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Climate change impacts on two European crop rotations via an ensemble of models

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ABSTRACT

Continuous long-term simulations of an ensemble of nine crop models covering the 1961–2080 period was employed to assess the expected impacts of climate change on the crop yield and water use for distinct crop rotations (CRs) in Europe. In this study, the likelihood of changes in two differently managed CRs (conventional and alternative) involving four important field crops (winter wheat, spring barley, silage maize, and winter oilseed rape) was assessed. The conventional agricultural practice (CR1) included only mineral fertilization with the removal of crop residues after harvest. The alternative agricultural practice (CR2) included cover crops and the application of mineral and organic fertilizers, with crop residues retained in the field. The simulations covered six sites in five European countries (Mühldorf and Müncheberg in Germany, Ukkel in Belgium, Ødum in Denmark, Milhostov in Slovakia and Lednice in Czechia) based on two distinct soil profiles (universal soil and site-specific soils). The universal soil was the same across all the sites, while the site-specific soils were typical of each region. Eight transient climate change scenarios (4 general circulation models (GCMs) under representative concentration pathways (RCPs) 2.6 and 8.5) were used to capture the possible evolution of future climatic conditions. Compared with those during the 1962–1990 period, the ensemble projections for the 2051–2080 period indicated average increases in the annual yields of all crops of 0.7 t/ha (RCP 2.6) and 0.8 t/ha (PCP 8.5) under both CRs and soil types. Under most climate change scenarios, the crop model ensemble projections of the winter wheat and winter oilseed rape yield increases agreed for CR2 but not for CR1. For spring barley, the simulated increase was more sporadic, with no significant difference between CR1 and CR2. In regard to silage maize, the changes in the simulated yields depended on site-specific climatic conditions. If the same varieties were planted in the future, yield reductions would be expected, except at the Ødum site, where the silage maize growth conditions would remain satisfactory, regardless of the CR and soil type. The results indicated greater

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cover crop biomass production, which could affect the long-term soil water balance and groundwater replenishment. The crop model ensemble further indicated a greater spatial variability in the yield can be expected, which is likely caused by the expected increase in the air temperature and not by the expected increase, or even decrease, in the total precipitation and increases in the actual evapotranspiration under climate change at all sites. This trend was greater under CR2 and could affect the long-term soil water balance and soil regime in the case of rainfed agriculture.

1. Introduction

Over the last decade, evidence of the impacts of climate change, including increasing average temperatures and an increased frequency, intensity and duration of heat waves or extreme weather events, has been observed as part of the European climate (Ossó et al., 2011). For example, heat waves occurring in 2018 and 2019 led to record-breaking temperatures in France, Benelux and western Germany (Becker et al., 2022). Future climate scenarios suggest that adverse climatic conditions, such as drought, heat, and increased variability in precipitation and temperature, will occur more frequently (EEA, 2017; Spinoni et al., 2018; Ceglar et al., 2019; Pullens et al., 2019). Climate change has already affected agriculture, both positively and negatively, with different responses across Europe (Zhao et al., 2022). Without the inclusion of suitable adaptation or mitigation measures, a critical decline in crop yields could occur in the future (Biesbroek et al., 2010; Olesen et al., 2011; Trnka et al., 2011; Toreti et al., 2019; Agnolucci and De Lipsis, 2020; Stella et al., 2021). One adaptation measure is the implementation of suitable agricultural practices, such as intensification of the cropping cycle with the inclusion of intercrops and cover crops, irrigation, timing of field operations, fertilization regime and drought-tolerant cultivars, which may maintain or improve the yield and product quality by affecting the actual evapotranspiration, the amount of soil nutrients, soil fertility and crop sensitivity to climate change (e.g., Eitzinger et al. 2013, Nendel et al. 2014, and Zhao et al. 2022). In terms of the effects of climate change on cropping systems, adaptation measures can be assessed in several ways, e.g., via data obtained from field experiments (in situ), growth chamber experiments (in vitro), crop models (in silico), or questionnaire surveys or via the use of integrated assessment and farming system analysis (Reidsma et al., 2015; Rötter et al., 2015; Hlaváčová et al., 2018; Pohanková et al. 2022; Zhao et al., 2022). All the listed options exhibit advantages and disadvantages. Field and growth chamber experiments can provide valuable information, but they are expensive and time consuming, and the results may not be transferable to larger territorial units (Barklund et al., 2007; Lipavský et al., 2015). Therefore, crop models have increasingly been employed for evaluating adaptation measures, despite the simplified view of reality and the inability to consider all relevant impacts of climate change and adaptation options such as extreme weather events (floods, hailstorms) or diseases and pests (e.g., Challinor et al. 2014; Rodríguez et al. 2019, and Ruiz-Ramos et al. 2018). In most studies involving crop models, single-year simulations and single-crop assessments are generally conducted (Eitzinger et al., 2013; Hlavinka et al., 2015; Olesen et al., 2011; White et al., 2011; Webber et al., 2018), although long-term simulations via single-crop systems have been applied (e.g., Ozturk et al. 2017, 2018). However, to accurately simulate real-world conditions and correctly evaluate adaptation measures, crop rotations (CRs) should be simulated continuously to include carry-over effects related to changes in soil physical, chemical and biological conditions. To achieve more reliable simulations, a crop model ensemble rather than a single crop model should be adopted (Martre et al., 2015; Wallach et al., 2018). Therefore, the assessment of the impacts of climate change and adaptation and mitigation options under current and future climatic conditions requires continuous long-term simulations of CRs (Basso et al., 2015; Kollas et al., 2015; Ewert et al., 2015; Pohanková et al., 2022; Grados et al., 2024). This research is a follow-up study to that of Pohanková et al. (2022), in which only sites in Czechia were simulated.

The aim of this study was to assess the impacts of projected climate change on the crop yield and water use for two CRs representing conventional and alternative agricultural practices across Europe. In this study, continuous simulations of CRs from 1961–2080 at sites across Europe were conducted via an ensemble of crop models, and the agreement or uncertainty in the projected results was evaluated. Impacts were evaluated in terms of individual crops (winter wheat, silage maize, spring barley and winter oilseed rape) and the different CRs, with a focus on the yield and water balance for comparing soils and representative sites across Europe. The objective was thus to expand the study of Pohanková et al. (2022) to sites beyond Czechia to determine whether simulations under climate change projections depend on site conditions (climate factors and soils).

2. Materials and methods

2.1. Simulation scheme

A crop model ensemble (nine models) was applied across six experimental sites in five European countries (Mühldorf and Müncheberg in Germany, Ukkel in Belgium, Ødum in Denmark, Milhostov in Slovakia and Lednice in Czechia; Figs. 1 and 2). The models were run on the basis of eight climate change scenarios, two CRs (CR1 and CR2) including four important field crops (winter wheat - *Triticum aestivum*, spring barley - *Hordeum vulgare*, silage maize - *Zea mays*, and winter oilseed rape - *Brassica napus*) and two soil profiles (universal soil, namely, Cambisol/Luvisol, and site-specific soils). The simulation scheme is shown in Fig. 1.

2.2. Crop model ensemble

This study, which is focused on future production and water use, presents continuous long-term simulation results of an ensemble comprising nine crop models (Agricultural Production Systems sIMulator (APSIM), Cropping Systems simulation model (CROPSYST), Soil Plant Atmosphere System Model (DAISY) (2 versions), Decision Support System for Agrotechnology Transfer (DSSAT), Environmental Policy Integrated Climate (EPIC), HERMES, and Model of Nitrogen and Carbon dynamics in Agroecosystems (MONICA) (2 versions)). All nine crop models are multiyear, multicrop, cropping system simulation models with daily time steps developed to serve as analytical tools to study the effects of the interaction among climate, soil, and management on cropping system productivity. The most important soil and plant processes are modeled mechanistically to simulate yields in response to management with the projection of the long-term consequences of farming practices on soil properties (e.g., soil organic matter dynamics) (Abrahamsen and Hansen, 2000; Keating et al., 2003; Nendel et al., 2011; Stöckle et al., 2003). The models vary in complexity and the approach to simulating relevant processes. For example, the DAISY crop model is the only ensemble model in which the Richards equation is used to calculate the water balance (Richards, 1931; Pachepsky et al., 2003). However, when no measured retention curves are available, retention curves are calculated via HYdraulic Properties of European Soils (HYPRES) in this model (Wösten et al., 1999). The HERMES crop model was originally a simple tool for calculating the mineral nitrogen (N) content in soil (Kersebaum et al., 2007). However, it has been improved to simulate multiyear sowing practices, calculate evapotranspiration, and integrate various approaches to assess the impacts of increased atmospheric CO_2 concentrations on the growth, development, and production of field crops (Kersebaum et al., 2009). The main characteristics of the ensemble of crop models employed in this study are summarized in Table 1.

In the case of the DAISY crop model, the simulations were conducted by two modeling teams involving two versions. The newer version of the DAISY crop model contains parameterization changes and aims to simulate 2D processes, thereby reorganizing the handling of pesticides. In the case of MONICA, the simulations were performed by one team but with different model versions. Compared with previous versions, MONICA 2.0.0 mainly encompasses extensive bug fixes and code renovations, which ultimately required complete reparameterization of the crop parameters. Additional functionalities have not been added.

2.3. Experimental sites

The six experimental sites (with elevations ranging from 8 to 416 m above sea level (a.s.l.)) were chosen to represent different temperature and precipitation gradients of the European climate (Fig. 2, Table 2). The Mühldorf site in Bavaria, Germany, exhibits the highest annual precipitation of 855 mm and is located in the southernmost region at the highest altitude (416 m a. s. l) with an annual temperature of 8.6 °C. It represents the area with the largest amount of precipitation. The site with the second-highest precipitation is Ukkel in the Brussels region of Belgium. The northernmost and coldest site is Ødum in Denmark. Milhostov is located in a fertile area in southeastern Slovakia. Müncheberg occurs in Brandenburg, Germany, and is representative of the Western European continental climate. The last site is Lednice in South Moravia, Czechia, which represents a warm and relatively dry region with an annual temperature 9.9 °C and annual precipitation 527 mm.

2.4. Climate scenarios

Gradual climate change from 1961–2080 was captured by a set of eight transient climate scenarios based on four general circulation models (GCMs), namely, the Geophysical Fluid Dynamics Laboratory (GFDL), HadGEM2, Institute Pierre Simon Laplace (IPSL), and NorESM1 models, run under two representative concentration pathways (RCPs), namely, RCP 2.6 and RCP 8.5. These transient scenarios, which represent different development possibilities, were chosen to sample the uncertainty in the ensemble and are a prerequisite for capturing the gradual development in the simulation system, which is possible through uninterrupted CR simulations. Weather files were compiled as series for the 1961–2080 period and included daily solar radiation (MJ/m2/day), maximum and minimum air temperatures (°C), relative air humidity (%), 2-m wind speed (m/s), precipitation (mm) and annual CO_2 concentration at the beginning of each year (ppm). For winter crops the CO_2 concentration changes on January 1st. However, this will not induce a great break since CO_2 steps are relatively small and growing at that time was usually stopped due to low temperatures. Weather series (used as inputs for the crop simulations) representing transient climate change comprised measured weather data (1961–2010) appended by synthetic weather series (2011–2080) produced by the M&Rfi weather generator (WG; Dubrovský et al., 2004). The synthetic series are transient time series that account for the gradually increasing climate change signal. This was achieved by modifying the WG parameters for each year separately via the pattern scaling approach (Dubrovsky et al., 2005), in which the standardized change (= the change corresponding to a 1 K increase in the global mean temperature) was multiplied by the change in the global mean temperature modeled by the simple Model for the Assessment of Greenhouse gas-Induced Climate Change (MAGICC) (Harvey et al., 1997; Hulme et al., 2000; Hlavinka et al., 2015; Pohanková et al., 2022, 2024). Twenty simulations (labeled as 01–20) were conducted for each of the eight GCM × RCP combinations.

Two sets of meteorological files were produced, namely, a "no_snow" weather series, which is based on direct measurements and the results of a WG without considering the effect of snow cover on meteorological variables, and a "snow_assumed" weather series, which is based on the SnowMAUS model (Trnka et al., 2010) to obtain modified weather data so that the expected influence of snow cover can be accounted for. In the latter version of the weather series, when snow cover is expected, the temperature and precipitation (assuming snow cover formation and snow melting) are modified. If the crop model does not aim to simulate the effect of snow cover, the snow_assumed version of the input data is used. If the crop model can account for snow cover, the no_snow version is used.

The warmest and driest scenario entailed a combination of the HADGEM2-CC climate model and the RCP8.5 scenario. The coldest and wettest scenarios were obtained via the NorESM1 model under the RCP 2.6 scenario (in the case of temperature) and RCP 8.5 scenario (in the case of precipitation) (Fig. 3).

The differences in the air temperature and total precipitation between the 1961–1990 and 1981–2010 periods and the shifts in conditions under the individual GCM scenarios for each experimental site are

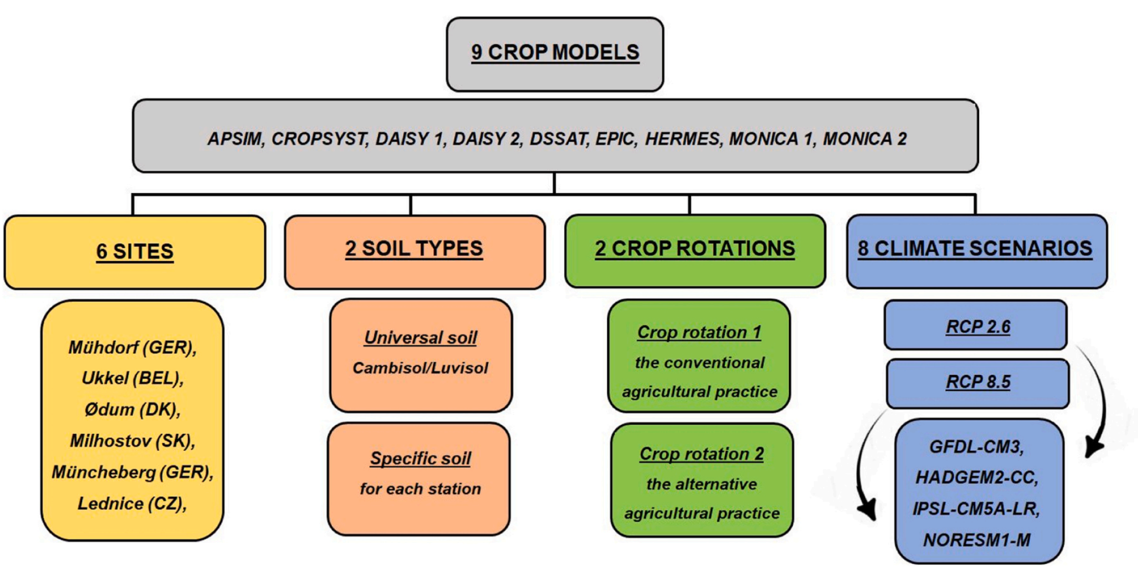


Fig. 1. Simulation scheme: Selected crop models, experimental sites, soil types, crop rotations and climate scenarios covering the 1961–2080 period.

shown in Fig. 4, A1 and A2.

2.5. Crop rotation and simulations

Model calibration and validation for the main crops were performed based on the data of acquired available data sets from rainfed variety trials conducted by the Central Institute for Supervising and Testing in Agriculture (CISTA). Data from the period 1991–2010 for the three selected experimental sites and for each crop were used. The observed experimental data that were available included the dates of sowing and harvest, amounts of seeds sown per m2, observed phenological phases (emergence, tillering, shooting, heading, flowering and maturity), the number of tillers per m2, the weight of 1000 seeds, fertilizer application data (timing and amount fully representing real field experiment management) and information on the previous crop. Winter-hardy cover crops correspond to the characteristics of the Brassica crop. More detailed information on model calibration and validation can be found in Kostková et al. (2021).

Simulations of the ensemble of crop models were obtained with assumed flat soil under two CRs (CR1 and CR2) with the same sequence of the main crops (winter wheat, spring barley, silage maize, winter wheat and winter oilseed rape) that differ in 1) the use of cover crops, 2) fertilizer type and 3) postharvest management of wheat and barley crop residues. CR1 represents the conventional agricultural practice that includes rotation of only the main crops, mineral fertilization and 80 % removal of crop residues (straw) after harvest. Postharvest tillage was applied up to the 20-cm soil depth (Fig. 5a). CR2 represents the alternative agricultural practice that focuses on the return of organic matter to the soil, in which the CR includes cover crops at two positions. Both mineral and organic fertilizers (cattle manure) are applied, and postharvest residues of wheat and barley straw are left in the field (Fig. 5b). Winter-hardy cover crops were included between winter wheat and spring barley and between spring barley and silage maize in the rotation. Organic fertilizer (cattle manure) was applied after the main crop (except for winter oilseed rape) at an amount of 40 t/ha (240 kg N/ha with 15 % ammonia and 85 % organic N). Residues and manure are accounted with their mineral and organic N compounds allocated to the mineral and organic pools at time of fertilization. Organic nitrogen is mineralized depending on soil water and temperature. We used an automatic mineral fertilization routine, which considers the available (simulated) soil mineral nitrogen at the plant specific fertilization dates (mainly driven by phenology). Uninterrupted simulation runs were conducted for the 1961–2080 period (1961–1990 as spin-up period; 1991–2080 consequent period) (Fig. 5c). The simulation runs were repeated five times to allow each crop to be planted first in the rotation, thus ensuring that all the crops were represented in all the years. The expected change in management (i.e., the timing of sowing, harvesting, and fertilization) was defined on the basis of the HERMES crop model simulations (its partial outputs served as input data for the other models). This approach was used to maintain methodological consistency in the case of future crop management. A spin-up period ranging from 1961 to 1990 and CR2 were used for all the models to initialize the short-term organic matter pools and the organic matter input rates. To generate realistic initial conditions for soil water one year spin-up period would be sufficient since the sites usually reached field capacity over winter during the past. Since models dont́ account for changes in soil hydraulic properties due to SOM change the long spin-up period was not really relevant for soil water dynamics here. CR2 was a common practice in Czechia until the 1990s. After 1990, when cattle began to decline and organic manure was no longer readily available, CR1 was included in the simulations in addition to CR2 (Fig. 5). More information on the two CRs and the simulation principles have been provided by Pohanková et al. (2022), (2024).

2.6. Soil profiles

All nine crop models were run involving two soil profiles at each site. The first soil profile was a universal soil (i.e., the same for each site),

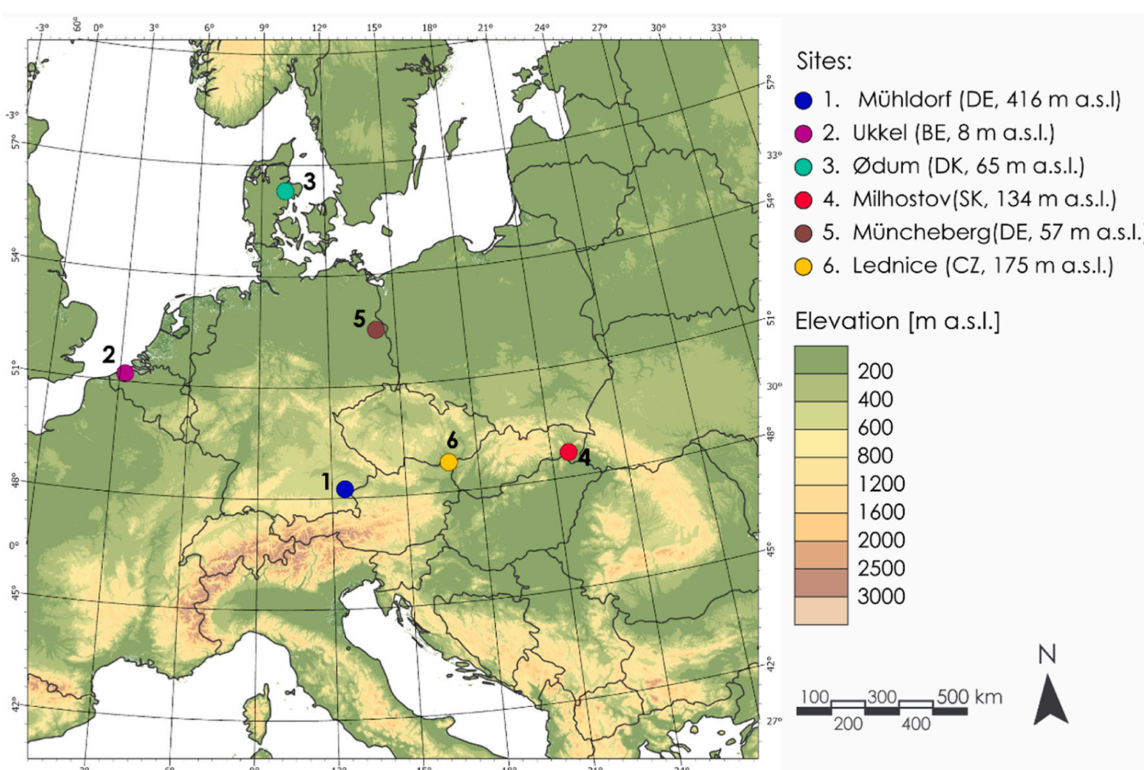


Fig. 2. Map of the six experimental sites in Europe. The experimental sites are ranked by the annual precipitation from highest (Mühldorf, 855 mm) to lowest (Lednice, 527 mm).

Table 1
List of crop models, parameters, modeling approaches, and references.

Leaf area development and LI[a]	Light utilization[b]	Yield formation[c]	Water dynamics[d]	Potential evapotranspiration[e]	Origin	Ref.
APSIM *(Agricultural Production Systems sIMulator)*, 7.7						
S	RUE	HI, AGB, GN, PRS	C	PT	Australia	Holzworth et al. (2014)
CROPSYST *(Cropping Systems simulation model)*, 3.04						
S	RUE	HI, AGB	C	PT	USA	Stöckle et al. (2003)
DAISY *(Soil Plant Atmosphere System Model), versions 5.24 and 4.01*						
D	P-R	PRS	R	PM	Denmark	Abrahamsen and Hansen (2000)
DSSAT *(Decision Support System for Agrotechnology Transfer)*, 4.7.5.11						
S	RUE	HI, GN, AGB	C	PT	USA	Jones et al. (2003)
EPIC *(Environmental Policy Integrated Climate)*, 0801						
S	RUE	HI, AGB	C	PM	USA	Williams et al. (1989)
HERMES, 4.26						
D	P-R	PRS	C	PM	Germany	Kersebaum (2007)
MONICA *(Model of Nitrogen and Carbon dynamics in Agroecosystems), versions 2.0.0 and 1.29*						
D	P-R	PRS	C	PM	Germany	Nendel et al. (2011)

Model, version

[a] Leaf area development and light interception: S – simple approach or D – detailed approach.
[b] Light utilization/biomass growth: RUE (simple approach) – radiation use efficiency and P-R (detailed approach) – gross photosynthesis minus respiration.
[c] Yield formation depends on HI, harvest index; AGB, total (aboveground) biomass; GN, number of grains; and PRS, partitioning at the reproductive stages.
[d] Water dynamics approach (app.): C – capacity app.; and R – Richards app.
[e] Potential evapotranspiration estimation methods: PM – Penman—Monteith; and PT – Priestley–Taylor.

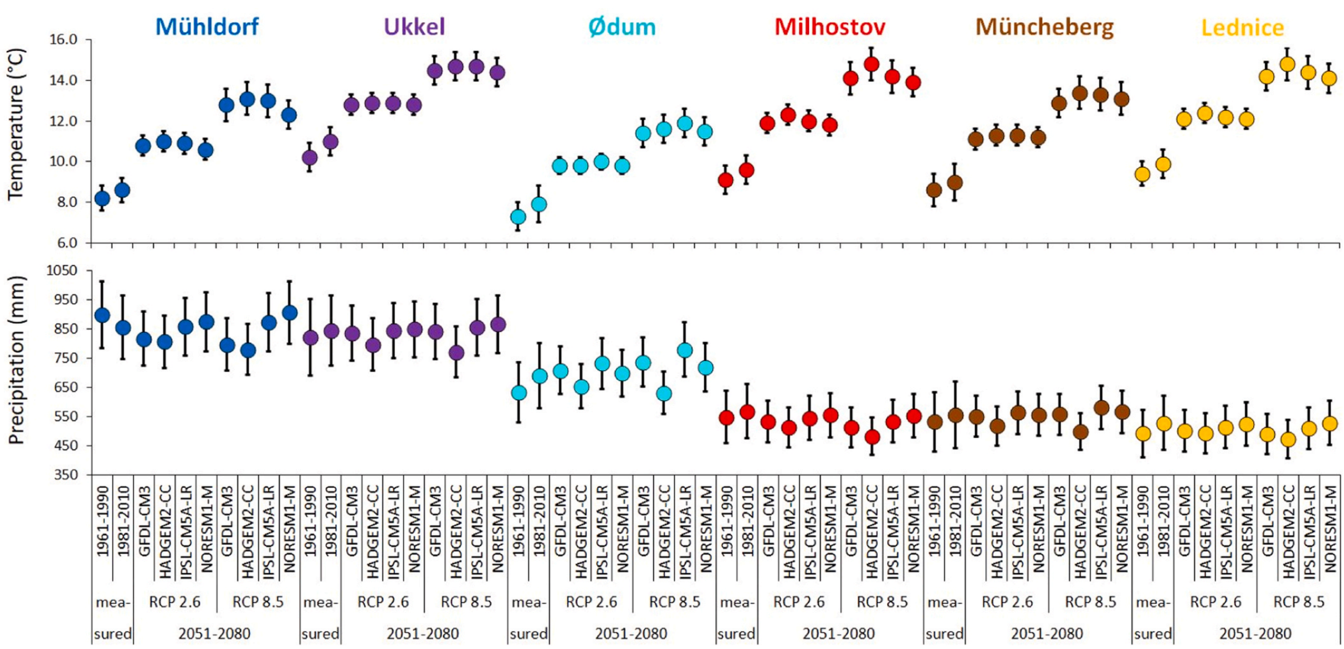


Fig. 3. Average annual air temperatures and precipitation totals (± standard deviation of the annual values) at the six experimental sites for the reference periods (1961–1990 and 1981–2010) and individual GCM projections for 2051–2080.

corresponding to Cambisol/Luvisol with a maximum rooting depth of 110 cm. The universal soil, with a soil water holding capacity of approximately 201 mm at the maximum root depth, represents the average soil conditions for crop cultivation. The second soil profile represents site-specific soil, which varies between the sites. At the Mühldorf site, Luvisol with a soil water holding capacity of approximately 270 mm at a rooting depth of 130 cm was used. At the Ukkel site, Podsoluvisol with a soil water holding capacity of approximately 380 mm at a rooting depth of 170 cm was employed. At the Ødum site, Luvisol with a soil water holding capacity of approximately 280 mm at a rooting depth of 150 cm was considered. At the Milhostov site, Chernozem with a soil water holding capacity of approximately 180 mm at a rooting depth of 120 cm was used. At the Müncheberg site, Albeluvisol with a soil water holding capacity of approximately 165 mm at a rooting depth of 100 cm was used. At the Lednice site, we used a Chernozem profile with a soil water holding capacity of approximately 260 mm at a rooting depth of 150 cm.

These two sets of soil profiles were selected to evaluate the possible influence of the soil type on the crop performance under changing climatic conditions. The characteristics of the soil profiles employed are summarized in Table B1. While soil organic matter and nutrients were treated as variables, the soil hydraulic parameters were maintained constant in the simulations.

2.7. *Output processing via the ensemble outcome agreement (EOA) index*

In this study, 172800 simulations over a 120-year period were conducted by combining nine crop models, six sites, four GCMs under two RCPs, 20 weather realizations (for greater representativeness and to limit the influence of any combination of weather and crop responses), two soil types at each site, and two CRs with five starting crops (with each crop serving as the starting crop in a given rotation). The ensemble

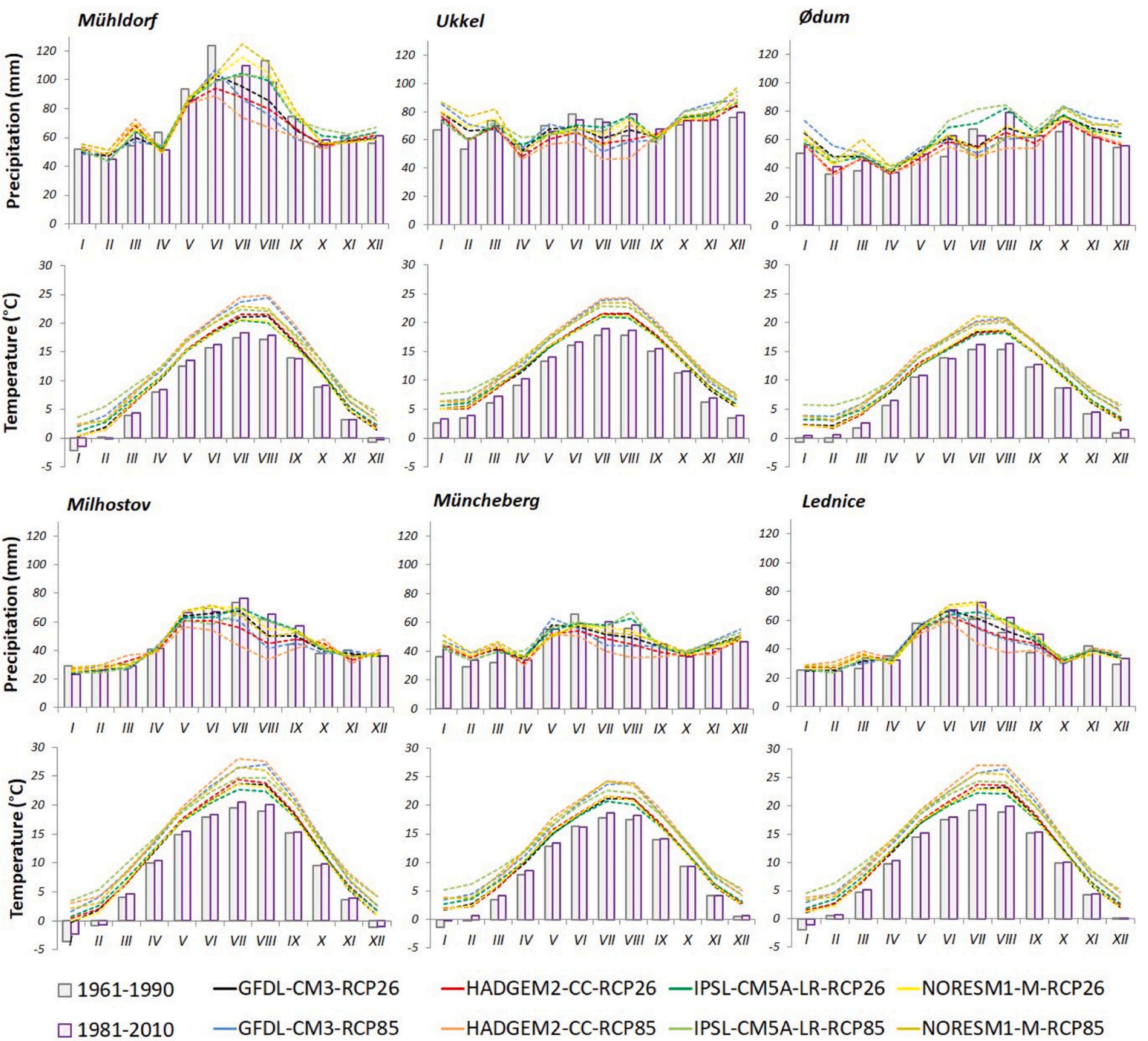


Fig. 4. Average measured monthly precipitation totals and air temperatures for the normal periods of 1961–1990 and 1981–2010 and shifts in the synthetic conditions for individual GCM scenarios from 2051–2080.

outcome agreement (EOA) index was used to evaluate the confidence of the ensemble results (with the range and interpretation shown in Fig. 6d). The EOA method accounts for all possible ensembles of different combinations and sizes on the basis of the models adopted and offers statistical tests of key hypotheses (Rodríguez et al., 2019). First, the following hypothesis was defined: Will the value of a specific variable (yield, actual evapotranspiration, or percolation) from 2051–2080 be greater (or lower) than the average value over the spin-up period (1962–1990)? On the basis of this hypothesis, the mean and standard deviation of a given variable were calculated. The EOA index was subsequently obtained by calculating the median value of a specific variable over a given period to assess the uncertainty in the crop model ensemble on the basis of the above defined hypothesis.

The EOA index was calculated for each climate scenario under each climate model and realization, crop, and initial crop of the rotation. An example of the processing outputs is shown in Fig. 6. The EOA index facilitates the interpretation of the simulation results across crop models (Fig. 6a). Fig. 6b shows the variation across all the crop models. The whiskers denote the EOA index variability for an individual realization and initial CR combination. The EOA index was visualized as a point chart (Fig. 6c) to focus on the information contained in the whisker plot. Notably, the minimum (min), 1st quartile (Q1), median (med), 3rd quartile (Q3) and maximum (max) of the EOA index were plotted as colored points for all climatic scenarios to facilitate visual interpretation. When higher EOA values occur under more climate scenarios and are reported at the lower whiskers, overall higher confidence in hypothesis fulfillment is indicated by the crop model ensemble. The same output processing procedure was applied in the study of Pohanková et al. (2022).

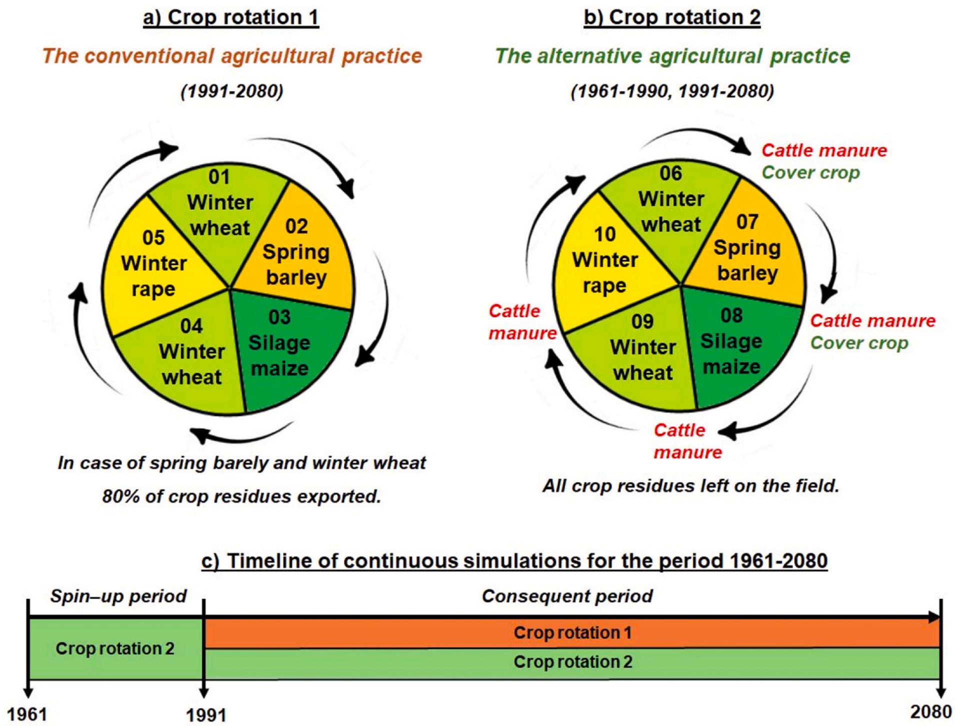


Fig. 5. Scheme of a) CR1 and b) CR2 with an indication of the first harvested crop. Each first main crop is harvested in 1962, while the last crop is harvested in 2080. c) Time scheme of the crop rotation simulations.

3. Results

3.1. Expected production and water balance

Precipitation varied across the sites, and a definite decreasing or increasing trend over time could not be observed (Fig. A2a). Compared with that from 1961–1990, the total precipitation will increase by 5.8 mm (RCP 2.6) and 6.0 mm (RCP 8.5) on average from 2051–2080. The average air temperature (Fig. A2b) consistently increases over time. Compared with that from 1961–1990, the average temperature will increase by 2.7°C (RCP 2.6) and 4.7°C (RCP 8.5) on average from 2051–2080.

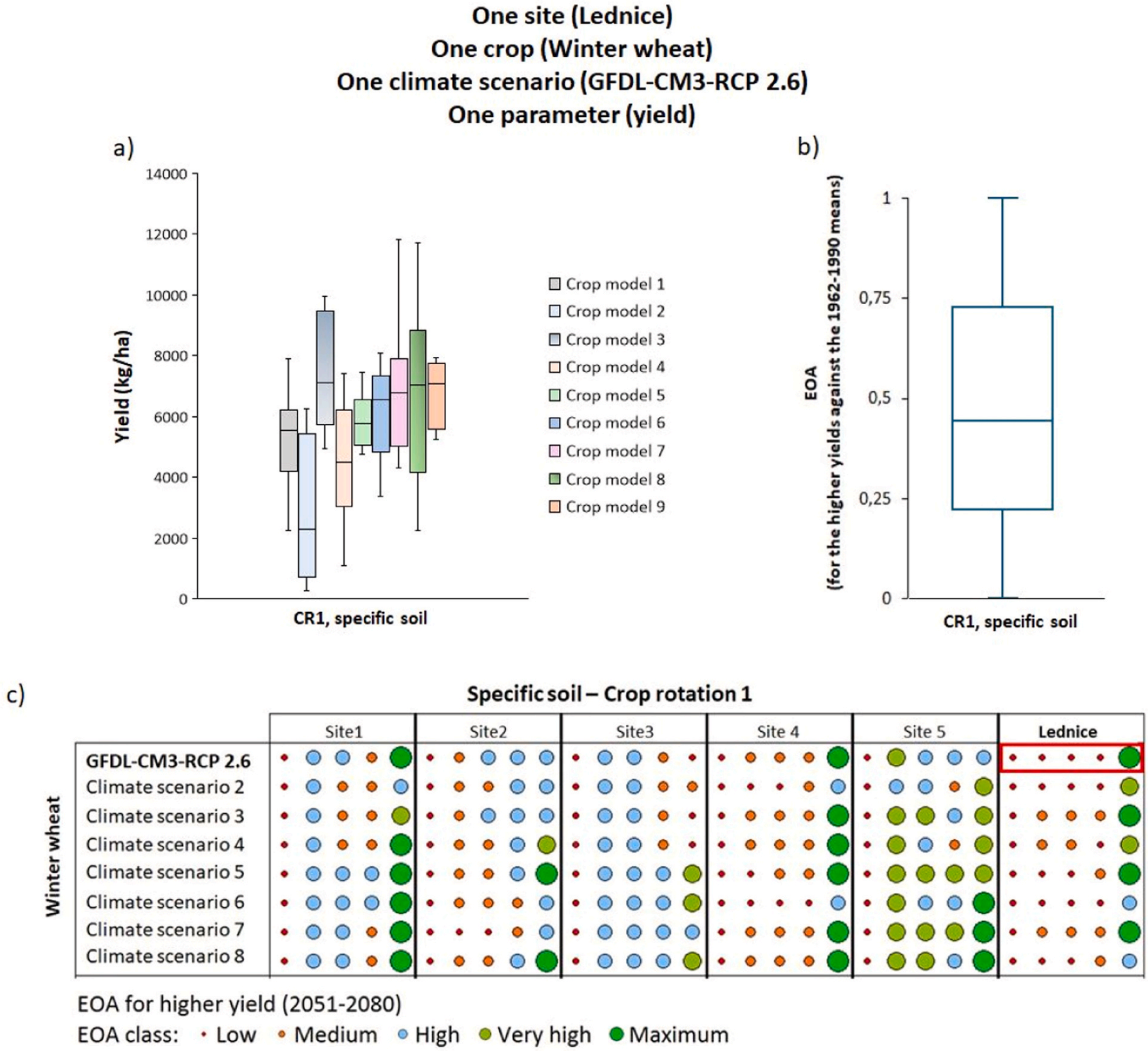
Fig. 7a, A3a, A3b, A4a, A4b, A5a and A6a show the differences in the average crop yields per CR (indicator of the overall productivity) between all six sites and between the two CRs (CR1 and CR2). The yields were generally greater for CR2 than for CR1. Fig. 7a, b, A5a and A6a show greater yield variability among sites when site-specific soils were used. Regardless of the soil type (universal or site-specific soil), the highest average yields were obtained in the coldest areas with sufficient precipitation and longer days during the growing season, namely, at the Ødum and Mühldorf sites. The lowest yields were obtained in Lednice and Milhostov (the driest sites with the greatest temperature increase) (Fig. 7a, b, A2, A3a, A3b, A4a, A4b, A5a and A6a). At the Milhostov and Lednice sites, the average yield from 1962–1990 was higher than that from 2051–2080, namely, 0.1 t/ha at Lednice (RPC 2.6) and 0.2 t/ha at Lednice and Milhostov (RCP 8.5). At the other sites, the average yield from 2051–2080 was higher than that from 1962–1990. The yield increased the most at the Ødum site, by 2.0 t/ha (RCP 2.6) and 2.4 t/ha (RCP 8.5) on average.

The lowest average yield was obtained under the combination of CR1 and site-specific soil at the Mühldorf, Milhostov, Müncheberg and Lednice sites, namely, 6.2, 4.6, 5.6 and 4.0 t/ha (RCP 2.6), respectively, and 6.3, 4.4, 5.7 and 3.9 t/ha (RCP 8.5), respectively. At the remaining two sites (Ukkel and Ødum), the lowest average yield was obtained for CR1 and universal soil, namely, 5.7 and 6.4 t/ha (RCP 2.6), respectively, and 5.4 and 6.7 t/ha (RCP 8.5), respectively. The highest average yield was achieved at the Ødum site under the combination of CR2 and site-specific soil, namely, 7.4 t/ha (RCP 2.6) and 7.9 t/ha (RCP 8.5).

From 2051–2080, the annual mean actual evapotranspiration from October to September (ETaY) was greater than 490 mm per year (the lowest average ETaY value was obtained at the Ødum site (492 mm for RPC 2.5 and 498 for RPC 8.5), likely because of its location at higher latitudes and the occurrence of a cooler climate with a lower atmospheric evaporative demand; the highest value was obtained at the Ukkel site (650 mm for RCP 2.6 and 647 mm for RCP 8.5)) (Fig. 7c, d, A3c, A3d, A4c, A4d, A5b and A6b). At all the sites, ETaY increased from 2051–2080 compared with that from 1962–1990. The greatest increase in ETaY was determined at Mühldorf, whereas the lowest increase was recorded at Milhostov. The differences between the soils (site-specific soil–universal soil) reached up to 8 mm on average for both RCPs. The differences between the CRs (CR1–CR2) reached up to −1 mm (RCP 2.6) and 2 mm (RCP 8.5) on average. With respect to the yield, a greater range of ETaY values was observed for the site-specific soil than for the universal soil.

The average simulated annual percolation from October to September below a depth of 150 cm (PerY) from 1962–1990 was 213 mm. The highest average PerY value was obtained at Mühldorf, and the lowest value was obtained at Lednice. The average simulated value from 2051–2080 decreased to 152 mm (RCP 2.6) and 150 mm (RCP 8.5). The greatest decrease occurred at Mühldorf, while the smallest decrease occurred at Ødum. The lowest PerY value was obtained for universal soil and CR1, whereas the highest PerY value was obtained for site-specific soil and CR2 (Fig. 7c, d, A3e, A3f, A4e, A4f, A5c and A6c).

Notably, percolation under CR2 was generally greater than that under CR1 (Fig. 7e and f, respectively). However, the models responded differently to the introduction of winter cover crops in CR2. Higher percolation under CR2 was simulated by the APSIM, CROPSYST, and DSSAT crop models and both versions of MONICA. Although no information on slopes was provided for the sites, these crop models could simulate surface runoff. The yield, ETaY and PerY results of the crop models that did not account for surface runoff (crop model ensemble 1: both versions of DAISY, EPIC and HERMES) and those that did account



EOA class	Symbol	EOA range	EOA value	ES	Interpretation
Low	• (small red)	[0, 0.25)	0	n/a	The aggregated ensemble value does not fulfil the hypothesis. No ES is found.
Medium	• (orange)	[0.25, 0.5)	0.25	(3/4)N+1	The minimum size for which all combinations fulfil H is three-quarters of the available members plus one.
High	● (blue)	[0.5, 0.75)	0.5	(N/2)+1	The minimum size for which all combinations fulfil His half of the available members plus one.
Very high	● (olive)	[0.75, 1)	0.75	(N/4)+1	The minimum size for which all combinations fulfil H is a quarter of the available members plus one.
Maximum	● (large green)	1	1	1	All available members fulfil the hypothesis.

EOA: ensemble outcome agreement; ES: minimum ensemble size for which all permutations fulfil the hypothesis H;

N: ensemble size

Fig. 6. Example of the simulated winter wheat yield (kg/ha) at Lednice for the 2051–2080 period (under the GFDL-CM3-RCP 2.6 climate scenario) obtained via the 9 crop models for CR1 and site-specific soil. The horizontal line indicates the mean simulated yield for the 1962–1990 period (a). To reveal the variability in the EOA index (for testing the hypothesis of higher yields compared with the mean over the 1962–1990 period), the results are presented in the form of a whisker chart (b) and a point chart for all climate scenarios, with the minimum (min), 1st quartile (Q1), median (med), 3rd quartile (Q3) and maximum (max) of the EOA index shown as colored points (c). The EOA index classes, ranges of values and basic interpretations are shown in (d). The EOA index calculation process is described in Rodriguez et al. (2019).

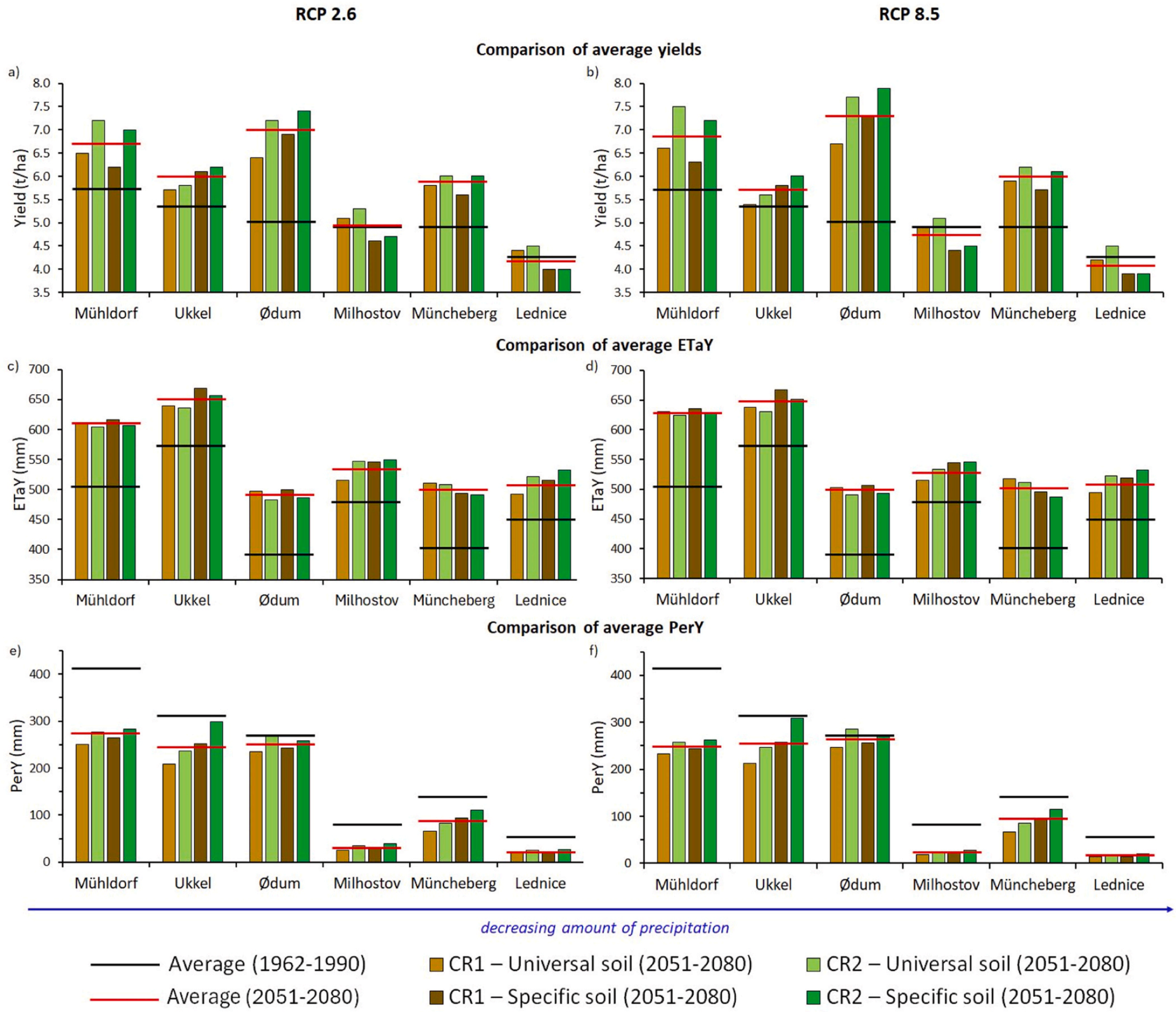


Fig. 7. Mean crop yield (a, b), annual actual evapotranspiration from October to September (ETaY) (c, d) and mean annual water percolation from October to September below a depth of 150 cm (PerY) (e, f) for the two crop rotations (CR1 and CR2) and the two soil types (universal and site-specific soils). The horizontal black line indicates the mean yield from 1962–1990. The horizontal red line denotes the mean yield from 2051–2080. The columns show the average yields from 2051–2080 for the two CRs (CR1 and CR2) and the two soil types (universal and site-specific soils). The sites are ranked from highest to lowest precipitation. Data are missing for the CROPSYST model over the spin-up period and for the DSSAT model in combination with site-specific soil in Ukkel (since 2010) and Müncheberg (since 2006) due to technical reasons.

for surface runoff (crop model ensemble 2: APSIM, CROPSYST, DSSAT, and both versions of MONICA) are shown in Fig. A3 and A4, respectively. The models of ensemble 1 generated different effects on percolation under the two CRs than did those of ensemble 2. Notably, percolation was typically reduced under CR2 in ensemble 1 due to water consumption of the cover crop, while it was higher compared to CR1 in ensemble 2 because surface runoff reduced infiltration under CR1. While the main difference occurred during the reference period, the climate change projection differences between the two model groups were much smaller.

The crop yields were linearly related to the water balance, which was calculated as the difference between the precipitation and reference evapotranspiration (ETo) (Fig. 8). According to the water balance, the sites could be ranked in the descending order of Mühldorf, Ødum, Ukkel, Müncheberg, Milhostov and Lednice. A comparison of the water balance with the average yield (Fig. 8a, c) from 1991–2020 and 2051–2080 confirmed that a lower yield could be expected in the future at the warmer and drier sites (Lednice and Milhostov), where water restrictions are likely to increase, whereas at the sites with sufficient precipitation and a lower average air temperature, the yield will increase owing to the lower ET0 value. Percolation will decrease at all sites under the climate change projections (Fig. 8b, d). Figs. 8a and c show a greater dependence between the yield and the water balance in the future (compared with the current level), and for percolation, the future dependence on the water balance will be lower (Fig. 8b and d, respectively).

3.2. *Confidence in the ensemble results*

To evaluate the yield simulation results, the EOA index was used (Figs. 9, 10, and A7-A9). The results indicated similar agreement for the yield increases in the future (expectations for 2051–2080 against

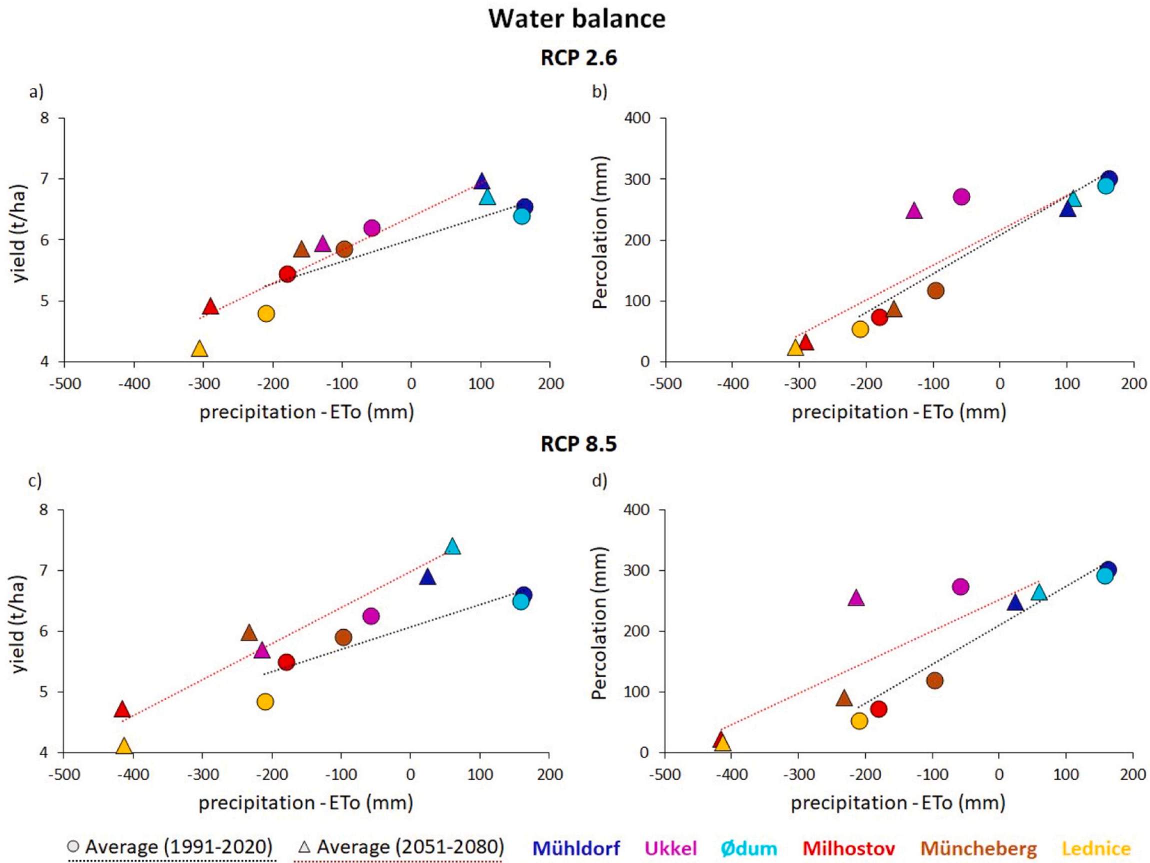


Fig. 8. Average simulated yield (a, c) and average simulated percolation (b, d) versus the water balance. The circles denote the average values for both soil types from 1991–2020. The triangles denote the average from 2051–2080. The dotted lines indicate linear trend lines. The experimental sites (Mühldorf, Ukkel, Ødum, Milhostov, Müncheberg, and Lednice) are distinguished by color. The water balance was calculated as the difference between the average total precipitation and the average reference evapotranspiration (ETo). Data are missing for the CROPSYST model over the spin-up period and the DSSAT model in combination with site-specific soil in Ukkel (since 2010) and Müncheberg (since 2006) due to technical reasons.

1962–1990) between the two soil types (universal soil and site-specific soil; Figs. 9, 10, and A7). For CR2, under most climate change scenarios, the crop model ensemble projected higher winter wheat and winter oilseed rape yields in the future (2051–2080) than for CR1.

At Mühldorf, Ukkel and Ødum, the obtained Q1 values of the EOA index reached at least the very high level of agreement for the yield increase of winter wheat under the projected climate changes in the case of universal soil. The maximum confidence for winter wheat and both soil types was observed at Mühldorf, which exhibits the highest total precipitation and altitude. The simulated yield of winter wheat depends on the previous crop, i.e., if it follows winter oilseed rape (WW-WRA) or silage maize (WW-SM). The confidence in the increase in the future yield was slightly greater when wheat followed maize in CR2. This represents the benefit of fertilization with manure. There was low confidence in the increase in the future yields of spring barley and silage maize for both soil types (regardless of the site and CR). The yield of spring barley under CR2 was slightly greater than that under CR1. The increase in the yield of spring barley exhibited high to maximum confidence only at the Mühldorf site for site-specific soil, with the maximum EOA index value (Fig. A7). In the case of crop C4 only, i.e., silage maize, the confidence in the simulated yield increase was relatively low. The only exception was Ødum, where the temperature, precipitation and irradiation conditions are optimal for silage maize, and the greatest confidence in the increase in the future yield was obtained, regardless of the soil type or CR. For the two CRs and all scenarios, a very high to maximum confidence was calculated. If the same hybrid were used in the future (i.e., no adaptation of varieties), a decrease or constant yield would be expected at all other sites. For the cover crops, there was a maximum EOA index value for the increase in future biomass production at all sites across all climate change scenarios, but the value was slightly greater for the site-specific soil simulations. A comparison of the GCM scenarios revealed the most pessimistic results for crop C3 with the HADGEM2 model, which is the warmest and driest scenario, especially during the second half of spring and early summer (Fig. 4).

On the basis of the crop model ensemble results, a higher annual actual evapotranspiration is expected in the future, with high confidence for most climate change scenarios and sites (Fig. 11a). This finding was obtained despite the shortening of the growing season due to the warmer conditions and the reduced water consumption due to the increasing CO_2 concentrations. The exceptions were the Ukkel, Milhostov and Lednice sites for CR1, where medium to high confidence was observed. Slightly higher values of the EOA index for the increase in ETaY were observed for universal soil (versus site-specific soil) and CR2 (versus CR1) (Fig. 11a and A10a). There was a low EOA index value for the decrease in ETaY for all combinations (Figs. A11a and A12a). At the warmer sites (Ukkel, Milhostov, and Lednice) under CR1, there was relatively low to high confidence in the increase in ETaY in the future. The lowest confidence was observed at Milhostov under the HADGEM2-CC-RCP 8.5 scenario.

Higher crop evapotranspiration is expected under standard conditions from October to September (ETcY, in mm) in the future, with the maximum confidence (Fig. 11b and A10b). There were only a few exceptions when the EOA index indicated medium to high confidence (e.g., Ødum and Ukkel).

The effect of changes in the water balance component of soil water percolation from October–September below a depth of 150 cm (PerY, in

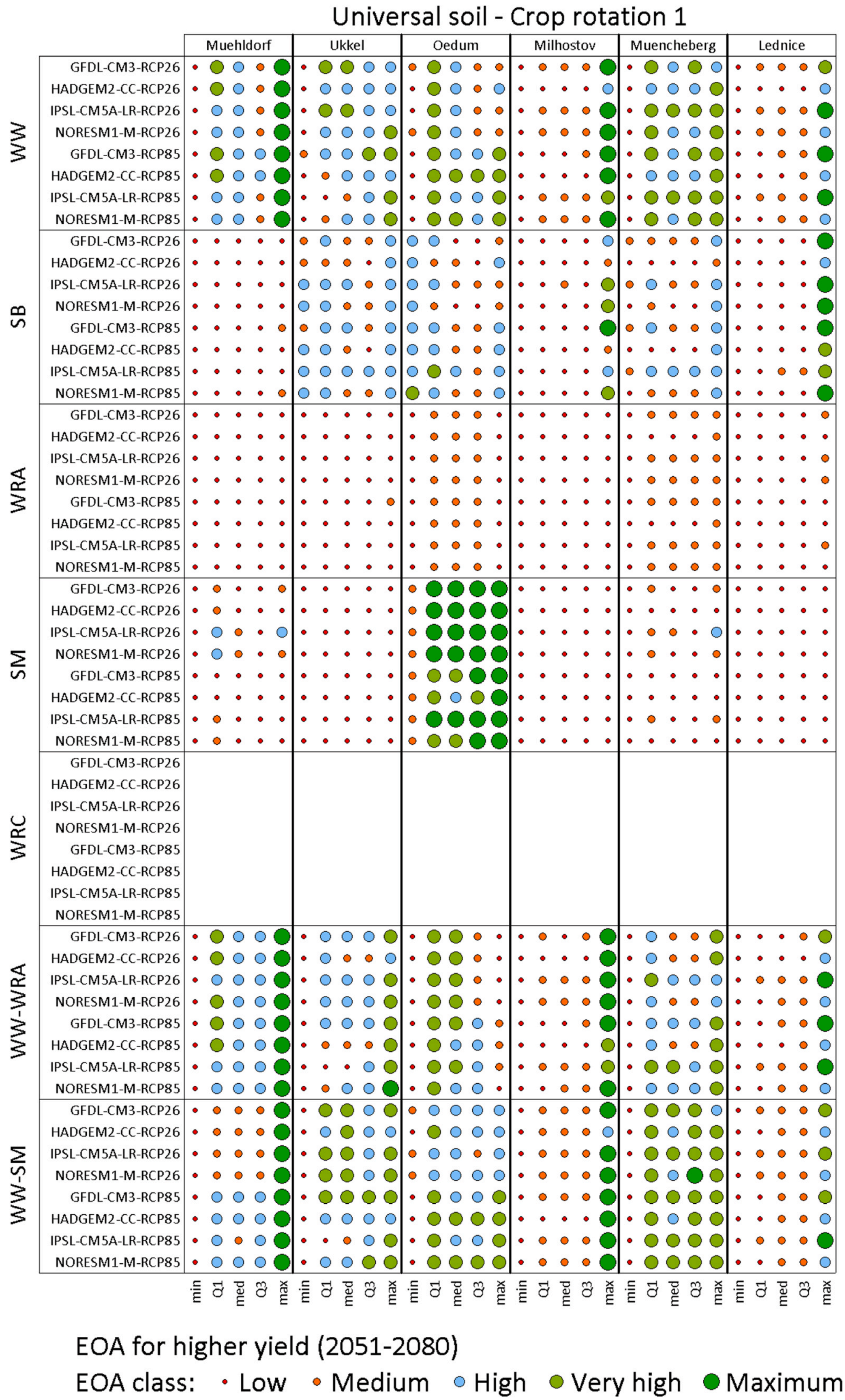


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Fig. 9. EOA index values for higher yields in the future under CR1 and universal soil, where the hypothesis is based on higher simulated yields over the 2051–2080 period than those over the 1962–1990 period. The minimum (min), 1st quartile (Q1), 2nd quartile (med), 3rd quartile (Q3) and maximum (max) of the EOA index derived from separate simulations are shown in the summary plot (x axis). The yield for silage maize and cover crops is the AGB; for all other crops, it is the grain yield. The rows show winter wheat (WW), spring barley (SB), winter oilseed rape (WRA), silage maize (SM), cover crop (WRC), winter wheat after winter oilseed rape (WW-WRA) and winter wheat after silage maize (WW-SM). Data are missing for the CROPSYST model over the spin-up period due to technical reasons.

mm) decreased under all scenarios and at almost all the sites (Fig. 11c). The exception was the Ødum site, where an increase in deep percolation was obtained under the IPSL-CM5A-LR (RCP 2.6 and RCP 8.5) and GFDL-CM3 (RCP 8.5) scenarios for CR2 (Fig. A10c).

4. Discussion

4.1. Effects of climate change and management

The increase in yield under climate change at four of the six experimental sites confirms the findings of Biesbroek et al. (2010) and Zhao et al. (2022), who noted that the impacts of climate change on crop yields are unevenly distributed across Europe, with differential effects on crop production systems depending on their climate sensitivity. The increase or decrease in crop yields under climate change using the crop model ensemble could be influenced by several factors. The first aspect could be the effect of increasing temperature, i.e., if the temperature at the site is presently below or above the optimum temperature range of the crops. The second aspect is the amount and temporal distribution of precipitation. Compared with the sites where the average yield is expected to decrease, the sites where the average yield is expected to increase are largely cooler, with higher total precipitation in the past (Fig. 7).

The model results suggest that climate change may affect crops and the water balance in Europe to varying degrees and that site conditions determine whether yield, evapotranspiration or water percolation will increase or decrease (Gobin et al., 2018; Kersebaum and Nendel, 2014; Taylor et al., 2013; Webber et al., 2020). Other model-based studies indicate that by the middle of the 21st century, the average heat stress may not increase for either maize or winter wheat in Europe, whereas drought stress may increase for maize only (Webber et al., 2018), which suggests an increase in the risk of crop failure for maize but not for winter wheat. In low-yield years, drought stress is the main driver of losses for both crops, and elevated CO_2 levels offer only limited yield benefits in these years (Stella et al., 2021). In current study, the model ensemble indicated that climate change and its associated factors, for example, caused an increase in the temperature and evapotranspiration, a shift in sowing or a shortening of the phenology, thereby affecting the yields of all the crops with more negative effects on spring barley, winter oilseed rape and silage maize than on winter wheat. Compared with the study of Pohanková et al. (2022), where only sites in Czechia (and other climate scenarios) were included, this negative impact was greater in the cases of spring barley and winter oilseed rape.

The results revealed a significant increase in the cover crop biomass at all sites, which could be caused by a longer growing season and warmer winter months. The simulations also indicated that despite the increase in cover crop biomass, the main crops following in the rotation are not subjected to drought stress. This likely occurs because, according to the simulation scenarios, mainly winter precipitation increases. de Frutos Cachorro et al. (2018) reported that winter crop yields will be, on average, greater than summer crop yields under climate change because extreme events such as drought and heat stress are more likely to occur during later summer periods. Notably, crop models do not account for all the effects of cover crops on soil conditions. Instead, only the water and nitrogen balance is simulated, whereas cover crops also affect the soil structure and fertility. From this perspective, yields and actual evapotranspiration levels were overestimated. A Brassica crop was used as the cover crop in current study, but cover crops are often grown as mixtures under real-world conditions, which could affect soil nitrogen and water differently over time.

The higher yield, higher actual evapotranspiration and lower percolation projected in current study were compared with those reported by Pohanková et al. (2022) for Lednice, which is the only site included in both studies. The EOA index indicates whether the value of a specific variable over the 2051–2080 period would be higher (or lower) than the ensemble mean over the 1962–1990 period. In the case of conventional agricultural practices (CR1), the EOA index values for the projected increase in the yield indicated higher confidence for winter wheat and spring barley, lower confidence for winter oilseed rape and low confidence for silage maize. In the case of alternative agricultural practices (CR2), the agreement, as indicated by the EOA index, obtained in current study for all crops except for the cover crops was lower than that obtained by Pohanková et al. (2022). These differences were due to the use of different climate scenarios, different crop models in the model ensemble and different soil types. The projection results for the actual evapotranspiration and percolation also differed. The EOA index in current study revealed lower agreement under CR1 and higher agreement under CR2 for higher actual evapotranspiration and higher agreement under both CRs for lower percolation.

The simulated percolation under CR2 was generally greater than that under CR1, even though cover crops (CR2) consume more water. A possible explanation is that the models simulating higher percolation under CR2 accounted for surface runoff when no crop was grown, and vice versa. Notably, the USDA–Soil Conservation Service procedure is employed in most of these models (Cichota et al., 2021; Mishra and Singh, 2003). This procedure is referred to as the curve number (CN) technique and accounts for the total daily precipitation, not the duration or intensity. Runoff is also triggered by heavy rainfall, where the soil becomes saturated and can no longer absorb water. The assumption behind this process is that there are slight microslopes even under approximately flat conditions, which is retained in the model settings. However, if runoff is simulated, a surface runoff input must be considered as well. Since the amount of simulated runoff is much greater than the simulated difference in evapotranspiration attributed to the cover crops, the ensemble means yield a decrease in percolation under CR1. The different ways of resolving surface runoff also explains the lower EOA index value for the actual evapotranspiration under CR1 than under CR2.

A meta-analysis of more than 1700 published simulations worldwide revealed that crop-level adaptive measures increase simulated yields by an average of 7–15 %; such adaptations include changes in cultivars, planting times, irrigation techniques, and crop residue management measures (Challinor et al., 2014). In the Netherlands, the impact of farm-level adaptations, including changing crops, is similar to that of crop-level adaptations (Reidsma et al., 2015). In Europe, average farm profits were calculated to increase modestly (1.5 %) with adaptation but could decline by 2.3 % without adaptation to climate change; these projections were based on both process-based models and statistical techniques (Moore and Lobell, 2014). Liu et al. (2019) evaluated the impacts of the expected range of global warming on wheat production without adaptation at 60 sites worldwide. At sites in Europe, the increase in revenue reached up to 5 %. The authors further revealed that cooler regions could benefit more from moderate warming. A study of Belgium (de Frutos Cachorro et al., 2018) also focused on addressing climate change and its effects on winter wheat without adaptation to climate change. For winter crops (winter wheat), higher yields with greater variability were simulated on average under climate change. However, because of climate change, the water demand of crops has

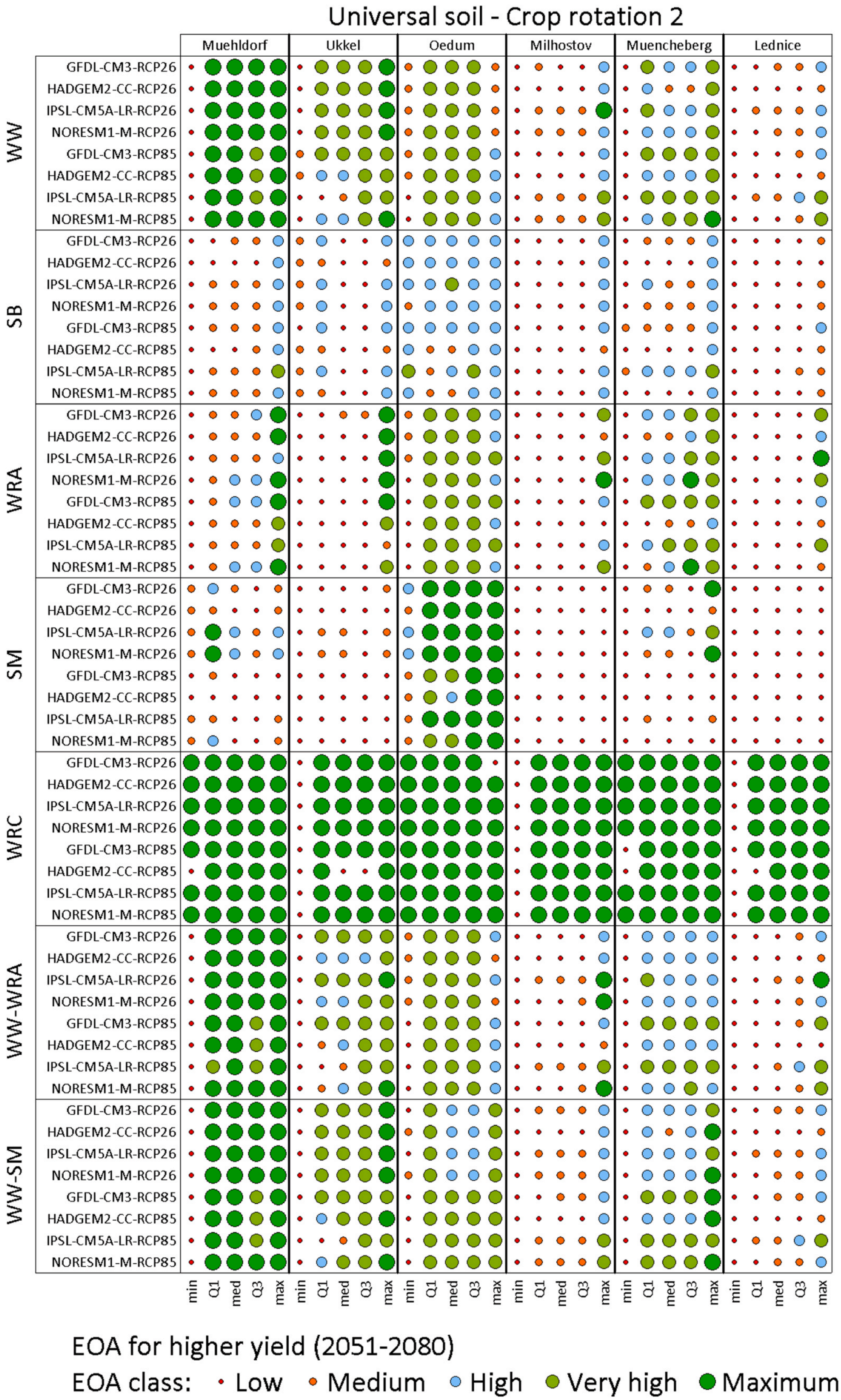

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Fig. 10. EOA index values for higher yields in the future under CR2 and universal soil, where the hypothesis is based on higher simulated yields over the 2051–2080 period than those over the 1962–1990 period. The minimum (min), 1st quartile (Q1), 2nd quartile (med), 3rd quartile (Q3) and maximum (max) of the EOA index derived from separate simulations are shown in the summary plot (x axis). The yield for silage maize and cover crops is the AGB; for all other crops, it is the grain yield. The rows show winter wheat (WW), spring barley (SB), winter oilseed rape (WRA), silage maize (SM), cover crop (WRC), winter wheat after winter oilseed rape (WW-WRA) and winter wheat after silage maize (WW-SM). Data are missing for the CROPSYST model over the spin-up period due to technical reasons.

increased.

4.2. Model limitations and uncertainties

The crop model simulations in current study indicated an average yield increase of approximately 11 % without the use of adaptation measures (CR1) and a yield increase of approximately 19 % if adaptation measures such as cover crops, organic manure fertilization and crop residue management were applied (CR2). With a possible change in cultivars, which is not considered in current study due to the lack of necessary data and the complexity of implementation, the increase in yields under the implementation of adaptation measures could be greater (Foulkes et al., 2007; Montesino-San Martín et al., 2014).

Other uncertainties not included in the crop model ensemble simulations that may significantly affect the outcomes and the required adaptation measures are the occurrence of extreme events (Rötter et al., 2018) and the interaction of field crops in terms of the effects of pests and diseases and the greater pressure due to the more favorable growth conditions under future climate conditions (Gobin, 2018; Reidsma et al., 2015; Nendel et al., 2013; Schaap et al., 2013; Chakraborty and Newton, 2011; Trnka et al., 2007). Each of the crop models could be affected by parameterization, specific uncertainty due to the model structure or limited available data for calibration (Palosuo et al., 2011). The results may also have been influenced by the fact that changes in the main crops in rotation (e.g., rye, oat, potatoes, sunflower, and sugar beet) in the future were not accounted for because of the number of crop models involved (not all models may be able to simulate other crops). Moreover, GCM projections exhibit uncertainties due to the model structure, considered scenarios and initial conditions (Woldemeskel et al., 2014). In current study, this issue was overcome through the implementation of four GCMs under contrasting scenarios, namely, RCP 2.6 and RCP 8.5. To obtain a corresponding statistical sample of outputs for robust evaluation, 20 individual implementations of meteorological elements in daily steps were employed for each possible scenario combination.

Since we used an algorithm to generate automatic mineral fertilization based on the available soil mineral nitrogen at the plant specific fertilization dates, the total amount of plant available nitrogen supply may not differ much during the growing period in both rotations. However, the temporal dynamic of N release from residues and manure is different from mineral fertilizer applications leading to differences, e. g., in nitrate leaching. On the long term application of organic material has an impact on soil organic matter and the mineralization potential of soils, which results in lower mineral fertilizer doses under CR2 after long term simulation. Soil organic carbon and nitrogen dynamics will be separately analyzed in an upcoming paper, similar to the study of Pohanková et al. (2024). Since the soil properties remained constant and the simulations were performed under no nitrogen limitations, the effects of climate change and CR on the crop yield and water balance could be analyzed independently in current study.

With regard to the crop models included in current study, certain outputs were missing due to technical reasons under continuous rotations (for example, CROPSYST model data for the spin-up period and DSSAT model outputs for CR2, Ukkel, Müncheberg and site-specific soil, etc.). However, the interpretation of the results remains valid. The EOA index is a measure of the confidence level according to the available information. In some cases, the availability of 8 or even 7 members instead of 9 is sufficient (Pohanková et al., 2022).

Similar to the study of Reidsma et al. (2015), the crop models also projected relatively positive impacts of climate change on crop yields. As mentioned above, certain hazards that may occur more frequently in the future were not considered in the projections. Therefore, it would be appropriate to consider and incorporate available adaptation and mitigation measures within field crop cultivation that could help mitigate the effects of climate change (e.g., new cultivars, technology changes, the return of organic matter to the soil, the reduction in soil erosion, measures against drought, the proper use of water resources for irrigation or the reduction in the impact of heat waves, for example, by establishing wider ridges for planting).

5. Conclusions

The expected effects of climate change on production and water use were evaluated under future climate conditions in Europe. The strength of this study is that continuous CR simulations (1961–2080) were used via an ensemble of nine crop models. The results indicated that, in the future, a greater spatial variability in the yield can be expected, which is likely caused by the expected increase in the air temperature and not by the expected increase, or even decrease, in the total precipitation. As a result, there will be a greater difference between currently drier and warmer sites where crops are already limited by water and where the yield will decrease and cooler and wetter sites with relatively sufficient precipitation and a lower average air temperature in the future, where the yield will increase.

The results indicated the smallest increase or even a decrease in the yield of spring barley (-11–20 %) and silage maize (-24–23 %, except at Ødum, where the increase reached 80 %) at almost all the sites, which was caused by changes in both the temperature and precipitation. The variability in precipitation, which increases in winter according to the scenarios considered, may have contributed to the positive yield trend in winter wheat and the higher biomass production of cover crops. The crop model ensemble projected increases in the actual evapotranspiration under climate change at all sites. This trend was greater under CR2 and could affect the long-term soil water balance and soil regime in the case of rainfed agriculture.

The availability of data for crop model calibration is limited, and varieties of crops are likely locally adapted, which was not considered in crop model calibration herein. Therefore, this study should be regarded as a first attempt to investigate the transient effects of climate change on differently managed CRs via a crop model ensemble.

CRediT authorship contribution statement

Sabina Thaler: Conceptualization. **Josef Eitzinger**: Conceptualization. **Camilla Dibari**: Conceptualization. **Roberto Ferrise**: Conceptualization. **Luisa Leolini**: Conceptualization. **Eva Pohanková**: Writing – review & editing, Writing – original draft, Methodology, Data curation, Conceptualization. **Jakub Bohuslav**: Conceptualization. **Petr Hlavinka**: Writing – original draft, Methodology, Conceptualization. **Monika Bláhová**: Visualization. **Kurt-Christian Kersebaum**: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Milan Fischer**: Supervision. **Claas Nendel**: Writing – original draft, Conceptualization. **Miroslav Trnka**: Supervision, Methodology, Conceptualization. **Alfredo Rodríguez**: Conceptualization. **Jan Balek**: Visualization, Conceptualization. **Juraj Balkovič**: Data curation, Conceptualization. **Martin Dubrovsky**: Methodology, Conceptualization. **Gerrit Hoogenboom**: Supervision. **Marco Moriondo**: Conceptualization. **Jorgene Olesen**: Writing – original draft, Conceptualization. **Johannes Wilhelmus Maria Pullens**: Conceptualization. **Reimund**

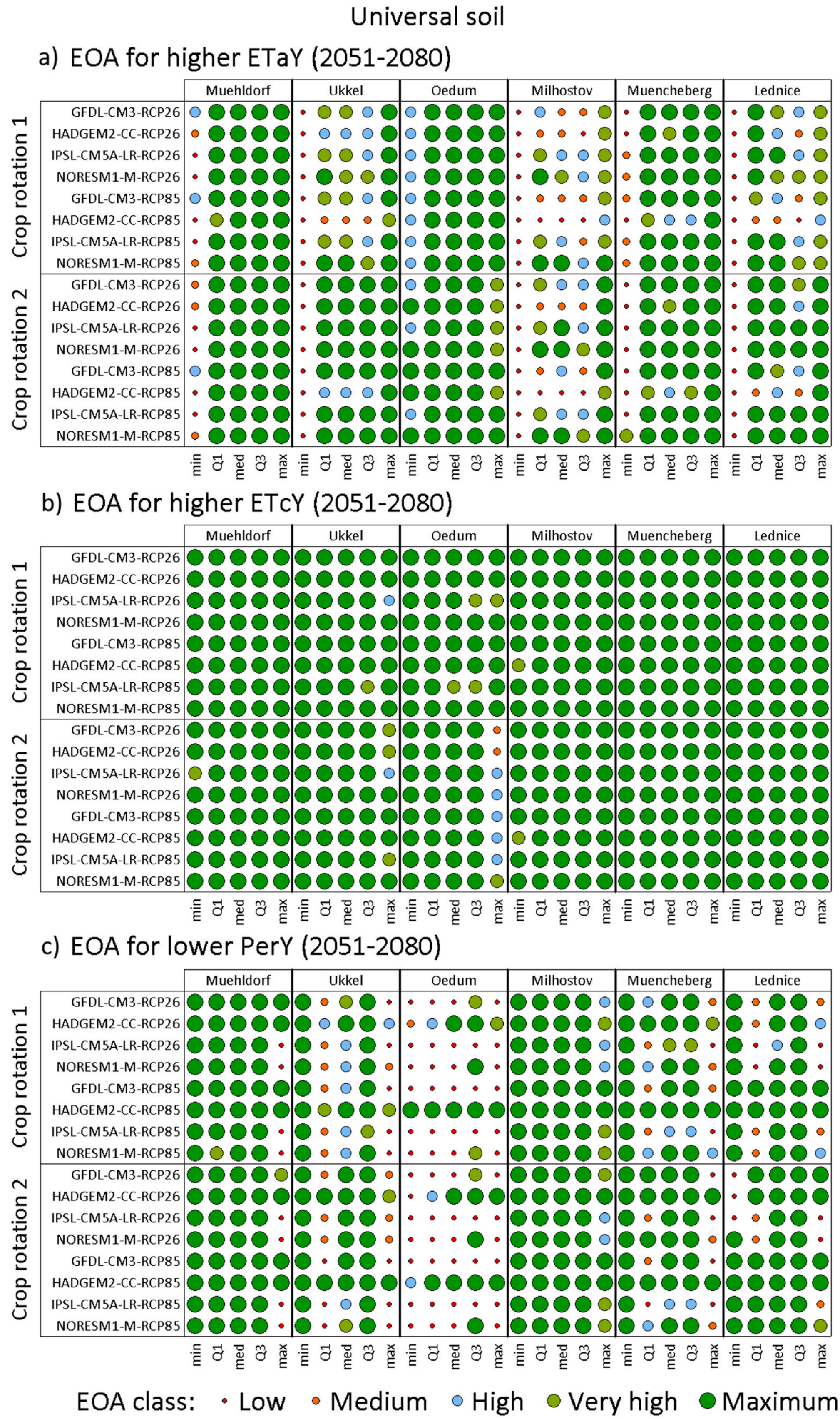

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Fig. 11. EOA index values for the simulated values for the 2051–2080 period compared with those during the 1962–1990 period for universal soil: a) for higher actual evapotranspiration from October to September (ETaY, in mm) in the future with higher simulated ETa; b) for higher crop evapotranspiration under standard conditions from October to September (ETcY, in mm) in the future with higher simulated ETcY; c) for lower total water percolation from October to September below a depth of 150 cm (PerY, in mm) in the future with lower simulated PerY. The minimum (min), 1st quartile (Q1), 2nd quartile (med), 3rd quartile (Q3) and maximum (max) of the EOA index derived from individual simulations are shown in the summary plot (x axis). Data are missing for the CROPSYST model over the spin-up period as well as all ETcY data for the DSSAT model due to technical reasons.

Rötter: Conceptualization. **Margarita Ruiz-Ramos**: Formal analysis, Conceptualization. **Vakhtang Shelia**: Conceptualization. **Rastislav Skalský**: Conceptualization. **Munir Hoffmann**: Conceptualization. **Jozef Takáč**: Formal analysis, Conceptualization.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2024.127456.

Data availability

Data will be made available on request.

References

Abrahamsen, P., Hansen, S., 2000. Daisy: an open soil-crop-atmosphere system model. Environ. Model. Softw. 15 (3), 313–330.

Agnolucci, P., De Lipsis, V., 2020. Long-run trend in agricultural yield and climatic factors in Europe. Clim. Change 159, 385–405.

Barklund, E., Pogaku, N., Prodanovic, M., Hernandez-Aramburo, C., Green, T.C., 2007. Energy management system with stability constraints for stand-alone autonomous microgrid (April). 2007 IEEE Int. Conf. Syst. Syst. Eng. 1–6.

Basso, B., Hyndman, D.W., Kendall, A.D., Grace, P.R., Robertson, G.P., 2015. Can impacts of climate change and agricultural adaptation strategies be accurately quantified if crop models are annually re-initialized? PloS One 10 (6), e0127333.

Becker, F.N., Fink, A.H., Bissolli, P., Pinto, J.G., 2022. Towards a more comprehensive assessment of the intensity of historical European heat waves (1979–2019). Atmos. Sci. Lett. 23 (11), e1120.

Biesbroek, G.R., Swart, R.J., Carter, T.R., Cowan, C., Henrichs, T., Mela, H., Rey, D., 2010. Europe adapts to climate change: comparing national adaptation strategies. Glob. Environ. Change 20 (3), 440–450.

Ceglar, A., Zampieri, M., Toreti, A., Dentener, F., 2019. Observed northward migration of agro-climate zones in Europe will further accelerate under climate change. Earth'S. Future 7 (9), 1088–1101.

Chakraborty, S., Newton, A.C., 2011. Climate change, plant diseases and food security: an overview. Plant Pathol. 60 (1), 2–14.

Challinor, A.J., Watson, J., Lobell, D.B., Howden, S.M., Smith, D.R., Chhetri, N., 2014. A meta-analysis of crop yield under climate change and adaptation. Nat. Clim. Change 4 (4), 287–291.

Cichota, R., Vogeler, I., Sharp, J., Verburg, K., Huth, N., Holzworth, D., Snow, V., 2021. A protocol to build soil descriptions for APSIM simulations. MethodsX 8, 101566.

Dubrovsky, M., Nemesova, I., Kalvova, J., 2005. Uncertainties in climate change scenarios for the Czech Republic. Clim. Res 29, 139–156.

Dubrovský, M., Buchtele, J., Žalud, Z., 2004. High-frequency and low-frequency variability in stochastic daily weather generator and its effect on agricultural and hydrologic modelling. Clim. Change 63, 145–179.

EEA, R., 2017. Climate change impacts and vulnerability in Europe 2016: An indicator-based report. European Environment Agency, Copenhagen.

Eitzinger, J., Trnka, M., Semerádová, D., Thaler, S., Svobodová, E., Hlavinka, P., Žalud, Z., 2013. Regional climate change impacts on agricultural crop production in Central and Eastern Europe–hotspots, regional differences and common trends. J. Agric. Sci. 151 (6), 787–812.

Ewert, F., Rötter, R.P., Bindi, M., Webber, H., Trnka, M., Kersebaum, K.C., Semenov, M. A., 2015. Crop modelling for integrated assessment of risk to food production from climate change. Environ. Model. Softw. 72, 287–303.

Foulkes, M., Snape, J., Shearman, V., Reynolds, M., Gaju, O., Sylvester-Bradley, R., 2007. Genetic progress in yield potential in wheat: recent advances and future prospects. Can. J. Agric. Sci. 145 (1), 17.

de Frutos Cachorro, J., Gobin, A., Buysse, J., 2018. Farm-level adaptation to climate change: the case of the Loam region in Belgium. Agric. Syst. 165, 164–176.

Gobin, A., 2018. Weather related risks in Belgian arable agriculture. Agric. Syst. 159, 225–236.

Grados, D., Kraus, D., Haas, E., Butterbach-Bahl, K., Olesen, J.E., Abalos, D., 2024. Agronomic adaptation strategies to climate change may increase soil greenhouse gas emission. Agric. For. Meteorol. 349, 109966.

Harvey L.D.D., Gregory J., Hoffert M., Jain A. and 5 others 1997 An introduction to simple climate models used in the IPCC Second Assessment Report. IPCC Tech Paper 2, Intergovernmental Panel on Climate Change, Geneva.

Hlaváčová, M., Klem, K., Rapantová, B., Novotná, K., Urban, O., Hlavinka, P., Trnka, M., 2018. Interactive effects of high temperature and drought stress during stem elongation, anthesis and early grain filling on the yield formation and photosynthesis of winter wheat. Field Crops Res. 221, 182–195.

Hlavinka, P., Kersebaum, K.C., Dubrovský, M., Fischer, M., Pohanková, E., Balek, J., Trnka, M., 2015. Water balance, drought stress and yields for rainfed field crop rotations under present and future conditions in the Czech Republic. Clim. Res. 65, 175–192.

Holzworth, D.P., Huth, N.I., deVoil, P.G., Zurcher, E.J., Herrmann, N.I., McLean, G., Moore, A.D., 2014. APSIM–evolution towards a new generation of agricultural systems simulation. Environ. Model. Softw. 62, 327–350.

Hulme M., Wigley T.M.L., Barrow E.M., Raper S.C.B., Centella A., Smith S., Chipanshi A. C. 2000 Using a climate scenario generator for vulnerability and adaptation assessments: MAGICC and SCENGEN Version 2.4 Workbook. Climatic Research Unit, Norwich.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Ritchie, J.T., 2003. The DSSAT cropping system model. Eur. J. Agron. 18 (3-4), 235–265.

Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. Eur. J. Agron. 18 (3-4), 267–288.

Kersebaum, K.C., 2007. Modelling nitrogen dynamics in soil–crop systems with HERMES. Nutr. Cycl. Agroecosyst. 77, 39–52.

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. 52, 22–32.

Kersebaum, K.C., Nendel, C., Mirschel, W., Manderscheid, R., Weigel, H.J., Wenkel, K.O., 2009. Testing different CO2 response algorithms against a face crop rotation experiment and application for climate change impact assessment at different sites in Germany. IdöJ. áR. áS. 113 (1-2), 79–88.

Kollas, C., Kersebaum, K.C., Nendel, C., Manevski, K., Müller, C., Palosuo, T., Conradt, T., 2015. Crop rotation modelling—a European model intercomparison. Eur. J. Agron. 70, 98–111.

Kostková, M., Hlavinka, P., Pohanková, E., Kersebaum, K.C., Nendel, C., Gobin, A., Trnka, M., 2021. Performance of 13 crop simulation models and their ensemble for simulating four field crops in Central Europe. J. Agric. Sci. 159 (1-2), 69–89.

Lipavský, J., et al. Long-term field experiments in the Czech Republic. 60th Anniversary of Longterm Field Experiments in the Czech Republic, 2015, 57-60.

Liu, B., Martre, P., Ewert, F., Porter, J.R., Challinor, A.J., Müller, C., Asseng, S., 2019. Global wheat production with 1.5 and 2.0° C above pre-industrial warming. Glob. Change Biol. 25 (4), 1428–1444.

Martre, P., Wallach, D., Asseng, S., Ewert, F., Jones, J.W., Rötter, R.P., Hatfield, J.L., 2015. Multimodel ensembles of wheat growth: many models are better than one. Glob. Change Biol. 21 (2), 911–925.

Mishra, S.K., Singh, V.P., 2003. SCS-CN method. Soil Conserv. Serv. curve Number (SCS-CN) Methodol. 84–146.

Montesino-San Martín, M., Olesen, J.E., Porter, J.R., 2014. A genotype, environment and management (GxExM) analysis of adaptation in winter wheat to climate change in Denmark. Agric. For. Meteorol. 187, 1–13.

Moore, F.C., Lobell, D.B., 2014. Adaptation potential of European agriculture in response to climate change. Nat. Clim. Change 4 (7), 610–614.

Nendel, C., Berg, M., Kersebaum, K.C., Mirschel, W., Specka, X., Wegehenkel, M., Wieland, R., 2011. The MONICA model: testing predictability for crop growth, soil moisture and nitrogen dynamics. Ecol. Model. 222 (9), 1614–1625.

Nendel, C., Kersebaum, K.C., Mirschel, W., Wenkel, K.O., 2014. Testing farm management options as climate change adaptation strategies using the MONICA model. Eur. J. Agron. 52, 47–56.

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.

Olesen, J.E., Trnka, M., Kersebaum, K.C., Skjelvåg, A.O., Seguin, B., Peltonen-Sainio, P., Micale, F., 2011. Impacts and adaptation of European crop production systems to climate change. Eur. J. Agron. 34, 96–112.

Ossó, A., Allan, R.P., Hawkins, E., Shaffrey, L., Maraun, D., 2011. Emerging new climate extremes over Europe. Clim. Dyn. 58, 487–501.

Ozturk, I., Sharif, B., Baby, S., Jabloun, M., Olesen, J.E., 2017. The long-term effect of climate change on productivity of winter wheat in Denmark: a scenario analysis using three crop models. J. Agric. Sci. 155 (5), 733–750.

Ozturk, I., Sharif, B., Baby, S., Jabloun, M., Olesen, J.E., 2018. Long-term simulation of temporal change of soil organic carbon in Denmark: comparison of three model performances under climate change. J. Agric. Sci. 156 (2), 139–150.

Pachepsky, Y., Timlin, D., Rawls, W., 2003. Generalized Richards' equation to simulate water transport in unsaturated soils. J. Hydrol. 272 (1-4), 3–13.

Palosuo, T., Kersebaum, K.C., Angulo, C., Hlavinka, P., Moriondo, M., Olesen, J.E., Trnka, M., 2011. Simulation of winter wheat yield and its variability in different climates of Europe: a comparison of eight crop growth models. Eur. J. Agron. 35 (3), 103–114.

Pohanková, E., Hlavinka, P., Kersebaum, K.C., Rodríguez, A., Balek, J., Bednařík, M., Trnka, M., 2022. Expected effects of climate change on the production and water use of crop rotation management reproduced by crop model ensemble for Czech Republic sites. Eur. J. Agron. 134, 126446.

Pohanková, E., Hlavinka, P., Kersebaum, K.C., Nendel, C., Rodríguez, A., Balek, J., Trnka, M., 2024. Expected effects of climate change on the soil organic matter content related to contrasting agricultural management practices based on a crop model ensemble for locations in Czechia. Eur. J. Agron. 156, 127165.

Pullens, J.W.M., Sharif, B., Trnka, M., Balek, J., Semenov, M.A., Olesen, J.E., 2019. Risk factors for European winter oilseed rape production under climate change. Agric. For. Meteorol. 272, 30–39.

Reidsma, P., Wolf, J., Kanellopoulos, A., Schaap, B.F., Mandryk, M., Verhagen, J., van Ittersum, M.K., 2015. Climate change impact and adaptation research requires integrated assessment and farming systems analysis: a case study in the Netherlands. Environ. Res. Lett. 10 (4), 045004.

Richards, L.A., 1931. Capillary conduction of liquids through porous mediums. physics 1 (5), 318–333.

Rodríguez, A., Ruiz-Ramos, M., Palosuo, T., Carter, T.R., Fronzek, S., Lorite, I.J., Buis, S., 2019. Implications of crop model ensemble size and composition for estimates of adaptation effects and agreement of recommendations. Agric. For. Meteorol. 264, 351–362.

Rötter, R.P., Appiah, M., Fichtler, E., Kersebaum, K.C., Trnka, M., Hoffmann, M.P., 2018. Linking modelling and experimentation to better capture crop impacts of agroclimatic extremes—a review. Field Crops Res. 221, 142–156.

Rötter, R.P., Tao, F., Höhn, J.G., Palosuo, T., 2015. Use of crop simulation modelling to aid ideotype design of future cereal cultivars. J. Exp. Bot. 66 (12), 3463–3476.

Ruiz-Ramos, M., Ferrise, R., Rodríguez, A., Lorite, I.J., Bindi, M., Carter, T.R., Rötter, R. P., 2018. Adaptation response surfaces for managing wheat under perturbed climate and CO2 in a Mediterranean environment. Agric. Syst. 159, 260–274.

Schaap, B.F., Reidsma, P., Verhagen, J., Wolf, J., van Ittersum, M.K., 2013. Participatory design of farm level adaptation to climate risks in an arable region in the Netherlands. Eur. J. Agron. 48, 30–42.

Spinoni, J., Vogt, J.V., Naumann, G., Barbosa, P., Dosio, A., 2018. Will drought events become more frequent and severe in Europe? Int. J. Climatol. 38 (4), 1718–1736.

Stella, T., Webber, H., Olesen, J.E., Ruane, A.C., Fronzek, S., Bregaglio, S., Ewert, F., 2021. Methodology to assess the changing risk of yield failure due to heat and drought stress under climate change. Environ. Res. Lett. 16 (10), 104033.

Stöckle, C.O., Donatelli, M., Nelson, R., 2003. CropSyst, a cropping systems simulation model. Eur. J. Agron. 18 (3-4), 289–307.

Taylor, R.G., Scanlon, B., Döll, P., Rodell, M., Van Beek, R., Wada, Y., Konikow, L., 2013. Ground water and climate change. Nat. Clim. Change 3 (4), 322–329.

Toreti, A., Belward, A., Perez-Dominguez, I., Naumann, G., Luterbacher, J., Cronie, O., Zampieri, M., 2019. The exceptional 2018 European water seesaw calls for action on adaptation. Earth'S. Future 7 (6), 652–663.

Trnka, M., Kocmánková, E., Balek, J., Eitzinger, J., Ruget, F., Formayer, H., Žalud, Z., 2010. Simple snow cover model for agrometeorological applications. Agric. For. Meteorol. 150 (7-8), 1115–1127.

Trnka, M., Muška, F., Semerádová, D., Dubrovský, M., Kocmánková, E., Žalud, Z., 2007. European corn borer life stage model: regional estimates of pest development and spatial distribution under present and future climate. Ecol. Model 207, 61–84.

Trnka, M., Olesen, J.E., Kersebaum, K.C., Skjelvåg, A.O., Eitzinger, J., Seguin, B., Žalud, Z., 2011. Agroclimatic conditions in Europe under climate change. Glob. Change Biol. 17 (7), 2298–2318.

Wallach, D., Martre, P., Liu, B., Asseng, S., Ewert, F., Thorburn, P.J., Biernath, C., 2018. Multimodel ensembles improve predictions of crop–environment–management interactions. Glob. Change Biol. 24 (11), 5072–5083.

Webber, H., Ewert, F., Olesen, J.E., Müller, C., Fronzek, S., Ruane, A.C., Ferrise, R., 2018. Diverging importance of drought stress for maize and winter wheat in Europe. Nat. Commun. 9 (1), 1–10.

Webber, H., Lischeid, G., Sommer, M., Finger, R., Nendel, C., Gaiser, T., Ewert, F., 2020. No perfect storm for crop yield failure in Germany. Environ. Res. Lett. 15 (10), 104012.

White, J.W., Hoogenboom, G., Kimball, B.A., Wall, G.W., 2011. Methodologies for simulating impacts of climate change on crop production. Field Crops Res. 124 (3), 357–368.

Williams, J.R., Jones, C.A., Kiniry, J.R., Spanel, D.A., 1989. The EPIC crop growth model. Trans. ASAE 32 (2), 497–0511.

Woldemeskel, F.M., Sharma, A., Sivakumar, B., Mehrotra, R., 2014. A framework to quantify GCM uncertainties for use in impact assessment studies. J. Hydrol. 519, 1453-146.

Wösten, J.H.M., Lilly, A., Nemes, A., Le Bas, C., 1999. Development and use of a database of hydraulic properties of European soils. Geoderma 90 (3-4), 169–185.

Zhao, J., Bindi, M., Eitzinger, J., Ferrise, R., Gaile, Z., Gobin, A., Olesen, J.E., 2022. Priority for climate adaptation measures in European crop production systems. Eur. J. Agron. 138, 126516.