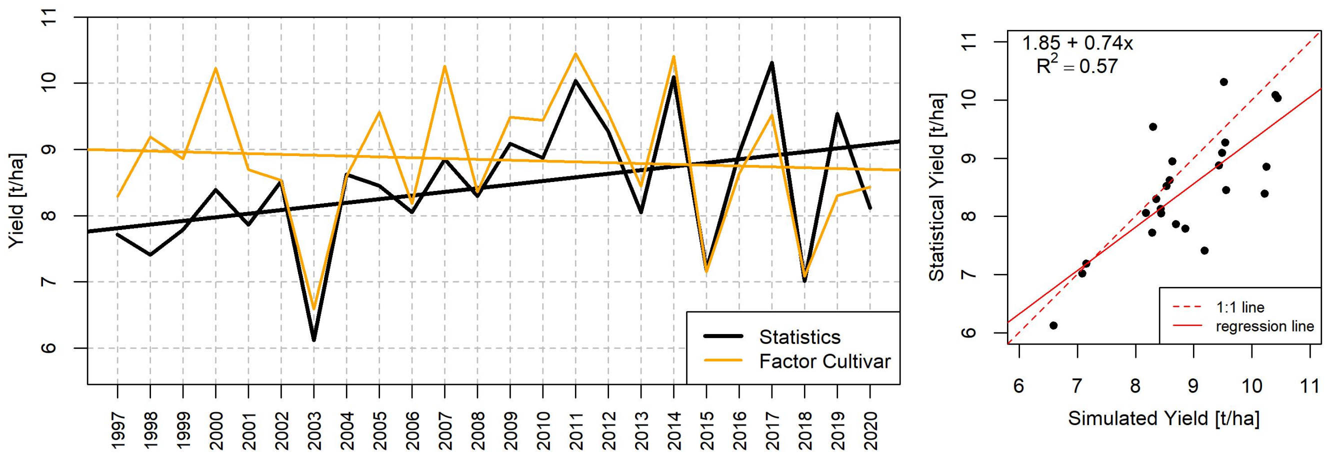

Figure 6. The timeline on the left side shows statistical yields (black line) and simulated yields depending on hypothetical cultivar adaptation by farmers (factor cultivar in Figure 3, orange line). Linear trend lines have the same colors as underlying course of yields. On the right side, the linear regression between statistical yields and simulated yields is shown with slope, intercept and coefficient of determination (R^2).

A further main factor in agriculture is nutrient supply. Nutrients through fertilization can only be taken up by the plants when they are mineralized. Mineralization is dependent on soil temperature and soil water. In the course of an increase in air temperature, soil temperatures also increase, but not necessarily in the same manner and magnitude. This can be seen when looking at the simulated soil temperatures in Figure 7and comparing them with the course of air temperature in Figure 2. The assumed constantly rising trend in nutrient availability in the simulation (factor nutrients in Figure 3) suggests that an enhanced nutrient uptake by plants due to higher nutrient availability contributes to the rising trend in yields. The results show a linear rising trend of 13% (1.07 t/ha) and an R^2 value of 0.76 (Figure 8). Moreover, PROMET is able to reproduce the interannual variability with a high consistency to the statistical data. The good agreement between the results of this simulation and statistics means that increasing nutrient availability can explain most of the rising trend in observed yields. It also qualifies this model's setup for further scenario simulations. A decreasing trend in the simulated soil moisture, depicted in Figure 9 (black line), suggests that there is, besides the positive effect of temperature, also a negative effect on mineralization. However, the simulated soil moisture also shows that moisture conditions can be divided into two collectives, with wet (around 18–20 vol.-%, blue line in Figure 9) and dry years (around 15 vol.-%, red line in Figure 9). The soil moisture of dry and wet years does not seem to show a temporal trend in Figure 9, which makes the overall decreasing trend over the simulation period a result of the more frequent occurrence of dry years in the recent past. Due to the slower reaction of the soil to air temperature than to precipitation, the limitation of mineralization is low when single rainfall events occur. Therefore, an increase in nutrient availability can be assumed due to an increase in soil temperatures, despite the decreasing simulated average soil moisture in the study region.

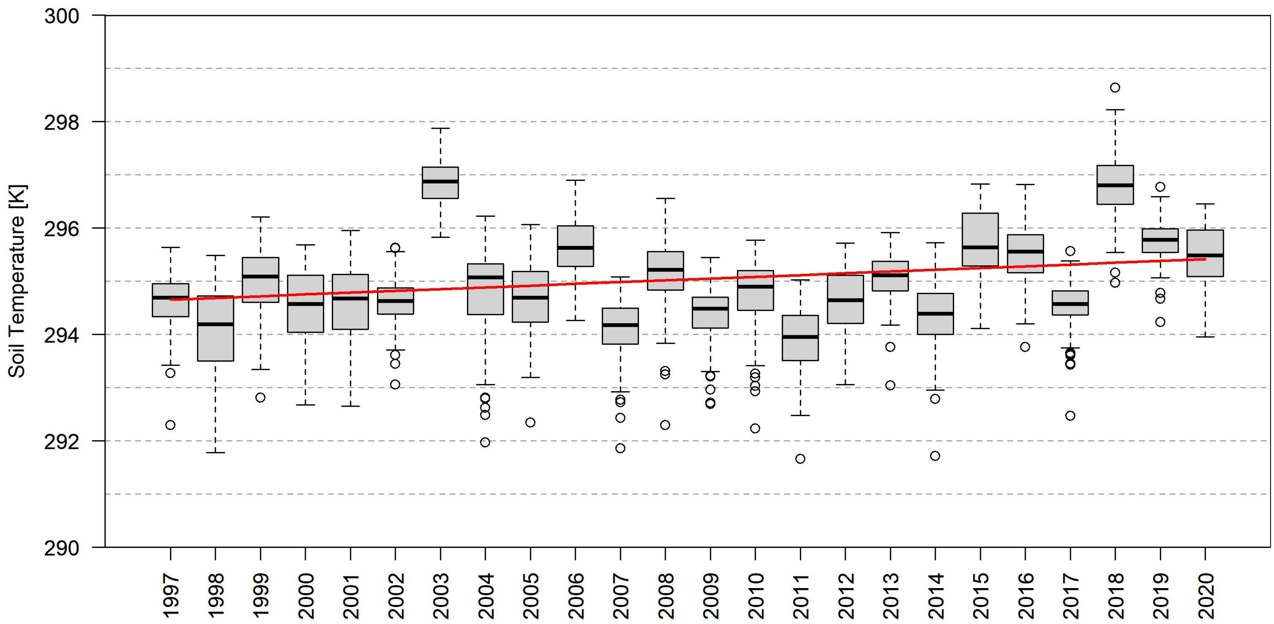

Figure 7. Simulated soil temperatures of the uppermost soil layer in agriculturally used areas for maize in the study region. Red line shows the rising trend in soil temperature.

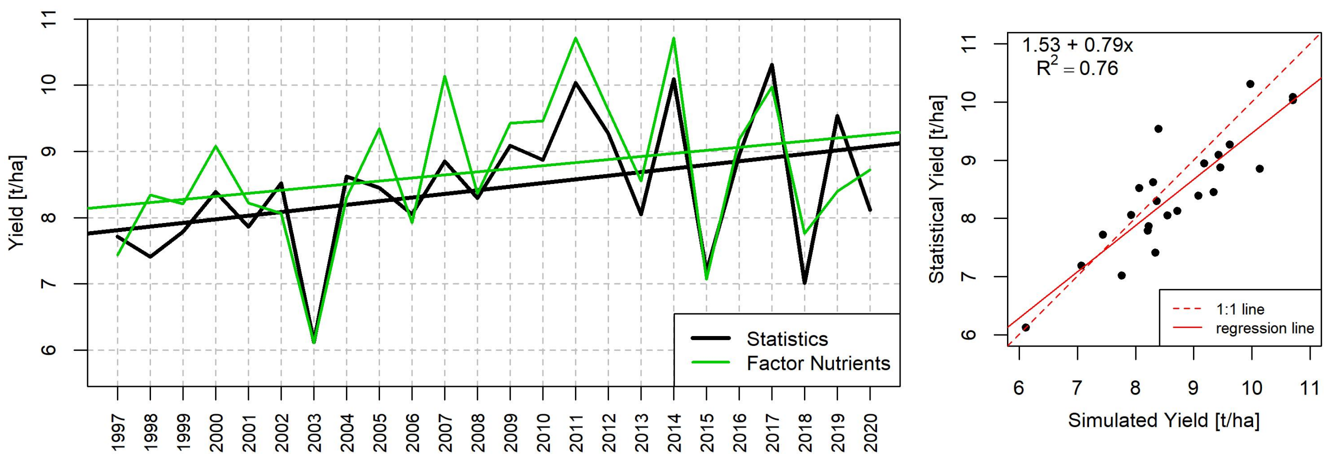

Figure 8. The timeline on the left side shows statistical yields (black line) and simulated yields depending on the assumption of an increase in nutrient availability (factor nutrients in Figure 3, green line). Linear trend lines have the same colors as underlying course of yields. On the right side, the linear regression between statistical yields and simulated yields is shown with slope, intercept and coefficient of determination (R^2).

3.2. Recent Yield Increase Potentials in Northern Bavaria

The considered scenarios to simulate yield potentials defined in Section 2.3 and Figure 3 lead to different levels of increase in the yield. The percent changes in yield due to each scenario are shown in Figure 10. In the course of changing precipitation amounts, the response pattern to irrigation (scenario 1) is low in the beginning of the considered time period and it rises with time. The simulated irrigation water demand of maize ranged from 5 to 35 mm per season during the considered time period (green line in Figure 10). Especially in dry years, such as 2015, 2018 and 2020, plants have a high irrigation demand and the response of plant growth and yield to irrigation is accordingly high. The rising trend in yield change due to irrigation, as well as the increasing interannual variability, are in line with the observed changes in precipitation amounts during the growing season (Figure 2).

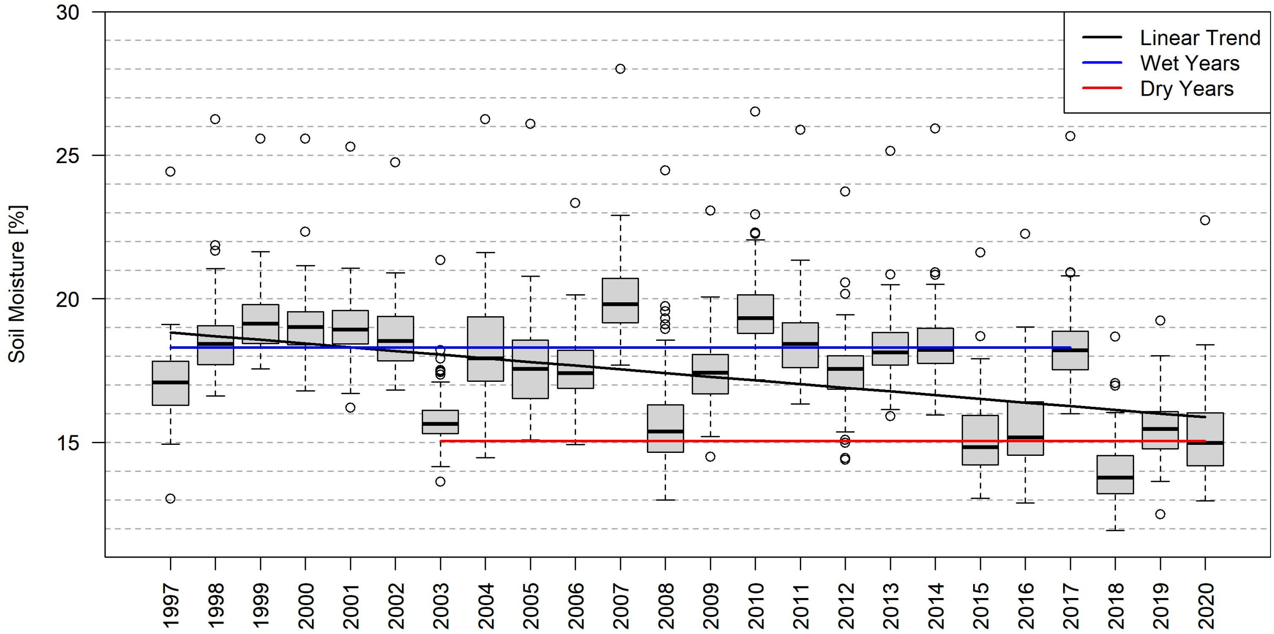

Figure 9. Simulated soil moisture of the uppermost soil layer in agriculturally used areas for maize in the study region. The black line shows the linear trend in soil moisture, the blue line indicates the wet years and the red line indicates the dry years.

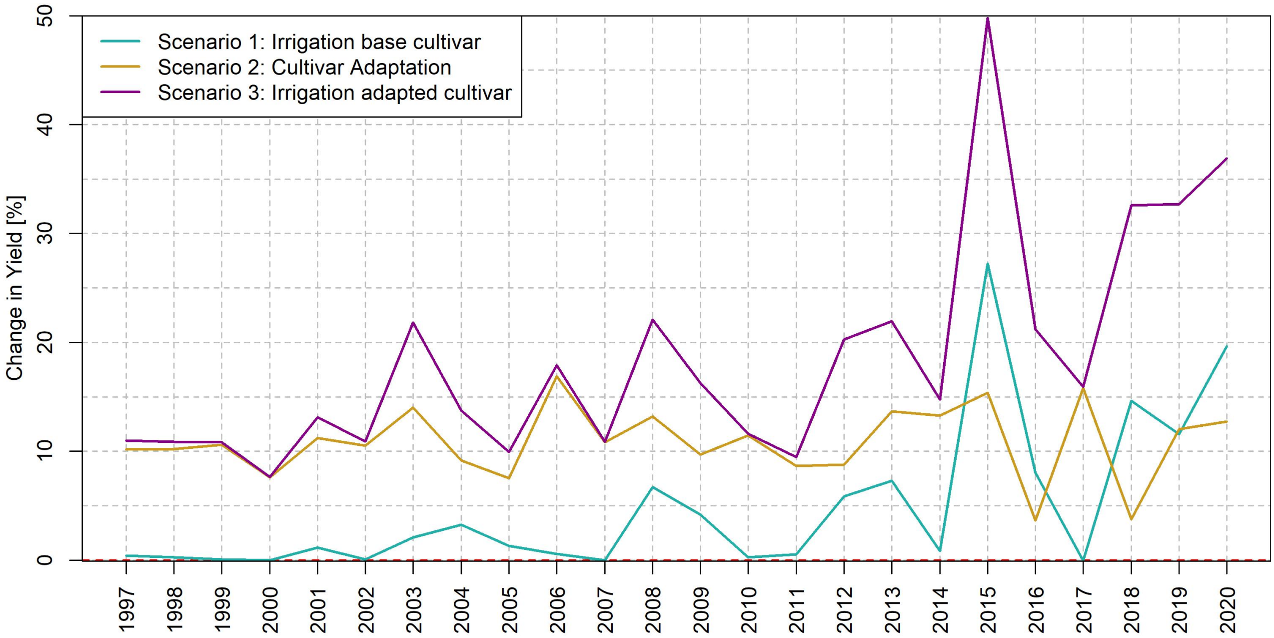

Figure 10. Percent changes in yield due to irrigation of the base cultivar, cultivar adaptation and irrigation of adapted cultivar related to the absolute yields of the rainfed base cultivar (factor nutrients).

The adaptation of the cultivar leads to an almost constant increase in yield throughout the whole time period (scenario 2, Figure 10). Towards the end of the considered time period the interannual variability becomes larger, suggesting that changes over time in temperature and precipitation patterns add variability to the response to cultivar adaptation.

When irrigation is applied to the adapted cultivar (scenario 3, Figure 10), the increase in yield at the beginning of the time period is as high as the increase due to rainfed cultivar adaptation. Over time, the increase in yield due to irrigation of the adapted cultivar rises similarly to the yield change due to irrigation of the base cultivar, but at a higher level. The interannual dynamic is determined by irrigation rather than cultivar adaptation, but the adapted cultivar enhances the level of increase. This shows that the relative irrigation demand and, therefore, the relative change in yield due to irrigation does not change significantly between the cultivars. In years with high precipitation amounts, such as 2007 and 2017, the increase in yield is mainly due to cultivar adaptation, whereas in dry and hot years, such as 2015, irrigation and cultivar adaptation in combination have a high potential for an increase in yield.

4. Discussion

Our study shows that the reconstruction of statistical yield trends and levels is possible with an uncalibrated mechanistical crop growth model, if the second-order effects of recent climate change are taken into account. We achieved a good agreement between the simulated and statistical maize yields and their temporal trends by assuming in the simulations that the increase in soil temperature associated with recent climate change enhanced soil nutrient availability during the last 24 years. Our simulation approach was to gradually increase the nutrient availability parameter in the model with time, and thereby dynamically consider the changing growth conditions of maize. This was the only one of the four tested assumptions that allowed us to reproduce the observed yields. To our knowledge this is the first study available for maize which attempts to reconstruct long-term statistical yield trends on a regional scale, while taking into account dynamic developments in recent second-order climate change effects, such as soil temperature and nutrient availability. Other studies have simulated crop yields with good correlation coefficients as well, but the underlying models were dependent on a site-specific calibration with data from controlled field experiments covering a time span of two to four years, e.g., the CERES-Maize model, whereas PROMET simulated good results without site-specific calibration and for a longer time period [26,65]. On a global scale, Yin and Leng [66] have modeled decades of maize yields with several process-based models; however, the model's performance in reproducing observed yield levels and trends was low. Discrepancies in our results between the modeled and statistical yields, especially the overestimation of yields by the model and the higher interannual variability in the simulation results, may mainly be explained by the influence of pests and diseases or unknown agricultural management practices that are reflected in the statistics but cannot be caught by the model's parametrization. Regarding the fact that PROMET was not calibrated with the measured data, the size and diversity of the simulated area and the unknown management practices conducted by local farmers, we consider our simulation results quite encouraging.

4.1. Recent Climate Change Factors and their Contribution to Explaining Observed Yield Trends

When solely considering the changing climate of the last 24 years (factor climate in Figure 3), supplement irrigation (factor irrigation in Figure 3) or cultivar adaptation (factor cultivar in Figure 3), each factor alone results in decreasing simulated yields of maize in Northern Bavaria, which is contradictory to the statistics. Since climate is the main driver of plant growth, many studies have investigated the impact of climate change on yield and found that multi-decadal changes in yield and yield variability can be mainly attributed to changes in climate conditions [67–69]. Depending on the considered study region and time period, the studies found that recent climate changes, and especially increasing air temperatures, are the cause for either an increase or a decrease in observed maize yields [66,70]. To our knowledge, none of these studies considered the secondary effects induced by recent climate change. Our simulation results show that a changing climate with an increase in air temperature and altered rainfall patterns alone cannot explain the measured increase in maize yields in the selected region. Climate change affects the growing conditions of agricultural plants in a broader way, which includes both secondary climate change effects, such as changes in soil temperature and moisture, and farmers' adaptation strategies, such as introducing irrigation or adapting cultivars. An increase in air temperature causes a decrease in the length of the growing period of maize due to accelerated phenological development, altered rainfall patterns may lead to an increase in water stress and changes in climate conditions may increase the difference between nutrient availability and demand. Thus, overall growing conditions may be altered in different ways by changes in climate, which strongly depend on the regional geographical setting. The simulation results show that it is important to also take the secondary effects of recent climate change, such as changing nutrient availability or cultivar adaptation, into account in order to understand the observed yield development. A model study using a coupled mechanistic crop growth model allowed us to study these secondary effects on yield development separately and to quantify the potential of each factor for explaining the observed yield development. What has become obvious throughout the analysis of the systematic simulations is that any static simulation approach, which assumes a constant set of plant or soil parameters throughout the simulation period, fails to explain the observed yield development in Northern Bavaria. Rather, a simulation approach, which as a first step dynamically took into account the steadily increasing nutrient availability associated with the increasing soil temperatures, was superior in reproducing the observed yield increases. The mitigation of decreasing yield trends through enhanced rates of nutrient availability was also found in a model study by Lopez et al. [71]. Fertilization is a major aspect of the supply of nutrients to plants. As a result of EU regulations and German legislation, fertilizer inputs were caped during recent decades to reduce groundwater pollution and atmospheric emissions, so that a constant or even decreasing fertilizer input can be assumed for maize fields in the region. However, besides fertilization, nutrients can also be provided to plants from already existing nitrogen pools that are increasingly mobilized by higher mineralization rates in the course of warming [21,72]. Nevertheless, in this first analysis we did not consider soil properties or soil management, which have a huge influence on nutrient availability and mineralization rates [73]. We rather considered the influence of recent climate trends on soil temperature, and thereby on mineralization rates [74], and showed that the secondary effects of recent climate change on maize yields in the region may be as large in magnitude or even larger than the direct effects, such as increasing temperatures or changes in precipitation patterns.

4.2. Adaptation Measures in Northern Bavarian Agriculture

Besides a rising trend, the course of the yield statistics also shows an increasing interannual variability during the last ten years of the considered time period. This may be a first indicator that more variable weather conditions, a postulated consequence of climate change [75], already show up in recent agricultural statistics and give an early hint for future periods, which will call for profound adaptation measures in agriculture [76]. The temporal change in the simulated yield response to hypothetical supplemental irrigation supports the assumption that irrigation might play an increasingly important role as time progresses and precipitation patterns change, or even rainfall amounts decrease during the growing season in the semi-humid region of Northern Bavaria. However, the results also show a high uncertainty about the benefits of irrigation in the recent past. Under recent climate change trends, the introduction of costly irrigation infrastructure is not realistic for the small, simulated supplemental irrigation water demand and the instability of the interannual weather patterns, which make investments in irrigation equipment unreliable [57]. In addition, several studies underpin the importance of phenological development, especially a prolongation of the reproductive stages of maize growth, in the course of progressing warming [77,78]. In particular, they point out that an integrated adaptation effort in agriculture, which combines irrigation, fertilization and a selection of cultivars that can better cover the observed prolonged growing season, has to be considered in order to ensure future yields and food security. Nevertheless, it is not at all clear from this first study, which relies on recent meteorological drivers, to what extent adaptation measures will be effective in the region under future climate change conditions. Saturation effects could set in or feedbacks, such as an early emptying of the soil water storage, could potentially also show strong negative effects on future yields. To assess the possible benefits and adverse effects of adaptation measures in the future, further investigations have to be conducted. They should be based on simulations which use available outputs of climate change scenario runs of regional climate models (e.g., climate projection data from the CORDEX initiative). The simulations, in order to be most realistic, should incorporate secondary effects on the growth conditions of maize and should be conducted without a calibration with past data, which in a strict sense may not be valid for future periods.

5. Conclusions

This model study shows that a reconstruction of a 24-year time series of observed statistical yields of a large area in Northern Bavaria can be conducted with good agreement, using a mechanistic and dynamic crop growth model without a site-specific calibration. The results highlight the importance of including in the simulations a dynamic consideration of recent climate-change-induced changes in plant growth conditions. Therefore, simulations of the impact of past as well as future climate change on yields should consider the secondary effects of climate change on growing conditions, namely nutrient and water availability as well as cultivar adaptation, to be as important as direct climate effects and research should be shifted towards this more holistic direction. It should be pointed out though, that all the findings of our study, specifically the effects of increased nutrient availability, are only valid for the time period and region under consideration. Due to the complex, nonlinear relations and feedbacks in dynamic growth models, the effects, especially the second-order effects, of a changing climate may vastly differ for different considered regions and with different (future) climate drivers. A recent yield increase could easily change into a future decrease by simply, e.g., reaching saturation of nutrient availability or by early depletion of soil water storage. Further research on the efficacy of future adaptation options (e.g., irrigation and cultivar adaptation) must be carried out for the region in order to further ensure the environmental and economic basis of its agriculture under conditions of climate change.

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