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Winter wheat–soybean relay intercropping in conjunction with a shift in sowing dates as a climate change adaptation and mitigation strategy for crop production in Germany

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ABSTRACT

Context: Given the negative impacts of climate change on crop production, it is vital to implement efficient adaptation and mitigation strategies. The diversification of cropping systems, particularly through intercropping combined with shifts in sowing times, could have the potential to offset such negative impacts. Yet, both experimental data and simulation studies are scarce to elucidate the intercropping performance under future climate change conditions, particularly for evaluating its potential to offset climate impacts on crop and protein yields in German wheat-based systems.
Objective: This study aimed to simulate the grain yield and grain protein performance of winter wheat-soybean relay-row intercropping across Germany under future climate conditions, comparing it to sole cropping systems.
Methods: We employed the MONICA agroecosystem model and its intercropping module to simulate the performance of an innovative winter wheat–soybean relay intercropping system. This was in combination with a wide range of shifts in sowing dates, and we compared it against standard sole cropping under low and high emission scenarios across Germany.
Results: The model projected a 15 % higher sole wheat yield under the future (2031–2060) high emission scenario than that of the historical period (1981–2020), while sole soybean yield increased by 8 % in the same case. Although the simulation of winter wheat–soybean relay intercropping across Germany indicated a 9 % yield penalty compared to sole cropping in the future, with a transgressive overyielding index of 0.91, intercropping emerged as particularly advantageous in terms of land-use efficiency and protein production. It saved 17 % of land compared to sole cropping, thus produced equal amounts of grain yield, and produced 16 % more protein than sole cropping in the high emission scenario. On top of that, shifting the sowing dates of the component crops to earlier times was found to substantially enhance the advantages of intercropping, resulting in a maximum of 44 % higher total yield production, and 47 % higher protein production than sole wheat without shifting sowing date in the future projection window.
Conclusion: Our findings highlight the grain yield and protein production potential of intercropping versus sole cropping under futuristic high emission scenarios (RCP 8.5), and underscoring its potential to create a win-win situation of increased crop diversity and productivity. The results affirm the crucial importance of selecting optimal sowing dates for the component crops in intercropping, to maximize production and ensure resilience in the face of a changing climate.

1. Introduction

Climate change is projected to pose significant challenges to efforts aimed at maximising crop yields in various environments (Asseng et al., 2019; Liu, Asseng, Müller, et al., 2016; Rezaei et al., 2023). Rising temperatures are likely to intensify extreme events such as heatwaves and droughts, shorten the growth cycle, and increase variability in crop yields, contributing to the risk of yield penalties (Liu et al., 2022). Wheat

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yield, one of the main pillars of food production, has stagnated in several regions around the globe, including in Western Europe (Brisson et al., 2010). Ensemble modelling projections suggest that for each degree-Celsius rise in the average global temperature, global wheat production will decrease by 6.0 % (Asseng et al., 2015). In Western Europe, the rate of wheat yield increase has been declining since the mid-90s (Schauberger et al., 2018), from 1.18 t ha^{-1} per decade between 1961 and 1995–0.05 t ha^{-1} per decade between 1996 and 2020 (FAOSTAT, 2023). Several factors have been suggested as potential causes of this yield stagnation in Europe. Some studies have proposed that climate extremes are the primary cause (Agnolucci and De Lipsis, 2020; Brisson et al., 2010; McCouch and Rieseberg, 2023). Globally, without adaptation strategies, the production of four key crops (wheat, maize, rice, and soybean) would fall by approximately 2 % in a high emission scenario (Müller et al., 2015). And even though the elevated CO_2 concentration can partly compensate for the yield reduction due to climate extremes, additional pressure on grain quality degradation in terms of protein concentration challenges food security and sustainability (Asseng et al., 2019). Protein production, which interlinks the carbon and nitrogen cycle and climate change, is considered paramount (Aiking and de Boer, 2020; Weindl et al., 2020). The boosting demand in protein will exacerbate the agricultural impacts on the environment, which potentially transgress the environmental limits for food system (Springmann et al., 2018). Consequently, it is imperative to implement adaptation and mitigation measures that offset the challenges of climate change.

Crop diversification has recently received more attention as a way to improve yield stability in the face of climate change (Hufnagel et al., 2020; Molénat et al., 2023; Reckling et al., 2022). Diversification enhances the functionality of cropping systems by regulating the competition for resources (Altieri et al., 2015). In addition, diversification prevents the synchronisation of sensitive phenological phases with extreme climatic events (Arenas-Corraliza et al., 2022). Intercropping, a well-established practice for diversifying cropping systems, is defined as the simultaneous cultivation of two or more distinct crop species in the same field during a single growing season (Mead and Willey, 1980; McAlvay et al., 2022). The primary benefits of intercropping include improved soil health (Layek et al., 2018), greater use efficiency of water, nutrients, and light (Kermah et al., 2017), increased biodiversity (Nourbakhsh et al., 2019), higher risk resilience (Huss et al., 2022), and better control of pests and diseases (Himmelstein et al., 2017). A set of meta-analyses revealed that intercropping reduced the amount of land required by approximately 18–23 % when compared to production of the same species in sole cropping (Li et al., 2023; Martin-Guay et al., 2018; Yu et al., 2015). A modelling study showed that maize–soybean intercropping could boost total yields by 41.3 % and increase economic revenue by 23.8 % compared to sole cropping in Northeast China (Zhang et al., 2022). Cereal–legume intercropping has been widely recognised as a synergistic combination. The cereal component benefits from the fixation of atmospheric nitrogen by the legume in the current or succeeding growing season, especially when the crops are not heavily fertilised (Mugi-Ngenga et al., 2022). However, the magnitude of that response needs to be evaluated in relay intercropping, where the sowing times of cereals and legumes differ. And the differences in root architecture between them result in niche differentiation, along with the other typical advantages of intercropping (Bedoussac et al., 2015). The legume component, generally considered as protein-rich crops, demonstrated the possibility for substituting part of the animal protein production, and thus potentially mitigate the emission from increasing unsustainable animal production and consumption (Willett et al., 2019).

Given the merits of crop diversification and intercropping showed by research, not much evidence demonstrated various diversification strategies were well adopted by farmers. Most farmers still go for simple rotation rotations (2–3 crops) (Hufnagel et al., 2020). Several factors, hinder the expansion of intercropping in the practice of large-scale and industrial agriculture, such as in Europe. These include a lack of adapted machinery, the complexity of agronomic management, gaps in knowledge and training, and challenges in selecting suitable crop pairs (Brooker et al., 2015; Li et al., 2020). Another particularly challenging factor is that greater niche differentiation can improve resource use efficiency, but it complicates field management due to inconsistencies in the timing of phenology and variations in plant morphology (Hernández-Ochoa et al., 2022). Since most of the agronomic management recommendations were formulated based on research on sole cropping systems, these guidelines would need to be revised for intercropping. Additional farming expertise would also be required to precisely time field operations, modify agronomic practices, and adjust the use of agrochemicals in managing intercropping systems (Burgess et al., 2022). Specific field arrangements, such as relay intercropping, offer new opportunities in agronomy by addressing some of the challenges of regular mixed cropping systems (Lamichhane et al., 2023). The main advantage is that crops are harvested separately and do not require additional sorting. Process-based crop or agroecosystem models are currently being used to help navigate the complexities of intercropping for agronomic decision-making and to bridge knowledge gaps (Kherif et al., 2022). One of the advantages of such models is their ability to assess the effectiveness of combined adaptation strategies to climate change, such as the combination of intercropping and modifying sowing dates, and simulating the impacts of the climate in the past as well as in the future.

Adverse effects of climate change on crop yield can be mitigated by adjusting sowing dates, especially in temperate regions with distinct seasonality. This helps avoid extreme weather events, aligns with shifting temperature and precipitation patterns, and extends the growing period (Waha et al., 2013; Wu et al., 2023; Zeleke and Nendel, 2016). Adapting sowing dates is a strategy that requires few resources and economic investment, yet is effective in helping capacity-constrained farmers (Waongo et al., 2015). It thus stands a greater chance of adoption by farmers when combined with new cropping systems compared to more fundamental changes that would require greater investment, such as in new machinery. Studies exploring the potential of intercropping in conjunction with changes in sowing dates to counteract the negative effects of climate change on large-scale crop productivity are rare, and currently do not exist for relay intercropping systems. This is mainly because most models designed for intercropping simulations demand extensive calibration and validation data, and this data is not typically available on a large scale. Moreover, shifting sowing dates not only alters how crops adjust to changing environmental patterns with respect to the temporal-spatial niches of intercropping, but it also affects the competitive ability of component crops in parallel. Furthermore, previous findings have demonstrated that the precise modelling of diversified cropping systems requires improved representations of crop interactions, the inclusion of a wider array of crop species options, the consideration of soil legacy effects, and refinements of biodiversity estimations (Hernández-Ochoa et al., 2022). One newly developed intercropping module for the MONICA agroecosystem model has provided an effective tool for simulating relay intercropping with minimal parameterisation effort (Yu et al., 2024).

To gain insights into integrated climate adaptation measures, we employ the process-based agroecosystem model, MONICA (Model for Nitrogen and Carbon dynamics in Agro-eco systems), to project the results of a winter wheat–soybean relay intercropping system interacting with a sowing date shift in various future climate scenarios in Germany. The research aims to address the following research questions: (a) How does climate change influence the yield of winter wheat and soybean in sole cropping as well as in intercropped systems? And (b) to what extent can a combination of intercropping and sowing date adjustments help crops adapt to climate change, maintaining crop grain and protein productivity without greater expansion in cultivated areas?

2. Materials and methods

MONICA (Nendel et al., 2011) is a process-based crop simulation model for nitrogen and carbon dynamics in agroecosystems. The model is driven by daily weather, soil characteristics, species/cultivar-specific inputs, and agronomic management practices at various spatial scales (Battisti et al., 2017, 2018; Nendel et al., 2014). MONICA simulates photosynthesis and respiration explicitly, using the Farquhar approach as laid out by Mitchell et al. (Mitchell et al., 1995) and stomatal conductance feedback as suggested by Yu et al. (2001). Photosynthesis in MONICA separates clear-sky and cloudy conditions to estimate biomass accumulation, as Goudriaan suggested for SUCROS (Goudriaan and Van Laar, 1978). The model takes into account the negative impacts of heat stress, water and nitrogen deficiency, and aeration deficits on crop growth processes and yield formation. The elevation of CO_2 under climate change increases the radiation use efficiency and decreases the transpiration rate in MONICA. These processes have been calibrated based on impact assessments published in previous studies for wheat and soybean (Asseng et al., 2019; Nendel et al., 2023). The original MONICA was developed for sole cropping systems, but Yu et al. recently developed and tested a new module to capture the relay-row intercropping of the winter wheat–soybean system using Tsubo and Walker's Horizontal Homogeneous Canopy concept (Tsubo and Walker, 2002). The new module separates the canopy into two layers based on the difference in plant height between the component crops. The leaf area index (LAI) of each layer depends on the plant height ratio between the two crops, and light interception is calculated based on the daily share of LAI in each layer accordingly (Yu et al., 2024). MONICA plant height simulation follows the logistic curve to the parameterized maximum plant height. To mimic the suppression effect of built crop to the relayed crop in intercropping, an empirical model of plant height suppression factor related to the built crop temperature sum was employed in intercropping version of MONICA (version 3.6.10 https://github.com/zalf-rpm/monica), thus the plant height plasticity of relayed crop in the intercropping from suppression of built crop can be accounted for.

2.1. Field experiment

The calibration and validation procedure was based on three years of field experiments (the 2020–2021, 2021–2022 and 2022–2023 growing seasons) for winter wheat–soybean relay-row intercropping. These experiments were conducted at ZALF's experimental station in Müncheberg, Germany (52̊31' N, 07̊38' E). The study treatments included sole winter wheat (cv. Reform), sole soybean (cv. Merlin), and their relay-row intercropping, each under both irrigated and rainfed conditions. Field experiment followed a split-plot arrangement, each plot with a size of 24 m^2 (3 m × 8 m). Six replicated plots followed a randomised complete block design. Within each plot, the row spacing for winter wheat and soybean were 12.5 cm and 50 cm, respectively. For intercrop plots, each soybean row was cultivated between double rows of wheat, keeping the soybean row distance of 50 cm. Information regarding field management can be found in previous study (Yu et al., 2024).

The crop phenology was visually estimated based on the BBCH scale. To rule out the border effect, aboveground biomass (AGB) was sampled from 1 m^2 of central rows in the plot, and then separated into leaves, stem, and spike (pod). Leaf area index and light interception was measured by a linear quantum sensor (Li-Cor, Lincoln, NE, USA). Soil moisture was taken from topsoil (7 cm) by soil moisture sensor. Plant heights were taken non-destructively. The aforementioned measurements were conducted throughout the growing season. Final grain yield was taken by a combined harvester with a unique extension customized for intercropping. Yield sampling area was 12 m^2 for each plot. The laboratory analysis of grain nitrogen content was conducted after harvest. To fulfill the model input, soil bulk densities and inorganic nitrogen content were measured from three soil layers in 0–30 cm, 30–60 cm, and 60–90 cm, separately sampled from three replicate soil cores.

2.2. Model inputs

The MONICA model (version 3.6.10; model and data can together be found through CASSIS simulation infrastructure (Berg-Mohnicke and Nendel, 2022)) requires crop, climate, site, and management for execution. Winter wheat (cv. RGT Reform), and soybean (cv. Merlin) were calibrated and validated using phenology, leaf area index (LAI), aboveground biomass (AGB) and grain yield as target variables. Species-specific light extinction coefficients were derived from field-measured light interception and LAI. The validated model against observations showed R-squared values of 0.84 and 0.73 for aboveground biomass and yield, respectively, with the root means square errors of 1.88 t ha^{-1} and 0.81 t ha^{-1} (Supplementary figure. 1). Daily climate inputs required are maximum and minimum temperatures, precipitation, solar radiation, wind speed, and relative humidity. These inputs for historical (1981–2010) and future (2030–2060) periods were obtained from the German weather service at a 5 km × 5 km resolution (www.dwd.de). The future climate projections are based on three general circulation models: ICHEC-EC-EARTH, MIROC-MIROC5, and MPI-M-MPI-ESM-LR from CMIP5 (Taylor et al., 2012), whose simulations were downscaled using regional climate models for Germany, including KNMI-RACMO22E, CLMcom-CCLM4–8–17, GERICS-REMO2015, and MPI-CSC-REMO2009 (Climate Service Center, 2017; Clmcom, 2016; Hübener et al., 2017; Royal Netherlands Meteorological, I, 2017). Two emission scenarios, RCP 2.6 and RCP 8.5, were used in the simulation setup as the "low-emission" and "high emission" future scenarios, respectively (Meinshausen et al., 2011). The high–emission scenario gives a much more rapid warming and more pronounced changes in indicators such as river flow, water temperature, and precipitation. Additional input variables including latitude, slope, soil profile parameters (such as the thickness of the soil layer, soil organic matter, soil texture according to the KA5 texture class (Eckelmann et al., 2005), and bulk density), were obtained from the BÜK200 dataset generated by the Federal Institute for Geosciences and Natural Resources (Krug et al., 2013). As the climate condition within Germany varies, the sowing date of winter wheat in Germany ranged between ordinal date 261–294. A default winter wheat sowing date across 6575 sites in Germany is available in the MONICA model, and used for the simulation (version 3.6.10 https://github.com/zalf-rpm/monica). The crop mask indicating the wheat cultivation field of Germany was applied (Blickensdörfer et al., 2022). Since soybean is a new crop for northern Germany (Karges et al., 2022), we fixed the sowing date to ordinal date 126 for all 1 km grids across the country. 40, 80, and 40 kg ha^{-1} of nitrogen fertiliser was applied at 60, 120, and 150 days, respectively, after winter wheat sowing in both sole and intercropping wheat (Söder et al., 2022). No extra nitrogen fertiliser was applied to soybean in the simulation. Both winter wheat and soybean have access to water, the water competition of relay-row intercropping in the model considers water sharing through copying the soil profile of the developed crop after its soil-plant process was calculated to the relayed crop. It is based on the assumption that water is always being uptaken up primarily by the dominant crop in a relay-row intercropping, remaining goes to the relayed crop, and excessive water is then back to the dominant crop soil profile for the calculation of the next day. Indirectly, the consequence of the aboveground competition naming the changed LAI contribute to the evapo-transpiration and the water uptake. The model calibrated and validated in both rain-fed and irrigated condition (Section 2.1), the model's sensitivity to indirect competition for water seems sufficient to capture the difference across water regimes (Yu et al., 2024). Facilitation was not considered. Nitrogen uptake and usage were calculated independently, no direct interaction was involved.

2.3. Management scenarios

The management scenarios under investigation included sole cropping for winter wheat and soybean, as well as intercropping systems in which both crops experienced a range of sowing date shifts. Sowing date for winter wheat shifted from −30 to +20 days, and soybean sowing date shifted from −20 to +10 days using 10-day as intervals, thus simulation ran a total of 24 (6 × 4) combinations of sowing dates. The shift of winter wheat sowing date was based on the default sowing date of winter wheat obtained from the sowing date map (Section 2.2). As soybean is a new crop in Germany, the default sowing date of 6th, May was used. The reason we selected sowing shift as a management scenario was its relevance as a primary method of adaptation to changes in temperature and precipitation patterns under climate change. All simulations were conducted under rainfed conditions with no irrigation applied. The simulation covered all of Germany in a 1 km^2 grid, further refined to current areas of wheat cultivation (Söder et al., 2022). There were 216 simulations per grid (92419 grids), covering all combinations of climate and management scenarios. The workflow of this study was illustrated (Fig. 1).

2.4. Intercropping performance indicators

The land equivalent ratio (LER) (Harris et al., 1987), is a standard indicator for comparing intercropping to sole cropping; it is calculated as the sum of the yields of the two intercrop components, each scaled by its sole crop yield (Eq. 1). The ratio between the intercrop yield and sole crop yield is the equivalent area of the component crop, referring to the area of sole cropping land required to achieve the same yield as one unit area of intercropping. An LER above 1 means intercropping has a higher land-use efficiency than sole cropping:

$$LER = \frac{Y_{i1}}{Y_{s1}} + \frac{Y_{i2}}{Y_{s2}} \quad (1)$$

where Y_{i1} and Y_{i2} are the intercropping yields for component crops 1 and 2 respectively. Y_{s1} and Y_{s2} are the corresponding sole cropping yields. However, the LER does not necessarily mean an increased overall yield compared to sole cropping. Therefore, we employed the transgressive overyielding index (TOI) to identify whether yield production per unit area was maximised. The TOI is calculated as the ratio between the intercropping yield sum and the maximum sole cropping yield (Eq. 2). A TOI larger than 1 indicates a relative increase in the absolute yield results from shifting away from the most productive sole cropping (Li et al., 2023):

$$TOI = \frac{Y_{i1} + Y_{i2}}{\max(Y_{s1}, \quad Y_{s2})} \quad (2)$$

Both grain yield and protein yield TOI were calculated as TOI_{grain} and $TOI_{protein}$. As the competition of nitrogen was not directly involved in the current version of inter-MONICA, the protein content was estimated using the measured N content (Soybean: 5.83 %, winter-wheat: 1.84 %) of the harvested grain from the three-year experiment (Supplementary figure. 2) multiplied by the protein content conversion factor suggested by FAO report (Soybean: 5.71, winter-wheat: 5.83) (Food and Agricultural Organization of the United Nations & World Health Organization, 2007) .

3. Results

3.1. Future yield projections – sole cropping

The simulated median yield of winter wheat in the sole cropping system during the historical period (1981–2010) was 5520 kg ha^{-1} across Germany (Fig. 2). The median wheat yield is projected to increase by 4 % under RCP 2.6 and by 15 % under RCP 8.5 compared to the baseline period. The highest simulated yield of wheat (7413 kg ha^{-1}) was obtained under RCP 8.5 (Fig. 2). The mean yield difference of wheat between the historical period and the future window was 123 kg ha^{-1} for RCP 2.6, and 683 kg ha^{-1} for RCP 8.5. There is also a spatial discrepancy in the yield difference of wheat and soybean between the future yield projections and the baseline across Germany. The eastern parts of the country indicated a soybean yield gain under climate change, whereas the northern and central parts showed the most negative yield responses (Fig. 2). The simulated median soybean yield planted in the wheat growing area for the historical period was 1599 kg ha^{-1} (Fig. 2). The median projected yield decreased by 7 % under RCP 2.6, whereas it increased by 8 % under RCP 8.5. The mean yield difference between historical and future conditions under RCP 2.6 was −81 kg ha^{-1}, with spatial discrepancies observed in the eastern and south-eastern parts of the country (Fig. 2). On the other hand, the high emission scenario (RCP 8.5) led to a marginal yield enhancement

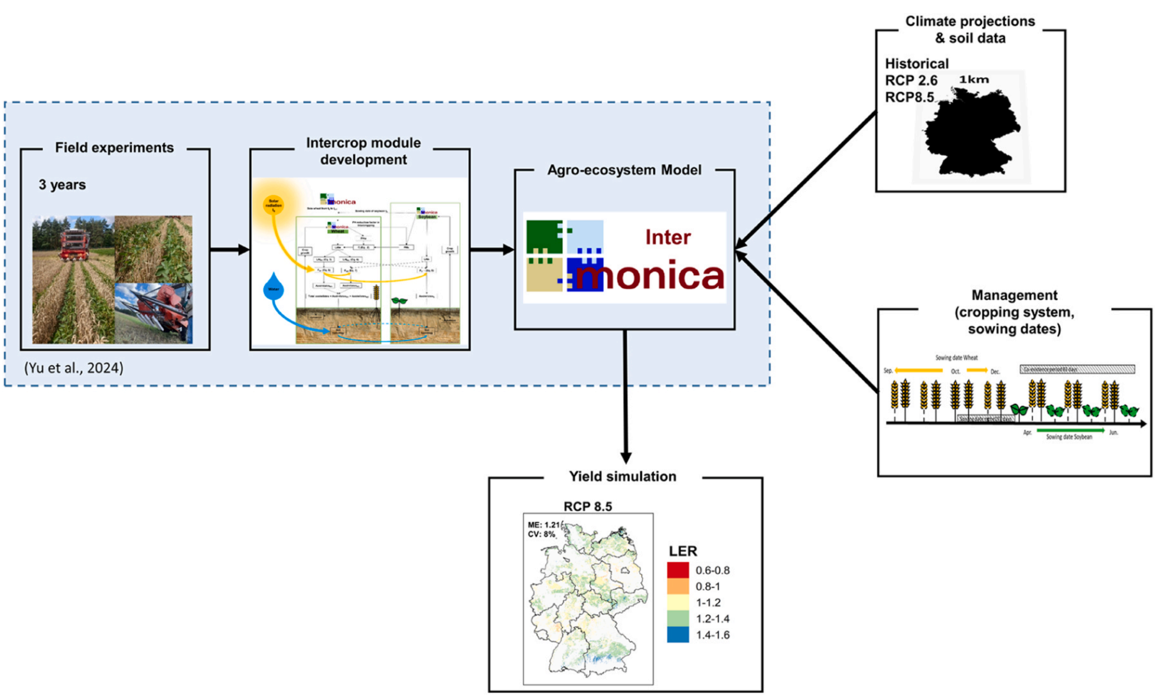

Fig. 1. Schematic workflow of simulating yield of winter wheat-soybean relay-row intercropping in conjunction with shifting sowing dates under climate scenarios.

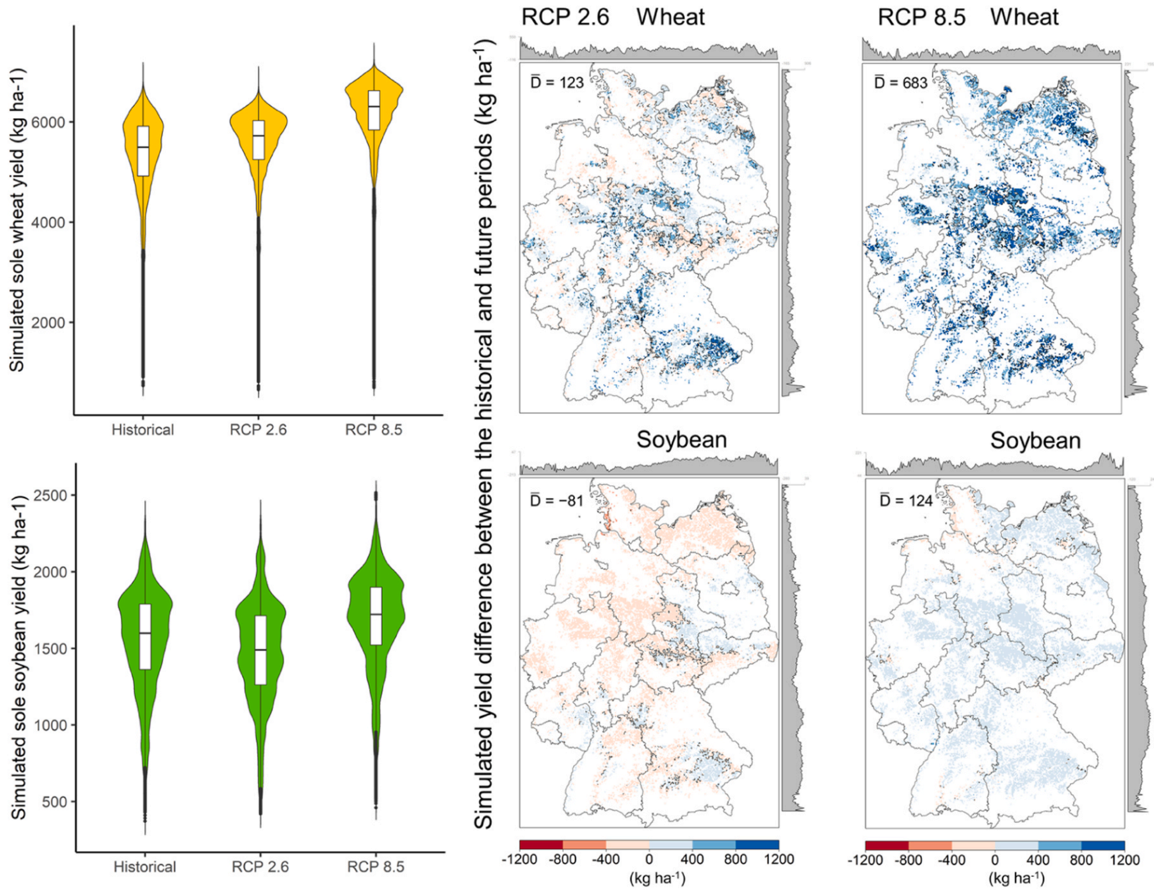

Fig. 2. The violin/box plot and spatial pattern of simulated winter wheat and soybean yield for sole cropping under historical (1981–2010) and future climate (2031–2060) scenarios (RCP 2.6 and RCP 8.5) across Germany. The discrepancy maps indicate the mean yield difference (D) between historical and future climate scenarios for each crop.

(124 kg ha^{-1}) of soybean across the entire country. The yield difference of soybean under RCP 8.5 was similar across Germany, except for the northwest which showed a decreased yield compared to the historical period (Fig. 2).

3.2. Future grain and protein yield projections – intercropping

The simulation of winter wheat–soybean relay intercropping across Germany indicated yield decreases relative to sole cropping, with a grain transgressive overyielding index (TOI_{grain}) of 0.86 for the historical period (Fig. 3 and Supplementary figure. 3). The median value of the TOI_{grain} fell to 0.83 under RCP 2.6 and increased to 0.91 under RCP 8.5. This meant that the TOI_{grain} s were mostly below one in all climate scenarios, indicating no overyielding in terms of grain yield of intercropping compared to the most productive sole crop, in this case, sole winter-wheat. However, under climate change scenarios, the potential for intercropping to achieve higher land-use efficiency was evident, with values ranging between 1 and 1.6 for the LER_{grain} across northeastern, central eastern, and southern parts of the country (Fig. 3). The median values of the LER_{grain} increased to 1.21 under the high emission scenario. The median of transgressive overyielding index of protein production ($TOI_{protein}$) ranged from 1.05 to 1.16, indicating that even though the total grain yield production of intercropping was not higher than sole winter wheat, intercropping potentially produced 5–16 % more protein than the most protein-productive sole crop (soybean or winter wheat). The RCP 8.5 future emission scenario had the lowest spatial variability, with 8 % for the LER_{grain}, 11 % for the TOI_{grain}, and 9 % for the $TOI_{protein}$. Variability under the historical scenario and emission scenario RCP 2.6 were marginally higher than RCP 8.5 (CV: 8 %) (Fig. 2). The grain yield of intercropped winter wheat under RCP 2.6 was marginally higher than under the historical scenario, while the yield projections of intercropped soybean decreased by 7 %. Under the RCP 8.5 scenario, intercropped winter wheat yield was 18 % higher than baseline period, and intercropped soybean yield increased by 20 % compared to baseline (Supplementary figure. 3). Under the RCP 8.5 future emission scenario, the spatial patterns of the LER_{grain} revealed that the central eastern and southern parts of the country could benefit substantially more in terms of land-use efficiency from intercropping than the northern and western parts of Germany could (Fig. 3).

3.3. Adjusting sowing dates as an adaptive strategy

Adjusting the sowing dates for winter wheat and soybean earlier separately in relay-row intercropping demonstrated the substantial potential of such shifts to enhance land-use efficiency in the intercropping system, particularly under the RCP 8.5 scenario (Fig. 4). In general, earlier sowing dates for both crops increased the land-use potential, but the effect was more pronounced when the winter wheat sowing dates were shifted as opposed to soybean. By shifting the sowing date of winter wheat 30 days earlier than the original date, the LER_{grain} increased by 50 % under RCP 2.6 and 35 % under RCP 8.5 (Fig. 4). When the sowing of winter wheat was delayed by 20 days, the LER_{grain} decreased by 7 % under RCP 2.6 and 8 % under RCP 8.5 (Fig. 4). In the latest sowing scenario for soybean (10 days later), the LER_{grain} increased slightly under both RCP 2.6 (2 %) and RCP 8.5 (2 %) (Fig. 4).

Despite the sowing date effects on land-use efficiency (Fig. 5 and Supplementary Figure 4), the dynamic changes in sowing dates for both crops also had a remarkable impact on the grain and protein production

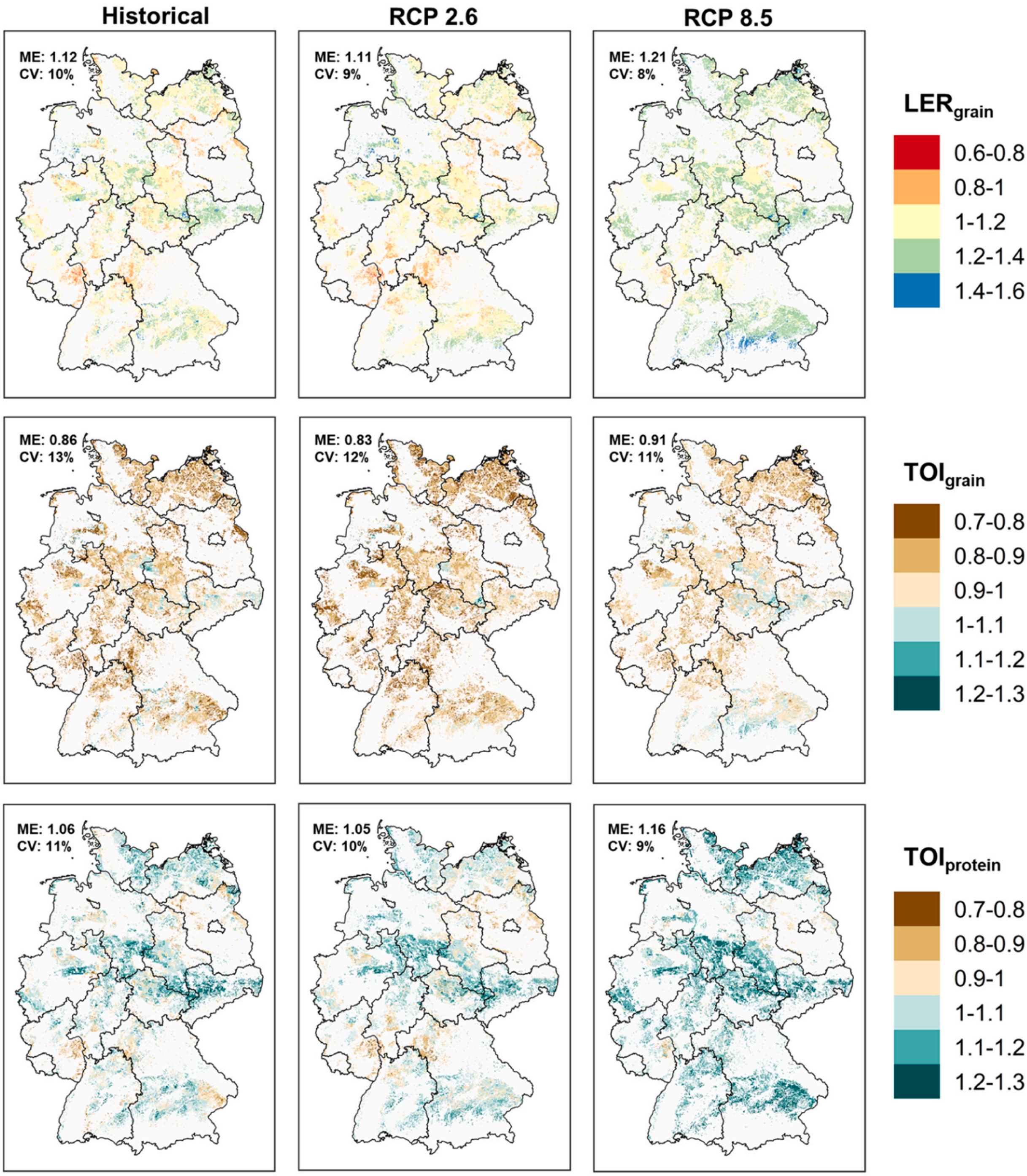

Fig. 3. The spatial pattern of the simulated grain yield land equivalent ratio (LER_{grain}) and the transgressive overyielding index of grain (TOI_{grain}) and grain protein ($TOI_{protein}$) for winter wheat–soybean relay-row intercropping under historical (1981–2010) and future climate (2031–2060) scenarios (RCP 2.6 and RCP 8.5) across Germany. ME: median and CV: coefficient of variation.

of the intercropping system (Fig. 5). The median TOI_{grain} reveals that overall yield production of intercropping only exceeded that of sole crops when winter wheat was sown at least 20 days earlier under the climate change scenarios (Fig. 5). Shifting winter wheat sowing to 20 days later, and delaying soybean sowing for 10 days caused a 26 % (RCP 2.6) and 16 % (RCP 8.5) loss of total grain yield compared to sole wheat. The highest median TOI_{grain} of 1.44 for Germany was obtained when winter wheat was sown 30 days earlier and soybean 10 days later under RCP 2.6, increasing TOI_{grain} by 58 % compared to that of the original sowing dates (TOI_{grain}: 0.91). Median values of $TOI_{protein}$ under future climate scenarios range from 0.96 to 1.47. The $TOI_{protein}$ below 1 appears only under RCP 2.6 when winter wheat sown 20–30 days earlier with the soybean sowing unchanged or delayed 10 days, indicating the protein production of intercropping was 1–4 % lower than the most protein-productive sole crop.

4. Discussion

4.1. Future yield projections for winter wheat–soybean intercropping and sole wheat

Our results illustrate that winter wheat–soybean relay-row

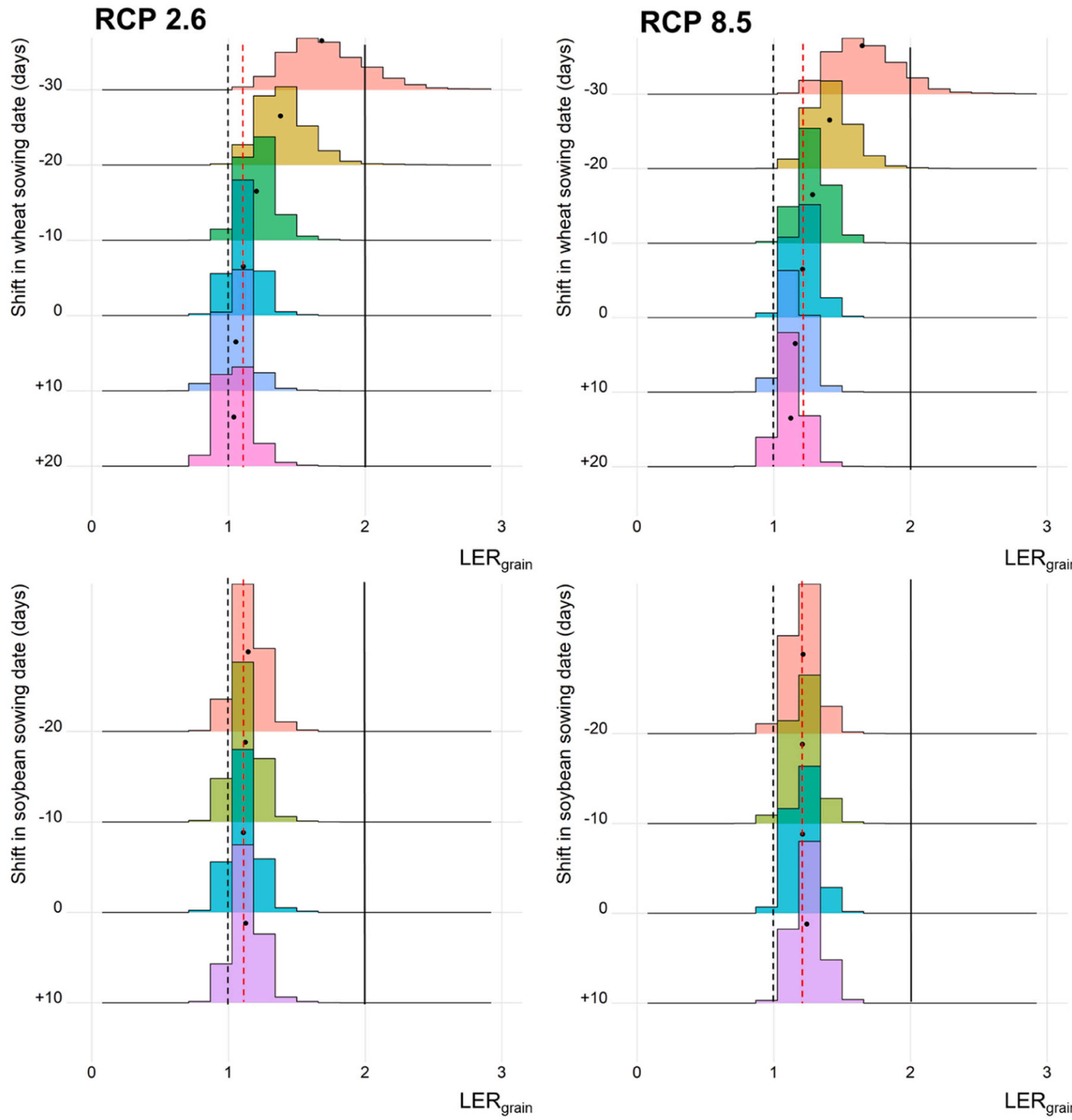

Fig. 4. Density ridgeline of the simulated grain yield land equivalent ratio (LER_{grain}) for various sowing scenarios of winter wheat and soybean intercropping (with the sowing date kept constant for the other crop) under RCP 2.6 and RCP 8.5 future climate scenarios (2031–2060). The black points represent median values. The sowing date of "-10" indicates crops sown 10 days earlier than the original sowing date, while "10" signifies a 10-day delay in the sowing date. The black vertical dashed line at 1.0 indicates the reference value for the LER_{grain} if intercropping were to provide the same LER_{grain} as the sole cropping approaches. The red vertical dashed lines represent the LER_{grain} with no sowing date shift. The black solid line at 2.0 indicates the LER_{grain} of sequentially sown. All LER_{grain} is based on an equivalent sole crop shift for the crop that is shifted in the intercrop.

intercropping can outperform sole cropping with respect to land-use efficiency in Germany's central eastern and southern regions, where temperatures are projected to be higher than other areas (Fig. 3). This is especially true under high emission scenario, with a substantial land reduction rate of 17 % (LER_{grain}: 1.21). The results indicate that intercropping can effectively produce diversified food crops with limited farming area. The high LER_{grain} across climate conditions is due to the relay-row arrangement. Intercropping benefits from higher light interception due to an increased total intercepting area and an extended growing season (Caviglia et al., 2004). Unlike intercropping with little to no temporal niche difference, winter wheat yield in relay-row intercropping was not drastically affected by soybean growth, combined with less intraspecific competition, the wheat yield ratio between intercropping and sole-cropping (Eq. 1) ultimately approached one. Thus, the minor losses in wheat equivalent area due to intercropping can be easily offset by the soybean equivalent area (Supplementary figure.3), which leads to higher land-use efficiency than sole cropping. A relay intercrop with vast temporal niche difference was always compared to double cropping, which refers to a rotation within one year with a LER of 2. However in temperate region the temperature sum and short growing season may not support the sequential sowing. The implementation of wheat-soybean intercropping in Germany presents a suitable option for crop diversification without significantly impacting the overall cropping system. Given that winter wheat occupies 25 % of the cropping area and grows for approximately 302 days annually, there is limited calendar space for introducing additional crops. Normally, farmers in Germany took winter barley and oil rape seeds as subsequent crops for winter wheat, with barley being sown in September and oil rape seeds in August. As the relayed soybean needs to remain in the field for longer than mid-August, the subsequent crops are suggested to turn into winter

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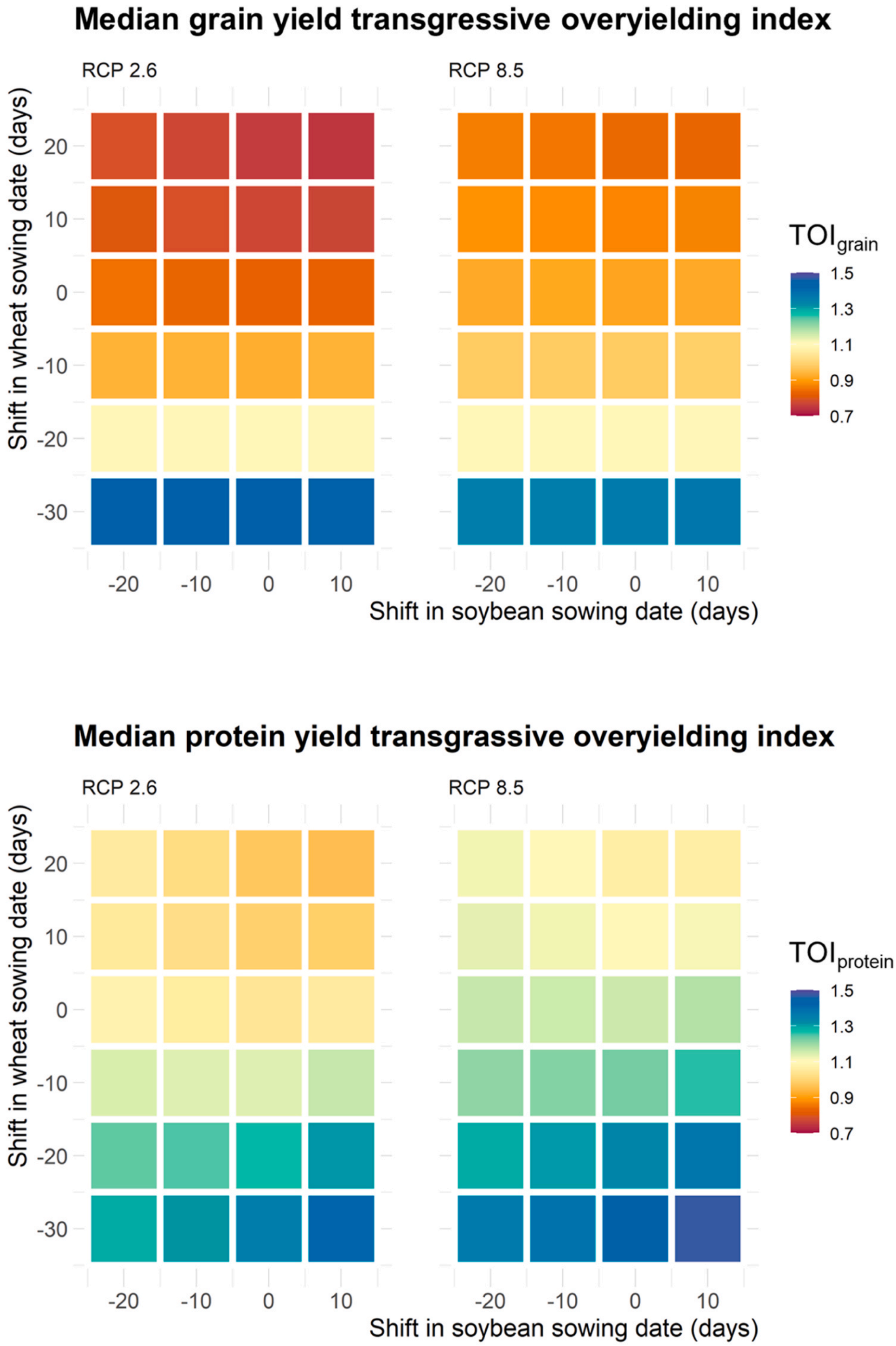

Fig. 5. Heat map displaying the median of the simulated transgressive overyielding index of grain yield (top row) and protein (bottom row) for various sowing scenarios of winter wheat and soybean (TOI_{grain}, $TOI_{protein}$), accounting for dynamic changes in the sowing dates of both crops. This is shown for RCP 2.6 (left column) and RCP 8.5 (right column), for the future climate period of 2031–2060. The sowing date of "-10" indicates crops sown 10 days earlier than the original sowing date, while "10" signifies a 10-day delay in the sowing date.

rye or a spring crop like maize. Even though shifting from sole winter wheat to relay intercropping has consequences for the subsequent crops, the introduction of soybean, a crop in high demand but with limited adoption in Europe, adds value to the rotation without sacrificing the dominant winter wheat production. This intercropping system, therefore, serves as a transitional phase towards greater diversification. It utilizes existing wheat-growing areas without displacing other crops spatially and maximizes land use efficiency. The studied relay of default sowing dates has co-growing period of 83 days with the total growing period of 361 days. Therefore a relay-intercropping in this region can substantially increase the land-use efficiency.

Grain yield transgressive overyielding was still not achieved, but this does not contravene the positive complementarity and elevated land-use efficiency and protein productivity of intercropping (Fig. 3). On the one hand, the TOI_{grain} reached the highest levels in high emission climate scenarios, with only a 9 % yield penalty compared to winter wheat sole crops. It implies the potential of intercropping as a possible adaptation strategy for reducing the negative impacts of excessive temperature and drought on crop productivity (Lobell, 2014). On the other hand, a $TOI_{grain} > 1$ has generally been harder to achieve when component crops possess contrasting yield levels, and stronger niche differentiation of species is required (Li et al., 2023). In our study, winter wheat yield was two times higher than that of soybean (Fig. 2). The intercropping winter wheat harvest was 15 days earlier under RCP 8.5 compared to the baseline, and the accelerated development reduced the period of extreme shading suppression for soybeans in relay-row intercropping (Supplementary figure. 5). These conditions were not present during the baseline, and most of the soybean growing period was significantly affected by wheat shading (Leoni et al., 2022). Unlike the TOI_{grain} which always compare the intercropping total yield to the sole winter wheat, the referenced sole crop in $TOI_{protein}$ became flexible, as protein content of soybean was almost 3 times of that for wheat. As a consequence, protein yield of intercropping was higher than the sole crops in all climate scenarios (Fig. 2), owing to the integration of a protein-rich crop. Although the protein content would rather decrease due to dilution effect (Taub et al., 2008), instead of remaining constant as calculated in this study under climate change, the increased amount of protein production in intercropping over sole cropping has the possibility to overcompensate the negative effects on the protein concentration. Management improvements to reduce the yield deficits of high-yield species resulting from the presence of low-yield species could help increase the TOI_{grain}. However, obtaining a high TOI_{grain} is less likely to be the aim of farmers, it would be rather important to combine TOI_{grain} and $TOI_{protein}$ to understand the trade-offs between grain production and protein production of intercrops, and eventually evaluating the profitability based on specific economic goal.

The mean projected yield of sole-cropped winter wheat across Germany indicated increases in both climate scenarios for the sole cropping system compared to the baseline period (Fig. 2). This result was consistent with previous impact assessments based on multi-model ensembles, which have indicated that increased CO_2 fertilisation resulting from climate change more than compensates for the negative impacts of increased temperatures in temperate regions such as Germany when discussing wheat yields (Asseng et al., 2019; Jägermeyr et al., 2021). The most recent study in this context projected a 7 % increase in winter wheat yield in Germany under climate change conditions (Söder et al., 2022). On the other hand, the mean projected yield of soybean showed a slight decrease under RCP 2.6 compared to the historical period (Fig. 2). This is partly due to the shortening of critical development phases, such as the grain-filling period (Supplementary figure. 5), owing to the acceleration of the development rate (Liu, Asseng, Liu, et al., 2016; Lobell et al., 2012; Senapati et al., 2019). However, the mean projected soybean yield increased under RCP 8.5, primarily because of CO_2 fertilisation and the higher favourable temperature range for soybean compared to winter wheat. This improved the leaf area expansion rate and biomass accumulation (Battisti et al., 2018; Kothari et al., 2022). Similar results were obtained in a European-scale impact assessment, showing a yield increase of up to 8.7 % under RCP 8.5 for sole soybean (Nendel et al., 2023). It is important to note that the soybean simulations in our study used a wheat growing area, as it is a 'new crop' introduced in Germany. Thus unfavourable growing conditions may cause variability in soybean yield (Manners et al., 2020).

4.2. Shifting the sowing dates of winter wheat and soybean during intercropping

Shifting the sowing dates of crops is a crucial strategy for adapting cropping systems to climate change, as this technique helps mitigate the effects of higher temperatures on shortening the total growing period, serving as an escape mechanism to prevent crops' exposure to terminal heat and drought (Dobor et al., 2016; Dueri et al., 2022). In relay intercropping, such a shift can significantly influence the dynamics of competition between species and thus affect the growth and productivity of each crop component (Ahmed et al., 2018; Raza et al., 2019). Changing the sowing date of wheat in the intercropped system had a more robust influence on land-use efficiency than changing soybean sowing dates (Fig. 4). Wheat is the dominant crop in winter wheat–soybean relay-row intercropping, as it is planted earlier and suffers less from intraspecific competition due to lower density. It also has developed significant leaf area by the time of soybean emergence. Soybean plants begin to recover from interspecific competition with winter wheat when winter wheat plants enter leaf senescence (Li et al., 2001). This makes the timing of sowing for each crop in relay intercropping extremely critical. In our simulations of climate change conditions, the earlier winter wheat sowing dates (10–30 days) linearly increased the land-use efficiency of intercropping compared to sole cropping by up to 35 % (Fig. 4), because wheat yields increased without any decline in soybean yields. Although late-sown winter wheat weakened the land-use efficiency in the simulation, in practice, this is generally compensated for by higher seeding density by farmers. Other studies have also shown compensatory effects of earlier sowing dates on winter wheat yield under climate change scenarios. Benefits arise from a better overlap between precipitation patterns and the most water-intensive growth stages (Nouri et al., 2017), improved vernalisation due to adaptation to shorter winters (Rezaie et al., 2022), a longer overall growing season (He et al., 2015), and reduced exposure to extreme events during critical development stages (Akter and Rafiqul Islam, 2017; Dubey et al., 2020). The model accounts for vernalization, overlapping water demands and precipitation, longer growing seasons, and extreme events, but it does not consider sowing density.

Shifting sowing dates for both crops increases the land-use efficiency and overall yield production of intercropping even further (Fig. 5). By changing the sowing dates, the TOI_{grain} (Fig. 5) increased substantially – by 58 %, and $TOI_{protein}$ by 19.5 % (winter wheat: 30 days earlier, soybean: 10 days later) compared to the traditional sowing dates (Fig. 5). Sowing soybeans close to the reproductive stage of winter wheat (in cases of early winter wheat and late soybean sowing) shortens the overlap between soybean leaf expansion and wheat shading dominance. This strategy opens up the growing window for soybean, thereby maximising the yield of both crops and resulting in a higher land equivalent ratio and total yield productivity. A similar negative relationship between the co-growth period and the LER has also been found in maize-based intercropping systems (Ahmed et al., 2020; Zhao et al., 2023). However, in practice, the early-sown winter wheat was shown to develop too soon, such that when the sowing tractor drives over the field to plant the soybean, mechanical damage to wheat occurred. This means that it is still necessary to fine-tune the process and use specially adapted machinery. Quantifying the biomass loss due to machinery and correlating it with the development of winter wheat can improve the model's ability to optimise the sowing dates for component crops. In addition, early-sown winter wheat combined with late-sown soybean can limit some of the benefits of legume–cereal intercropping, such as better utilisation efficiency due to resource sharing and facilitation mechanisms (Kermah et al., 2017; Latati et al., 2016), weed management in soybean resulting from an earlier closed canopy, and ecosystem services facilitated by biodiversity (Afrin et al., 2017; Hüber et al., 2022). Nevertheless, these intercropping benefits are difficult to quantify according to the commonly used LER and TOI. Any reduction in environmental impact through the reduced inputs of herbicides, pesticides, and fertilisation (which are extremely important in the current sustainability context) were outside the scope of this study. Better indicators and multi-criteria for evaluating intercropping performance are necessary to encourage the transformation of agri-food systems to those based on agro-ecological principles.

4.3. Limitations and outlook

The limitations of the modelling approach employed here must be considered when interpreting the results. The specific focus of the intercropping routine in MONICA is on aboveground interactions and competition for light interception (Yu et al., 2024), direct interactions for belowground processes regarding nitrogen are not considered in this modelling setup. Existing conflict between remaining with current yield levels and at the same time reducing pollution in water bodies by excess nitrogen reinforced the urgency of adopting a more nitrogen-efficient cropping system. Even though the biological N fixation from the intercropping legumes alone would not fully address the problem (Martre et al., 2024), our results of elevated protein yield production illustrated that without further increase of N fertilizer use, intercropping showed greater potential in N use efficiency. Therefore, even with the limitation in nitrogen competition, this work implies that intercropping, along with its yield potential will be an important unit in the integrative strategy addressing the crisis in fertilization use.

Indirect competition for water in the model was sufficient to capture the yield and biomass variability of rain-fed and irrigation condition in the specific field experiment environment, particularly when the nitrogen demands of both crops are met. However, whether this holds true for other environments needs further investigation. The model accounts for the dodging of extreme heat and drought through shifting sowing dates, but the alleviated stresses deriving from changed micro-climate, facilitation and nutrient sharing during co-growing period was not quantified. Developing a comprehensive modelling routine to consider belowground crop–crop interactions is more challenging, since exploring root growth in intercropping systems is difficult to monitor with field conditions (Aguilar et al., 2021) and exhibits a high level of phenotypic plasticity (Schneider and Lynch, 2020). We also assumed the use of a specific amount of nitrogen fertiliser (160 kg ha^{-1}) for wheat, because higher nitrogen application can intensify the dominance of winter wheat in interspecific competition and potentially inhibit soybean establishment.

Significant adjustments to field machinery are also required to sow soybeans between fully expanded wheat plants and harvest wheat ears without damaging the soybean plants in the field (Lamichhane et al., 2023), considering shifting sowing dates for component crops in our study better tapped the production and land use potential than the traditional sowing dates. Therefore, the feasibility of transitioning from sole cropping to intercropping systems requires a system-wide perspective. This transition necessitates a thorough analysis of the necessary investments and socioeconomic impacts arising from changes in agronomic practices, especially in the context of future climatic conditions (Huss et al., 2022). In addition, future intercropping strategies will require the targeted breeding of cultivars that are more suitable for these specific cropping systems (Bourke et al., 2021; Fletcher et al., 2016).

Our study reveals the substantial potential of relay-row intercropping for certain regions, combined with shifts in sowing dates, to compensate for the negative effects of climate change on crop yield and protein productivity compared to the sole wheat cropping system. Despite the lack of data concerning belowground competition when using MONICA and the need to improve field machinery for intercropping management, this extensive spatial-temporal simulation across Germany depicted a future in which diversified cropping systems can significantly increase the resilience of specialised farming. The model's capabilities allow more options for relay-row intercropping to be explored with long-term simulations under diverse climate scenarios to support the transformation in agriculture.

5. Conclusion

Our work presents the first intercropping prediction on a national scale. As an endeavour towards a transformative redesign of the agri-food system, our findings corroborate intercropping's potential in providing diverse products with less farming land. Intercropping yields still cannot exceed sole cropping at the current management level, but the elevated protein production is evident. To tackle this, efforts are needed to test favourable crop combinations, optimise agronomic management (sowing, spatial patterns, water, and nutrients). We have taken a step further by manipulating sowing dates of component crops on top of transforming the farming system. Our results reveal that by adjusting sowing times for intercropping, we can further enhance TOI_{grain}, $TOI_{protein}$ and $LER_{protein}$ by 58 %, 20 % and 39 %, respectively, emphasising the potential of intercropping as an adaptation and mitigation strategy for climate change in the future. While our analysis provides information on yield and protein, a thorough quantification of the agro-ecological services that intercropping provides still remain a topic of study for promoting crop diversification.

CRediT authorship contribution statement

Jing Yu: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Ehsan Eyshi Rezaei:** Writing – review & editing, Supervision, Resources, Conceptualization. **Claas Nendel:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Moritz Reckling:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

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.fcr.2024.109695.

Data availability

Data will be made available on request.

References

Afrin, S., Latif, A., Banu, N., Kabir, M., Haque, S., Ahmed, M.E., Tonu, N., Ali, M., 2017. Intercropping empower reduces insect pests and increases biodiversity in agro-ecosystem. Agric. Sci. 8 (10), 1120. https://doi.org/10.4236/as.2017.810082.

Agnolucci, P., De Lipsis, V., 2020. Long-run trend in agricultural yield and climatic factors in Europe. Clim. Change 159 (3), 385–405. https://doi.org/10.1007/s10584-019-02622-3.

Aguilar, J.J., Moore, M., Johnson, L., Greenhut, R.F., Rogers, E., Walker, D., O'Neil, F., Edwards, J.L., Thystrup, J., Farrow, S., Windle, J.B., Benfey, P.N., 2021. Capturing in-field root system dynamics with RootTracker. Plant Physiol. 187 (3), 1117–1130. https://doi.org/10.1093/plphys/kiab352.

Ahmed, S., Raza, M.A., Yuan, X., Du, Y., Iqbal, N., Chachar, Q., Soomro, A.A., Ibrahim, F., Hussain, S., Wang, X., Liu, W., Yang, W., 2020. Optimized planting time and co-growth duration reduce the yield difference between intercropped and sole soybean by enhancing soybean resilience toward size-asymmetric competition. Food Energy Secur. 9 (3), e226. https://doi.org/10.1002/fes3.226.

Ahmed, S., Raza, M.A., Zhou, T., Hussain, S., Khalid, M.H., Feng, L., Wasaya, A., Iqbal, N., Ahmed, A., Liu, W., Yang, W., 2018. Responses of Soybean Dry Matter Production, Phosphorus Accumulation, and Seed Yield to Sowing Time under Relay Intercropping with Maize. Agronomy 8 (12). https://doi.org/10.3390/agronomy8120282.

Aiking, H., de Boer, J., 2020. The next protein transition. Trends Food Sci. Technol. 105, 515–522. https://doi.org/10.1016/j.tifs.2018.07.008.

Akter, N., Rafiqul Islam, M., 2017. Heat stress effects and management in wheat. A review. Agron. Sustain. Dev. 37 (5), 37. https://doi.org/10.1007/s13593-017-0443-9.

Altieri, M.A., Nicholls, C.I., Henao, A., Lana, M.A., 2015. Agroecology and the design of climate change-resilient farming systems. Agron. Sustain. Dev. 35 (3), 869–890. https://doi.org/10.1007/s13593-015-0285-2.

Arenas-Corraliza, M.G., López-Díaz, M.L., Rolo, V., Cáceres, Y., Moreno, G., 2022. Phenological, morphological and physiological drivers of cereal grain yield in Mediterranean agroforestry systems. Agric., Ecosyst. Environ. 340, 108158. https://doi.org/10.1016/j.agee.2022.108158.

Asseng, S., Ewert, F., Martre, P., Rötter, R.P., Lobell, D.B., Cammarano, D., Kimball, B.A., Ottman, M.J., Wall, G., White, J.W., 2015. Rising temperatures reduce global wheat production. Nat. Clim. Change 5 (2), 143–147. https://doi.org/10.1038/nclimate2470.

Asseng, S., Martre, P., Maiorano, A., Rötter, R.P., O'Leary, G.J., Fitzgerald, G.J., Girousse, C., Motzo, R., Giunta, F., Babar, M.A., Reynolds, M.P., Kheir, A.M.S., Thorburn, P.J., Waha, K., Ruane, A.C., Aggarwal, P.K., Ahmed, M., Balkovič, J., Basso, B., Biernath, C., Bindi, M., Cammarano, D., Challinor, A.J., De Sanctis, G., Dumont, B., Eyshi Rezaei, E., Fereres, E., Ferrise, R., Garcia-Vila, M., Gayler, S., Gao, Y., Horan, H., Hoogenboom, G., Izaurralde, R.C., Jabloun, M., Jones, C.D., Kassie, B.T., Kersebaum, K.-C., Klein, C., Koehler, A.-K., Liu, B., Minoli, S., Montesino San Martin, M., Müller, C., Naresh Kumar, S., Nendel, C., Olesen, J.E., Palosuo, T., Porter, J.R., Priesack, E., Ripoche, D., Semenov, M.A., Stöckle, C., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Van der Velde, M., Wallach, D., Wang, E., Webber, H., Wolf, J., Xiao, L., Zhang, Z., Zhao, Z., Zhu, Y., Ewert, F., 2019. Climate change impact and adaptation for wheat protein. Glob. Change Biol. 25 (1), 155–173. https://doi.org/10.1111/gcb.14481.

Battisti, R., Parker, P.S., Sentelhas, P.C., Nendel, C., 2017. Gauging the sources of uncertainty in soybean yield simulations using the MONICA model. Agric. Syst. 155, 9–18. https://doi.org/10.1016/j.agsy.2017.04.004.

Battisti, R., Sentelhas, P.C., Boote, K.J., 2018. Sensitivity and requirement of improvements of four soybean crop simulation models for climate change studies in Southern Brazil. Int. J. Biometeorol. 62 (5), 823–832. https://doi.org/10.1007/s00484-017-1483-1.

Bedoussac, L., Journet, E.-P., Hauggaard-Nielsen, H., Naudin, C., Corre-Hellou, G., Jensen, E.S., Prieur, L., Justes, E., 2015. Ecological principles underlying the increase of productivity achieved by cereal-grain legume intercrops in organic farming. A review. Agron. Sustain. Dev. 35 (3), 911–935. https://doi.org/10.1007/s13593-014-0277-7.

Berg-Mohnicke, M., Nendel, C., 2022. A case for object capabilities as the foundation of a distributed environmental model and simulation infrastructure. Environ. Model. Softw. 156, 105471. https://doi.org/10.1016/j.envsoft.2022.105471.

Blickensdörfer, L., Schwieder, M., Pflugmacher, D., Nendel, C., Erasmi, S., Hostert, P., 2022. Mapping of crop types and crop sequences with combined time series of Sentinel-1, Sentinel-2 and Landsat 8 data for Germany. Remote Sens. Environ. 269, 112831. https://doi.org/10.1016/j.rse.2021.112831.

Bourke, P.M., Evers, J.B., Bijma, P., van Apeldoorn, D.F., Smulders, M.J.M., Kuyper, T. W., Mommer, L., Bonnema, G., 2021. Breeding Beyond Monoculture: Putting the "Intercrop" Into Crops [Review]. Front. Plant Sci. 12. ⟨https://www.frontiersin.org/articles/10.3389/fpls.2021.734167⟩.

Brisson, N., Gate, P., Gouache, D., Charmet, G., Oury, F.-X., Huard, F., 2010. Why are wheat yields stagnating in Europe? A comprehensive data analysis for France. Field Crops Res. 119 (1), 201–212. https://doi.org/10.1016/j.fcr.2010.07.012.

Brooker, R.W., Bennett, A.E., Cong, W.F., Daniell, T.J., George, T.S., Hallett, P.D., Hawes, C., Iannetta, P.P., Jones, H.G., Karley, A.J., 2015. Improving intercropping: a synthesis of research in agronomy, plant physiology and ecology. N. Phytol. 206 (1), 107–117. https://doi.org/10.1111/nph.13132.

Burgess, A.J., Correa Cano, M.E., Parkes, B., 2022. The deployment of intercropping and agroforestry as adaptation to climate change. Crop Environ. 1 (2), 145–160. https://doi.org/10.1016/j.crope.2022.05.001.

Caviglia, O.P., Sadras, V.O., Andrade, F.H., 2004. Intensification of agriculture in the south-eastern Pampas: I. Capture and efficiency in the use of water and radiation in double-cropped wheat–soybean. Field Crops Res. 87 (2-3), 117–129. https://doi.org/10.1016/j.fcr.2003.10.002.

Climate Service Center, G. (2017). *cordex EUR-11 MPI-CSC REMO2009* World Data Center for Climate (WDCC) at DKRZ. ⟨http://hdl.handle.net/21.14106/64bf48fa23cae9263da6c76ece1872870bb14180⟩.

Clmcom. (2016). *CLMcom CORDEX data for Europe (EUR-11) based on CCLM4-8-17 model simulations* World Data Center for Climate (WDCC) at DKRZ. ⟨http://hdl.handle.net/21.14106/65c6e1e7d10dae63cfaf35b7d456c0973348be6f⟩.

Dobor, L., Barcza, Z., Hlásny, T., Árendás, T., Spitkó, T., Fodor, N., 2016. Crop planting date matters: Estimation methods and effect on future yields. Agric. For. Meteorol. 223, 103–115. https://doi.org/10.1016/j.agrformet.2016.03.023.

Dubey, R., Pathak, H., Chakrabarti, B., Singh, S., Gupta, D.K., Harit, R.C., 2020. Impact of terminal heat stress on wheat yield in India and options for adaptation. Agric. Syst. 181, 102826. https://doi.org/10.1016/j.agsy.2020.102826.

Dueri, S., Brown, H., Asseng, S., Ewert, F., Webber, H., George, M., Craigie, R., Guarin, J. R., Pequeno, D.N.L., Stella, T., 2022. Simulation of winter wheat response to variable sowing dates and densities in a high-yielding environment. J. Exp. Bot. 73 (16), 5715–5729. https://doi.org/10.1093/jxb/erac221.

Eckelmann, W., Sponagel, H., & Grottenthaler, W. (2005). Bodenkundliche Kartieranleitung.-5. verbesserte und erweiterte-Auflage. ⟨http://www.schweizerbart.de/pubs/isbn/bgr/bodenkundl-3510959205-desc.html⟩.

FAOSTAT. (2023). *Crops and livestock products.* ⟨https://www.fao.org/faostat/en/#data/QCL⟩.

Fletcher, A.L., Kirkegaard, J.A., Peoples, M.B., Robertson, M.J., Whish, J., Swan, A.D., 2016. Prospects to utilise intercrops and crop variety mixtures in mechanised, rain-fed, temperate cropping systems. Crop Pasture Sci. 67 (12), 1252–1267. https://doi.org/10.1071/CP16211.

Food and Agricultural Organization of the United Nations & World Health Organization, 2007. Cereals, pulses, legumes and vegetable proteins, 1st ed.). Food and Agricultural Organization of the United Nations & World Health Organization, Rome, Italy ⟨https://www.fao.org/4/a1392e/a1392e00.htm⟩.

Goudriaan, J., Van Laar, H., 1978. Calculation of daily totals of the gross CO2 assimilation of leaf canopies. Neth. J. Agric. Sci. 26 (4), 373–382. https://doi.org/10.18174/njas.v26i4.17080.

Harris, D., Natarajan, M., Willey, R.W., 1987. Physiological basis for yield advantage in a sorghum/groundnut intercrop exposed to drought. 1. Dry-matter production, yield, and light interception. Field Crops Res. 17 (3), 259–272. https://doi.org/10.1016/0378-4290(87)90039-6.

He, L., Asseng, S., Zhao, G., Wu, D., Yang, X., Zhuang, W., Jin, N., Yu, Q., 2015. Impacts of recent climate warming, cultivar changes, and crop management on winter wheat phenology across the Loess Plateau of China. Agric. For. Meteorol. 200, 135–143. https://doi.org/10.1016/j.agrformet.2014.09.011.

Hernández-Ochoa, I.M., Gaiser, T., Kersebaum, K.-C., Webber, H., Seidel, S.J., Grahmann, K., Ewert, F., 2022. Model-based design of crop diversification through new field arrangements in spatially heterogeneous landscapes. A review. Agron. Sustain. Dev. 42 (4), 74. https://doi.org/10.1007/s13593-022-00805-4.

Himmelstein, J., Ares, A., Gallagher, D., Myers, J., 2017. A meta-analysis of intercropping in Africa: impacts on crop yield, farmer income, and integrated pest management effects. Int. J. Agric. Sustain. 15 (1), 1–10. https://doi.org/10.1080/14735903.2016.1242332.

Hübener, H., Bülow, K., Fooken, C., Früh, B., Hoffmann, P., Höpp, S., Keuler, K., Menz, C., Mohr, V., Radtke, K., Ramthun, H., Spekat, A., Steger, C., Toussaint, F., Warrach-Sagi, K., & Woldt, M. (2017). *cordex-reklies EUR-11 GERICS REMO2015* World Data Center for Climate (WDCC) at DKRZ. ⟨http://hdl.handle.net/21.14106/107016b2a75a1a1e4329441ebfa540b52d9b3831⟩.

Hüber, C., Zettl, F., Hartung, J., Müller-Lindenlauf, M., 2022. The impact of maize-bean intercropping on insect biodiversity. Basic Appl. Ecol. 61, 1–9. https://doi.org/10.1016/j.baae.2022.03.005.

Hufnagel, J., Reckling, M., Ewert, F., 2020. Diverse approaches to crop diversification in agricultural research. A review. Agron. Sustain. Dev. 40 (2), 1–17. https://doi.org/10.1007/s13593-020-00617-4.

Huss, C.P., Holmes, K.D., Blubaugh, C.K., 2022. Benefits and Risks of Intercropping for Crop Resilience and Pest Management. J. Econ. Entomol. 115 (5), 1350–1362. https://doi.org/10.1093/jee/toac045.

Jägermeyr, J., Müller, C., Ruane, A.C., Elliott, J., Balkovic, J., Castillo, O., Faye, B., Foster, I., Folberth, C., Franke, J.A., Fuchs, K., Guarin, J.R., Heinke, J., Hoogenboom, G., Iizumi, T., Jain, A.K., Kelly, D., Khabarov, N., Lange, S., Lin, T.-S., Liu, W., Mialyk, O., Minoli, S., Moyer, E.J., Okada, M., Phillips, M., Porter, C., Rabin, S.S., Scheer, C., Schneider, J.M., Schyns, J.F., Skalsky, R., Smerald, A., Stella, T., Stephens, H., Webber, H., Zabel, F., Rosenzweig, C., 2021. Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. Nat. Food 2 (11), 873–885. https://doi.org/10.1038/s43016-021-00400-y.

Karges, K., Bellingrath-Kimura, S.D., Watson, C.A., Stoddard, F.L., Halwani, M., Reckling, M., 2022. Agro-economic prospects for expanding soybean production beyond its current northerly limit in Europe. Eur. J Agron. 133, 126415. https://doi.org/10.1016/j.eja.2021.126415.

Kermah, M., Franke, A.C., Adjei-Nsiah, S., Ahiabor, B.D.K., Abaidoo, R.C., Giller, K.E., 2017. Maize-grain legume intercropping for enhanced resource use efficiency and crop productivity in the Guinea savanna of northern Ghana. Field Crops Res. 213, 38–50. https://doi.org/10.1016/j.fcr.2017.07.008.

Kherif, O., Seghouani, M., Justes, E., Plaza-Bonilla, D., Bouhenache, A., Zemmouri, B., Dokukin, P., Latati, M., 2022. The first calibration and evaluation of the STICS soil-crop model on chickpea-based intercropping system under Mediterranean conditions. Eur. J. Agron. 133, 126449. https://doi.org/10.1016/j.eja.2021.126449.

Kothari, K., Battisti, R., Boote, K.J., Archontoulis, S.V., Confalone, A., Constantin, J., Cuadra, S.V., Debaeke, P., Faye, B., Grant, B., Hoogenboom, G., Jing, Q., van der Laan, M., Macena da Silva, F.A., Marin, F.R., Nehbandani, A., Nendel, C., Purcell, L. C., Qian, B., Ruane, A.C., Schoving, C., Silva, E.H.F.M., Smith, W., Soltani, A., Srivastava, A., Vieira, N.A., Slone, S., Salmerón, M., 2022. Are soybean models ready for climate change food impact assessments? Eur. J. Agron. 135, 126482. https://doi.org/10.1016/j.eja.2022.126482.

Krug, D., Stegger, U., & Eckelmann, W. (2013). Bodenübersichtskarte 1: 200.000 (BÜK 200)–Status und Perspektiven 2013 (Homogenisierung, Qualitätssicherung, Auswertung, Präsentation).

Lamichhane, J.R., Alletto, L., Cong, W.-F., Dayoub, E., Maury, P., Plaza-Bonilla, D., Reckling, M., Saia, S., Soltani, E., Tison, G., Debaeke, P., 2023. Relay cropping for sustainable intensification of agriculture across temperate regions: Crop management challenges and future research priorities. Field Crops Res. 291, 108795. https://doi.org/10.1016/j.fcr.2022.108795.

Latati, M., Bargaz, A., Belarbi, B., Lazali, M., Benlahrech, S., Tellah, S., Kaci, G., Drevon, J.J., Ounane, S.M., 2016. The intercropping common bean with maize improves the rhizobial efficiency, resource use and grain yield under low phosphorus availability. Eur. J. Agron. 72, 80–90. https://doi.org/10.1016/j.eja.2015.09.015.

Layek, J., Das, A., Mitran, T., Nath, C., Meena, R.S., Yadav, G.S., Shivakumar, B.G., Kumar, S., Lal, R., 2018. Cereal+Legume Intercropping: An Option for Improving Productivity and Sustaining Soil Health. In: Meena, In.R.S., Das, A., Yadav, G.S.,

Lal, R. (Eds.), Legumes for soil health and sustainable management. Springer Singapore, pp. 347–386. https://doi.org/10.1007/978-981-13-0253-4_11.
Leoni, F., Lazzaro, M., Ruggeri, M., Carlesi, S., Meriggi, P., Moonen, A.C., 2022. Relay intercropping can efficiently support weed management in cereal-based cropping systems when appropriate legume species are chosen. Agron. Sustain. Dev. 42 (4), 75. https://doi.org/10.1007/s13593-022-00787-3.
Li, C., Hoffland, E., Kuyper, T.W., Yu, Y., Zhang, C., Li, H., Zhang, F., van der Werf, W., 2020. Syndromes of production in intercropping impact yield gains. Nat. Plants 6 (6), 653–660. https://doi.org/10.1038/s41477-020-0680-9.
Li, C., Stomph, T.-J., Makowski, D., Li, H., Zhang, C., Zhang, F., van der Werf, W., 2023. The productive performance of intercropping. Proc. Natl. Acad. Sci. 120 (2), e2201886120. https://doi.org/10.1073/pnas.2201886120.
Li, L., Sun, J., Zhang, F., Li, X., Rengel, Z., Yang, S., 2001. Wheat/maize or wheat/ soybean strip intercropping: II. Recovery or compensation of maize and soybean after wheat harvesting. Field Crops Res. 71 (3), 173–181. https://doi.org/10.1016/S0378-4290(01)00157-5.
Liu, B., Asseng, S., Liu, L., Tang, L., Cao, W., Zhu, Y., 2016. Testing the responses of four wheat crop models to heat stress at anthesis and grain filling. Glob. Change Biol. 22 (5), 1890–1903. https://doi.org/10.1111/gcb.13212.
Liu, B., Asseng, S., Müller, C., Ewert, F., Elliott, J., Lobell, David B., Martre, P., Ruane, Alex C., Wallach, D., Jones, James W., Rosenzweig, C., Aggarwal, Pramod K., Alderman, Phillip D., Anothai, J., Basso, B., Biernath, C., Cammarano, D., Challinor, A., Deryng, D., Sanctis, Giacomo D., Doltra, J., Fereres, E., Folberth, C., Garcia-Vila, M., Gayler, S., Hoogenboom, G., Hunt, Leslie A., Izaurralde, Roberto C., Jabloun, M., Jones, Curtis D., Kersebaum, Kurt C., Kimball, Bruce A., Koehler, A.-K., Kumar, Soora N., Nendel, C., O'Leary, Garry J., Olesen, J.ørgen E., Ottman, Michael J., Palosuo, T., Prasad, P.V.V., Priesack, E., Pugh, Thomas A.M., Reynolds, M., Rezaei, Ehsan E., Rötter, Reimund P., Schmid, E., Semenov, Mikhail A., Shcherbak, I., Stehfest, E., Stöckle, Claudio O., Stratonovitch, P., Streck, T., Supit, I., Tao, F., Thorburn, P., Waha, K., Wall, Gerard W., Wang, E., White, Jeffrey W., Wolf, J., Zhao, Z., Zhu, Y., 2016. Similar estimates of temperature impacts on global wheat yield by three independent methods. Nat. Clim. Change 6 (12), 1130–1136. https://doi.org/10.1038/nclimate3115.
Liu, F., Li, X., Hogy, P., Jiang, D., Brestic, M., & Liu, B. (2022). *Sustainable Crop Productivity and Quality under Climate Change Responses of Crop Plants to Climate Change*. Elsevier Science & Technology San Diego. 〈https://public.ebookcentral.proquest.com/choice/PublicFullRecord.aspx?p= 7012363〉.
Lobell, D.B., 2014. Climate change adaptation in crop production: Beware of illusions. Glob. Food Secur. 3 (2), 72–76. https://doi.org/10.1016/j.gfs.2014.05.002.
Lobell, D.B., Sibley, A., Ivan Ortiz-Monasterio, J., 2012. Extreme heat effects on wheat senescence in India. Nat. Clim. Change 2 (3), 186–189. https://doi.org/10.1038/nclimate1356.
Manners, R., Varela-Ortega, C., van Etten, J., 2020. Protein-rich legume and pseudo-cereal crop suitability under present and future European climates. Eur. J. Agron. 113, 125974. https://doi.org/10.1016/j.eja.2019.125974.
Martin-Guay, M.-O., Paquette, A., Dupras, J., Rivest, D., 2018. The new green revolution: sustainable intensification of agriculture by intercropping. Sci. Total Environ. 615, 767–772. https://doi.org/10.1016/j.scitotenv.2017.10.024.
Martre, P., Dueri, S., Guarin, J.R., Ewert, F., Webber, H., Calderini, D., Molero, G., Reynolds, M., Miralles, D., Garcia, G., Brown, H., George, M., Craigie, R., Cohan, J.-P., Deswarte, J.-C., Slafer, G., Giunta, F., Cammarano, D., Ferrise, R., Gaiser, T., Gao, Y., Hochman, Z., Hoogenboom, G., Hunt, L.A., Kersebaum, K.C., Nendel, C., Padovan, G., Ruane, A.C., Srivastava, A.K., Stella, T., Supit, I., Thorburn, P., Wang, E., Wolf, J., Zhao, C., Zhao, Z., Asseng, S., 2024. Global needs for nitrogen fertilizer to improve wheat yield under climate change. Nat. Plants 10 (7), 1081–1090. https://doi.org/10.1038/s41477-024-01739-3.
McAlvay, A.C., DiPaola, A., D'Andrea, A.C., Ruelle, M.L., Mosulishvili, M., Halstead, P., Power, A.G., 2022. Cereal species mixtures: an ancient practice with potential for climate resilience. A review. Agron. Sustain. Dev. 42 (5), 100. https://doi.org/10.1007/s13593-022-00832-1.
McCouch, S.R., Rieseberg, L.H., 2023. Harnessing crop diversity. Proc. Natl. Acad. Sci. 120 (14), e2221410120. https://doi.org/10.1073/pnas.2221410120.
Mead, R., Willey, R., 1980. The concept of a 'land equivalent ratio'and advantages in yields from intercropping. Exp. Agric. 16 (3), 217–228. https://doi.org/10.1017/S0014479700010978.
Meinshausen, M., Smith, S.J., Calvin, K., Daniel, J.S., Kainuma, M.L.T., Lamarque, J.F., Matsumoto, K., Montzka, S.A., Raper, S.C.B., Riahi, K., Thomson, A., Velders, G.J.M., van Vuuren, D.P.P., 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Clim. Change 109 (1), 213. https://doi.org/10.1007/s10584-011-0156-z.
Mitchell, R.A.C., Lawlor, D.W., Mitchell, V.J., Gibbard, C.L., White, E.M., Porter, J.R., 1995. Effects of elevated CO2 concentration and increased temperature on winter wheat: test of ARCWHEAT1 simulation model. Plant, Cell Environ. 18 (7), 736–748. https://doi.org/10.1111/j.1365-3040.1995.tb00576.x.
Molénat, J., Barkaoui, K., Benyoussef, S., Mekki, I., Zitouna, R., Jacob, F., 2023. Diversification from field to landscape to adapt Mediterranean rainfed agriculture to water scarcity in climate change context. Curr. Opin. Environ. Sustain. 65, 101336. https://doi.org/10.1016/j.cosust.2023.101336.
Mugi-Ngenga, E., Bastiaans, L., Zingore, S., Anten, N.P.R., Giller, K.E., 2022. The role of nitrogen fixation and crop N dynamics on performance and legacy effects of maize-grain legumes intercrops on smallholder farms in Tanzania. Eur. J. Agron. 141, 126617. https://doi.org/10.1016/j.eja.2022.126617.
Müller, C., Elliott, J., Chryssanthacopoulos, J., Deryng, D., Folberth, C., Pugh, T.A.M., Schmid, E., 2015. Implications of climate mitigation for future agricultural production. Environ. Res. Lett. 10 (12), 125004. https://doi.org/10.1088/1748-9326/10/12/125004.
Nendel, C., Berg, M., Kersebaum, K., Mirschel, W., Specka, X., Wegehenkel, M., Wenkel, K., Wieland, R., 2011. The MONICA model: Testing predictability for crop growth, soil moisture and nitrogen dynamics. Ecol. Model. 222 (9), 1614–1625. https://doi.org/10.1016/j.ecolmodel.2011.02.018.
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. https://doi.org/10.1016/j.eja.2012.09.005.
Nendel, C., Reckling, M., Debaeke, P., Schulz, S., Berg-Mohnicke, M., Constantin, J., Fronzek, S., Hoffmann, M., Jakšić, S., Kersebaum, K.C., 2023. Future area expansion outweighs increasing drought risk for soybean in Europe. Glob. Change Biol. 29 (5), 1340–1358. https://doi.org/10.1111/gcb.16562.
Nourbakhsh, F., Koocheki, A., Mahallati, M.N., 2019. Investigation of Biodiversity and Some of the Ecosystem Services in the Intercropping of Corn, Soybean and Marshmallow. Int. J. Plant Prod. 13 (1), 35–46. https://doi.org/10.1007/s42106-018-0032-0.
Nouri, M., Homaee, M., Bannayan, M., Hoogenboom, G., 2017. Towards shifting planting date as an adaptation practice for rainfed wheat response to climate change. Agric. Water Manag. 186, 108–119. https://doi.org/10.1016/j.agwat.2017.03.004.
Raza, M.A., Bin Khalid, M.H., Zhang, X., Feng, L.Y., Khan, I., Hassan, M.J., Ahmed, M., Ansar, M., Chen, Y.K., Fan, Y.F., Yang, F., Yang, W., 2019. Effect of planting patterns on yield, nutrient accumulation and distribution in maize and soybean under relay intercropping systems. Sci. Rep. 9 (1), 4947. https://doi.org/10.1038/s41598-019-41364-1.
Reckling, M., Albertsson, J., Vermue, A., Carlsson, G., Watson, C.A., Justes, E., Bergkvist, G., Jensen, E.S., Topp, C.F.E., 2022. Diversification improves the performance of cereals in European cropping systems. Agron. Sustain. Dev. 42 (6), 118. https://doi.org/10.1007/s13593-022-00850-z.
Rezaei, E.E., Webber, H., Asseng, S., Boote, K., Durand, J.L., Ewert, F., Martre, P., MacCarthy, D.S., 2023. Climate change impacts on crop yields. Nat. Rev. Earth Environ. 4 (12), 831–846. https://doi.org/10.1038/s43017-023-00491-0.
Rezaie, B., Hosseinpanahi, F., Siosemardeh, A., Darand, M., Bannayan, M., 2022. Shifting the Sowing Date of Winter Wheat as a Strategy for Adaptation to Climate Change in a Mediterranean-Type Environment. Int. J. Plant Prod. 16 (4), 595–610. https://doi.org/10.1007/s42106-022-00202-7.
Royal Netherlands Meteorological, I. (2017). *cordex EUR-11 KNMI RACMO22E* World Data Center for Climate (WDCC) at DKRZ. 〈http://hdl.handle.net/21.14106/3da82a0eabc05fbf334d180445f312d431b8b4b9〉.
Schauberger, B., Ben-Ari, T., Makowski, D., Kato, T., Kato, H., Ciais, P., 2018. Yield trends, variability and stagnation analysis of major crops in France over more than a century. Sci. Rep. 8 (1), 16865. https://doi.org/10.1038/s41598-018-35351-1.
Schneider, H.M., Lynch, J.P., 2020. Should Root Plasticity Be a Crop Breeding Target? [Review]. Front. Plant Sci. 11 https://www.frontiersin.org/articles/10.3389/fpls.2020.00546.
Senapati, N., Brown, H.E., Semenov, M.A., 2019. Raising genetic yield potential in high productive countries: Designing wheat ideotypes under climate change. Agric. For. Meteorol. 271, 33–45. https://doi.org/10.1016/j.agrformet.2019.02.025.
Söder, M., Berg-Mohnicke, M., Bittner, M., Ernst, S., Feike, T., Frühauf, C., Golla, B., Jänicke, C., Jorzig, C., Leppelt, T., Liedtke, M., Möller, M., Nendel, C., Offermann, F., Riedesel, L., Romanova, V., Schmitt, J., Schulz, S., Seserman, D.-M., & Shawon, A.R. (2022). Climate change-related changes in yield and land use (KlimErtrag) *Braunschweig: Thünen Institute, Federal Research Institute for Rural Areas, Forests and Fisheries*, 234 p. 10.3220/WP1659347916000.
Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J., Willett, W., 2018. Options for keeping the food system within environmental limits. Nature 562 (7728), 519–525. https://doi.org/10.1038/s41586-018-0594-0.
Taub, D.R., Miller, B., Allen, H., 2008. Effects of elevated CO2 on the protein concentration of food crops: a meta-analysis. Glob. Change Biol. 14 (3), 565–575. https://doi.org/10.1111/j.1365-2486.2007.01511.x.
Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. AN OVERVIEW OF CMIP5 AND THE EXPERIMENT DESIGN. Bull. Am. METEOROLOGICAL Soc. 93 (4), 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1.
Tsubo, M., Walker, S., 2002. A model of radiation interception and use by a maize–bean intercrop canopy. Agric. For. Meteorol. 110 (3), 203–215. https://doi.org/10.1016/S0168-1923(01)00287-8.
Waha, K., Müller, C., Bondeau, A., Dietrich, J.P., Kurukulasuriya, P., Heinke, J., Lotze-Campen, H., 2013. Adaptation to climate change through the choice of cropping system and sowing date in sub-Saharan Africa. Glob. Environ. Change 23 (1), 130–143. https://doi.org/10.1016/j.gloenvcha.2012.11.001.
Waongo, M., Laux, P., Kunstmann, H., 2015. Adaptation to climate change: The impacts of optimized planting dates on attainable maize yields under rainfed conditions in Burkina Faso. Agric. For. Meteorol. 205, 23–39. https://doi.org/10.1016/j.agrformet.2015.02.006.
Weindl, I., Ost, M., Wiedmer, P., Schreiner, M., Neugart, S., Klopsch, R., Kühnhold, H., Kloas, W., Henkel, I.M., Schlüter, O., Bußler, S., Bellingrath-Kimura, S.D., Ma, H., Grune, T., Rolinski, S., Klaus, S., 2020. Sustainable food protein supply reconciling human and ecosystem health: A Leibniz Position. Glob. Food Secur. 25, 100367. https://doi.org/10.1016/j.gfs.2020.100367.
Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L.J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J.A., De Vries, W., Majele Sibanda, L., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S.E., Srinath Reddy, K., Narain, S., Nishtar, S., Murray, C.J.L., 2019. Food in the Anthropocene:

the EAT–Lancet Commission on healthy diets from sustainable food systems. Lancet 393 (10170), 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4.

Wu, F., Guo, S., Huang, W., Han, Y., Wang, Z., Feng, L., Wang, G., Li, X., Lei, Y., Yang, B., Xiong, S., Zhi, X., Chen, J., Xin, M., Wang, Y., Li, Y., 2023. Adaptation of cotton production to climate change by sowing date optimization and precision resource management. Ind. Crops Prod. 203, 117167. https://doi.org/10.1016/j.indcrop.2023.117167.

Yu, O., Goudriaan, J., Wang, T.-D., 2001. Modelling Diurnal Courses of Photosynthesis and Transpiration of Leaves on the Basis of Stomatal and Non-Stomatal Responses, Including Photoinhibition. Photosynthetica 39 (1), 43–51. https://doi.org/10.1023/A:1012435717205.

Yu, J., Rezaei, E.E., Thompson, J.B., Reckling, M., Nendel, C., 2024. Modelling crop yield in a wheat–soybean relay intercropping system: A simple routine in capturing competition for light. Eur. J. Agron. 153, 127067. https://doi.org/10.1016/j.eja.2023.127067.

Yu, Y., Stomph, T.-J., Makowski, D., van der Werf, W., 2015. Temporal niche differentiation increases the land equivalent ratio of annual intercrops: A meta-analysis. Field Crops Res. 184, 133–144. https://doi.org/10.1016/j.fcr.2015.09.010.

Zeleke, K.T., Nendel, C., 2016. Analysis of options for increasing wheat (Triticum aestivum L.) yield in south-eastern Australia: The role of irrigation, cultivar choice and time of sowing. Agric. Water Manag. 166, 139–148. https://doi.org/10.1016/j.agwat.2015.12.016.

Zhang, Y., Sun, Z., Wang, E., Du, G., Feng, C., Zhang, W., Xu, H., Li, S., Li, Q., Zhang, L., Li, L., 2022. Maize/soybean strip intercropping enhances crop yield in rain-fed agriculture under the warming climate: a modeling approach. Agron. Sustain. Dev. 42 (6), 115. https://doi.org/10.1007/s13593-022-00839-8.

Zhao, J., Bedoussac, L., Sun, J., Chen, W., Li, W., Bao, X., van der Werf, W., Li, L., 2023. Competition-recovery and overyielding of maize in intercropping depend on species temporal complementarity and nitrogen supply. Field Crops Res. 292, 108820. https://doi.org/10.1016/j.fcr.2023.108820.