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SESSION 2 – CLIMATE CHANGE – IMPACTS, ADAPTATION, MITIGATION

Climate Change – Impacts, Adaptation, Mitigation

Warming winters enable water-saving shift to autumn sugar beet cultivation in Iran

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Keywords: Irrigation; Frost damage; Impact assessment; Modelling; SUCROS

Introduction

Sugar beet supplies >50% of Iran's sugar but requires intensive irrigation, depleting scarce water resources (Rajaeifar et al., 2019). Conventional spring sowing demands ~1000mm irrigation annually, challenging sustainability in arid regions. Autumn sowing could reduce irrigation needs by exploiting winter precipitation and cooler temperatures. However, frost damage has historically prevented adoption, limiting yields in cold-prone areas. Climate change may alter this constraint through warming winters and reduced frost frequency. This study evaluated autumn vs spring sowing viability across 21 diverse Iranian locations under current and future climates, testing seven irrigation strategies from full to minimal supplementary applications according to phenology to identify water-efficient adaptation pathways.

Materials and Methods

We simulated sugar beet yields across 21 locations representing Iran's major agricultural zones using SUCROS model modified for frost damage assessment. Simulations covered baseline (1980-2010) and future periods (2040-2070) under RCP4.5 and RCP8.5 emission scenarios using five GCMs. The SUCROS model was previously calibrated and evaluated for sugar beet across diverse agro-climatic zones in Iran (Deihimfard et al., 2021). Two sowing dates (spring and autumn) were compared under seven irrigation scenarios: full irrigation and six supplementary strategies applying 100mm at different developmental stages (emergence, mid-growth, root-filling). Frost stress functions were integrated to quantify damage at three phenological stages.

Results and Discussion

Spring-sown sugar beet failed under all supplementary irrigation scenarios, confirming its reliance on full irrigation for successful cultivation. Under full irrigation at baseline, simulated root yields for spring-sown sugar beet ranged from 82.79 to 118.78 t ha^{-1}, while autumn-sown sugar beet showed a wider range, from 22.69 to 138.06 t ha^{-1}, when averaged across all climate classes. In contrast, autumn-sown sugar beet was able to produce viable yields (23.25 t ha^{-1}) even with only supplementary irrigation at baseline (Figure 1). Climate change projections revealed that autumn yields would increase 21.87% (RCP4.5) and 27.80% (RCP8.5), driven by reduced frost events (63% and 76% respectively) and elevated CO_2. Single irrigation at mid-root filling (SC3) optimized yields across most locations, achieving 38.84 tha^{-1} averaged across sites, demonstrating superior water use efficiency compared to multiple irrigations. Significant spatial variability emerged, southern locations experienced no frost, while northeastern sites, maintained frost risk even under warming scenarios. The synergy between reduced frost damage and CO_2 fertilization under climate change transforms autumn sowing from a risky practice to a viable adaptation strategy. This shift could save ~700mm irrigation water annually while maintaining economically viable yields. Implementation requires adjusting sowing dates to local frost patterns and delivering irrigation at critical growth stages.

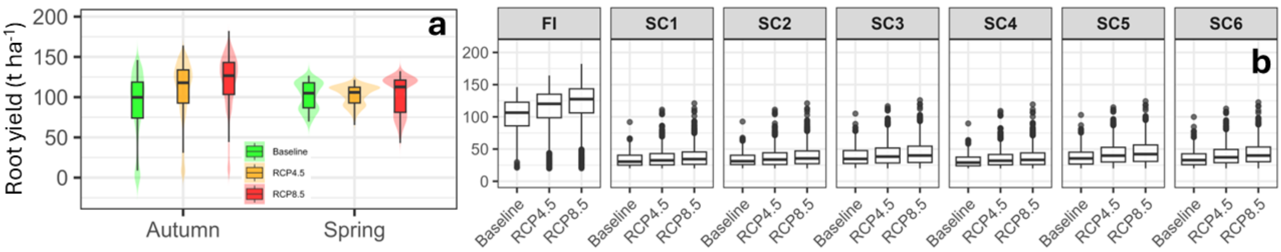

Figure 1. Simulated potential root yield (without drought and frost damage) for autumn- and spring-sown sugar beet under baseline and future emission scenarios. The length of the box plots represents the variability among locations, years, and GCMs (a). Simulated water- and frost-limited root yield of autumn-sown sugar beet under baseline and future emission scenarios and different irrigation scenarios. Irrigation scenarios (FI: full irrigation, SC1: only at emergence [DVS: 0.1], SC2: only at the middle of sugar beet growth [DVS: 1], SC3: only at mid-root filling [DVS: 1.5], SC4: at emergence and the middle of sugar beet growth, SC5: at the middle of sugar beet growth and mid-root filling, and SC 6: at all three stages) (b).

Conclusions

Our findings suggest Iran's water-stressed agricultural system could benefit from transitioning to autumn cultivation, particularly in warmer regions where frost constraints are minimal, offering a practical pathway to enhance water security under climate change.

Acknowledgements

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Air temperature thresholds of extreme heat exposure for maize and soybean in Northern Hemisphere breadbaskets

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Keywords: Extreme Degree Days, critical temperature thresholds, spatial variability, Global Gridded Crop Models Intercomparison, growing season adaptations

Introduction

Exposure to extreme high temperature emerges as a critical risk factor constraining global crop productivity (IPCC, 2023), yet the temperature thresholds at which this exposure translates into substantial yield loss and their spatial variability remain poorly understood. Here, we compiled sub-national yield census over Northern Hemisphere (20°N-55°N), and analyzed the exposure to Extreme Degree Days (EDD) to identify the critical heat exposure threshold ($\mathrm{EDD_{threshold}}$). With our new estimated $\mathrm{EDD_{threshold}}$, we then projected future change in extreme heat exposure for maize and soybean based on outputs from eleven Global Gridded Crop Models (GGCMs). We also evaluated the potential difference of the projected heat exposure that arise from widely-applied spatially fixed threshold (30℃ (Lobell et al., 2011; Schlenker and Roberts, 2009)) with our new estimated threshold. Finally, we assessed how growing season adaptations by advanced sowing dates and adoption of long-maturity cultivars may help crops to escape heat exposure.

Materials and Methods

We harmonized nearly 8000 district or county level yield records. A spatially generalized statistical model was applied to each of the county to estimate the $\mathrm{EDD_{threshold}}$, as exemplified by the following equation

$$Y_{c_i,t} = \sum_{k=1}^{m} \beta_{k,c_i} X_{c_i,t} + C_{c_i} + \varepsilon_{c_i,t}\, , i = 0,1, \dots , r \; (0 \le r \le n) \qquad (1)$$

where Y is the county-level yield, X contains m variables (here X=(GDD, EDD, growing season precipitation, quadratic yield trend)) in county c_i and year t, C is a county-fixed constant which capture time-invariant effect and ε is an error term, c_i is the i-st nearest county to target county c_0, n is the total number ofthe counties. We estimated equation (1) over all possible thresholds between T_{opt} and the maximum air temperature within the entire growing season. $EDD_{threshold}$ was selected as the temperature threshold of the best fit where RMSE was minimized. Lots of robustness tests were also conducted to validate our methods are robust in assessing heat exposure threshold.

Results and Discussion

Our findings reveal mean±std $EDD_{threshold}$ for maize and soybean are 34.8±4.0℃ and 33.7±3.9℃, respectively. The estimations of $EDD_{threshold}$ are broadly consistent with reported thresholds in the observation locations, and robust under multiple methodological assumptions relating to model structure, data source alternatives and growth stage definition adjustments.

We applied the same data-driven approach to hindcast spatial variations in $EDD_{threshold}$ from 11 GGCMs outputs. We found that all crop models showed a much narrower range of the spatial variabilities of $EDD_{threshold}$ than observation.

Leveraging our spatially explicit of $EDD_{threshold}$, we found a substantial increase in future heat exposure for maize and soybean. Without adaptions, growing season heat exposure is projected to increase by 2.4%-16.1% for maize and 4.9%-16.0% for soybean by the end-of-century. Importantly, ignoring spatial variations in $EDD_{threshold}$ by adopting a fixed 30°C threshold led to systematic overestimation of heat exposure during both hindcast and projection period. However, widely discussed adaptation strategies (Minoli et al., 2022) against heat-induced yield loss such as adjusting the sowing dates and adopting new varieties to maintain the growing season length are insufficient to fully offset escalating heat exposure. This further highlights the urgency of climate mitigation actions, without which adaptation efforts would fail in containing the increasing risk of extreme climate events.

Conclusions

Accurate depiction of crop exposure to heat stress is fundamental for reliably quantifying heat-induced yield loss and crop failure. Previous studies have adopted spatially invariant but largely different thresholds for assessing heat exposure. With fine-scale yield census data, our study provided spatially explicit estimations of the heat exposure threshold ($EDD_{threshold}$) for maize and soybean across the Northern Hemisphere, which partially reconcile large differences in previous assumptions on heat exposure. As climate gets warmer, crop heat exposure will increase, but less pronounced than previously expected. However, state-of-the-art crop models significantly underestimated $EDD_{threshold}$ and its spatial variations, leading to overestimated heat exposure in future, which partially explained why models underestimated yield loss during extreme heat events. Should global warming continue, adaptations through adjusting sowing dates alone cannot fully mitigate increasing heat exposure.

Acknowledgements

We are grateful to S. Asseng for his insightful comments and suggestions.

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Climate change impacts and adaptation strategies for smallholder farmers in Madagascar

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Keywords: Crop modelling, APSIM, household data, sowing dates, crop varieties

Introduction

Madagascar ranks among the most food-insecure countries globally, with 40% of its population undernourished and 90% unable to afford a healthy diet (FAO et al., 2024). The majority of the population relies on agriculture for their livelihood, predominantly practicing low-yielding rainfed subsistence farming. The strong dependence on seasonal rainfall, combined with limited adaptive capacity, makes Malagasy smallholder farmers highly vulnerable to climate change. The objective of this study was to quantify climate change impacts on crop yields and to identify effective and low-cost adaptation strategies by integrating household survey data into a process-based crop modelling framework.

Materials and Methods

Maize and peanut yields were simulated with the Agricultural Production Systems Simulator (APSIM), using high-resolution, bias-corrected climate projections (CMIP6/ISIMIP3b) and diverse spatial datasets. Crop growth simulations were conducted for a historical baseline period (1985–2014) and future conditions up to 2100 under three shared socio-economic pathways (SSP1-2.6, SSP3-7.0, SSP5-8.5). Household survey data from 624 smallholder farmers provided insights into farmers' climate change perceptions and likely adaptation choices (Fig. 1). Simulated adaptation scenarios explored the combined effects of adjusting sowing dates and changing crop cultivars on maize yields under a high emission scenario. For peanuts, the CO_2 fertilization effect was isolated by comparing simulations with dynamic atmospheric [CO_2] against a constant [CO_2] level of 360 ppm.

Panel a) Weather shock experience **Panel b) Adaptation intentions**

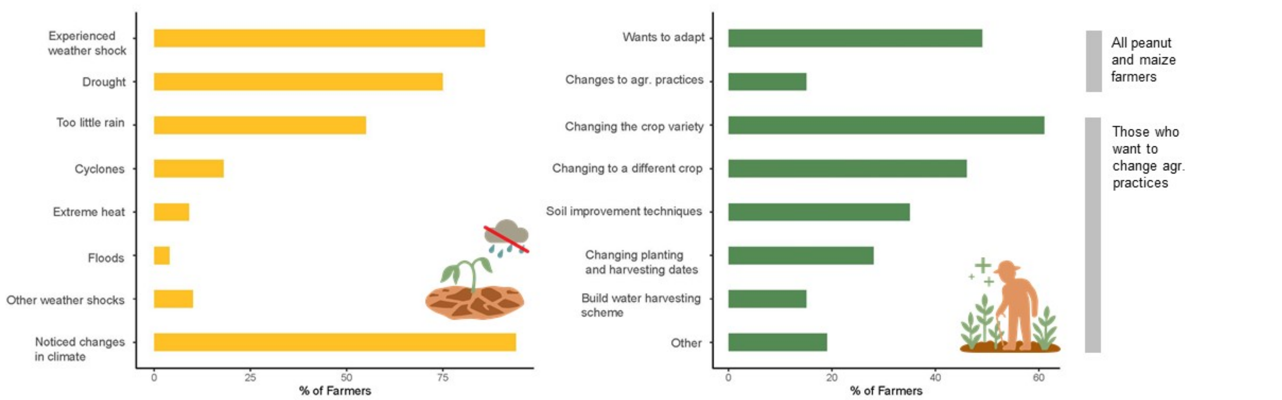

Figure 1: Weather shock experience (a) and adaptation intentions (b) among surveyed smallholder maize and peanut producers in South-East Madagascar. Data source: AGRICA Madagascar baseline survey.

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Results and Discussion

Madagascar is projected to undergo substantial warming during the main cropping season (mid-October to mid-April), particularly under high-emission scenarios by the end of the century. These temperature increases are accompanied by shifts in rainfall patterns, with currently dry regions becoming wetter and wet regions becoming drier. Crop simulations reveal contrasting responses between maize (C4) and peanut (C3). Maize yields are projected to decline by –8% to –52%, with losses increasing under higher-emission pathways and later in the century. In contrast, peanut yields are projected to rise by +4.6% to +10%, largely driven by a positive CO_2 fertilization effect. Without this effect, peanut yields would decline, highlighting the severity of future climatic stress.

Among the adaptation strategies tested, a combination of late sowing dates and short-cycle cultivars performed best for maize, yet no tested combination could reverse negative yield impacts. Climate change is also projected to alter interannual yield variability: peanut yield variability remains relatively stable, whereas maize yield variability shows a substantial increase under high-emission scenarios. Given farmers' limited access to credit and insurance, greater maize yield variability heightens the risk of food insecurity in unfavourable seasons.

Conclusions

This study underscores the severe challenges climate change poses for smallholder farming in Madagascar and the distinct responses of C4 and C3 crops to global warming, shifting rainfall patterns and increased [CO_2]. Low-cost adaptation strategies can buffer, but not reverse negative climate change impacts on maize yields, highliting the need for a broader portfolio of effective and accesible adpatation measures to safeguard food security under a changing climate.

Acknowledgements

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Potential of crop diversification and integrated crop-livestock systems for climate change adaptation and mitigation

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Keywords: ecosystem services; resistance; greenhouse gas; soil organic carbon; spatialization.

Introduction

Farming systems play a central role in providing vital ecological benefits, but how they are managed can either support sustainability or create environmental problems. Over the past fifty years, agriculture has largely shifted toward specialized, high-yield systems that prioritize productivity at the expense of other ecosystem functions (Garrett et al., 2020). This shift has come with considerable ecological costs. Addressing these issues now requires moving back toward more diversified and integrated farming practices, which are increasingly recognized as essential for reconciling food production with environmental stewardship (Gaudin et al., 2015).

Scientific literature on the impacts of increasing crop rotation complexity and integrating livestock within cropping systems is limited. Most of the existing research – whether grounded in field trials or simulation modeling – tends to concentrate on a narrow set of sites over relatively short timescales. What remains lacking is work that delivers a more detailed understanding of both productivity and environmental outcomes by (*i*) incorporating integrated crop-livestock systems, (*ii*) extending across broader geographic regions, and (*iii*) examining patterns and effects over the long term.

Materials and Methods

Here we investigate the impacts of different agroecological levers, ranging from efficiency-oriented measures – reducing nitrogen fertilization – to the substitution of practices – replacing fallows in winter by cover crops – and, finally, to the full redesign of the systems – increasing crop diversity and integrating pastures grazed by beef cattle with different grazing intensities.

Eighteen management scenarios are compared: corn monocultures, and rotations with corn-soybean, corn-soybean-winter wheat, and corn-soybean-winter wheat-pasture with four increasing grazing intensities by beef cattle, each scenario being with full and reduced nitrogen fertilization modalities. These scenarios are simulated with the soil-crop model SALUS (Basso et al., 2006) over a 30-year period, at 40,000 distinct locations in 934 counties that cover 46.2 million hectares across 12 US Midwest states. The model was previously validated using a diversity of field experiments.

The impacts of the different scenarios are assessed on various indicators: productivity, soil organic carbon, greenhouse gas emissions, nitrate leaching and stability and resistance to extreme climatic events. This last indicator is carefully computed through the characterization of extreme climatic events, from the SPEI drought index, and through the comparison of yields under *normal* climatic conditions versus under *moderately/extremely wet* or *dry*.

Results and Discussion

We demonstrate that reducing nitrogen fertilization and implementing cover crops are key levers to mitigate greenhouse gas emissions (up to 68% reduction), increase carbon soil sequestration (up to 60% more) and reduce nitrate leaching (up to 22% reduction). Reducing fertilization by 20% even proves to slightly improve economic profitability (up to 3% more) through a cost decrease greater than reduced productivity. Further diversifying crop rotations by including temporary pastures stocked at optimal intensity provides greater financial stability (159% more) and resistance to droughts (5% more), increasingly crucial with ongoing climate change.

Figure 1 illustrates the greenhouse gas budget computed at a fine scale over the whole Midwest region, and the mitigation impact of adding cover crops.

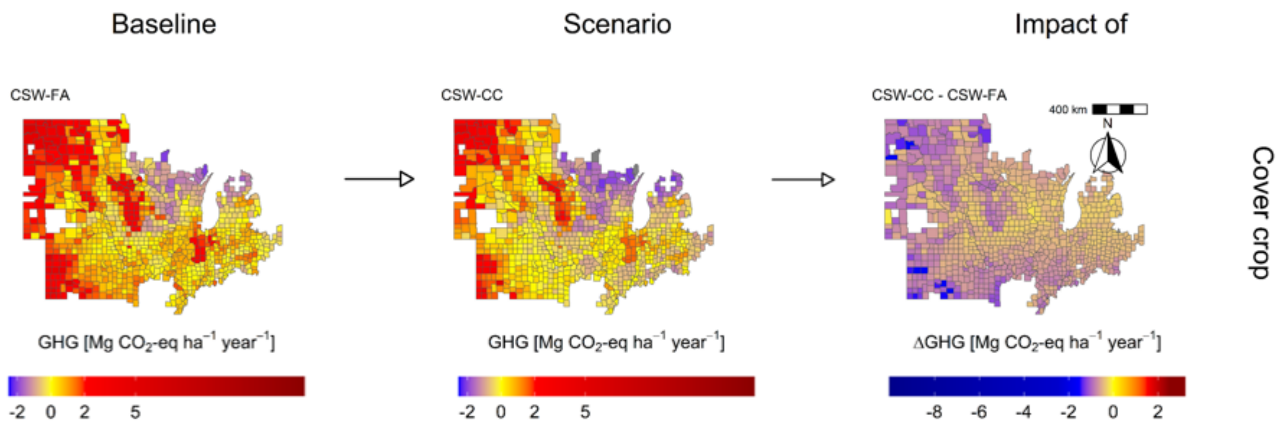

Figure 1. Greenhouse gas (GHG) budget (CO_2, N_2O and CH_4; Mg CO_2-eq ha^{-1} year^{-1}) for CSW-FA and CSW-CC scenarios, and their change using GWP for global warming potentials. Black lines on the maps display county boundaries. CSW-FA = corn-soybean-wheat rotation with fallow periods; CSW-CC = corn-soybean-wheat rotation with cover crops. Adapted from Delandmeter et al. (in review).*

Conclusions

This study is, to our knowledge, the first to jointly assess a wide range of farming practices – including crop diversification and integrated crop-livestock systems – together with multiple ecosystem services, across large geographic and temporal scales. It is yet performed at a detailed level of analysis, which includes an innovative characterization of crop resistance to extreme climatic events. Our results indicate that agricultural landscapes achieve the most substantial gains when several ecological strategies are combined. At the same time, the analysis makes clear how these strategies generate both complementarities and trade-offs among different ecosystem services.

Acknowledgements

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Fertilizer dependency of ground-level ozone impact on photosynthesis in rice: implications for crop modelling

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Keywords: Tropospheric ozone, Phytotoxic ozone dose (POD), Climate change, Air pollution

Introduction

Tropospheric (ground-level) ozone (Figure 1) is a threat to crop productivity because it reduces photosynthesis. Current ozone impact assessments typically apply species-specific ozone sensitivities, but assume these sensitivities are constant regardless of plant nutritional status. This study aimed to investigate whether fertilizer application modifies the photosynthetic sensitivity to absorbed ozone in rice (*Oryza sativa L.* cv. 'IR64').

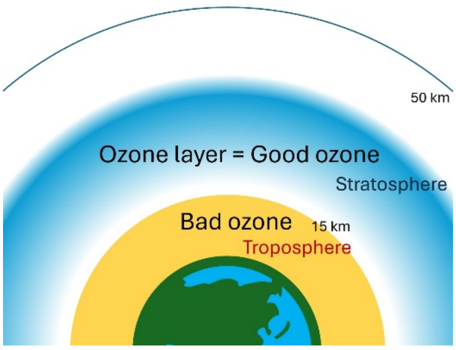

Figure 2 Ozone in the troposphere harmful to plants.

Materials and Methods

Rice plants were grown under two fertilizer levels (low and high) and exposed to either ozone (80 ppb) or filtered air from one week after flowering, using sunlit growth chambers (Figure 2a). Photosynthesis and stomatal conductance were measured weekly on flag leaves after flowering (Figure 2b).

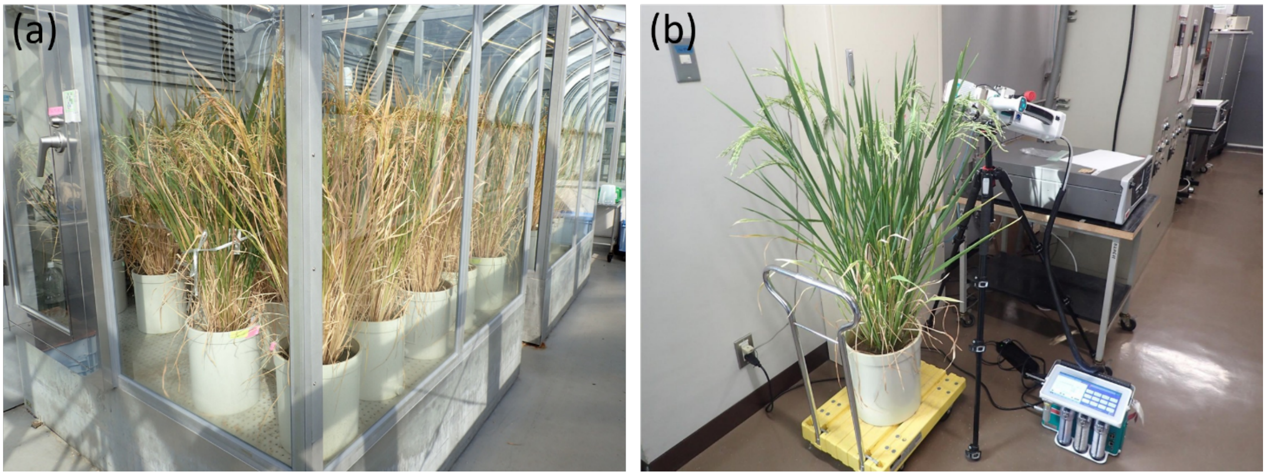

Figure 3 Rice plants in ozone exposure chamber (a), and measurement of photosynthesis and stomatal conductance on flag leaves using a LI-6800 gas-exchange system (b).

Results and Discussion

Higher fertilizer application reduced the photosynthetic sensitivity to absorbed ozone (Figure 3). These results suggest that ozone risk assessments should consider plant nutritional status. In regions with limited fertilizer inputs, common in many developing countries, crops may be more vulnerable to ozone pollution.

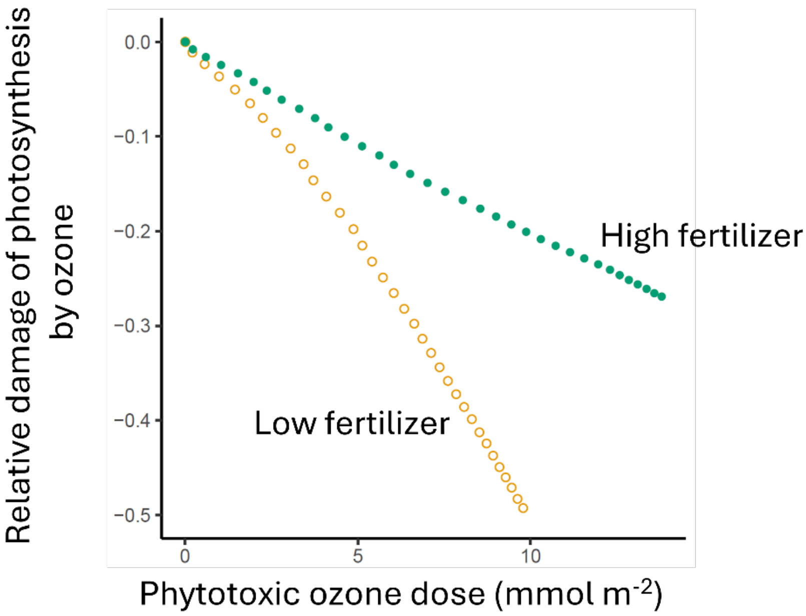

Figure 4 Reduced sensitivity of photosynthesis to absorbed ozone under high fertilizer application.

Conclusions

Considering global variation in cultivation practices, interactions between ozone and nutrient status should be incorporated into crop models to improve the assessment of ozone impacts on crop productivity.

Acknowledgements

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Climate Change and Vineyard Irrigation in Tuscany: Environmental Impacts from a Multi-Model Perspective

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Keywords: Dynamic LCA, AquaCrop, Scenario analysis, Environmental Impact, water management

Introduction

Viticulture and grapevine production account for a significant portion of global crop production, representing 9% of the area dedicated to perennial crops and fostering strong economic, territorial and cultural relationships in the regions where they are grown. Italy alone accounts for 19.3% of global grapevine cultivation, with 718,198 hectares. Irrigation is not a common practice in Italian vineyards. However, climate change is worsening vine development due to water stress and prolonged heatwaves in areas where these drought effects were minimal (e.g., central Italy). In this changing context, irrigation is becoming a common practice in the establishment of vineyards in coastal areas, and it may be necessary to extend it to inland parts of central Italy. While water requirements are increasing, sustainability and the efficient use of resources are also becoming increasingly important in the agricultural sector. ISO standardized methodology, such as Life Cycle Assessment (LCA) and LCA based Water Footprint (WF), are now commonly used for organizational certifications (Renzi et al., 2025).This research aims to examine the impact of climate change on the water requirements of vineyard crops using AquaCrop crop growth model and the effect of this increased water volume on the organizational Water scarcity footprint (WSF) .

Materials and Methods

A winegrower organization is selected as a case study. Based in Tuscany, it holds vines in a inland municipality (Radda in Chianti: 43.42° N, 11.35° E) and a costal ones (Massa Marittima: 43.01° N, 10.85° E). The FAO AquaCrop model is adapted to simulate vineyard irrigation water requirements using literature and in situ data to set up the model. The model is calibrated and validated for several life stages of the vineyards: Plantation (PL), young plants (YP) and old plants (OP) for both vineyards. Climate change scenarios are created using bias-corrected climatic data downloaded from the ISIMIP 2b repositories. Climatic forcing from GFDL-ESM2M, HadGEM2-ES and IPSL-CM5A-LR are used for the RCP 2.6 and RCP 8.5 emission scenarios from 2001 to 2090. First, a baseline scenario is simulated without irrigation. Then, three different irrigation scenarios are created based on farm management. We simulate a drip irrigation event with a water depth of 19 mm for each event. The following irrigation scenarios are analyzed: low irrigation (LI) with two events, medium irrigation (MI) with four events, and high irrigation (HI) with an automatic event generator that activates every time the readily available water is depleted. A Mann-Kendall trend test for yields was performed with and without irrigation. The SimaPro LCA software is used to model the organizational environmental impacts related to water consumption (ie O-WSF). A baseline scenario of the organization is created, gathering data from the 2022 and 2024 agricultural activities. Finally, the irrigation water volume, simulated with AquaCrop as mentioned above, is imported into the SimaPro LCA software. An annual dynamic life cycle inventory was created to observe the effects on the O-WSF with temporal detail and as accumulated throughout the course of the century

Results and Discussion

Preliminary results show that the AquaCrop model performs satisfactorily in simulating vineyard yield. The R^2 value ranged from 0.78 to 0.85 for both vineyards at all life stages modelled. As expected, the RCP 8.5 scenario has the greatest impact on the vineyards due to the 2.0 °C threshold being surpassed in all the climate forcing models a by mid-century. Without irrigation, yield trends tend to decrease, albeit at different rates. The GFDL model and the old plant life stage are the most resilient conditions; a 5–10% yield reduction i s observed, in line with previous studies in the same area (Moriondo et al., 2011). IPSL and HadGEM are the most sensitive ones, with inland vineyards being more affected than coastal ones. However, a yield reduction of between 20% and 60% is observed throughout the century. The effect of irrigation on yield is heterogeneous. The LI scenario does not show a statistically significant increase compared to the no irrigation scenario in any of the climatic scenarios. HI scenarios maintain constant yields throughout the century but require an increased volume of irrigation water. Finally, adding the irrigation water volumes of the LI and HI scenarios to the O-WSF analysis increases it sixfold, even though a slight reduction is observed over the course of the century due to reduced yields.

Conclusions

The research has shown the potential impact of climate change on an important crop, such as wine grapes, in areas where irrigation is not currently a common agricultural practice. The combination of different models (climatic, crop and environmental) has enabled us to evaluate and track the performance of the agricultural organization under study, and to investigate how introducing irrigation would affect its environmental impact.

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Accelerated Variety Replacement Need for Climate Adaptation of Maize and Rice

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Abstract

Novel crop varieties play a pivotal role in agricultural adaptation to climate change. However, the feasibility, timing and pattern that adopting alternative varieties to keep pace with the rapid climate change remain poorly understood. Here, performing an ensemble of variety-specific simulations based on a field observation dataset encompassing 734 field trials for 103 crop varieties over the past four decade across China for wheat, maize and rice, we found that varietal differences in yield response to climate change can exceed the differences between scenarios and climate models in the first half of the 21st century. Adaptation through adopting varieties that can keep a high and stable yield can not only alleviate, but reverse the negative warming impacts. Under the business as usual scenario (SSP585), only ~40% of the current varieties remain productive in end-of-the-century. The timing of emergence of first varietal replacement will occur before 2050 over half of current cultivation area in China, outpacing current speed of new variety breeding. Our findings highlights the urgent need to accelerate climate adapted crop breeding.

Keywords: climate change, yield response, varietal replacement, crop modeling

Introduction

A significant challenge facing global agriculture is the need to increase crop production by over 50% within three decades to feed a growing population (Van Dijk et al., 2021). This must be accomplished sustainably, without expanding cropland and while reducing agricultural inputs (Erb et al., 2016; Yang et al., 2024). Recent findings of widespread negative impacts of climate change on agricultural productivity further exacerbate the challenge of increasing crop yields and call for a profound and rapid adaptation of agricultural systems (Rezaei et al., 2023). While vital, enhancements in agronomic management are insufficient to fully counteract climate change impacts (Hultgren et al., 2025). Crop variety replacement is therefore an indispensable asset in climate change adaptation in every sustainable future scenario (Bailey-Serres et al., 2019).

Although field evidence underscores the importance of alternative crop varieties for yield stability (Van Etten et al., 2019), their potential to mitigate climate change impacts remains poorly quantified and highly debated. This uncertainty stems from the inadequate integration of varietal diversity into climate impact assessments. Prominent studies, including the latest IPCC report, frequently employ crop models parameterized with a limited selection of varieties, thereby overlooking the substantial spatiotemporal variability in cultivated crops (Jägermeyr et al., 2021; IPCC, 2023). Furthermore, approaches that attempt to incorporate diversity often rely on 'pseudo-varieties' generated by perturbing model parameters (Jiang et al., 2023), which rests on simplified and often unrealistic assumptions about crop traits being continuous, independent, and devoid of trade-offs..

Historically, the replacement of crop varieties has contributed significantly to yield gains, accounting for approximately 30-60% of yield improvement (Yu et ai., 2012). Yet, the rate of varietal turnover is neither uniform nor persistent, with widespread yield stagnation recently observed in many regions implying a deceleration of this rate (Gerber et al., 2024). The breeding programs established during the relatively stable climate of the Green Revolution are now failing to produce varieties resilient enough for the accelerating pace of modern climate change (Xiong et al., 2024). This creates a sharp contrast with the optimistic assumptions of persistent technological growth used in many integrated assessment models (Chang et al., 2021). Given that developing new varieties is a long-term and expensive effort, whether the current rate of varietal replacement can adequately keep pace with accelerating climate change remains elusive.

As the world's largest cereal producer with a vast germplasm repository and comprehensive varietal data for maize, wheat, and rice, China offers a unique opportunity to address this knowledge gap: (1) How does the current portfolio of crop varieties affect projected yield responses to climate change? (2) When, where, and at what rate should varietal replacement occur to effectively adapt to climate change?.

Materials and Methods

Crop variety data

A consolidated dataset of 734 unique variety trials from 206 stations (Fig. 1a) was compiled for maize, wheat, and rice. Maize data came from the "Science and Technology Innovation Project of Improving Food Yield and Efficiency" (44%) and the China Meteorological Administration (CMA) network (54%). All wheat and rice trial data were sourced from the CMA. The dataset comprises 103 varieties, including maize (30), wheat (26), and rice (47), encompassing over half of the main cultivated varieties released since 1980 (Fig. 1b). To the best of our knowledge, this is the largest crop variety database of its kind in China. It captures the real-world variation in agronomic traits, yield levels and climate adaptability (promotion characteristics), providing a robust foundation for our analysis (Fig. 1c,d). Soil properties were obtained from the Global High-Resolution Soil Profile Database. Daily weather data (temperature, precipitation, sunshine hours) from 2400 CMA stations were used to calculate solar radiation. Crop cultivation area was determined from the ChinaCropPhen1km dataset, and management data like sowing dates and planting density were sourced from 625 CMA stations and interpolated spatially.

Climate projections

Future climate scenarios were sourced from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b), which provides bias-corrected and downscaled CMIP6 data. The study used historical (1980-2015) and future (2021-2100) data from five structurally independent Global Climate Models (GCMs), including GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0, IPSL-CM6A-LR and UKESM1-0-LL, that represent the full range of climate sensitivity in the CMIP6 ensemble. Three SSP scenarios (SSP126, SSP370, SSP585) were used, resulting in 15 total climate scenarios to project a warming range from less than 2° C to about 5° C.

Crop modeling

The study used the DSSAT (V4.8.5)-CERES models for maize, wheat, and rice. DSSAT is well-suited for this research due to its ability to simulate the interaction of genetics, environment, and management (GEM) using specific genotype parameters. The models were calibrated for each specific variety using established uncertainty estimation and gradient search methods. Simulations were run on a 0.5° grid, assuming non-limiting nitrogen fertilizer application and irrigation based on local practices. Spring wheat was excluded due to its minor contribution to national production.

Yield response estimation and variation attribution

To estimate future yield responses, we calculated the annual yield change between 2021 and 2100 relative to a 1980-2015 baseline for each simulated scenario. We then quantified the uncertainty in these projections using the standard deviation across all ensemble members. To identify the primary sources of this uncertainty, a three-way ANOVA was used to partition the total variation in yield response among three factors: crop variety diversity, Global Climate Model (GCM) spread, and Shared Socioeconomic Pathway (SSP) range. The factor contributing the most to the total sum of squares was identified as the dominant driver of variation.

Time of emergence of varietal replacement

To determine when new crop varieties would be needed, we used the Time of Climate Impact Emergence (TCIE) method (Grant et al., 2025). This approach identifies the point when a climate-driven change ("signal") becomes larger than the natural historical variability ("noise"). We defined "noise" as the standard deviation of the average historical yield (1980-2015) across all varieties. The "signal" was defined as the 20-year moving average of the projected mean yield response for each variety. The "time of varietal failure" was marked as the moment the signal-to-noise ratio exceeded 1. The "timing of the first varietal replacement" for a location was when the average yield response across all varieties surpassed the historical range of variation. The "frequency of varietal replacement" was the total number of such emergence events projected over the next 80 years.

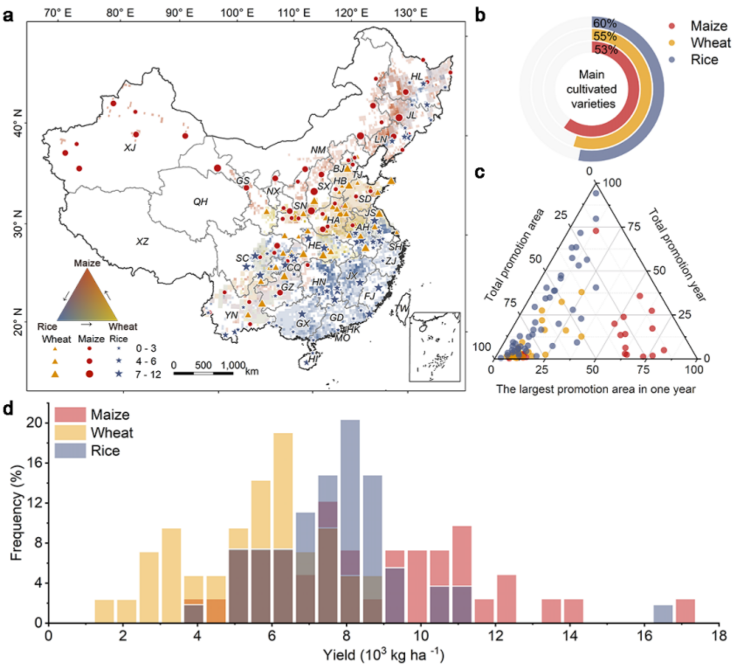


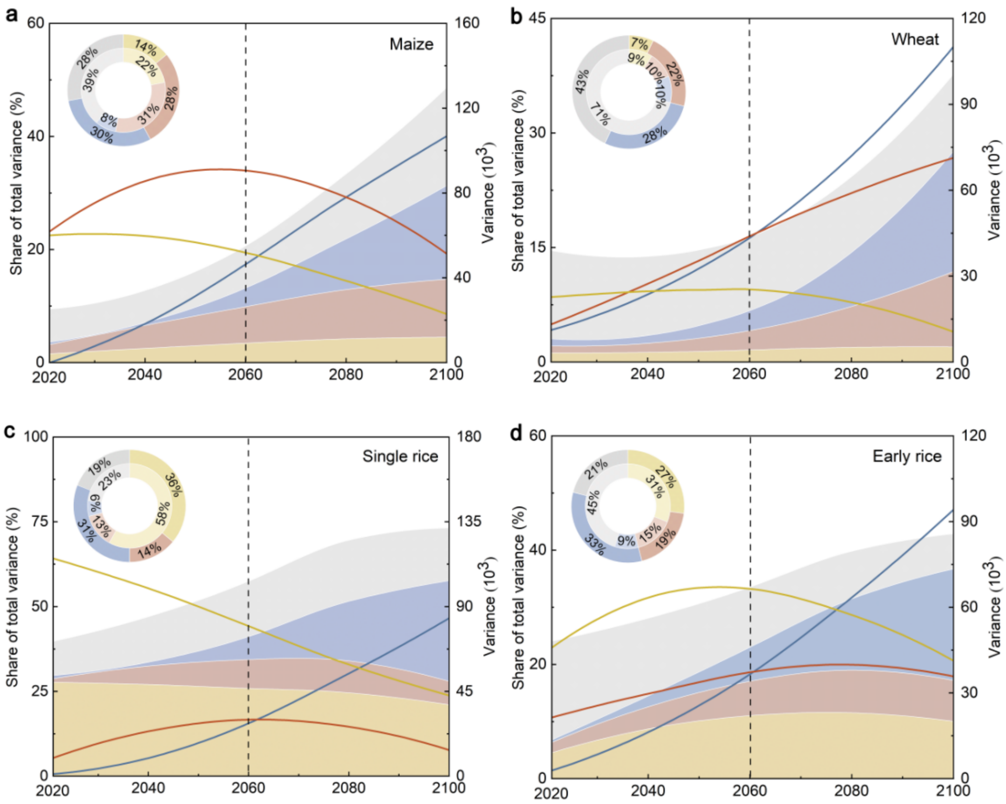
Figure 1 Representation of our crop variety database. a, Geographical distribution of crop variety trials. The size of red dots, orange triangles and blue stars indicates the number of trials in each site for maize, wheat and rice, respectively. b, Proportion of main cultivated varieties of the three cereal crops in China represented in our database. c, Relationship between different varietal promotion characteristics. d, Frequency distribution of crop yields from field experiments.

Results

Varietal differences shape yield response to climate change

Our projections incorporating varieties actually cultivated by farmers align broadly with previous assessments, showing a generally negative impact of climate change on crop yields as well (Supplementary Fig. 1). Notably, when real-world varietal diversity is considered, we observed variety-related differences in yield projections is comparable to or even exceeds the spread of using different climate models and scenarios, particularly for rice. Specifically, the yield response differed by a factor of five between the most and least suitable rice varieties, even in the opposite directions (+/-) for single rice (Supplementary Fig. 2c-e). These findings suggest that traditional yield impact assessments based on the simulation with few fixed varieties have systematically underestimated the range of possible outcomes and may even produce biased conclusions regarding climate change impacts..

A variance partitioning analysis confirmed that before mid-century (2021-2060), crop variety is the dominant factor explaining the variation in yield projections, particularly for rice (Fig. 2). While GCM spread is also significant for dryland crops, variety choice remains a key contributor. However, by the late 21st century (2061-2100), the choice of SSP emission scenario becomes the most important driver of yield uncertainty. This shift indicates that while long-term outcomes depend heavily on global mitigation efforts, short-term adaptation through selecting optimal existing varieties can significantly offset potential yield losses, especially in cooler regions like Northeast China and the Yangtze River basin (Supplementary Figs. 3-5).



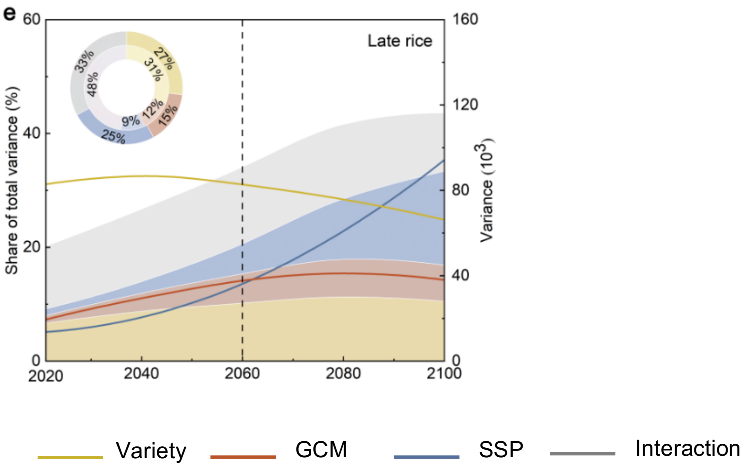


Figure 2 Relative contribution of crop variety, GCMs and SSPs to variation in projected yield response. a-e, Solid lines (left axis) indicate the fraction of total uncertainty (variance) in projected crop yield response attributable to variety, GCM and SSP. Shaded areas (right axis) represent the absolute variance associated with the three factors and the sum of their interactions. Doughnut plots show the mean contribution of each ensemble member to the total uncertainty for the first half of the century (2021-2060, inner ring) and the second half (2061-2100, outer ring).

Widespread varietal collapse under climate change

A large portion of current crop varieties are projected to become unsuitable under future climate scenarios (Fig. 3). In a high-emission scenario (SSP585), it is anticipated that over 60% of existing varieties could become unsuitable by the end of the century, leaving fewer than 15 viable options for each crop studied. This issue is particularly acute for maize, where the proportion of unsuitable varieties could reach 80%, a vulnerability linked to the greater genetic homogeneity of current maize cultivars. Varieties identified as low-unstable and high-unstable are the most susceptible to climate change, making up, on average, 70% of the varieties projected to become unsuitable. Even varieties known for stable yields are at risk of significant losses as climate change intensifies. These results highlight the urgent need to breed new, better-adapted varieties, with a focus on stress resilience and broad environmental adaptability over singular yield potential.

Importantly, our analysis revealed a prevailing "breeding paradox" that newer varieties typically have higher average yields but experience greater yield losses (Supplementary Figs. 7 and 8). While the ratio of climate impact to mean yield has improved for maize and wheat in recent decades, this trade-off remains a significant challenge in rice breeding(Supplementary Fig. 9). The research also identified that mid-to-late maturing varieties with high grain-filling rates, such as the maize variety Zhengdan 958, the wheat variety Yannong 19, and the rice variety Wuyujing 3, can offer climate resilience without a significant compromise in yield.

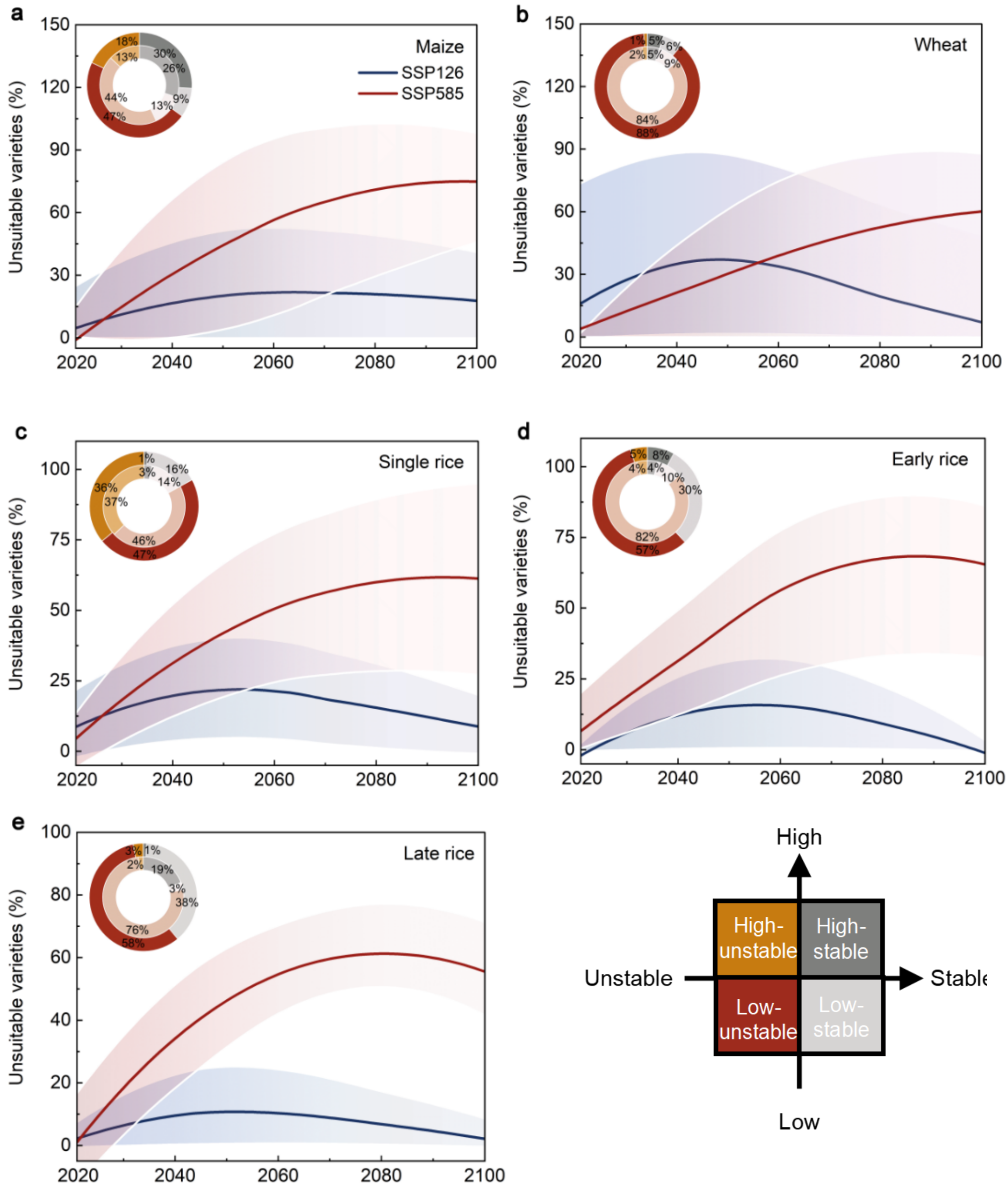


Figure 3 Proportion and characteristics of unsuitable varieties. a-e, Solid blue and red lines indicate the percentage of unsuitable varieties under SSP126 and SSP585, respectively, with the upper and lower bounds representing the 90th and 10th percentiles. Doughnut plots show the characteristics of the first eliminated varieties under the SSP126 (inner ring) and SSP585 (outer ring) scenarios. The varieties tested for each crop were classified into four categories according to their yield level (mean yield) and stability (coefficient of variation) simulated for the baseline period (1980-2015). The classification thresholds for high/low yield and stable/unstable performance were defined as the mean yield and mean coefficient of variation, respectively, calculated across all evaluated varieties of the crop.

Varietal replacement for climate change adaptation

Under a high-emission scenario (SSP585), there is an urgent and widespread need for varietal replacement across China (Fig. 4). By mid-century, over half of the current cropland will require new varieties to mitigate severe yield losses. Rice is under the most immediate pressure, with 60% of its cultivation area needing new varieties before 2050, followed closely by maize at 54%. While the need for wheat is delayed, 65% of its growing areas will still require replacement by the end of the century. Given the lengthy process of developing and adopting new varieties, there is a critical 25-year window to invest in breeding programs, especially in the nation's key agricultural regions.

In contrast, under a low-warming scenario (SSP126), current varieties could remain viable in 60% of cropland throughout the century, delaying the need for the first varietal replacement by about two decades. Furthermore, effective climate mitigation would reduce the required frequency of varietal replacement by 80% and significantly decrease the area needing intensive intervention (Supplementary Fig. 10). This highlights that global climate mitigation is a powerful adaptation strategy, buying crucial time for breeders to develop more resilient crops and enhance food system stability.

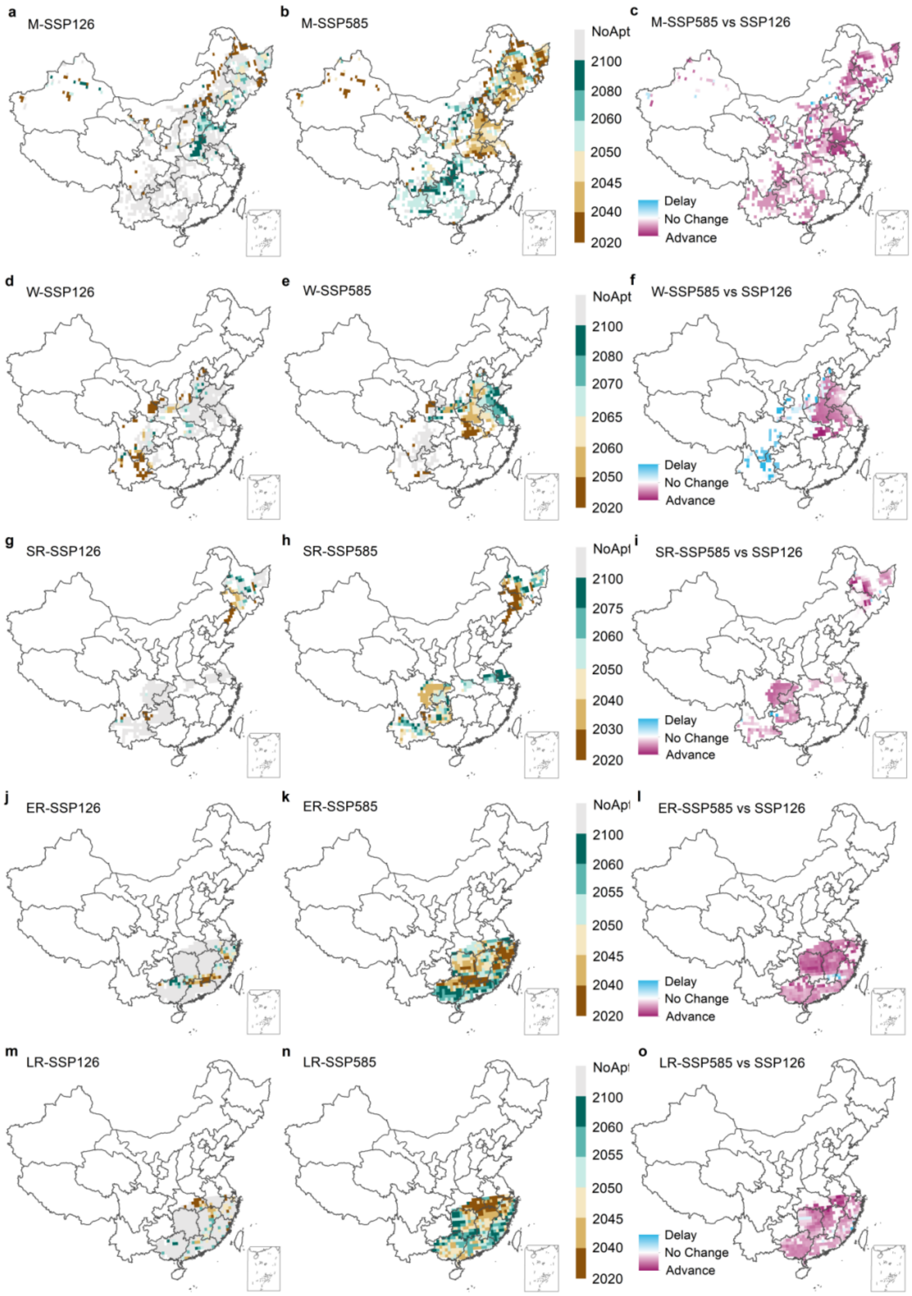


Figure 4 Time of emergence of crop variety replacement for climate change adaptation. Maps show the time of emergence of the first varietal replacement requirement for maize (a, b, c), wheat (d, e, f), single rice (g, h, i), early rice (j, k, l) and late rice (m, n, o) under SSP126 (a, d, g, j, m), SSP585 (b, e, h, k, n). The time point is defined as the moment when the average yield response of all varieties exceeds their historical natural variability range, which indicates that continuing to cultivate existing varieties would face significant yield losses, thus necessitating the introduction of new, more adaptable varieties to mitigate climate impacts. Grey areas indicate the areas where yield losses are within the range of historical yield variability, i.e. where new variety is not needed under the SSPs by the end of the century. c, f, i, l, o, The delay or advance in the initial year of varietal replacement between SSP585 and SSP126.

Discussion

By integrating an extensive, newly-compiled database of real-world crop varieties into a large-scale impact analysis for the first time, our study demonstrates that varietal diversity has a substantial and previously underappreciated influence on yield responses to climate change. This diversity accounts for 26% of the total variation in yield projections, a larger share than that induced by different climate scenarios. We reveal that conventional parameter-perturbation methods fail to capture the significant varietal differences observed in farmers' fields, consequently underestimating their impact (Wang et al., 2024). As biophysical yield estimates inform subsequent economic and policy analyses, overlooking varietal characteristics can propagate uncertainty through the entire assessment chain (Benami et al., 2021). These findings underscore the critical need to explicitly incorporate actual varietal variability into future climate change impact and adaptation assessments.

Our analysis confirms that varietal replacement is an effective climate change adaptation strategy. However, the increasing frequency with which it is required presents significant practical challenges, including higher input costs for farmers, adjustments in management practices, and the potential to exacerbate inequalities in adaptation. The scale of this challenge is stark: under a high-warming scenario (SSP585), 60% of existing varieties are projected to lose climate resilience by the century's end, and over half of today's cultivated areas will necessitate varietal replacement before 2050. While strategic switching may temporarily mitigate yield losses for about two decades, widespread replacement will be essential by 2040 even under lower emissions scenarios (SSP126). Ultimately, these findings emphasize that on-farm adaptation must be complemented by rapid climate mitigation to maintain long-term crop productivity.

The future necessity for varietal replacement presents significant challenges to crop breeding programs. Our analysis provides a spatially explicit roadmap that identifies priority crops, regions, and intervention timelines, underscoring the need for breeding strategies to explicitly incorporate climate change. However, traditional phenotypic selection is too slow to meet this accelerated demand, necessitating advanced approaches like genomic selection and speed breeding to shorten breeding cycles (Watson et al., 2018; Occelli et al., 2024). Climate-driven shifts also alter trait prioritization, requiring an increased focus on resilience and the management of critical yield-heat tolerance trade-offs. The growing complexity of genotype-environment-management (GEM) interactions further demands more precise, region-specific breeding. Addressing these challenges requires substantial investment from governments, research institutions, and development organizations; without it, breeding efforts risk falling short, leaving smallholder farmers particularly vulnerable and exacerbating inequalities in climate adaptation.

Although new crop varieties are released each year, their adoption by farmers remains slow (Kholová et al., 2021). Without widespread adoption, supply-side innovations can be inefficient. A principal impediment is the frequent mismatch between novel technologies and the complex realities of farming systems, where successful adoption depends not only on yield but also on congruence with local labor demands, production environments, and socio-economic structures. Market failures, including informational asymmetries regarding new varietal attributes and inadequate access to risk-management tools, further hinder dissemination. Critically, past negative experiences can erode farmers' trust in scientists and seed dealers, creating reluctance to abandon traditional practices. These barriers, however, are not insurmountable. Participatory approaches that directly involve farmers in the development process are essential for creating innovations tailored to local agro-ecological and socioeconomic contexts, thereby rebuilding trust and promoting widespread adoption (Kholová et al., 2024; Gesesse et al., 2023).

Climate change impacts on global agriculture are highly uneven, with tropical, lower-latitude regions projected to experience significant crop productivity reductions within the next two decades, sooner than other areas (Wang et al., 2020; Jägermeyr et al., 2021). Given that many developing economies in these regions are agriculture-dependent, the livelihoods of their smallholder farmers and broader economic development are particularly vulnerable. Smallholder farms in these areas often lack access to improved seed technologies and exhibit low adoption rates for agricultural innovations. This confluence of high climate risk and low adaptive capacity risks exacerbating global inequalities in climate adaptation. Therefore, ensuring global food security and fostering resilient food systems necessitates that international organizations and regional collaborations prioritize not only the development of climate-resilient crop varieties but also equitable access to these improved varieties.

Acknowledgements

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Identifying new agrometeorological zones for lucerne in present and future European climates using STICS model

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Keywords: Lucerne, STICS model, calibration, climate change.

Introduction

In Europe, lucerne varieties adapted to temperate ("Northern" type) and Mediterranean zones ("Southern" type) differ in terms of phenology, summer production potential and sensitivity to abiotic stresses (frost, water stress). In a context of climate change and increasing protein production, these varieties therefore present quite different profiles in terms of risks of yield loss (hotter and drier in summer) and opportunities for increased production in spring or in new, more northerly zones (earliness, frost tolerance). The objectives of this study were to use the STICS crop model to i) calibrate different Northern and Southern varieties, ii) define adaptive management rules applicable on large agrometeorological zones and iii) simulate current and future potential production maps at the European level.

Materials and Methods

STICS (Brisson et al., 2009) model can simulate lucerne yields in response to soil, climate and cutting management for Northern varieties (Strullu et al., 2020). A dataset of 10 experimental sites on 6 to 20 years (variety trial network) comparing Northern and Southern varieties was used to assess the model ability to capture the absolute forage production of each type, and their differences of responses to climatic events. Automatic sowing and harvest management rules were defined using surveys and recommendation maps in France, and applied at European scale using Agri4Cast climate series. Finally, a first exploratory study was performed across 1500 locations sampled in Europe, considering soil map, automatic management and IPCC climate scenarios (present, RCP 4.5) for growing lucerne over three years.

Results and Discussion

The first results show a good ability of the model to predict the interannual variations of forage yield in the different experimental sites used for validation. Difference between Northern and Southern varieties were limited in most of the Year x Cut x Variety situations. However, significant differences were apparent in spring and autumn, and properly captured by the model. Suitability maps for sowing lucerne and achieving a particular potential yield are now being produced in the BELIS European Project (2024-2027). The design and application of the adaptative management rules give the possible dates for sowing (figure 1) that will be used as inputs for the simulation of STICS at European scale.

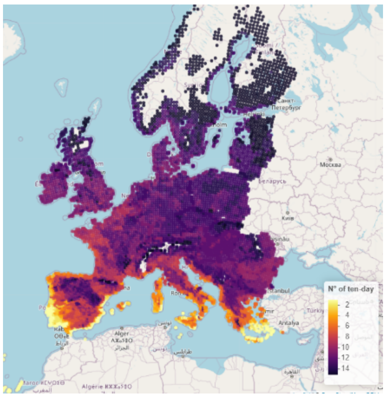

Figure 1. Beginning of the favorable period for sowing alfalfa in current climate context

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Predicting the impact of climate change on grass growth in the Republic of Ireland

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Keywords: pasture productivity, simulation, modelling

Introduction

Grassland and rough grazing cover 92% of the utilised agricultural area in the Republic of Ireland (ROI). The temperate maritime climate allows an extended grass-growing season, with peak growth between May and August. However, climate change has the potential to disrupt this system. Warmer, drier summers and warmer, wetter winters are projected over the coming century (O'Brien and Nolan, 2023). To assess the potential impact of varying levels of climate change on Irish grasslands, grass growth was simulated for forecasted future weather scenarios.

Materials and Methods

The Moorepark St Gilles grass growth (MoSt GG) model was used to simulate daily grass growth across the ROI. MoSt GG is a mechanistic model with a daily time step (Ruelle et al., 2018). Daily weather data (precipitation, min and max temperature) under different climate change scenarios were provided by Met Eireann's TRANSLATE project (O'Brien & Nolan, 2023). The scenarios comprised a baseline (1976–2005) and five global warming levels of 1.5, 2.0, 2.5, 3.0, and 4.0 °C. The weather data represent a typical annual profile at a resolution of 1 km^2.
43,277 of the TRANSLATE grid points are located on grassland soils in the Irish Soil Information System (Creamer et al., 2014). Each grid point was linked to an average of 5.3 possible soil types (range: 1 - 10) from the 103 grassland soil types defined in the system. Based on differences in simulated grass growth under fixed weather inputs, the 103 soil types were clustered into eight groups using a clustering algorithm (partitioning around medoids). The medoid of each cluster was chosen as the representative soil type. Eight clusters provided a practical balance between computational feasibility and within-cluster similarity to the medoid.

Simulations were conducted at paddock scale, one for each of the representative soil types present at each grid-point. Paddock management was set to reflect standard Irish practice, comprising eight grazing events on fixed dates and 150 kg N supplied in six fixed applications. The daily growth for each grid point was calculated as the mean daily growth of all representative soil types present.

Results and Discussion

The mean annual yield across the ROI increased under all climate change scenarios relative to the baseline scenario (Figure 1a). The baseline mean was 11.8 t DM ha^{-1}, rising to a maximum of 12.9 t DM ha^{-1} under the 3.0 °C scenario. However, the annual increase varied by location. Ranging from 0.2 t DM ha^{-1} (+1.4 %) at the 10th percentile of locations to 1.8 t DM ha^{-1} (+15.5 %) at the 90th percentile, under the 3.0 °C scenario.
Monthly yields experienced a more varied response, with decreases in some regions between June and September. August showed the largest reduction in daily growth under the 3.0 °C warming scenario (Figure 1b) with an average change of -3.7 kg DM ha^{-1} (-7.1 %) per day relative to the baseline scenario. The monthly impact of climate change on yield was also highly location dependent. In August, the daily impact of climate change ranged from a decrease of 12.5 kg DM ha^{-1} (-24.4 %) at the 10th percentile to an increase of 8.0 kg DM ha^{-1} (+13.5 %) at the 90th percentile.

Conclusions

Although annual yields are projected to increase, changes in the seasonal distribution of grass growth will require adaptation of management practices. Further research is required to evaluate how altered seasonal growth patterns will influence farm-level strategies, and to assess potential increases in intra-annual variability.

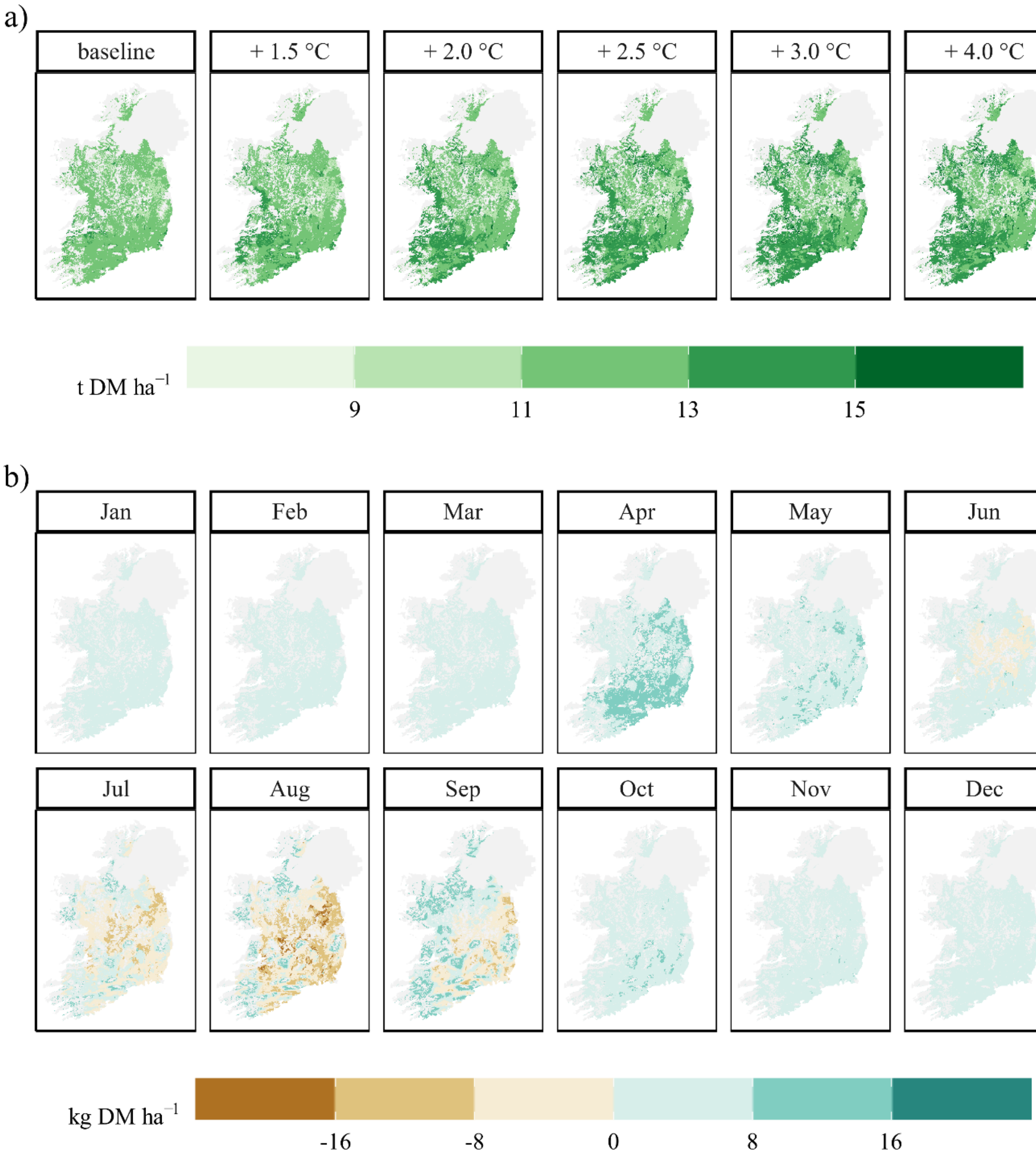

Figure 1. Panel A: annual yield (t DM ha^{-1}) across the ROI under the baseline and five different Global Warming Levels (1.5, 2.0, 2.5, 3.0, 4.0 °C). Panel B: change in average daily yield (kg DM ha^{-1}) between the baseline scenario and 3.0 °C of Global Warming by month.

Acknowledgements

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Modelling cereal–cowpea intercropping to close the yield gap while reducing N demand under climate variability and climate change in West Africa

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Keywords: sustainable intensification, nitrogen use efficiency, climate-smart agriculture, diversification, sub-Saharan Africa

Introduction

Agriculture in West Africa (WA) faces severe climate risks and N limitations, with large yield gaps in rainfed cereals that must be closed sustainably to ensure food security. Mineral N fertilisation can increase productivity but entails increased sensitivity to climate variability and environmental risks. Cereal–legume intercropping has emerged as a promising sustainable intensification strategy for its potential to enhance crop productivity and resource use efficiency (Namatsheve et al., 2020). Yet, long-term assessments of intercropping remain scarce. A modelling approach can complement the learnings of short-term field experiments and to project future climate change adaptations. The aim of our study was to assess the potential of cereal–cowpea intercropping to increase energy and protein productivity compared to cereal sole cropping, while reducing N demand across three sites in WA, facing both climate variability and climate change.

Materials and Methods

We used the process-based STICS soil-crop model (Brisson et al., 2004; Vezy et al., 2023), calibrated under semi-arid conditions of Senegal, Mali, and Burkina Faso with correct accuracy and robustness (results submitted). A thirty-historical-year simulation compared cereal sole cropping (SC) with cereal–cowpea intercropping (IC) across N fertilisation levels (0–200 kg N ha^{-1}). For each season and site, the difference in N rate necessary to reach 80% of cereal potential energy and protein productivity in both cereal SC and IC ($\Delta N_{80} = N_{80,SC} - N_{80,IC}$) was calculated. Next, we explored how climate extremes influenced these N requirements. We analysed the sensitivity of ΔN_{80} to drought and wet conditions, after classification of climate years based on the frequency of climatic events during specific growing stages. Further analysis of the frequency of specific climate events in projections from GCM models will help assess whether intercropping systems will remain beneficial in WA under future climate.

Results and Discussion

The preliminary results for the site in Mali showed that sorghum-cowpea intercropping reduced N requirements by 53% (34 kg N ha^{-1} less) and 100% compared to sorghum sole cropping to achieve 80% of potential energy and protein productivity respectively. The cumulative distribution of ΔN_{80} indicated that in 96% of years, intercropping achieved target energy productivity with lower N inputs than sorghum. Wet conditions during the vegetative phase reduced the N savings from intercropping, while dry conditions enhanced them (*see Figure 1*). A similar pattern was observed in the reproductive phase, except under extreme drought, which severely limited N use efficiency in intercropping. This suggests that sorghum dominated under wet conditions, whereas cowpea compensated for cereal losses in moderate droughts but contributed little under severe stresses. The ongoing climate analyses will help quantify the future frequency of moderate and extreme drought during vegetative and reproductive phases, clarifying the potential of intercropping in WA.

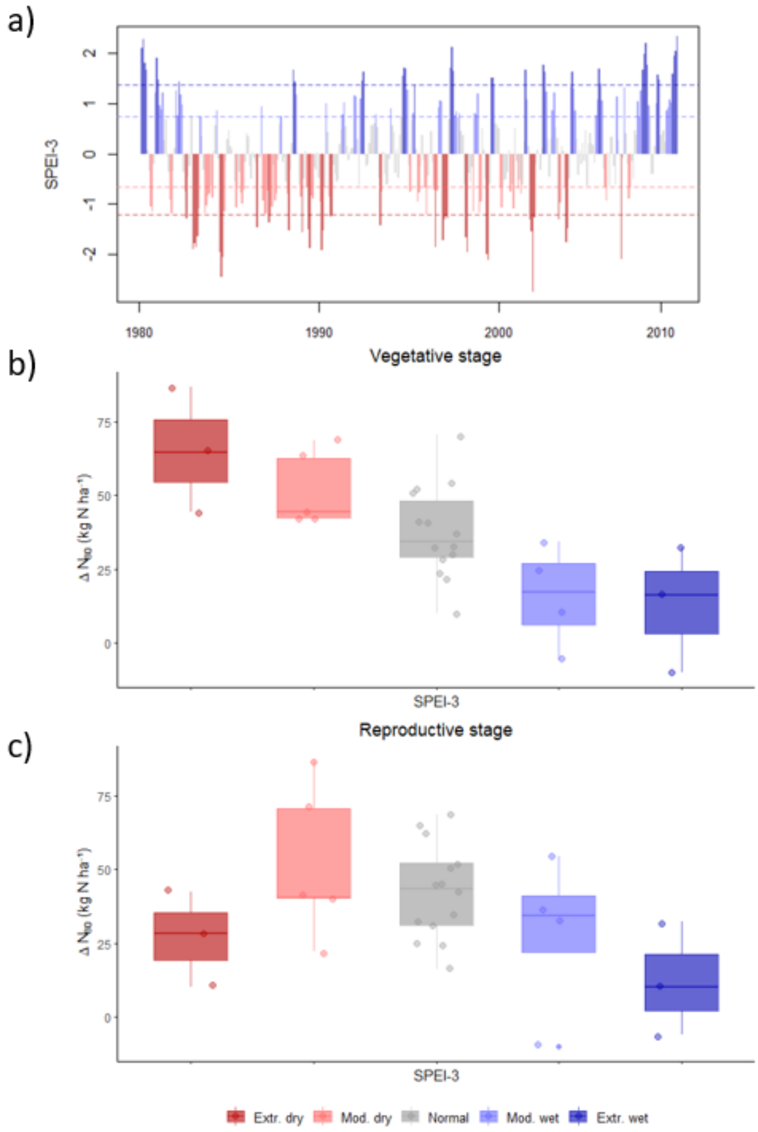

Figure 1: a) SPEI-3 index (expressing the dryness/wetness, computed monthly from the water balance over the current and the two-preceding months), of the historical period 1980–2009 in the station N'tarla in Mali. The colours designate the category of climatic events (extremely/moderately dry/wet). Dashed lines refer to the quantiles q0.1, q0.25, q0.75 and q0.9, which determine the category of climatic events (Vicente-Serrano et al., 2010; Delandmeter et al., 2024). b, c) Comparison of simulated ΔN_{80} for energy productivity, between different classes of SPEI-3 during two growing stages.

Conclusions

The use of the STICS model allows us to generate novel insights, showing that cereal–cowpea intercropping significantly reduces fertiliser requirements, suggesting that intercropping is a relevant intensification strategy for West Africa. However, this finding needs to be confirmed across all study sites.

Acknowledgements

This article was supported by CIRAD and the European Union, as part of the IntercropVALUES project, funded by the Horizon Europe Research and Innovation programme (Grant agreement No.101081973). Data acquisition for this work was supported by the Fonds de Solidarité Prioritaire (FSP) of the French Ministry of Foreign Affairs and International Development (MAEDI), the Fondation Avril via the ORACLE project, the AFD 'Ecological Intensification and Inequality' project, the USAID SIMCO project (Grant agreement No.201403286-10), the EU LEAP-Agri RAMSES II project (Grant agreement No.840727715) and the EU H2020 SustainSAHEL project.

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Combining ozone-T-FACE experimental data and crop models to assess elevated ozone and temperature effects on wheat growth in China

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Keywords: Ozone, Warming, Wheat Growth, Photosynthesis, Leaf area index

Introduction

Despite ongoing efforts to curb carbon emissions and reduce air pollution, disproportionate declines in anthropogenic emissions of greenhouse gases and ozone (O_3) precursors may lead to persistently elevated O_3 levels accompanied by rising temperatures in China's wheat-producing regions soon. It is therefore essential to quantify the impacts of of O3 pollution and climatic warming on wheat yields, to assess adaptive strategies in crop production that can help to safeguard grain yields and ensure national self-sufficiency.

Crop models that integrate multiple climatic factors and their interactions with phenological development, photosynthesis, biomass accumulation, and yield formation can be valuable tools for climate impact assessment. In recent years, several models have been extended to simulate O_3 effects on leaf photosynthesis, aboveground biomass, and yield. However, due to the scarcity of field observational datasets, process-based crop models have rarely been tested against experimental evidence for the interactive effects of O_3 and temperature.

Field experiments investigating the combined impacts of O_3 and warming on wheat using a free-air O_3 and temperature elevation (O_3–T–FACE) facility have recently been established in China (Xu et al., 2025). Here, for the first time, we combined the trial data from O_3–T–FACE experiments and a process-based crop model, to investigate and understand the individual and interactive effects of elevated O_3 and temperature. This study will facilitate the modeling performance evaluation and improvement, which will be an important step for projecting the interactive effects O_3 and increasing temperature on wheat production at regional scales under future climate scenarios.

Materials and Methods

The field experiment was conducted at an O_3–T-FACE research facility in Wuqiao Town, Jiangsu Province, within the Yangtze River Delta region of China (119.75°E, 32.42°N), during the 2024–2025 wheat growing seasons. There were four treatments here, including ambient temperature and ambient air (CKA), elevated temperature and ambient air (WA), ambient temperature and elevated O_3 (CKE), elevated temperature and elevated O_3 (WE). The treatments were applied from the regreening stage to maturity. Three locally major wheat cultivars： Nongmai 88 (NM88), Lianmai 7 (LM7), and Yannong 19 (YN19) were grown. Phenological stages (flowering and maturity) were recorded for each plot through field observations. From the onset of treatments until harvest, aboveground biomass, and leaf area index (LAI) were measured weekly. Photosynthetic rate, and A–C_i curves were assessed using four LI-6800s, while chlorophyll content was estimated with a SPAD meter. At maturity, grain yield and aboveground biomass were determined by harvesting 1.5-2 m² samples from each plot.

To simulate the effects of O_3 and temperature on wheat growth, we employed the crop model LINTULCC2, which incorporates phenology, leaf growth, assimilate partitioning, water balance, and root growth processes. Both instantaneous and cumulative effects of O_3 exposure were considered in the model (Feng et al. 2024). The impacts of O_3 and temperature on aboveground biomass and yield were significant in 2024, and the observed data on phenology, aboveground biomass, leaf area index, leaf photosynthesis, and chlorophyll content in this year were used for model calibration. The 2025 dataset was subsequently used for model validation.

Results and Discussion

Across the two experimental years, warming significantly advanced anthesis and maturity, thereby shortening both the vegetative growth period (sowing to anthesis) and the reproductive growth period (anthesis to maturity). Elevated O_3 had no effect on phenology, while the combined treatment of elevated temperature and O_3 further shortened the entire growth duration. Elevated O_3 significantly reduced grain yield and aboveground biomass across all cultivars, although their sensitivities to O_3 differed. Yield losses under elevated O_3 were 18%, 10%, and 16% for LM7, NM88, and YN19, respectively, mainly due to reductions in single grain weight. In contrast, the number of ears per unit area, grains per ear, and harvest index did not differ significantly between O_3 treatments. The responses of yield, aboveground biomass, and single grain weight to O_3 also varied between years, with stronger effects observed in 2024 than in 2025. Warming decreased LM7 yield by 11%, primarily through a reduction in ear density rather than other yield components. No significant interaction between O_3 and warming was detected for wheat yield and its components.

The calibrated LINTULCC2 model simulated anthesis and maturity dates within 5 days of the observations. Using cultivar-specific parameters (thresholds for photosynthetic damage and slopes of photosynthetic decline), wheat cultivars exhibited distinct cumulative O_3 fluxes and sensitivities (LM7>YN19>NM88). The simulated biomass, yield, and relative yield loss due to elevated O_3 and/or warming were compared with the field observations (Figure 1). By incorporating stomatal O_3 uptake flux and accounting for both short-term and cumulative effects on leaf photosynthesis, the LINTULCC2 model successfully reproduced biomass, yield, and O_3 -induced yield losses for the calibration year 2024 (Figure 1a), and reasonably captured these responses for the evaluation year 2025 (Figure 1b) across all three cultivars. Moreover, the LINTULCC2 model was able to simulate the reduction in O_3 uptake flux and the alleviation of yield loss under warming.

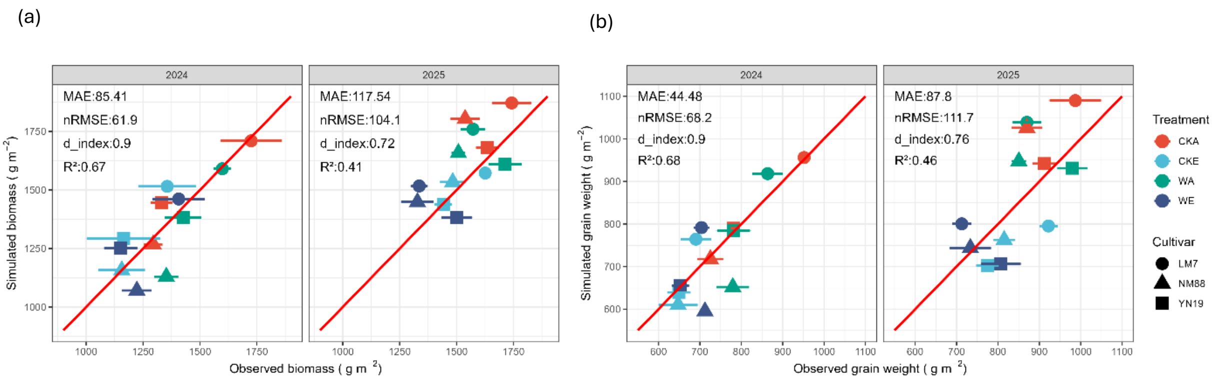

Figure 1. Comparison of simulated and observed (a) aboveground biomass (g m-2) and (b) grain yield (g m-2) at maturity for two growing seasons 2024 (calibration) and 2025 (validation). The blue line represents the fitted linear model, while the red line indicates the 1:1 reference line.

Conclusions

Elevated O_3 significantly reduced yields of all three wheat cultivars, while warming decreased yield only in the sensitive cultivar LM7. No interactive effects of O_3 and warming on yield were observed. The LINTUCC2 model was able to simulate advancement of developmental stages due to increased temperature. By incorporating stomatal O_3 uptake flux and both short-term and cumulative effects on photosynthesis, the LINTULCC2 model successfully reproduced negative impacts of O_3 on biomass and yield. the shortened growth duration and increased vapor pressure deficit due to warming reduced O_3 uptake flux, thereby alleviated simulated yield losses due to O_3 under elevated O3 and warming. Our findings highlight the necessity to consider combined effects of O_3 and warming on crop growth and yield in the crop models towards the future impact assessment of elevated O_3 and increasing temperature.

Acknowledgements

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Insights on the impact of climate change on maize production in Italy using Convection Permitting climate Models

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Keywords: APSIM, maize yield projection, CPMs

Introduction

Maize yield has been severely affected by the observed climatic changes (IPCC, 2022). Cereal harvest in Italy is reported to experience negative consequences due the rising temperature and the shift in precipitation patterns. Under a 2°C warming a decrease of -10/-25% in fully irrigated maize yield is expected, while the crop will fail under rainfed conditions (Hristov et al., 2020).

The combined use of crop and climate models offers insights on the relationship between agricultural productivity and global warming. While several studies applied Global or Regional Climate Models together with crop model to project future maize yield, there is still limited information on the impacts of climate change on maize production at high-resolution spatial scale (Mereu et al., 2021). Convection Permitting Models (CPMs), with their km scale resolution (less than 4km) could close this gap. CPMs represent deep convection explicitly (Fosser et al., 2024), provide an improved representation of the orography and a more realistic simulation of hourly precipitation and extremes (Kendon et al., 2021).

This study evaluates the possibility of applying CPMs to drive a crop model to provide detailed information on maize yield in Italy at province scale and uses CPMs to simulate maize yields during the historical period (1996-2005) and at the end of the century (2090-2099) under Representative Concentration Pathway (RCP) 8.5.

Materials and Methods

The study foresees three steps:

1. Assessment of the performance of APSIM in reproducing observed maize yield at province scale. APSIM is driven from climate data from the ERA5-Land reanalysis, soil information from the WorldSoil database and crop management practices from documents released by Italian regions. Observed yield data comes the Italian National Institute for Statistics (ISTAT) archive.
2. Assessment of the capability of eight CPMs in simulating maize yield over the evaluation period (2000-2009). APSIM is driven with climate data from CPMs; yield outputs are compared with those obtained when the crop model is run with ERA5-Land.
3. Estimation of the average maize yield over the historical period and at the end of the century and computation of the yield variation.

Results and Discussion

The performance of APSIM driven by ERA5-Land in simulating the observed yield varies according the province. The model demonstrates a good ability in reproducing year-to-year yield variability over Northern Italy. On average APSIM tends to overestimate maize yield (+9% with respect to the observed yield). The overestimation involves the central and southern provinces, while there is a slightly underestimation in Northern Italy.

When APSIM is driven by climate data from the CPMs, maize yield is instead underestimated with respect to that derived from the same model driven by climate from ERA5-Land. The underestimation is concentrated in the northern provinces, depends on the CPM (from -4.7% to -19%, average over the country), and is linked with remarkable overestimation of temperature in CPMs with respect to ERA5-Land during the maize growing season. However, the year-to-year variability is accurately reproduced.

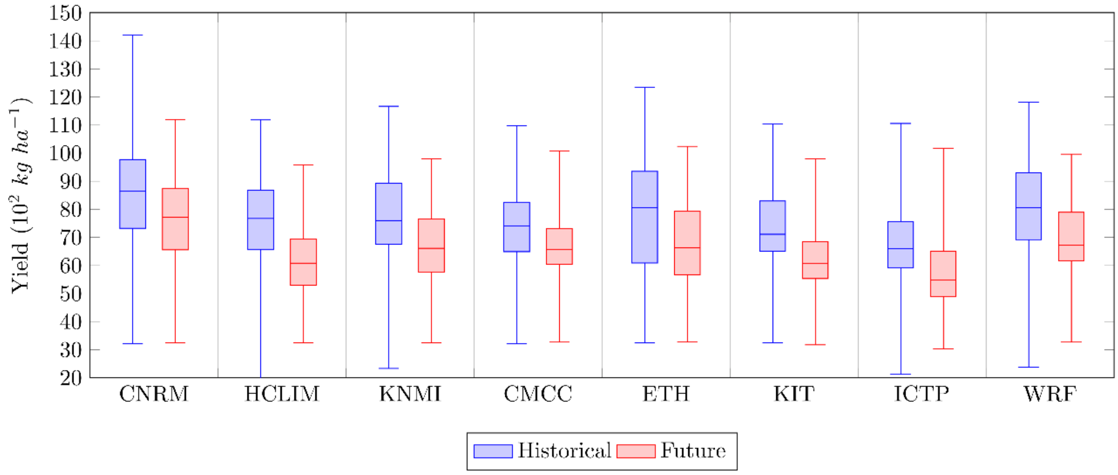

Figure 1. Yield decrease over the 2090-2099 period under RCP 8.5 (Future) with respect to the historical period (1996-2005) as projected by APSIM driven by the eight CPMs over the whole Italy.

Independently from the CPM, future maize yield will decrease at the end of the century with respect to the historical period (Figure 1); the yield loss will be between -10% and -20% (average over Italy) and is due to both a temperature increase and a precipitation decrease.

Conclusions

APSIM was capable of correctly reproducing observed maize yield over the most of Italian provinces when initialized with climate data from ERA5-Land. When driven by CPM climate data, the crop model tends to underestimate maize yields since CPMs are hotter and drier than ERA5-Land and thus the crop growing cycle is shorter. At the end of the century under RCP 8.5 maize yield will decline over Italy, with yield losses in the range from -10% to -20% when averaged over the whole country.

Acknowledgements

The authors gratefully acknowledge the WCRP-CORDEX-FPS on convective phenomena at high resolution over Europe and the Mediterranean (FPSCONV-ALP-3). Moreover, the analysis was carried out on the High-Performance Computing DataCenter at IUSS, co-funded by Regione Lombardia through the funding programme established by Regional Decree No. 3776 of November 3, 2020.

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Modelling the carbon footprint of oat across environments for plant-based milk substitutes

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Introduction

Plant based alternative products have grown increasingly popular, driven by their sustainability benefits, rising consumer awareness and concerns about climate change, in general plant-based milks such as oat milk have a lower carbon footprint (CFP) compared to dairy milk, oat and soy milk reduced greenhouse gas (GHG) emissions by 59-71% per 250 ml serving compared to dairy milk (Craig et al. 2023), using oat protein concentrate (OPC) in food products such as bread, pasta, and yogurt can significantly reduce CFP with reduction 50-70% in GHG emissions per kilogram of protein (Yadav et al. 2025).The carbon footprint of oat is relatively lower compared to some other grains, CFP of conventional oat production was reported as 0.349 kg CO_2 eq/kg of grain (Viana et al. 2022), Compared to dairy proteins, oat has more than 50% lower CFP per kg protein, and its land use is also favorable at 8.6 m^2 per kg protein. However, environmental impacts are highly sensitive to allocation methods and the economic value of co-products (Heusala et al. 2020). In this study, we evaluate the potential of oat protein concentrate as a sustainable ingredient for various food products.

Materials and methods

This study based on field data collected from the state variety trails (Landessortenversuche, LSV) in Germany, data from 24 locations, over a period (2005-2024), the dataset includes yield and management data for 67 Oat cultivars, the CFP of each location was calculated using a life circle assessment (LCA) approach, The system boundaries included all on farm operations (e.g., seedbed preparation, sowing, fertilization, plant protections, harvesting) as well as upstream processing and transport to processing, Direct and indirect nitrous oxide (N_2O) emissions from fertilizer application were calculated according to IPCC Tier2 methodology, to assess the influence of varicose factors (location, years, and cultivars), to analyze the variability in CFP across experimental factors (locations, years, cultivars), a linear mixed model using (lme4) package R studio, To analyse the variability in CFP across experimental conditions, a linear mixed-effects modelling framework was employed using the lme4 package in R. In this model, year and location were treated as random effects to account for temporal and spatial heterogeneity, whereas cultivar was treated as a fixed effect to assess genetic influences. Yield was included as a covariate to adjust for productivity differences when comparing CFP values expressed per ton of grain. Post hoc pairwise comparisons were performed using Tukey's HSD test to determine statistically significant differences among cultivars and locations.

Results and discussion

The average of CFP contributions by source. Fertilizer production and application represent the largest share, contributing 38.4% to total emissions, followed closely by (N_2O) emissions at 34.9%, Diesel use accounts for 21%, while seed production and pesticides make up smaller contributions (4.9% and 0.9% respectively). These results highlight the critical role of nitrogen management and fertilizer-related emissions in shaping the overall carbon footprint of Oats. Spatial variability across trial sites shows significant differences ($p < 0.05$) were observed among locations, with some sites, such as Bernburg and Köllitsch, exhibiting markedly higher emissions per kilogram of grain. This can be attributed to differences in soil, local climate, and yield levels. Sites with higher yields generally displayed lower emission intensities. Showed significant variation across the years, with the lowest levels recorded in 2018 and the highest in 2011. Also, there are differences in CFP by growing regions. Fig (1)

Fig(1. Regional variation in oat carbon footprint (Germany)

Acknowledgements

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Effect of change in surface ozone pollution during the 2020 COVID-19 lockdown on wheat yields in Europe.

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Keywords COVID-19, Ozone, wheat, yield, air pollution

Introduction

In 2020, the COVID-19 pandemic had a profound impact on society and economy. During several months in spring and summer of 2020, severe restrictions on mobility, economic and social activities caused strong reductions in air pollutant emissions. Among them NOx, a precursor gas of tropospheric ozone (O_3), that in turn affects quantity and quality of several food crops such as wheat, barley, legumes, maize, hybrid rice and vegetables (i.e. Mills, 2023). The magnitude and scale of the COVID-19 lockdown represent an involuntary in-vivo experiment instrumental to assess the impacts of O_3 on crop growth (Dentener et al. 2020). In this study, we combine evidence on how air pollutant emissions changed, use atmospheric chemical transport models to estimate the impacts on O_3, and an O_3-crop model to determine the impact of O_3 changes during the 2020 lockdown across Europe. Interestingly, the results show that the largest impacts of O_3 changes on yields are traceable to emission reductions outside of Europe.

Materials and Methods

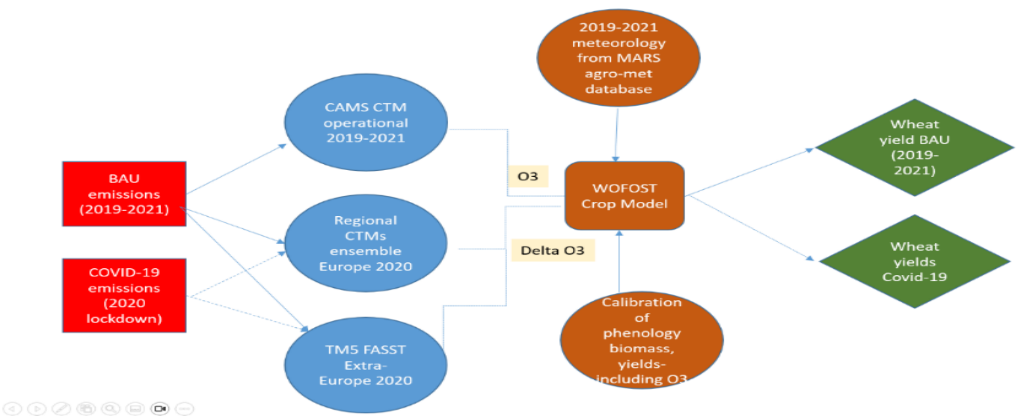

Figure 1: Model chain

The model chain involves the combination of a high-resolution multi-member ensemble of regional air quality models, a global atmospheric chemistry model to assess long-range O_3 changes, and the WOFOST-O_3 crop model (Nguyen et al., 2024), simulating impacts of O_3 on wheat yields at 100 data points across Europe. WOFOST-O_3 is a process-based crop model with a flux-based ozone damage module that reduces the daily rate of gross photosynthesis and accelerates leaf senescence once a critical stomatal flux threshold is exceeded. The model was calibrated with recent field experiments, and adjusted to represent the diversity of wheat growing conditions across Europe.

Simulations were performed for 2019-2020-2021 and multiple combinations of emissions scenarios (business-as-usual; versus COVID-19 in 2020), and assessing O_3, water and O_3-water as limiting factors under nitrogen-sufficient conditions. To ensure accurate representation of O_3 levels, all simulations were adjusted to operationally calculated O_3 levels provided by the CAMS model of the EU Copernicus programme.

Results and Discussion

Heterogeneous O_3 changes were found throughout Europe, with the largest declines in Southern Europe, and some positive response in Northern European high emission regions. The highest impacts on yields (up to 80 kg ha^{-1}) were found in Southern Europe, coinciding with the timing of the emission reductions, atmospheric chemistry and transport of O_3, and the sensitive growing phase of wheat.

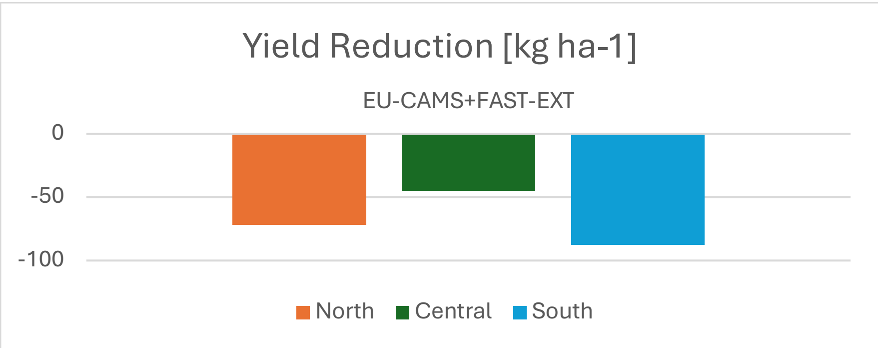

Figure 2: Wheat yield reductions [kg ha^{-1}] in 2020 due to COVID-19

Conclusions

COVID-19 lockdown conditions caused strong reductions in emissions of air pollutants. The effects on O_3 were mixed, at many locations, in urban regions O_3 increases to NOx emission reduction were observed. In rural, wheat growth areas, we can only rely on models, that show mostly moderate negative impacts on seasonal surface O_3 concentration. The models also show that, during the COVID-19 lockdown, the largest O_3 impact is from long-range continental O_3 transport. The WOFOST O_3 crop growth model evaluation of the impacts of O_3 on wheat yields shows yield changes in the order of 50-80 kg ha^{-1} or a few percent. While significant, these losses do not exceed the normal inter-annual yield variability. In other words it is difficult to show a unique O_3 signal in the yields, and air pollution emission reductions will play out over longer timescales. We also show that O_3 may be substantially more harmful under warmer conditions, consequently limiting irrigation as a viable adaptation option under climate change conditions.

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Adaptation strategies for winter wheat under climate change using CERES-Wheat and N-Wheat models and CMIP6 climate scenarios

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Keywords: Future climate, sensitivity analysis, nitrogen and irrigation management, sowing time

Introduction

Global warming with shifts in rainfall patterns and temperature regimes is threatening wheat production world-wide. Policymakers and farmers require evidence on risks and practical adaptations for sustainable wheat production for food security. Recent studies have confirmed that increasing temperature trends are increasingly determining potential yield losses (Asseng et al., 2015), while targeted adaptation management can help to reduce these risks for wheat production (Bracho-Mujica et al., 2024). This study aimed to evaluate the effects of a warming climate, fluctuating precipitation, and rising CO_2 levels on winter wheat production in a temperate monsoon, semi-humid climate (North China Plain). Additionally, we developed adaptation strategies, such as modifying sowing time and adjusting irrigation and nitrogen fertilizer levels, to mitigate the negative impacts of a changing climate.

Materials and Methods

Field experiments were conducted during the 2015 to 2017 and 2020–2022 winter wheat seasons under a warm temperate, semi-humid continental monsoon climate (Tongzhou, Beijing, China) and a cool temperate semi-humid climate (North China Plain, Hebei, China). Winter wheat cultivar Nongda-211 (mostly adopted in this region) was grown (39°41′N, 116°41′E and 39°27′N, 115°5′E with an elevation of 21 m and 42 m) under five nitrogen regimes at critical crop growth stages (fertigation at regreening (22-BCH), jointing (32-BBCH), anthesis (60-BBCH) and grain filling (70-BBCH)) with 69, 69, 35, and 34 kg N ha^{-1}. In the other experiment at Baoding Hebei, China the same cultivar was grown with five different nitrogen regimes (54, 121, 187, 254, and 321 kg N ha^{-1}) in four splits (basal, at regreening (22-BCH), jointing (32-BBCH), and anthesis (60-BBCH)). Irrigation followed local practice across overwintering, regreening, jointing, heading, anthesis, and grain filling stages.

Two DSSAT v4.8 wheat models were used, CERES-Wheat and N-Wheat (Hoogenboom et al., 2024). Generalized likelihood uncertainty estimation (GLUE) and trial-and-error approaches were used for model parameterization. For calibration data from low-stress treatments (2015–2017) including observed phenology, total above-ground dry matter, grain yield, and harvest index, and validated against the other treatments and years. Input data for calibration included daily weather, soil properties (bulk density, organic matter, field capacity, NH_4^+, and NO_3^- content, and soil textural data), crop management, and measured traits (days to anthesis and maturity, grain number, TDM, grain yield, HI, and genotype traits). The calibrated DSSAT CERES-Wheat model was applied to analyze climate change impacts on grain yield in Hebei, region of North China Plain. Sensitivity analysis was conducted for CO_2 increments under CMIP6 scenarios using the seasonal analysis tool. Adaptation strategies tested included varying sowing dates (24 September, 1, 8, 15, 22, 29 October, 5, and 12 November), nitrogen fertilizer rates (0–400 kg ha^{-1}), and irrigation levels (0–500 mm) to evaluate management options under future climate conditions. Future climate inputs used 12 global climate models (GCMs) from the CMIP6 data set (i.e. ACCESS-CM2, CanESM5, EC-Earth3, GFDL-CM4, GFDL-ESM4, INM-CM5-0, IPSL-CM6A-LR, MIROC6, MPI-ESM1-2-LR, MRI-ESM2-0, NorESM2-LM, and TaiESM1) run under SSP2-4.5 and SSP5-8.5 emissions scenarios. The statistical downscaling was applied with a delta-change method that maps monthly or daily GCM anomalies to the observed 2001–2020 series, preserving observed day-to-day variability while shifting means. Climate-change sensitivity was evaluated with the DSSAT environmental modification tool by perturbing temperature by plus or minus 1, 2, 3, and 4 °C while holding other drivers fixed, and with a CO_2 sensitivity analysis aligned to IPCC AR6 values: fixed CO_2 levels of 460, 522, 575, and 601 ppm for Time slice-1 (2021–2040), Time slice-2 (2041–2060), Time slice-3 (2061–2080), and Time slice-4 (2081–2100) under SSP2-4.5, and 476, 603, 804, and 1067 ppm for Time slices 1, 2, 3, and 4 under SSP5-8.5. Adaptation strategies were tested with the seasonal analysis tool using the calibrated models for sowing dates (end September to 1, 12 November), nitrogen rates (0, 50, 100, 150, 200, 250, 300, 350, and 400 kg N ha^{-1}) split across basal, regreening, jointing, and anthesis and seasonal irrigation (0, 100, 200, 300, 400, and 500 mm) scheduled at the standard local growth stages.

Results and Discussion

Model calibration and validation revealed that N-Wheat and CERES-Wheat reproduced the observed crop behavior well with good statistical indices especially for grain yield (RMSE= 402 and 526 kg ha^{-1} and d= 0.96 to 0.94, respectively). N-Wheat was marginally better performing overall, while CERES-Wheat matched N-Wheat for yield and phenology but trailed a bit related to TDM and HI. Against the 2001 to 2020 baseline climate average Tmax (14.2 °C), average Tmin (1.1 °C), and seasonal precipitation (160 mm), the CMIP6 ensemble projected warmer and slightly wetter winters in the study area region, with ensemble mean changes in Tmax (+0.89 °C), Tmin (+0.74 °C) and precipitation (+8%) in Time slice-1 (2021–2040), while further rising in Tmax (+3.1 °C), Tmin (+3.0 °C) and precipitation (+23%) in Time slice-4 (2081–2100), larger under SSP5-8.5 than SSP2-4.5. These changes shortened the growing season by 4-17% and reduced grain number 3-21%, which translated to yield losses of 4-20% relative to baseline when reference CO_2 was used (380 ppm).

Further, both crop models reproduced the climate impact. Regarding grain yield, CERES-Wheat often showed a slightly stronger sensitivity to future warming than N-Wheat. CERES-Wheat is found to be more climate sensitive than N-Wheat for duration to anthesis and often also for duration to maturity for all time slices, where SSP5-8.5 amplifies the reductions compared to SSP2-4.5. Across scenarios, CERES-Wheat shows a 5% and 7% larger decrease in grain number and grain yield than N-Wheat, indicating greater susceptibility to warming and precipitation variability, with stronger reductions under SSP5-8.5. This indicates that CERES-Wheat is more responsive to warming as it uses a simple threshold for thermal time, while N-wheat uses heat response functions for hot environments (Kassie et al. 2016). Raising the temperature between 1 and 4 °C beyond the baseline climate reduced grain yield between 13 and-42% in N-Wheat and between 17 and 44% by CERES-Wheat. Asseng et al. (2015) reported that warming accelerates development and shortens the crop's phenological period. Likewise, CERES-Wheat consistently exhibits slightly greater yield reduction under the same warming as it is more temperature sensitive. CO_2 sensitivity analysis showed that both crop models reached their highest grain yield in Time slice-4 at 1067 ppm under SSP5-8.5, showing a 30% increase over the 380-ppm baseline. The smallest gain occurred in Time slice-1 at 460 ppm under SSP2-4.5, with only a 4% increase over the baseline. The increased production of grains is due to the improved absorption of carbon during photosynthesis, more efficient utilization of nitrogen, and less water loss caused by partially closed stomata under higher CO_2 environments (Asseng et al., 2019). Adaptations improved yield early sowing in October, (since each day delay reduced 16% yield significantly per day). Seasonal irrigation (300 to 400 mm) and nitrogen application (250 to 300 kg ha^{-1}) consistently increased yield in both models under near-term (Time slice-1) warming.

Conclusions

The study demonstrated using CERES-Wheat and N-Wheat models that rising temperatures and changes in precipitation significantly impact on phenology, grain numbers, and yields of winter wheat, while adaptation measures could improve the wheat yield in the region. CERES-Wheat is more climate sensitive than N-Wheat and showed higher yield losses

(20%) compared to baseline with reference CO_2. Temperature increases in the region (1-4 °C) would reduce grain yield by about 13-42% in N-Wheat and about 17-44% for CERES-Wheat compared with baselines. Practical adaptation, like sowing in start of October, applying 250 - 300 kg ha^{-1} nitrogen and applying irrigation of 300 to 400 mm would increase the yield and offset the negative impacts of climate change in the region. Early maturing, nitrogen and water efficient genotypes could also be alternative adaptation measures for sustainable wheat production under changing climate.

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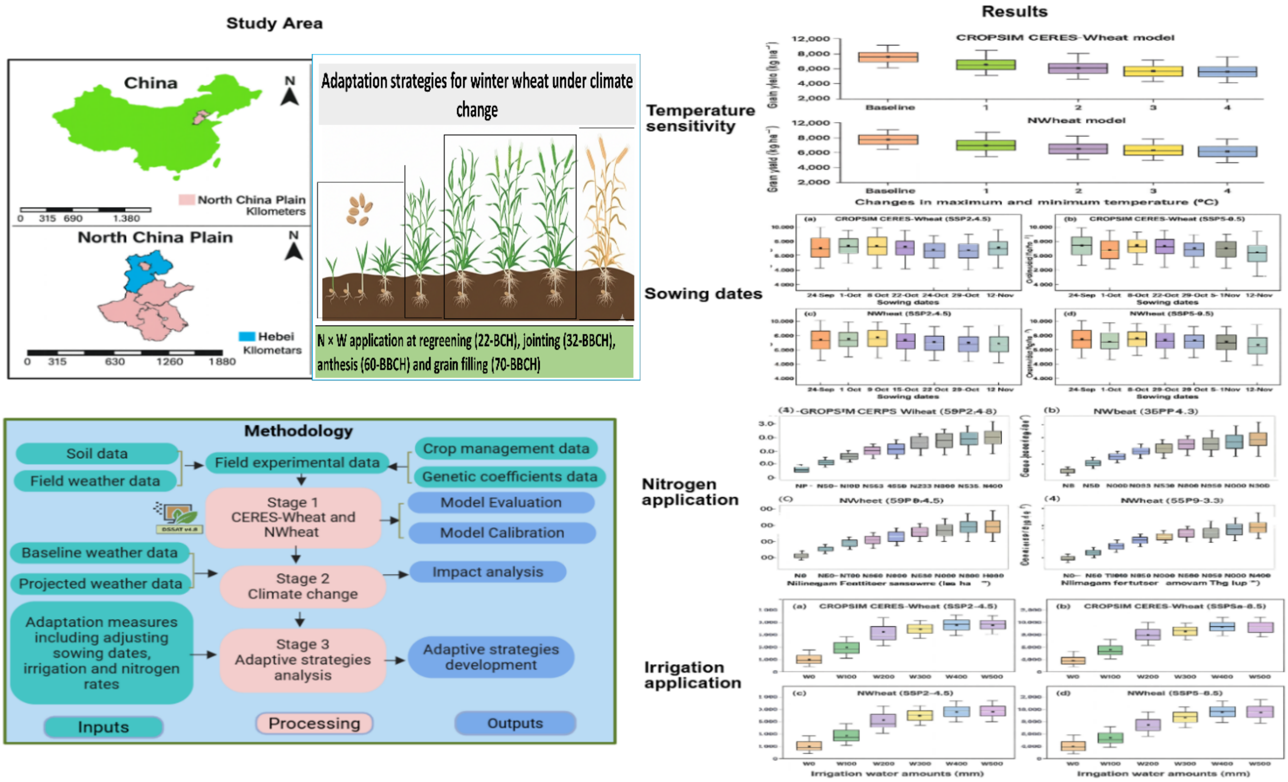
Graphical Abstract



Simulating water and nitrogen stress in maize and groundnut: Implications for climatic risk in sub-humid Zimbabwe

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Keywords: crop model, sustainable intensification, sub-Saharan Africa, leaching, legume

Introduction

The currently low productivity and low profitability of smallholder cropping systems in sub-Saharan Africa can be improved through sustainable intensification. Yet, intensifying crop production of rainfed agriculture can lead to higher climatic risk. Integration of legumes in cropping systems offers the prospect to reduce the variability of the performance of intensified cereal-based systems: legumes have a contrasting crop cycle duration and sensitivity to water stress, and can fix nitrogen from the atmosphere which makes them less dependent on fertilization. The objective of this study was to explore the sensitivity to interannual rainfall variability of cereals and legumes in the context of smallholder farms, based on a case study in sub-humid Zimbabwe.

Materials and Methods

We parameterised the STICS crop model (Brisson et al., 2002) with observations of maize and groundnut growth obtained through the detailed monitoring of on-farm trials and farmers' fields, during two growing seasons in the Murehwa district in sub-humid Zimbabwe. A virtual experiment with the parameterised model was used to assess the response of maize fertilized with 80 kg N ha^{-1} and groundnut (unfertilized) to historical climate variability (1996-2023). We explored the STICS simulation results of water and nitrogen (N) stress during three periods of the crop cycle (vegetative phase, grain number setting and grain filling) to identify the type of stress and its timing.

Results and Discussion

In our simulations, maize yield variability was primarily driven by N stress and occasionally by water stress. Water stress only marginally explained maize yield variability, but was the main driver of groundnut yield losses. Analysing rainfall patterns at the start of the season proved to be critical for understanding crop response to climate variations: wetter starts were associated with N leaching, which was detrimental to maize, but not so much to groundnut (which relied on nitrogen fixation). Drier starts strongly impacted the grain number setting of groundnut, while maize, still in its vegetative phase, was less impacted. Over the 27 simulated growing seasons, groundnut reached its potential yield whereas maize did not. Groundnut yield was on average closer to its maximum water- and N-limited yield and showed a lower risk of substantial yield decline due to water stress than maize. Based on these metrics of performance, we concluded that groundnut was less sensitive to interannual rainfall variability than intensified maize.

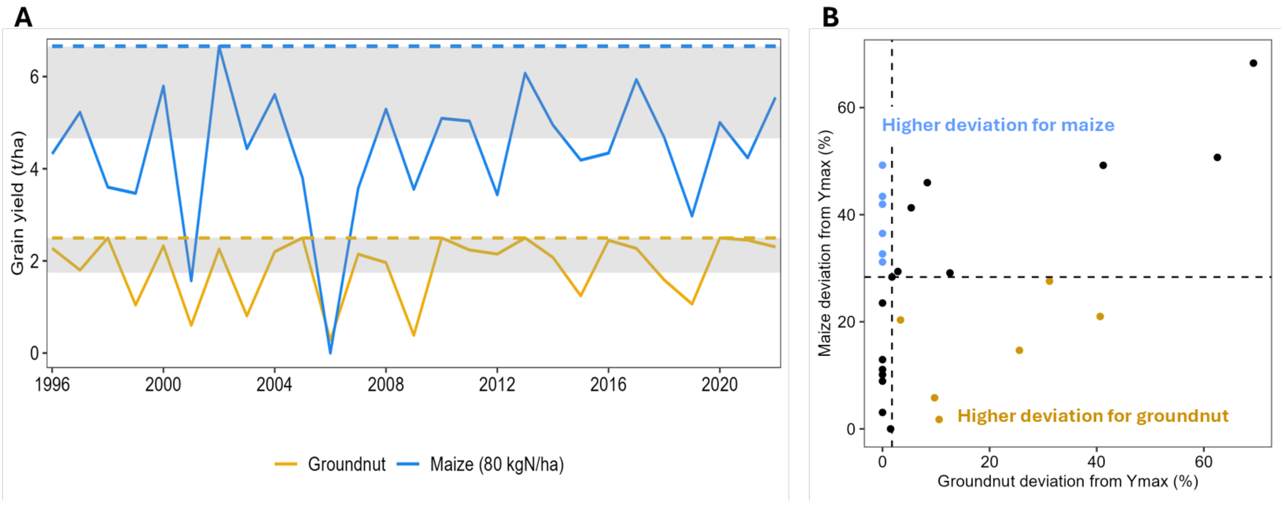

Figure 1:A) Simulation of 27 seasons of water- and N-limited yield for groundnut and maize fertilized with 80 kg N ha^{-1} (plain line). Dashed line is the maximum water- and N-limited yield of the 27 seasons (Ymax). The grey shaded area indicates growing seasons with no seasonal climatic risk, i.e. seasons with deviation from Ymax lower than 30%. B) Maize deviation from Ymax (vertical axis) and groundnut deviation from Ymax (horizontal line) for 27 simulated growing seasons. Dashed lines are the median deviation from Ymax for maize (vertical) and groundnut (horizontal). Black dots represent growing seasons when maize and groundnut deviations are both above or below their respective median deviation, blue dots represent growing seasons with higher deviation for maize and yellow dots represent growing seasons with higher deviation for groundnut.

Conclusions

This analysis was useful to show emergent properties arising from simulated water and N stress on maize and groundnut yields across crop stages. It highlights the importance to accurately assess N leaching in sub-humid climates to understand the sensitivity of intensified maize to rainfall variability. Our findings underscore the potential to integrate groundnut into maize-based cropping systems to help decrease cropping sensitivity to climate variations.

Acknowledgements

We are thankful to the EU-DESIRA program under Grant Agreement No 424-933, project RAIZ (Promoting agroecological intensification for resilience building in Zimbabwe).

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Can deforestation-free cocoa production meet demand by 2060 under climate change? A crop-modelling study

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Keywords: *Theobroma cacao*, yield gap, yield projections.

Introduction

Cocoa (Theobroma cacao L.), is a globally important commodity tree crop, the production of which supports the livelihoods of about six million mostly small-holder farmers. Global cocoa production has expanded at the expense of forests and croplands, a trend likely to worsen with rising demand and climate change. To halt this, the European Union's Deforestation Regulation (EUDR) will ban cocoa imports from areas deforested after 2021. In the meantime, climate-change associated warming and changes and rainfall may negatively impact cocoa production, while current yields are very low, on average ~10% of potential yields, especially in West and Central Africa where >70% of cocoa is produced.

The question that urgently concerns the whole cocoa sector is to what extent West/Central can meet growing cocoa demands in coming decades. We explored the extent to which cocoa production can meet future demand and under three scenarios under three climate scenarios (warm/wet, mid, hot/dry) using three pathways: Farmer Management Practice (FMP, meaning yield gaps will not change and farmers will not expand into new areas), Extensification (EXT, yield gaps will not change but farmers will expand into all suitable areas that are current not either forest or food crops), and Intensification (INT, farmers reduce yield gaps but do not expand into new areas).

Materials and Methods

We focused on the four principal cocoa-producing countries in West (Côte d'Ivoire, Ghana, Nigeria) and Central (Cameroon) Africa. We obtained annual mean yields on cocoa farms following good agronomic practices with fertilizer (INT) and without fertilizer application (INT+F) for 2021-2023 at 220 locations across the four cocoa-producing countries in West and Central Africa as part of the Cocoasoils project (CocoaSoils, 2024; Vasquez-Zambrano et al., 2025). Future and current water-limited potential yields (Yp) were calculated with using the CASEJ cocoa model for each farm (Asante et al. 2025). For 'historical' (1980-2010) conditions we used recorded weather data at 25 km spatial resolution from the Global Meteorological Forcing Dataset (GMFD) for Land Surface Modeling. For 'future' (2030-2060) we used the (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6) derived from the General Circulation Model (GCM). Five GCMs were selected to reflect hot or warm, dry or wet and intermediate conditions. Soil information was obtained following the approach of Asante et al. (2022). Relative yield gaps were determined as Ya/Yp with Ya actual yields. Three scenarios of future actual yields and yield gaps were assumed:

(i) 'Current-farmer-practices (FMP) pathway: Yield gaps are assumed to remain the same and equal to those determined from current National level annual mean cocoa yield (kg/ha) for 2021-2023 was obtained from FAOSTAT.

(ii) Intensification (INT) pathway: Yield gaps obtained from good agronomic practices treatment with (INT-F+) and without (INT-F-) fertilizer in 220 on-farm trials (CocoaSoils, 2024; Vasquez-Zambrano et al., 2025).

(iii) Extensification (EXT) pathway: Yield gaps as in FMP scenario but extension of cocoa production allowed into areas not currently under forest or used for food crops.

To estimate future cocoa demand by 2060, we modelled historical cocoa demand (1986 to 2023) as a function of year using a simple linear regression model, assuming that demand will continue to increase at a similar rate as observed in the past (1986 to 2023) and shares of demand covered by the respective countries remain constant.

Results and Discussion

The projected effects of climate change on yields (change relative to historical) differed between scenario's being more positive under the warm/wet than under the hot/dry scenario. There was a clear north-west south-east gradient; for Ivory coast and to a lesser extent Ghana predicted yields tended to decline especially in the northern part of the cocoa region there. In Cameroun on the other hand predictions were mostly positive. These results are noteworthy as about 70% of current global cocoa production comes from Ivory Coast and Ghana, and thus under future climates the balance could shift more towards Central Africa. Regarding meeting future demands under the FMP pathway (no reductions in yield gap and no extension), the region would fail to meet projected demand in any climate scenario. In fact, only about half of future cocoa demand would be met. The EXT pathway, allowing expansion into suitable non-forested/cropland areas, met demand except under hot/dry scenario. Note however restriction to non-forested and non-crop land would not exclude biodiversity losses, e.g., if savanna were to be converted to cocoa. Only the INT-F+, where yield gaps are reduced through good agronomic practices and fertilizer use, met demand across all scenarios even without exploiting new areas. However, without fertilizer, INT fell short in hot/dry conditions. Data from 220 on-farms trials has shown that such reductions in the needed yield increases are possible on small-holder farms in West/Central Africa (Vasquez-Zambrano et al., 2025). However, cocoa yields in Africa have lingered at very low levels for decades, and more concerted efforts would be needed to provide with necessary inputs and knowledge.

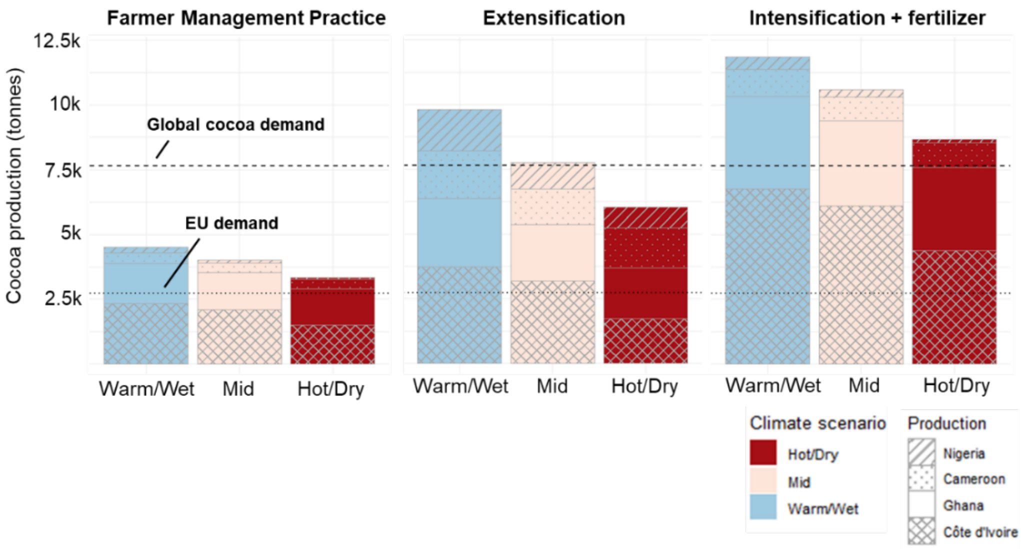

Figure 1. Predicted future (2060) deforestation-free cocoa production under a) Farmer Management Practice (FMP); b) Extensification (EXT) and c) Intensification with fertilizer application (INT+F) under three climate scenarios (blue/pink/red colors) for the four principal cocoa producing countries in West and Central Africa - Côte d'Ivoire, Ghana, Nigeria, Cameroon. Projected demand (dashed lines) for the European Union (in dashed line) and other consuming countries (in dotted line) are indicated.

Conclusions

FMP, assuming no plantation expansion and maintaining current yield gaps, failed to meet projected demand in any climate scenario. EXT, allowing expansion into suitable non-forested/cropland areas, met demand except under hot/dry scenario. Only INT, which uses achievable closure of yield gaps through good agronomic practices and fertilizer use, met demand across all scenarios. These findings highlight the need for strategies that could ensure deforestation-free cocoa production under changing climatic conditions.

Acknowledgements

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Quantifying what matters in carbon farming: SOC and N_2O driven by practices and crops

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Keywords: Carbon Farming, Cropping Systems, SOC, N_2O, Europe

Introduction

Soil organic carbon (SOC) and nitrous oxide (N_2O) are foundational metrics for assessing the climate performance of agricultural systems (Gabbrielli et al., 2025). The credibility of carbon farming relyes on quantification models that not only estimate absolute SOC and N_2O values, but also discern how specific practices and crop types drive increases in SOC and reductions in N_2O emissions. A rigorous calibration and validation framework must address not only the magnitude of SOC and N_2O responses, but also the differential contributions of practices relative to a baseline. This study focuses on developing a robustly calibrated model, ARMOSA (Valkama et al., 2020, Perego et al., 2023), calibrated for European soils, crop systems, and agronomic practices based on VERRA requirements (VM0042, Improved Agricultural Land Management Version 2.1, 2024). The calibration framework was designed to ensure consistency with MRV (monitor, report, verification) requirements, thereby providing scientifically credible and policy-relevant tools for carbon farming.

Materials and Methods

The study examined the ARMOSA process-based model used in carbon farming standards, assessing its calibration and validation performance comapring observed variability with model bias. Long-term field experiments across diverse European agroecosystems provided datasets on SOC dynamics and N_2O fluxes under varying management practices and crop rotations. Model calibration was conducted not only to improve predictions of absolute SOC and N_2O values but also to validate the models' ability to capture the relative impact of specific practices (e.g., cover cropping, reduced tillage, fertilizer management) and crop types on soil carbon gains and N_2O reductions. Sensitivity analysis, automatic calibration based on genetic symplex, and validation with external and independent datasets were carried out across soil textures, organic matter levels, and climate zones.

Results and Discussion

Calibration using long-term experimental data significantly reduced prediction errors, particularly for SOC accumulation under crop rotations and cover cropping. Validation demonstrated that models could reproduce trends in SOC changes andrequired parameter adjustment of a low number of parameters to capture the magnitude of practice effects (Figure 1a). For N_2O, uncalibrated models tended to overestimate emissions in low-input systems and underestimate peaks following fertilizer application. Once recalibrated, models achieved improved alignment with chamber-based field measurements, reducing uncertainty bands. Results also indicated that crop choice exerted a strong influence on SOC responses, while management intensity shaped N_2O variability (Figure 1b). A robust validation must therefore focus not only on mean absolute values but also on the responsiveness of models to changes in management.

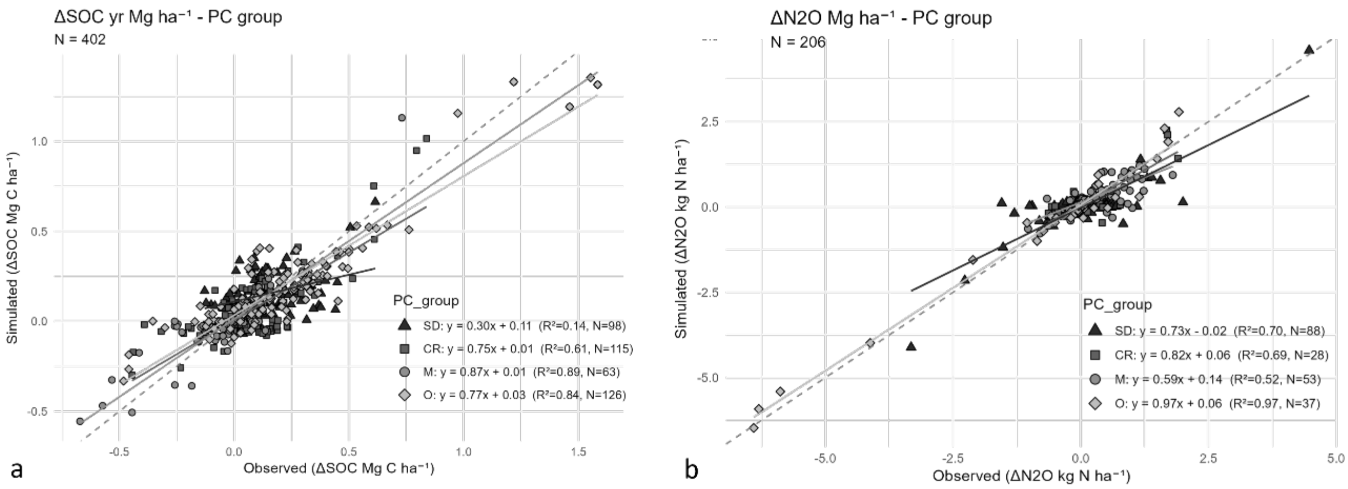

Figure 1. ARMOSA performance for SOC (a) and N_2O (b) changes from baseline to practice implementation (PC). The simulated practices are related to soil disturbance (SD), multi-crop rotation (CR), sub-optimal N input (M), organic fertilizer (O).

Conclusions

The low-bias performance of ARMOSA in simulating changes in SOC and N_2O emissions due to the implementation of practices across a wide set of cropping combinations is crucial for crediting schemes, as carbon markets depend on accurate differentiation between business-as-usual baselines and improved practices. The findings reinforce calls for EU-specific calibration frameworks that integrate pedoclimatic diversity, ensuring scientifically defensible and policy-relevant SOC and N_2O quantification for MRV projects in carbon farming.

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Modeling the impact of climate and management scenarios on olive production and olive tree-olive fly interaction

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Keywords: Mediterranean Basin; multi-trophic models; climate change; *Bactrocera oleae*, fly predators.

Introduction

Climate change will severely affect food security worldwide making crop adaptation strategies vital for both herbaceous and tree cropping systems. Beside direct impacts on crops, climate variation will also affect the interaction between cultivated and wild species, with consequences for crop management largely difficult to predict. In this context, crop simulation models represent a powerful support tool thanks to their ability of exploring, *in silico*, a broad range of agro-climatic conditions. However, they have been rarely used for climate change studies targeting the evaluation of the interaction between different species under alternative management scenarios. Considering the olive tree as a case study crop, this is the first time a crop simulation model has been used to explicitly simulate olive tree- olive fruit fly interaction under multiple management scenarios in the frame of global climatic changes.

Materials and Methods

A spatially distributed analysis was carried out focusing on the Mediterranean Basin that, besides being the world's main olive producing district with more than 96 % of the global olive harvested area (FAOSTAT, average values from 2019 to 2023), it is considered a climate change hotspot. Climate data were retrieved from the global high resolution Multi Source Weather (MSWX) database, while information on soil properties was found on the FAO Harmonized World Soil Database. For what concern olive tree distribution, the CORINE Land Cover database was used for Europe, whereas GAEZ FAO data portal and FAOSTAT statistic on olive harvested areas have been used to derive the olive crop mask for the remaining regions. The study considered both traditional and high-density orchards, the latter being increasingly adopted in many olive producing countries. Considering the importance of water management, information about irrigated and rainfed areas has been retrieved from the European Crop-specific IRrigated Area (ECIRA) database for European countries whereas data from AQUASTAT and Olive International Council have been used for the other countries. In order to handle the uncertainty in future climate projections, two different General Circulation Models (IPSL-CM6A-LR and MPI-ESM1-2-LR) coupled with two Shared Socioeconomic Pathways (SSP2-4.5 and SSP3-7.0) have been considered for a timeframe centred on 2050. Olive tree- olive fruit fly interaction was simulated using the new modelling approach proposed by Movedi et al. (2025), which considers also fly predators and the effect of key abiotic stressors. The tree model extends the approaches proposed by Villalobos et al. (2006) and Moriondo et al. (2019), whereas the interaction between olive tree, olive fly and fly predators is simulated according to Gutierrez et al. (2009). Model outputs consisted in olive tree yield, number of olives, percentage of infected olives and the number of insecticides treatments which are of fundamental importance to assess the environmental impact of olive tree-olive fruit fly interaction under climate change scenarios.

Results and Discussion

Results showed that climate change will have a clear impact not only on growth and development of the olive tree and olive fly individually, but it will have also a strong influence on their interaction dynamics. Additionally, the model highlighted that management scenarios characterized by high plant density and highly mechanized orchards will see an increase in olive fruit fly pressure on olive production, especially because of the increasing number of olive fruits available after harvest (lower efficiency of the mechanized harvesting). Unharvested fruits will indeed support fruit flies during the winter, increasing the fly population size at the beginning of the following season. Dynamic simulation of pesticides applications to contain fly population enabled also estimates on the environmental impact of alternative management scenarios, and allowed to evaluate changes in the suitability of different areas for olive cultivation in the mid-term.

Conclusions

This study highlighted the importance of analyzing the impact of climate and management scenarios on the interactions between cultivated and wild species, and provided insight into long-term effects of different crop cultivation systems. Given the differential impacts across the olive producing areas, the study also underlined the need of evaluating climate change impacts on global import/export olive oil trade flows.

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Uncertainty of the rising atmospheric CO2 concentration on the global wheat productivity

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Keywords: AgMIP, CO2, Wheat

Introduction

The increasing levels of atmospheric CO_2 over the past decades have significant implications for crop production, particularly for wheat, a major food crop, as it is essential to understand how wheat yields are influenced by CO_2 under climate change. Most climate change assessments, including studies on CO_2 effects, have focused on controlled environments such as growth chambers, open-top chambers (OTC), and free-air CO_2 enrichment (FACE) experiments, along with analyses of the combined effects of rising temperatures and nitrogen availability. Elevated atmospheric CO_2 (eCO_2) is also reported to have positive effects on rice productivity, potentially alleviating some negative impacts of global warming. To project the effects of eCO_2 on wheat across different climate zones, considering factors such as temperature and nitrogen, we ran 21 crop models and analyzed their sensitivity to combined changes in nitrogen, temperature increases, and atmospheric CO_2 concentrations (from 450 to 990 ppm compared to a baseline of 360 ppm) based on a location-specific high-emission late-century climate scenario (Asseng et al., 2013).

Materials and Methods

We collected eCO_2 effect data from field experiments published in peer-reviewed journal articles (Fig. 1). To minimize the potential impact of other factors, we excluded experiments with environmental or biological stress (that is, natural disasters, heat or drought stress), experiments with N fertilizer rates below local recommendations. To compare the measured and simulated wheat data regarding the effects of CO_2, we also extracted biomass data for each study to assess how biomass accumulation aligns with the model's CO_2 simulation effects, which were evaluated using two subroutines (Fig. 2). Based on the differences in biomass derived from assimilation or radiation use efficiency methods, the data can be categorized into two groups. Similarly, in terms of water consumption, the data can be divided into two groups based on either stomatal conductance or transpiration.

Results and Discussion

Decades of wheat CO_2 research have demonstrated that elevated CO_2 (eCO_2) generally has a positive effect on wheat production across various methods (Fig. 1). Over the past thirty years, CO_2 enrichment experiments in wheat fields have been conducted using growth chambers, open-top chambers (OTC), and free-air CO_2 enrichment (FACE) setups, although the effects vary depending on conditions. Crop models are valuable tools for assessing the long-term impacts of climate change on wheat yields, but their performance can vary due to differences among models. While increased CO_2 can enhance crop production, rising temperatures may offset these gains by exerting negative effects (Long, 2006). Additionally, considerable variation exists between FACE and chamber experiments, partly due to other stress factors such as nitrogen availability and temperature stress. This variation is partly caused by the high sensitivity of crop models to changes in air temperature (Tair) and nitrogen (N), especially when interacting with different levels of eCO_2. Crop models can simulate CO_2 levels up to 1000 ppm, whereas FACE and OTC experiments rarely reach such high concentrations. The observed relative effects of CO_2 on biomass and water consumption from the literature can be encompassed within the range of variation of the two subroutines (Fig. 2).

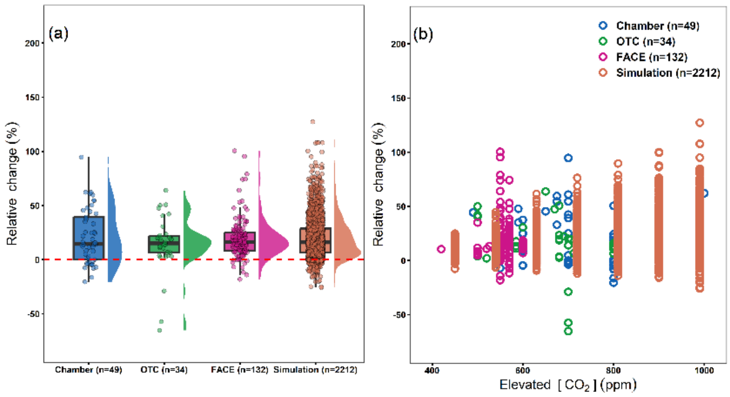

Figure 1. Simulated wheat, barley and potato yield under organic and conventional optimal fertilzer rate at long term conditions. The simulation is from 21 different crop models

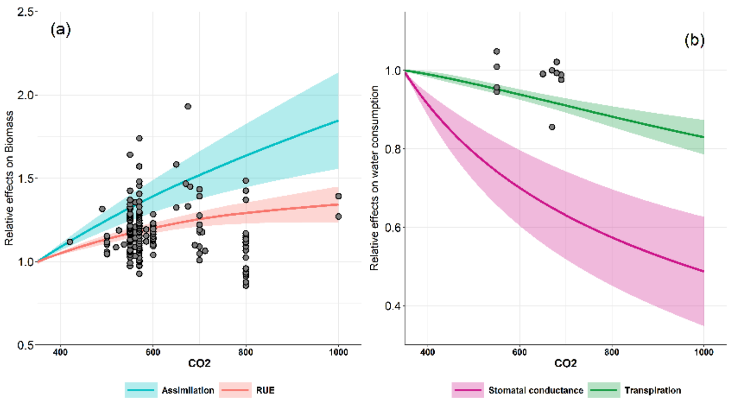

Fig. 2 Different model subroutines for biomass and water consumption. The points in (a) are observed relative biomass change from the literature. The points in (b) are observed relative ET change from the literature.

Conclusions

Our simulations suggest that wheat production under higher CO_2 levels is expected to be more uncertain, with model performance varying depending on the underlying mechanisms of biomass and water consumption simulations.

Acknowledgements

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Coffee yields in a changing climate: insights from multi-scale process-based modelling

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Keywords: Arabica, Robusta, Adaptation, Agroforestry

Introduction

Coffee agroecosystems, dominated by *Coffea arabica* and *C. canephora*, are among the most important globally but are threatened by climate change, which may reduce yields and shift cultivation areas (DaMatta et al., 2019; Bilen et al., 2023). Addressing these risks requires linking physiological processes with spatial and environmental gradients and assessing adaptation options. Shade trees in an agroforestry approach can buffer microclimate and enhance ecosystem services, though sometimes at the cost of yield (Koutouleas et al., 2022). Process-based models offer a valuable approach to integrate physiological mechanisms, environmental drivers, and management practices to assess vulnerabilities and guide adaptation (Vezy et al., 2020; van Oijen et al., 2022).

Materials and Methods

This study assessed the impact of climate change on coffee yields by simulating physiological interactions between crop growth, climate, and management. The process-based DynACof model (Vezy et al., 2020) was validated for Arabica with datasets from different countries. This was expanded into G-DynACof, enabling large-scale applications by integrating ensembles of climate projections and other environmental data. Using G-DynACof, potential yield trends were projected at a continental scale for Arabica in Latin America and Africa for 2036–2065 using an ensemble of downscaled and biased-corrected climate projections under two Shared Socioeconomic Pathways (SSPs), compared with historical data (1985–2014). In addition, we implemented a new, exploratory parameterization for Robusta, which, together with Arabica, was used to evaluate the effect of different degrees of shading on projected yields at the local scale in selected farms in Costa Rica, Mexico and Vietnam.

Results and Discussion

Model simulations project potential Arabica yield declines of 23–35% in Latin America and 16–21% in Africa (Figure 1A), depending on SSP scenario (SSP1-2.6 vs. SSP5-8.5, respectively). Results varied spatially, with potential yield gains at sites with lower temperatures and higher altitudes (Fig. 1B), suggesting a geographical shift of suitable growing areas, with potential implications for displacing natural ecosystems especially over mountain areas.

The impact of increasing shade tree density on projected coffee yield was variable for both Arabica and Robusta species. Yields generally improved with higher shade levels – despite reduced coffee plant densities and increased competition for light and water – but only up to a threshold, beyond which they began to decline. These findings highlight the need to better understand the conditions under which agroforestry can function as an effective adaptation strategy.

Conclusions

Climate change will likely reduce coffee yields, with marked regional differences and possible displacement of productive areas. While increasing shade tree density may help buffer temperature extremes and enhance resilience, its effectiveness as an adaptation measure is not universal. The G-DynACof tool offers a robust framework to explore future scenarios and guide climate-smart strategies. Further research is needed to refine shade management practices and integrate socio-economic factors for holistic risk assessment and policy support.

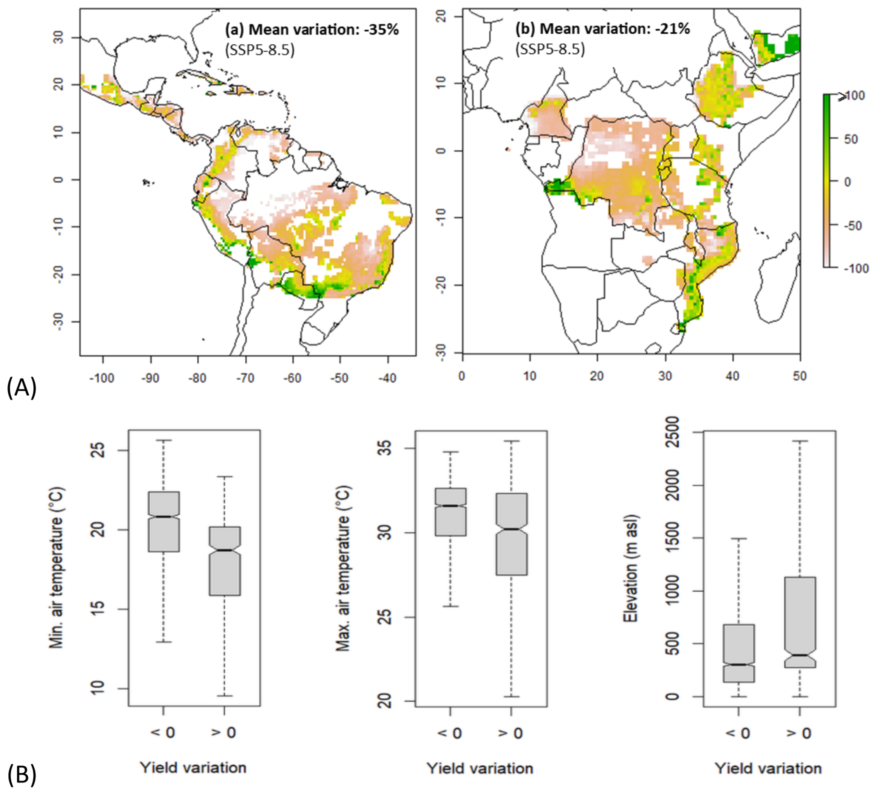

Figure 1. (A) Predicted percent variation of potential yield in Latin America (a) and Africa (b), climate projection (2036-2065) vs. historical climate (1985-2014). (B) Multi-model average for SSP5-8.5.Distribution of minimum and maximum annual temperatures and elevation, comparing areas where yield is predicted to decrease (yield variation < 0) versus areas where yield is predicted to increase (yield variation > 0), in Latin America. Multi-model averages of historic climate (1984-2015). All differences are statistically significant ($p < 0.01$).

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Genomics-informed predictions reveal breeding and sowing co-adaption potential in stabilizing wheat phenology under global warming for China and Europe

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Keywords: global warming | heading date | genomic prediction | SNP-based model | ideotype design

Introduction

Climate warming is projected to shorten wheat growth duration and reduce yields globally, threatening food security (Asseng et al., 2015). Wheat provides nearly 20% of global calories and protein, and stabilizing its phenology, especially heading date (HD), is essential to ensure sufficient biomass accumulation and yield under changing environments (Craufurd & Wheeler, 2009). Existing crop growth models require extensive phenotyping and are often limited in predicting new cultivars, while data-driven genomic predictions do not explicitly capture genotype × environment interactions. Integrating genomic information with process-based crop models has recently been proposed as a promising pathway, but its application across multiple populations and continents remains scarce (Bogard et al., 2021). To address this, we developed a SNP-based WheatGrow framework, combining genome-wide markers with ecophysiological modeling, to evaluate breeding potential and sowing management co-adaptation for stabilizing wheat HD under future climate warming.

Materials and Methods

We assembled three representative populations (GABI, iwheat, MCC; 881 genotypes) grown in 20 environments. Four genotype-specific parameters (intrinsic earliness, photoperiod sensitivity, physiological vernalization time, thermal sensitivity) of WheatGrow were calibrated by differential evolution and associated SNPs were detected using a multi-GWAS ensemble. BayesC models translated SNPs into genotype-specific parameters to build a SNP-based WheatGrow able to simulate HD for untested genotypes. Climate forcing used NEX-GDDP-CMIP6 daily temperatures for a historical baseline (2001–2021) and future warming (2050–2070, SSP5-8.5). Seven representative sites in China and Europe were evaluated under a ±30-day sowing window (7 dates, 10-day steps). HD stability was defined as $|\Delta HD|<3$ days; ideotypes were genotypes stable in ≥3 sites.

Results and Discussion

Across calibration and evaluation environments, the process-based model reproduced observed HD with low error. The SNP-based WheatGrow accurately predicted HD for new genotypes and environments and outperformed data-driven genomic prediction methods. Future warming substantially shortened time to heading at all sites, with heterogeneous sensitivity (greater in Lindau, Switzerland; smaller in Seligenstadt, Germany; in China, larger in Yangling than in Shunyi). Optimizing sowing dates mitigated these impacts: advancing sowing by approximately 10–20 days at several sites maximized stability. Under site-specific optimal sowing, 32–48% of genotypes were identified as ideotypes with stable HD across multiple sites. Shared alleles at 6–20 SNPs were enriched among ideotypes, providing targets for marker-assisted selection and ideotype design. These findings demonstrate a practical co-adaptation pathway that integrates genomic selection with sowing management, captures G×E interactions, and supports regionalized breeding strategies.

Conclusions

A SNP-based, genotype-to-phenotype WheatGrow enables rapid HD prediction for diverse wheat germplasm and quantifies breeding and management co-adaptation under warming. Advancing sowing and exploiting shared alleles underlying stable HD can buffer phenology shifts in China and Europe. The framework is modular and transferable to other traits and crops to guide ideotype-oriented adaptation.

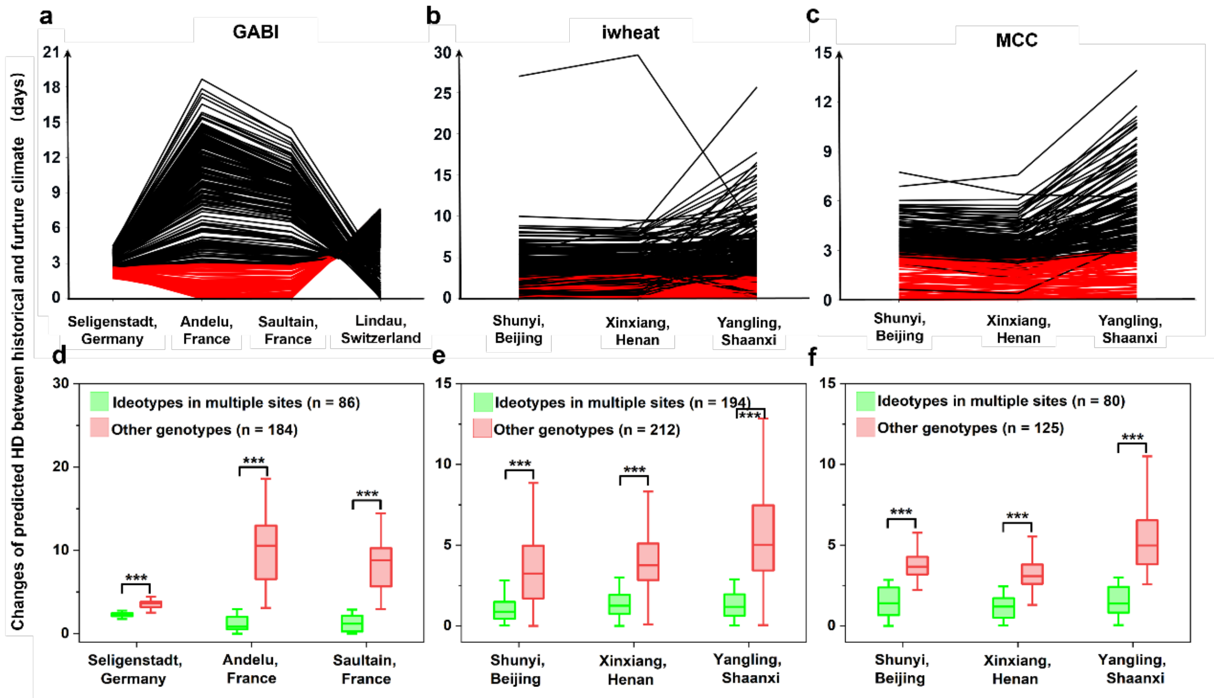

Figure 1. Ideotypes identified with adaptation potential in stabilizing phenology and adaptation potential comparison between ideotypes and other genotypes. **a-c**, Ideotypes identified at least three representative sites across the three wheat populations. Red lines indicate the ideotypes that repeatedly identified in at least three representative sites. **d-f**, Comparison of the differences in predicted heading dates between the genotypes with and without adaptation potential in stabilizing phenology. The 7 representative sites were Andelu and Saultain from France, Seligenstadt from Germany, Lindau from Switzerland; Shunyi from Beijing, China, Xingxiang from Henan Province, China, and Yangling from Shaanxi Province, China. * indicates $p < 0.05$, ** indicates $p < 0.01$, *** indicates $p < 0.001$. Three wheat populations used in this study, namely genome analysis of the biological system of plants wheat population (GABI), iwheat and mini-core collection of Chinese wheat (MCC), respectively. We have compared the ideatypes of the GABI population in four representative European sites and found that the ideatypes in Lindau, Switzerland were different from those in the other three sites. Therefore, we only selected ideatypes that appeared in all three representative European sites for further analysis.

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Attributable economic impacts of climate change for crop production in Germany are positive and significant

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Keywords: APSIM, PALUD, land use, adaptation, attribution

Introduction

Quantifying the economic impacts of climate change is of interest to society and policy. However, the aggregate economic impact of climate change on the agricultural sector is still uncertain, as numerous climate change impact assessments regard crop yields only (see e.g., Jägermeyr *et al*. 2021), which do not determine economic output alone. Instead, aggregate production and plot-level gross margins of farmed crops are further important, which in turn depend on the farmed crop mix, input costs, and crop prices. Here, we present a quantification of climate change-attributable impacts in aggregate crop production and agricultural economic output in Germany to date by linking the process-based crop model APSIM-NG (Holzworth *et al*. 2018) with the economic optimisation model PALUD (Sponagel *et al*. 2022). This gives us an extended impact transfer function that connects climate change impacts on crop yields to changes in production and economic output.

Materials and Methods

APSIM-NG was calibrated for seven major crops, namely winter wheat, winter rape, spring barley, winter barley, grain maize, silage maize, and potato, representing approx. 75% of agricultural area in Germany using district-level yield and phenology data. Using factual simulations, representing climate with forcings as historically observed (hist; ISIMIP3b (Frieler *et al*., preprint) and counterfactual simulations, representing climate without anthropogenic forcings (hist-nat, analogously processed), yields of all crops were simulated on a 0.125° grid for Germany. The contribution of the CO_2 fertilisation effect was further separated from overall impacts of climate change by simulating both climate scenarios once with preindustrial and once with historically evolving atmospheric CO_2 concentrations. Simulated crop yields for both scenarios were then passed to PALUD and used to allocate cropped areas as to maximise overall gross margins using extensive economic input data with the reference period 2019-2021. Crop-specific yields and areas were then used to calculate aggregate production and normalised to cereal units. This approach enables the attribution of climate change impacts on crop yields, aggregate agricultural production, and gross margins in Germany with high space specificity.

Results and Discussion

Our results indicate that climate change –defined as the change in climate in response to changes in the atmospheric composition such as CO_2, as well as the change in the atmospheric composition itself – has had an overall beneficial effect on both gross margins and aggregate production with an increase in approx. 500 million € and 30 million cereal units per year (Table 1). The results vary by crop and district (Figure 1). Yield impacts of current climate change are positive for all crops, and most prominent for winter wheat and grain maize. Yield increases are predominantly driven by the CO_2 fertilisation effect, except for maize.

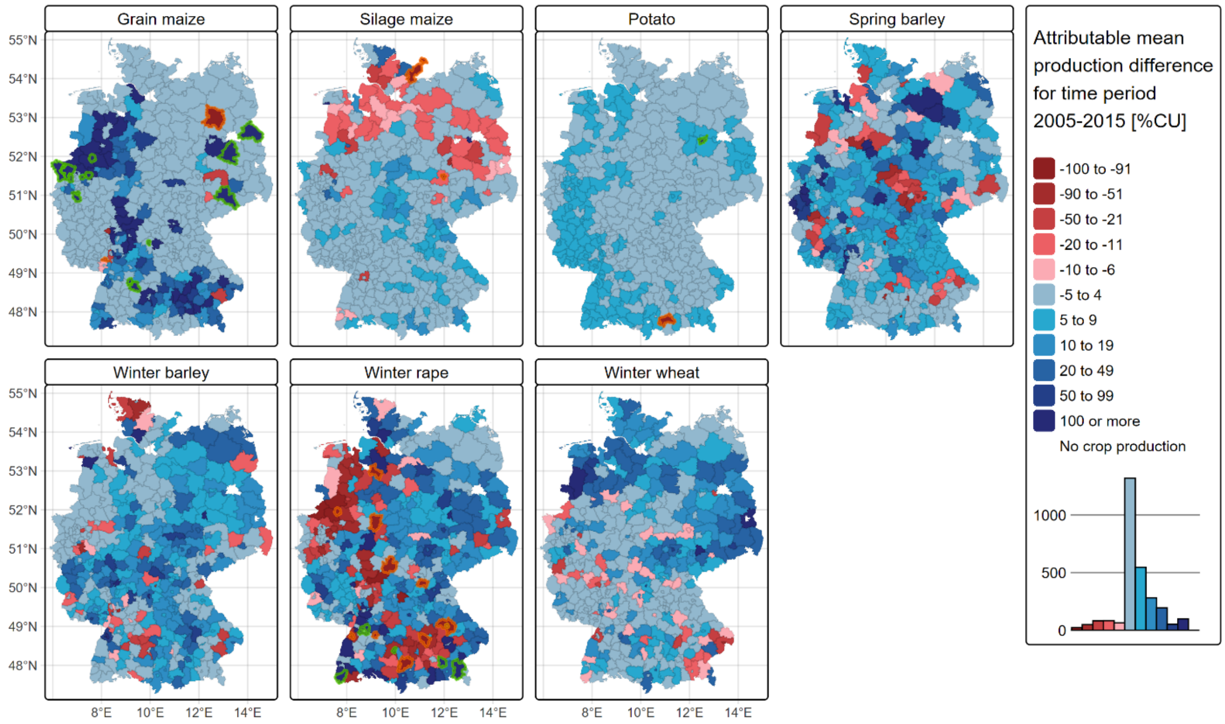

Figure 1. Maps of district-level attributable mean production changes in percent cereal units (%CU) for 2005-2015. Differences are given relative to the counterfactual scenario, i.e. the change attributable to anthropogenic climate change is shown. District outlines denote districts where all counterfactual production of the particular crop has ceased (orange outline), or production of the particular crop has started in a district with zero counterfactual production (green outline).

Table 1. Total and per-hectare gross margins and cereal units (CU) for factual and counterfactual climate scenarios across all simulated crops in Germany. Differences are given relative to the counterfactual scenario and reflect annual values. Numbers are rounded.

Parameter	Unit	Counterfactual climate	Factual climate	Difference (absolute)	Difference (relative)
Total gross margin	1,000€	7,436,676	7,929,609	492,933	6.6%
Average gross margin	€/ha	947	1,010	63	6.6%
Total cereal units	1000 CU	611,777	640,568	28,791	4.7%
Average cereal units	CU/ha	77.9	82	4.1	4.7%

Conclusions

We find that based on the climate, economic, and agricultural data and models used, attributable impacts of climate change on agricultural production in Germany are overall positive, leading to significant annual economic gains for the current time period. This impact is driven by yield increases for all simulated crops, mainly through the CO_2 fertilisation effect on yields. The results are interesting in terms of thinking about climate justice and adaptation funding and may have implications for policymaking regarding both the agricultural and other economic sectors.

Acknowledgements

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Integrating stakeholder knowledge and crop modeling to assess climate adaptation options in Northern European agriculture

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Keywords

Participatory research; Regional workshops; Model calibration; Adaptation response surfaces; Scenario analysis

Introduction

In northern Europe, where climate change is progressing faster than the global average, it has become increasingly critical to develop robust, context-specific adaptation strategies. Agriculture is particularly vulnerable to these changes due to its direct dependence on climatic, biological, and socio-economic conditions. Finding effective and robust solutions to this challenge requires co-producing agricultural adaptation options through a participatory, transdisciplinary approach that combines stakeholder knowledge with science-based assessments.

Materials and Methods

We have developed a modelling framework integrating stakeholder engagement with process-based crop models to evaluate the feasibility and effectiveness of adaptation strategies in current and projected climate conditions. The framework operates at two spatial scales: Point-based simulations at representative sites using detailed soil, weather and management data; and regional-scale simulations using gridded datasets to assess adaptation strategies across broader landscapes.

Stakeholder engagement is central to this approach. Semi-structured interviews were conducted with key agricultural stakeholders in Estonia, Denmark, Finland, Norway and Sweden. These were complemented by a review of national and regional adaptation strategies to compile an initial list of adaptation options. Regional workshops were held in 11 agricultural regions across the five countries in autumn 2025. These workshops brought together a variety of stakeholders to finalize the list of adaptation options and to identify the associated barriers and enablers to implementation. The outcome is an adaptation matrix that incorporates both scientific and local knowledge.

The modelling platform uses DSSAT, WOFOST and APSIM Next Gen, which have been calibrated using local experimental data, to simulate the impact of selected adaptation measures under historical and projected climate scenarios (RCP2.6, RCP4.5 and RCP8.5) between 2040 and 2069. The climate data are derived from CORDEX-based projections and have been bias-adjusted and downscaled to a resolution of 12.5 km. Soil data are sourced from the Harmonized World Soil Database (HWSD v2.0) and supplemented with national and regional datasets where available. The modelling workflow includes baseline and adaptation simulations, sensitivity analyses using perturbed weather data and the generation of impact and adaptation response surfaces (Pirttioja et al. 2019; Ruiz-Ramos et al. 2018), which visualize the effectiveness and robustness of adaptation strategies under climate uncertainty.

Results and Discussion

We will present the adaptation matrix developed with stakeholders, including the identified enablers and barriers, and demonstrate how these options are assessed using the modelling framework. As a first application, we will present preliminary results for wheat systems across regions, including model calibration, stakeholder-informed adaptation options and an example of their testing within this framework.

Conclusions

This work marks the initial stage of creating a regionally relevant and scientifically evaluated portfolio of adaptation options to support long-term planning for climate-resilient agriculture in the Nordic and Baltic regions and discusses the opportunities and challenges to support the process with crop modelling.

Acknowledgements
This research was funded by the PRECILIENCE project under the European Union’s Horizon programme.

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Developing energy cover crops in France: potential production for biogas and greenhouse gas balance

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Keywords: soil carbon storage, nitrogen, fertilization, leaching, STICS model.

Introduction

To replace fossil gas that emits carbon towards the atmosphere, producing biogas from renewable resources such as biomass is a promising way. In cropping systems, cover crops are sown to provide some ecosystem services (i.e. reduced nitrate leaching, carbon storage) and are usually not harvested. They could be used as a resource for biogas production while still producing these services. They also could avoid food/fuel competition since thy do not required dedicated fields. In this simulation study, we aimed to assess the potential of cover crops to produce biogas in France and their associated greenhouse gas (GHG) balance at high resolution. We used a modelling chain of four models to simulate the cropping systems and the biogas plan and tested over 30 years two energy cover crop scenarios.

Materials and Methods

The current French cropping systems in their pedo-climates for the baseline scenario were described at the scale of a few km^2, based on Launay et al. (2021). They used the 8km x 8km SAFRAN climate grid, the 1:1,000,000 French soil map, the French Land Parcel Identification System and the Agricultural Practices' Surveys 2006 and 2011 by the French Ministry of Agriculture, Agri-food and Forestry. For each pedoclimatic unit, predominant soil types to cover at least 70% of the area and one to three predominant rotations over the period 2006-2012 were selected. Field crop management was defined per crop and former administrative region.

The energy cover crop insertion scenario introduced anaerobic digestion of energy cover crops without modifying crop rotation while the extension scenario changes some crops from winter to spring type and crop precocity to allow more energy cover crops. Cover crop species were sorghum in summer fallow and winter barley in winter fallow. They were systematically fertilized and exported only when the harvestable biomass was over 5 t DM.ha^{-1}. Exported biomass was digested to produced biogas, injected into the gas network. The digestate produced was spread on the following crops.

We chose the STICS crop model (Coucheney et al., 2015) for the simulations of crops and N, water and C balances at the field scale. We added the N balance model proposed by the French Comity for Fertilization (COMIFER, 2013) to calculate N mineral fertilization, the SYS-Metha model (Bareha et al., 2021) to simulate the transformation of cover crop biomass into biogas and digestate and the ALFAM2 model to estimate ammonia volatilization following organic fertilizer applications (Moinard, 2021). The simulation chain was coded on R version 4.0.3. Simulations were carried out over 32 years (1987-2019), with the first two years used to initialize soil water and mineral nitrogen stocks. GHG balance (GHG_B, kg CO2e.ha^{-1}.yr^{-1}) was calculated as:

$$GHG_B = 296 \times \frac{44}{28}(N_2O_D + N_2O_I) - \frac{44}{12}\Delta SOC + 5.34 \times N_F + E_{dig} - 63.1 \times Gas_{subst}$$

N_2O_D is the direct N_2O emitted from the soil, N_2O_I the indirect N_2O emitted through NH_3 volatilization and nitrate leaching (kg N.ha^{-1}.yr^{-1}). ΔSOC is the variation of soil organic carbon over the first 0.3m (kg C.ha^{-1}.yr^{-1}). N_F, E_{dig} and Gaz_{subst} (kg CO_2e.ha^{-1}.yr^{-1}) are the emissions during the production of mineral N fertilizer, the anaerobic digestion process and the substitution of fossil gas by biomethane, respectively.

Results and Discussion

Over the 13.9 Mha simulated (76% of the 18.4 Mha of arable crops and temporary grasslands), the insertion scenario modified 11.0 Mha, while the extension one modified 13.6 Mha. The annual area covered by cover crops was 1.6, 4.2 and 6.8 Mha in the baseline, the insertion and the extension scenario, respectively.

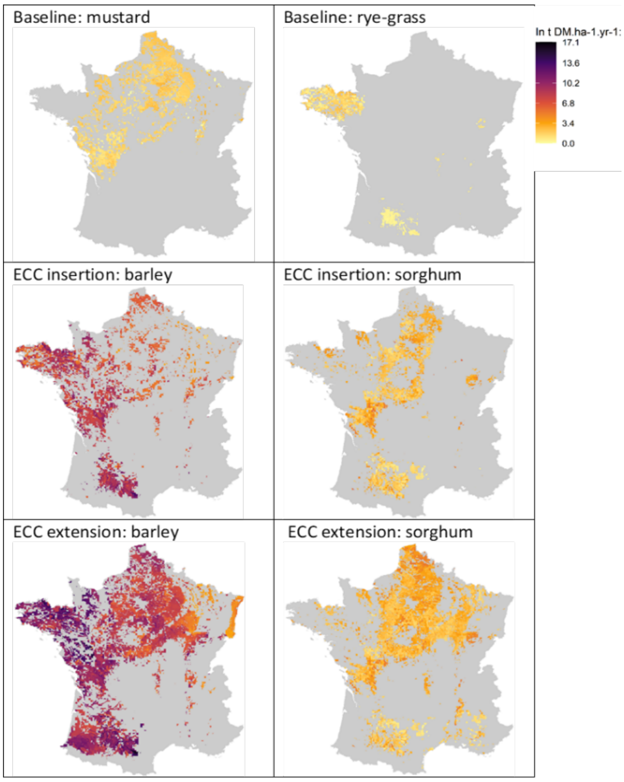

Figure 2. Aerial biomass production (t DM.ha^{-1}) of cover crops in the baseline and the energy cover crop (ECC) scenarios.

Biomass production was highly increased, multiplied by more than 6 and 16 in the insertion and extension scenario, respectively (Fig 1). Barley was exported on average 6-7 years out of 10 depending on the scenario while sorghum almost never reach the profitability threshold to be exported. On the simulated area, exportations reached 4.4 out of 12.5 Mt produced in the insertion scenario, and 18.8 out of 42.7 Mt in the extension scenario. Considering a 4 t DM.ha^{-1} threshold and 1 t DM.ha^{-1} of aerial residues instead of 33% of aerial biomass could have increased exportations to 8.9 and 31.1 Mt in the insertion and extension scenario, respectively. These biomasses correspond to 33 to 115 TWh.yr^{-1} of gas, i.e. 8 to 27% of the gas consumption in France in 2021. Extrapolated to the 18.4 Mha, it could produce at best 41.4 Mt or 153 TWh.yr^{-1}, covering one third of our current consumption. The most impactful assumption concerned the widespread adoption of winter energy cover crops.

Current cropping systems without livestock emitted 1786 kg CO_2e.ha^{-1}.yr^{-1} in average in the baseline. The insertion and extension scenarios reduced the GHG balance by 447 and 1031 kg CO_2e.ha^{-1}.yr^{-1} in the area where they were implemented, i.e. -28 and -51% respectively, compared to the baseline. It is mainly due to the substitution of fossil gas by biomethane and soil C storage despite increased N_2O emissions and fertilizer consumption (Tab. 2).

Table 4. Differences in GHG balance and its components (kg CO_2e.ha^{-1}.yr^{-1}) between the ECC scenarios and the baseline for non-livestock systems

	Δ GHG balance	Δ total N_2O emissions	Δ carbon storage	Δ N fertilizer emissions	Δ digester emissions	Δ energy production
ECC insertion	- 447 ±597	+ 77 ±85	- 308 ±318	+ 60 ±121	+ 177 ±302	- 453 ±774
ECC extension	- 1031 ±1030	+ 110 ±123	- 471 ±415	+ 120 ±112	+ 508 ±575	- 1298 ±1470

Conclusions

To conclude, energy cover crops are a potential important resource to produce renewable gas in France and could enhanced the GHG balance of cropping systems. A careful application should be done to avoid competition with food production and maximise provision of a large variety of services in addition to energy production.

Acknowledgements

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Simulating Productivity of Climate-Resilient Opportunity Crops Across Africa

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Keywords: Model calibration, impact adaptation, Africa agriculture, traditional crops, VACS.

Introduction

Africa is home to a rich diversity of traditional and indigenous crops that have long supported smallholder livelihoods across varied agroecological zones (Akinola et al., 2020). Despite their nutritional value and climate resilience, many of these "opportunity crops" remain underutilized due to historical investment biases favoring globally traded staples such as maize and soybean (van Zonneveld et al., 2023). As climate change intensifies, marked by increasing heat extremes and rainfall variability (Jägermeyr et al., 2021), these underutilized crops offer a potential pathway toward food security and adaptation. This research contributes to the Vision for Adapted Crops and Soils (VACS), an initiative focused on fostering resilient food systems and restoring soil fertility under changing climatic conditions. The study aims to identify climate-resilient crops and vulnerable regions in Africa, providing preliminary insights for future breeding, investment, and policy strategies.

Materials and Methods

Crop yields were simulated for 24 species, comprising of 19 opportunity crops and 5 staples, across the African continent using standardized protocols from the Agricultural Model Intercomparison and Improvement Project (AgMIP) (Yang & Guarin et al., 2025). Simulations were conducted under rainfed, non-nitrogen-limiting conditions using the SIMPLE process-based crop model, which is well-suited for exploratory applications due to its minimal input requirements. The modeling framework spanned a historical baseline period (1990-2019) and two mid-century climate scenarios (2035-2064) aligned with low (SSP1-2.6) and high (SSP3-7.0) greenhouse gas emissions pathways. This approach enabled relative productivity comparisons across diverse agroecological zones, offering a scalable alternative where field trials are infeasible and agronomic data are limited. The consistent structure of the SIMPLE model across crops supported identification of climate-resilient species with strong performance potential in vulnerable regions.

Results and Discussion

Simulations indicate that over half of the opportunity crops exhibit average yield increases under both mid-century climate scenarios. Teff, grass pea, sesame, and cassava consistently rank among the most resilient, showing strong performance across diverse agroecological zones. In contrast, four of the five staple crops are projected to decline, with maize experiencing the most pronounced losses. Several cereals, finger millet, fonio, pearl millet, sorghum, and teff, outperform maize across many regions, suggesting their potential as climate-adaptive alternatives (Fig. 1). Cassava and sesame demonstrate spatially consistent yield gains, while maize and lablab show widespread declines. Regional patterns reveal pronounced vulnerability in the Sahel, particularly for legumes, but also show promise for drought-tolerant cereals. Central and East Africa benefit from projected increases in precipitation, enhancing productivity for roots/tubers and oilseeds. Vegetables remain sensitive to climate stress, with tomato and African eggplant showing mixed results and likely requiring irrigation or protected cultivation. Full interactive results available at: https://vacs.theplotline.org/.

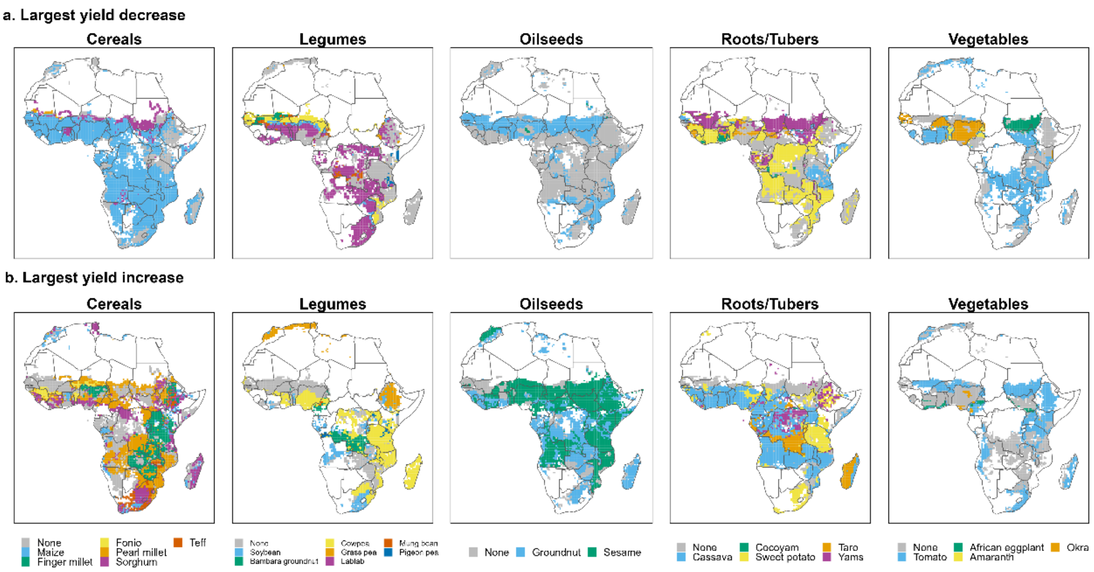

Figure 1. Maps display the crops with the largest simulated average yield decrease (a) and increase (b) within each crop type across grid cells under the high emissions scenario, SSP3-7.0. Simulations are constrainaed to current harvest areas, so not all crops are simulated in each grid cell. Cells labeled “None” indicate that no crop within that type exhibited a yield decrease or increase. Benchmark staple crops for each type are in blue.

These findings underscore the relative resilience of opportunity crops and their projected potential to support food security and climate adaptation when strategically integrated into regional agricultural systems. As productivity declines for staples like maize and soybean, a shift toward diversified cropping systems offers a timely and impactful complement. This includes targeted breeding for stress-resilient and nutrient-dense traits, increased investment in opportunity crop research and market development, and capacity building for smallholder farmers. Such efforts must extend beyond subsistence to ensure long-term viability and regional food system stability.

Conclusions

Strengthening empirical datasets for opportunity crops remains a critical next step to support robust yield projections and model ensemble assessments under the AgMIP framework. Expanded field data collection will enable the use of more comprehensive crop models and improve calibration across diverse African environments. In parallel, integrating socioeconomic and nutritional dimensions is essential to guide context-sensitive adaptation strategies and ensure that opportunity crops contribute meaningfully to resilient, equitable food systems across the continent.

Acknowledgements

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Modeling genetic adaptation to support food security under climate change. A case study on barley in Ethiopia

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Keywords: iMAGIC; STICS crop model; sensitivity analysis; ideotyping; G × E × M interactions.

Introduction

Climate change is threatening agricultural productions worldwide because of raising temperatures and unfavorable rainfall patterns. Crop breeding is crucial to adapt cropping systems in the mid-term, by developing new cultivars more suited to future climate conditions. However, the need to swiftly identify the genetic material to prioritize to address this challange calls for new approaches explicitly modelling G×E×M interactions. By using barley in Ethiopia as a case study, we used cutting-edge approaches of model-aided ideotype design to show how breeding programs targeting an innovative barley recombinant population (iMAGIC, Kassaw et al., 2017) and locally adapted ideotypes can provide safe pathways to ensure food security in the mid-term.

Materials and Methods

Weather data for historical series (ERA5, 1995-2014) and downscaled future climate projections (CMIP6, 2030-2050) of two general circulation models and two diverging shared socio-economic pathways from the Copernicus Climate Change Service were used to analyze the spatial variability of climate during the main barley season (June-December). From the intersection of climate and soil data (Harmonized Soil World Database), three grid cells were identified as simulation units (Fig. 1a). The crop model STICS (Brisson et al., 2002) was parameterized for the study area and used to identify key traits for yield and yield stability through global sensitivity analysis (SA, E-FAST method) and genotype specific distributions of functional traits derived from field trials involving the 16 founders of the iMAGIC barley population, including both lines developed from Ethiopian landraces and improved materials. Phenotyping methods included both direct measurements and model-assisted decomposition of performance traits through optimization algorithms (Paleari et al., 2025). Ideotypes were designed by selecting the best 1% of virtual genotypes obtained via exploration of parameter hyperspace through SA (Clerici et al., 2025). Yield benefits were quantified by comparing ideotypes performance with those of current cultivars simulated under the same management and climate conditions.

Results and Discussion

Traits involved with photosynthetic efficiency proved essential to ensure high grain yield under all the conditions explored, to counterbalance the shortening of the crop cycle induced by warmer temperatures and to take full advantage of the projected increase in rainfalls (Fig. 1b). Ideotypes also showed an optimized canopy architecture to maximize light interception. Selection targeting the ideotypes designed would clearly improve barley yield and its stability across seasons, and it appears as a feasible target given the large genetic potential of the germplasm analyzed (Caproni et al., 2023).

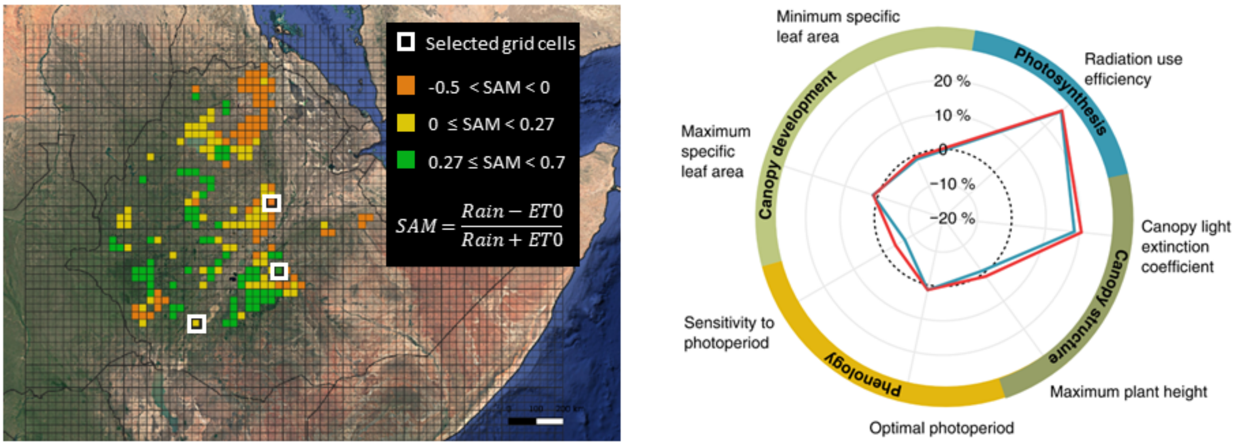

Figure 1. (a) Study area with grid cells identified as representative of the variability in agro-climatic conditions. (b) Sample results of ideotypes designed for one of the agroclimatic context and two future climate projections (blue line: MPI-SSP1-2.6; red line: IPSL-SSP3-7.0). Ideotype profiles are reported as variation (%) suggested for each trait as compared to current cultivars (dotted black line).

Conclusions

Our results showed how interdisciplinary approaches integrating crop modeling, sensitivity analysis and model-assisted phenotyping can provide insight into the potential of local landraces for the development of new barley cultivars targeting food security in challenging environments.

Acknowledgements

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What did climate-change scenarios of Swedish agricultural crop production predict for 2000 onward, and what actually happened?

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Keywords: crop modelling; scenario evaluation; process-based models; yield trends; Sweden.

Introduction

Scenarios have since the 1980-90s predicted that the climate in Sweden probably would become warmer in the future. Accordingly, in the early 2000s, a state public inquiry (SOU, 2007a) elucidated possible consequences for nationally important functions, one of which was crop production of Swedish agriculture (SOU, 2007b). Around 2000-2010, Swedish researchers generated multiple climate-change crop scenarios using diverse modelling approaches using climate scenarios driven by the Swedish Meteorological and Hydrological Institute (SMHI) and regional climate projections linked to e.g. IPCC A2/B1 scenarios (≈RCP8.5/2.6, respectively). These scenarios guided policy debates, but have rarely been systematically confronted with what actually occurred. Here we evaluate 12 published crop scenarios against official yield data from 2000-2024, asking: how do those legacy scenarios compare with what actually happened?

Materials and Methods

The work focused on cereals and ley, nationally and in three Swedish production regions: Götaland southern plains (Gss), Svealand plains (Ss), and South Norrland (Nn). Official Statistics Sweden/Swedish Board of Agriculture (SCB/SJV) time series for arable area and crop yields were used. Some crop models used alternative climate change scenarios as input, but in all cases could a scenario be referred to one of the four IPCC socio-economic scenarios: A1 (global, growth oriented society), A2 (regional, growth-oriented society), B1 (global, environmental oriented society) B2 (regional, environmental oriented society), respectively. Scenario trends reported as relative rates were converted to absolute trajectories and compared to observed linear trends. Crop models included SOIL/SOILN, a mechanistic soil-plant-atmosphere suite used for winter wheat; the Grass-ley model (Eckersten & Torssell) for simulating fertilized and unfertilized ley; FOPROQ32, a spring barley model based on temperature, radiation, and soil water indices; MAISPROQ, a cultivar-specific forage maize model with harvest defined by dry matter thresholds (Audsley E. et al., 2006); and the ACCELERATES crop-growth module (ROIMPEL), which represented biogeophysical crop growth processes within the broader European land-use framework. All projections were standardized as relative changes (%/30 yr) and compared to observed linear trends for winter wheat, spring barley, ley, and forage maize in three production regions.

Results and Discussion

Of the 12 crop–region comparisons, 10 scenarios captured the correct direction of yield change, though magnitudes diverged (Figure 1). Process-based models successfully captured winter wheat gains in Götaland (Gss) and Svealand (Ss), and ley increases in Svealand(Ss)/Norrland(Nn), but strongly underestimated ley productivity in Götaland (Gss)(+57% observed vs. ~+17% projected). Underestimation is consistent with models emphasising summer water deficits while observed precipitation partly offset drought impacts. Models proved highly sensitive to baseline choice; for spring barley in Norrland they diverged from observed strong yield growth (+41%), highlighting the danger of linear extrapolation. Observed yield trends (2000–2024) were positive overall but heterogeneous: winter wheat +3% (Gss) and +24% (Ss) per 30 years; spring barley +5% (Gss), +6% (Ss), +41% (Nn); ley +57% (Gss), +22% (Ss), +35% (Nn); forage maize (2011–2023) +39% nationally (Table 1). It is noteworthy that the heat/drought years of 2018 and 2023 depressed spring barley disproportionately, affecting the overall performance and raising attention to the challenges of extreme events. Climate scenario methods performance was crop-region specific: for spring barley the best alignments were geographical (G)

(Gss, Nn and Ss), while time-trend extrapolations (T) under-performed in Nn; for winter wheat, process-based (P) (Gss) and geographical (G) (Ss) were best; for ley, all methods captured positive trends but P strongly underestimated the magnitude in Gss. Model horizons (~2050) did not align perfectly with the evaluation window, which may explain underestimation of near-term yield growth. Sparse site-based model applications limited spatial representativeness. Climate forcings assumed drier summers than actually occurred, biasing yield projections downward. Nevertheless, model ensembles or medians across methods generally produced more reliable signals than individual studies.

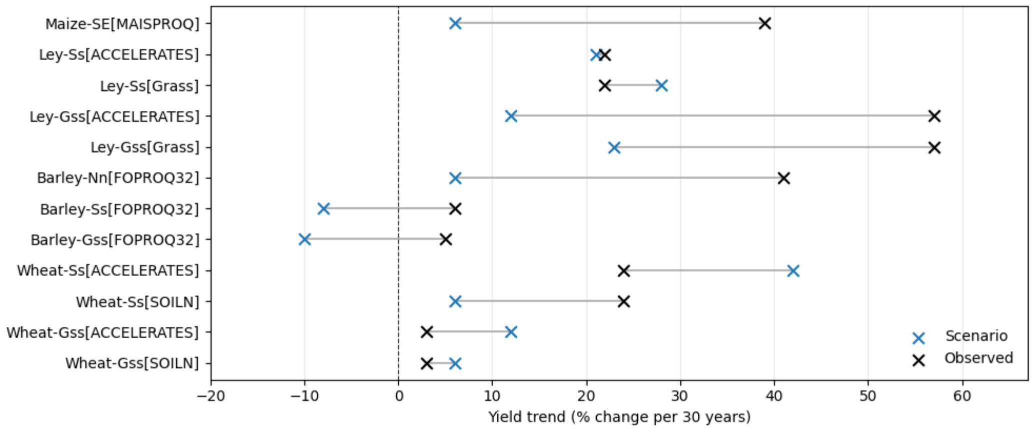

Figure 5 Comparison of climate change-based scenario projections and observed yield trends in Sweden (2000-2024), expressed as % change per 30 years. Blue markers denote projections from process-based models (SOILN, Grass-ley, FOPROQ32, MAISPROQ) and integrated frameworks (ACCELERATES); black markers show observed data. Grey lines connect scenario-observation pairs for each crop-region combination, illustrating cases of underestimation (e.g. ley in Götaland, maize) and overestimation (e.g. wheat in Svealand).

Table 1 Predicted and observed crop yield trends in Sweden. Observed trends are based on the linear regressions of previous studies. Process-models are indicated in brackets in the first column. Target area given in parenthesis indicate that the scenario partly represents the observed area.

Crop yield for [model]:	***Scenario period***	***Target area***	***Trend** (% change of yield per 30 year)*		
Winter wheat			*Scenario*	*Observed 2000-2024*	*Scenario-observed*
Halmstad [SOIL/SOILN]	1985-2050	(Gss)	+6	+3	+3
South Sweden [Accelerates]	2000-2050	Gss	+12	+3	+9
Uppsala [SOIL/SOILN][a]	1985-2050	(Ss)	+6	+24	-18
Middle Sweden [Accelerates]	2000-2050	Ss	+42	+24	+18
Spring barley					
Lund [FOPROQ-model]	1995-2025	(Gss)	-10 (-7[d])	+5	-15
Uppsala [FOPROQ-model]	1995-2025	(Ss)	-8 (-8[d])	+6	-14
Luleå [FOPROQ-model]	1975-2025	(Nn)	+6	+41	-35
Ley					
Halmstad [Grass-ley model][b]	1987-2085	(Gss)	+23	+57	-34
South Sweden [Accelerates]	2000-2050	Gss	+12	+57	-45
Uppsala & Örebro [Grass-ley model][c]	1987-2085	(Ss)	+28	+22	+6
Middle Sweden [Accelerates]	2000-2050	Ss	+21	+22	-1
Forage maize					
Cultivar Jasmic, Uppsala [MAISPROQ]	2007-2025	(Sweden)	+6 (-4[e])	+39	-33

Averages of: [c]sand +3, clay soil +8; [b]unfertilised +32, fertilised +13; [c]Uppsala unfertilised +32, Uppsala fertilised +13, Örebro unfertilised +48, Örebro fertilised +20. [d]Harvest date not changed and scenario period is 2005-2025; [e]Early maturing cultivar Janna and scenario period 1995-2025; [i]Blombäck et al. (2013).

Conclusions

Two decades of observations confirm that legacy crop models captured the direction of change, e.g yield increases for major cereals and ley, but often mis-scaled the magnitude. Process-based models remain essential but require better representation of cultivar adaptation, management shifts, and extreme-event sensitivity. Evaluating model families together suggests that multi-method ensembles provide more robust guidance than single approaches. For Sweden, future crop modelling should (i) integrate updated climate scenarios reflecting realized precipitation patterns, (ii) improve spatial sampling of soils and management, and (iii) explicitly test model skill against observed extremes.

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The climate change mitigation potential of improved crop rotations – a long-term simulation study for Germany for the 21st century

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Keywords: rotation simulation; cover crops; carbon sequestration; soil-plant-atmosphere model

Introduction

Agriculture is a major contributor to global climate change, while it is severely affected by its consequences at the same time. Mitigating climate change is therefore of vital importance for future agriculture. Improving crop rotations including cover crops (CC) can potentially contribute to climate change mitigation through increased soil organic carbon (SOC) sequestration or SOC loss mitigation. However, on the long term, this beneficial effect may be overestimated with SOC eventually reaching a saturation point over time, while N_2O emissions from decomposing crop residues increase with CC biomass. It is therefore crucial to consider the trade-off between N_2O emissions and SOC sequestration when designing improved crop rotations.

Therefore the present study aims to: (i) determine the impact of alternating legume and non-legume CCs into 4-year crop rotations compared to no-CC and business-as-usual (BAU) rotations regarding crop yield, SOC development, N related variables, as well as GHG emissions, and (ii) explore the potential outcomes of these suggested management options at Germany-wide scale under future climate conditions until the end of the century. While the investigated rotations reflect typical practices at the research sites, it should be noted that other cropping systems are also common across Germany. However, to implement a straightforward approach and ensure comparability and consistency across regions, a standardized rotation design was applied in this study.

Materials and Methods

Building on long-term crop rotation data and additional Germany-wide multi-environment field trial data we first calibrated and evaluated the DSSAT-DayCent model regarding major crops' yields (Shawon et al., 2024; Shawon et al., 2025) and SOC built up in crop rotations (Attia et al., 2024). We then used the parameterized model to investigate the effect of improved crop rotations throughout Germany under conditions of climate change until the end of the 21st century. We used projected daily weather data available until 2099 from the DWD core-ensemble (DWD, 2025) comprising six scenarios for RCP 4.5 and six for RCP 8.5. Gridded soil data was obtained from the WISE soil database (Batjes, 2009). Improved rotations included diversified crop sequence as well as the inclusion of leguminous and non-leguminous cover crops. For cover crop simulations we used winter oilseed rape to mimic mustard (*Sinapis alba*) and mustard dominated mixtures, green bean (*Phaseolus vulgaris* L.) for all legume cover crops and legume dominated mixtures, and rye (*Secale cereale*) for all Poacea species and respective mixtures.

We investigated the effects of improved crop rotations and cover cropping on the development of soil organic N and C contents, N leaching, N_2O emissions and crop yields. We developed and applied a novel approach to estimate N_2O emissions. We used regional Tier 2 emission factors (EF) to estimate direct emissions based on Mathivanan et al. (2022), and utilized site-year- and rotation-specific model outputs on Nitrogen in above and below ground residues after harvest plus N leached to derive indirect N_2O emissions dynamically at Tier 3 level.

Using the process-based DSSAT model, we simulated yield, SOC, nitrogen (N) dynamics, and greenhouse gas (GHG) emissions for eight rotation scenarios under six climate projections (RCPs 4.5 and 8.5) with gridded soil and weather data.

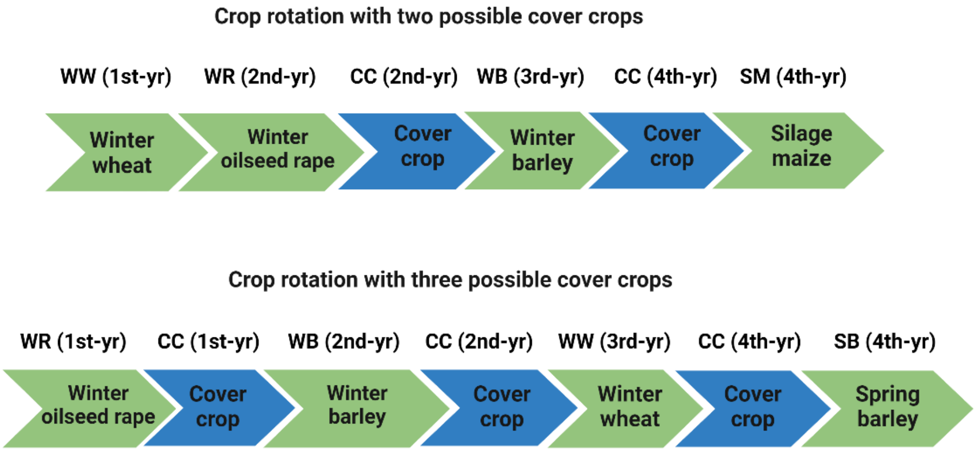

Figure 1 Schematic representation of the improved 4-year crop rotations with cover crops (CCs). The top panel illustrates the rotation with two possible CCs, while the bottom panel represents the rotation with three possible CC.

Results and Discussion

Results indicate that improved rotations, particularly those including legume CCs, significantly increased crop yields (16-33%), enhanced N use efficiency, and reduced N leaching (~40%) compared to business-as-usual (BAU) scenarios. Additionally, these systems sequestered more SOC and reduced cumulative N_2O emissions, resulting in an average 40% lower net GHG footprint (26.9 vs. 74.5 Mg CO_2-eq ha^{-1}) by 2099. Spatial analysis revealed region-specific benefits of legume-inclusive rotations in enhancing system resilience under changing climate. These findings emphasize the importance of targeted crop diversification strategies to optimize productivity while minimizing environmental trade-offs, offering actionable insights for climate-smart agricultural policies in temperate regions.

Conclusions

The Germany-wide assessment of improved crop rotations emphasize the importance of targeted crop diversification strategies to optimize productivity while minimizing environmental trade-offs, offering actionable insights for climate-smart agricultural policies in temperate regions.

Acknowledgements

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Maize productivity under low-N input: a modelling approach to a future climate scenarios in Malawi

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Keywords: crop-modelling, climate change, low-input systems

Introduction

In Malawi, about 5.4 million people in rural and secondary urban communities experience moderate to severe chronic food insecurity, largely driven by poverty, recurrent shocks, and limited access to resources (IPC, 2022). Limited access to agricultural inputs and financial resources constrains smallholder farmers to maintain maize production under low nitrogen input conditions. Climate change is projected to exacerbate the fragility of these systems, increasing yield variability and undermining food security. This study aims to assess the effects of future climate on maize yields in Malawi under business-as-usual management as a basis for developing adaptation pathways.

Materials and Methods

Field experimental data were obtained from mother trials conducted during the 2020-2021 season across five Agricultural Extension Planning Areas in Malawi (Karonga, Machinga, Nkhatabay, Rumphi, and Zomba). Maize (cv. SC-537) was cultivated under three N fertilization systems: full inorganic (IN, 92 kg N ha^{-1}), full organic (OR, 3 Mg manure ha^{-1}), and a combination of organic and inorganic (CO, 46 kg N ha^{-1} + 1.5 Mg manure ha^{-1}). Field data on soil, management, phenology, and crop yields were collected.

Alongside, semi-structured interviews were conducted with farmers and staff from the Ministry of Agriculture to gather insights into the perception of climate change, awareness of Good Agricultural Practices (GAPs), and constraints in accessing crop inputs. Responses consistently indicated that, although farmers recognized the yield benefits of higher N fertilizer application, widespread poverty and limited access to market make mineral fertilizers largely unaffordable and unavailable in rural communities. This co-design process provided the insights to design the modeling exercise a business-as-usual scenario with low N input, reflecting the prevailing condition of a subsistence farming system in Malawi.

The CERES-Maize model, provided by the Decision Support System for Agrotechnology Transfer (DSSAT v4.8) (Hoogenboom et al., 2019), was used to run simulations. The Rumphi site was selected for cultivar calibration as it was considered to provide the most accurate representation of cultivar performance under non-limiting conditions. The model was parameterized using the Rumphi IN dataset, with evaluation across the other treatments and sites. Model performance was assessed by calculating RMSE, CV(RMSE), and the Willmott (1982) D-index.

Long-term climate projections were used for scenario analysis, comparing two future periods (2015–2044; 2045–2074) with a baseline (1985–2014). Daily outputs from five General Circulation Models (GCMs: GFDL, IPSL, MPI, MRI, UKES) were applied under three Shared Socioeconomic Pathways (SSP1-2.6, SSP3-7.0, SSP5-8.5). The baseline was generated from the ISIMIP (CMIP6, https://doi.org/10.5194/gmd-9-1937-2016) historical climate dataset, projected by the same GCMs and bias-corrected to match local observations.

Results and Discussion

The model calibration with the Rumphi IN dataset showed good agreement between observed and simulated data. Emergence and maturity dates were reproduced within 1–4 days *vs*. observations. The observed grain yield was 8.85 Mg ha^{-1} dry matter (DM), whereas the simulated average yield was 10.08 Mg ha^{-1} DM. The standard deviation of observed yield was 1.84 Mg ha^{-1} DM, hence the simulated yield was consistent within the confidence interval of the field observations.

The model evaluation across sites and treatments confirmed the robustness of the calibration (Fig. 1-a). A good agreement was observed between the observed and simulated yields (R^2 = 0.82), with a low prediction error (RMSE = 1.25 Mg ha^{-1} of DM; CV(RMSE) = 0.19%) and a high index of agreement (D = 0.94). These results demonstrate that the model reliably captures phenology and yield dynamics under low-input conditions, supporting its use for climate change scenario analysis.

In Rumphi, average yields and standard deviations derived from long-term simulations highlighted differences among fertilization strategies (Fig 1-b). The CO treatment showed highest yields (13.0 – 14.5 Mg ha^{-1} DM) with reduced variability compared to the baseline. The IN treatment maintained stable yields close to baseline values (12 – 13 Mg ha^{-1} DM), while the OR treatment, although the least productive, showed marked gains in the near-future scenarios (up to +2 Mg ha^{-1} DM), due to enhanced nitrogen mineralization under warmer conditions. Overall, the CO and IN fertilization systems exhibited stable yield across SSPs, whereas the OR management showed higher variability. The absence of a strong decline across future scenarios reflects the relatively modest projected temperature increases, which remained below critical thresholds for maize productivity.

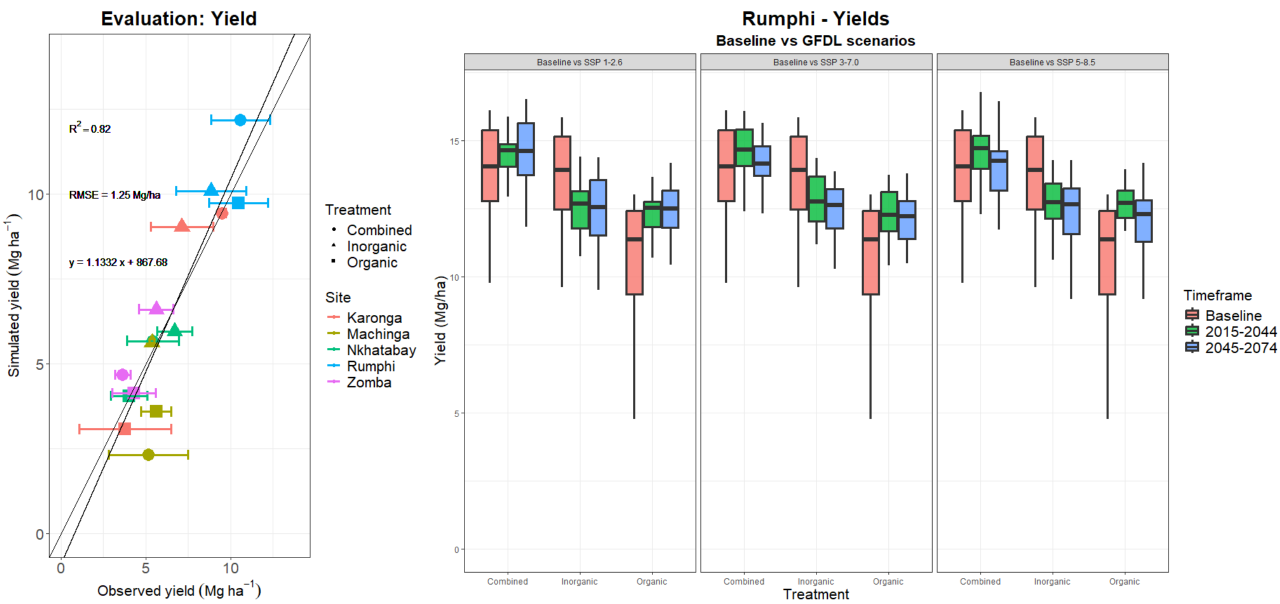

Figure 1. a) Model calibration and evaluation for phenology (emergence and maturity dates [DAP]), and yield (Mg ha^{-1}). b) Maize yield GFDL scenario at Rumphi across fertilization systems and SSPs.

Conclusions

The CERES-Maize model, once calibrated and evaluated, proved to be suitable for simulating maize phenology and yield under low-input fertilization in Malawi. The Rumphi simulations indicated stable yields under future climate scenarios, with significant differences between fertilization treatments. Future analyses will extend the simulations to the other experimental sites, comparing projected scenarios with baseline to assess site-specific yield responses to climate change, providing insights into the yield gaps and vulnerability of the local subsistence farming system and providing effective support to the development of adaptation pathways.

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Modeling Adaptive Management Strategies: Yield Outcomes and Emission Implications

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Keywords: crop modeling, climate change adaptation, irrigation, nitrogen fertilization, ideotyping

Introduction

Global agricultural systems face accelerated climatic changes with rising atmospheric CO_2 concentrations, temperature increases, and shifting precipitation patterns, which significantly alter agroecosystem dynamics. To maintain productivity and ensure food security, it is essential to implement adaptive management strategies that respond to these changing environmental conditions. In the context of climate change, agricultural management practices must balance two often-competing goals: increasing food production and minimizing greenhouse gas (GHG) emissions, as agricultural practices both respond to and contribute to the atmospheric GHG burden. This study evaluates adaptive management strategies and ideotypes not only for their yield outcomes but also for their effects on the carbon footprint of agricultural systems during the current century.

Materials and Methods

In this study, we utilize multiple crop models (CERES-Wheat, CERES-Barley, CERES-Maize, and CROPGRO-Canola) within the DSSAT framework to simulate adaptive management strategies for spring barley, grown as part of a common crop rotation. The rotation sequence includes wheat, grain maize, and spring barley, with mustard as a cover crop before maize, simulated by the CROPGRO-Canola model. The tested management strategies were applied to the spring barley crop, while other crops in the rotation follow fixed management aligned with best practices for German agricultural systems. The tested treatments include four irrigation levels, two sowing dates, and three nitrogen application rates. Irrigation is applied automatically at three thresholds of plant available water (PAW): 30%, 50%, and 70%, along with a rainfed control. Sowing dates include early and late treatments. Nitrogen levels consist of a baseline (defined according to German fertilizer regulation), along with +10% and -10% variations from this baseline. In addition, we evaluate the performance of two ideotypes of spring barley in comparison to the RGT Planet genotype. The ideotypes differ in phenological development: one with growth stages extended by 10% and the other shortened by 10% relative to RGT Planet, representing slower-growing and faster-growing varieties, respectively. Simulations run from 2020 to the end of the century, using weather projections from 12 future climate scenarios combining two RCPs and six GCMs from the DWD core ensemble. Simulation outputs are utilized in a hybrid approach that combines crop modeling with life cycle assessment (LCA) to estimate greenhouse gas (GHG) emissions. To assess the effects of management strategies and genotype variation on crop growth, yield, and GHG emissions, linear mixed models are applied, with treatments as fixed effects and years and climate scenarios as random effects.

Table 1. Soil quality rating (based on the Müncheberg Soil Quality Rating (SQR), (Mueller et al., 2007)) and yearly precipitation of contrasting locations used for the simulations of crop rotations

Location	Soil quality rating	Sand (%)	Silt(%)	Mean yearly precipitation (mm)
Euskirchen	94	9.0	76	595
Neuhof	55	63	32	642
Ostinghausen	93	11.5	78	761
Bollberg	28	30	57.5	694

Results and Discussion

Preliminary simulation results for the RGT Planet genotype indicate that early sowing consistently yields higher results across all management treatments and climate scenarios. Higher yields achieved through 70% PAWC irrigation and 10% + baseline in N fertilization in good soil quality locations. Water use efficiency (WUE) was highest under moderate irrigation levels, specifically at irrigation thresholds of 30% and 50% plant available water capacity (PAWC), particularly in low-quality soils (Neuhof and Bollberg). By contrast, the lowest WUE occurred under the highest irrigation level (70% PAWC), reflecting diminishing returns and excessive water use in sandy soils (Neuhof). Marginal Nitrogen Use Efficiency (mNUE) (defined as the yield change in kg per additional kilogram of nitrogen applied) varied significantly depending on soil type. Increasing nitrogen application by 10% above the baseline improved yields under good soil conditions, with little to no modulation from irrigation treatments. However, under poor soil conditions, this nitrogen increase had a neutral effect on yield. Across locations, higher yield potential (driven by soil quality and water-holding capacity) was associated with greater profitability from increased nitrogen inputs. At Neuhof, characterized by sandy soils and a low Soil Quality Rating (SQR), yield variability was high across the century.

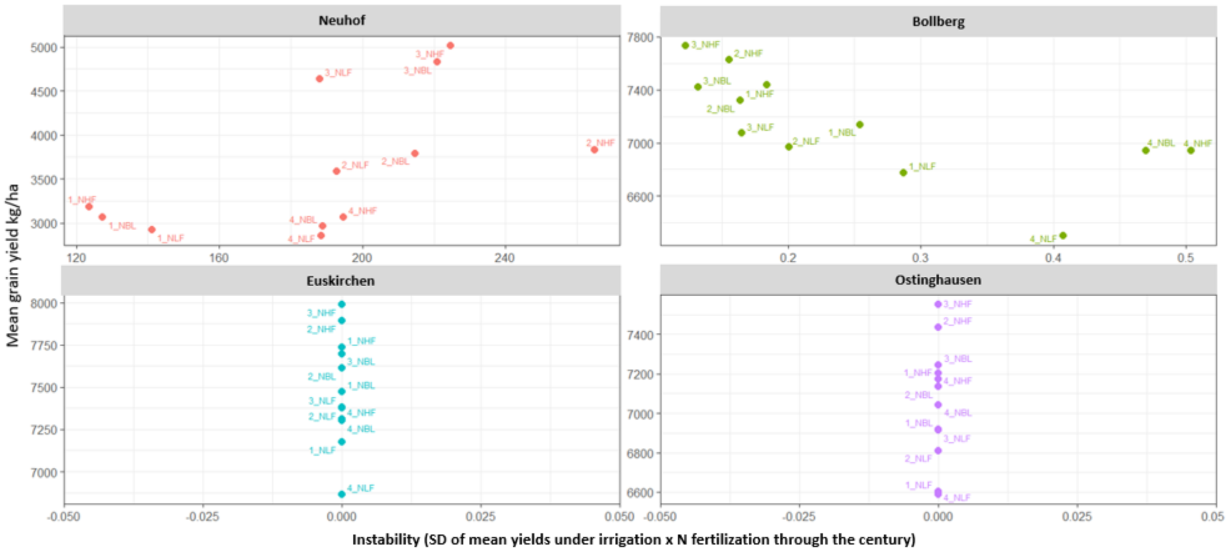

Figure 1. Mean yield and temporal stability of irrigation × nitrogen fertilization treatments across locations (Neuhof, Bollberg, Euskirchen, Ostinghausen). Irrigation levels: 1 = 30% PAWC, 2 = 50% PAWC, 3 = 70% PAWC, 4 = rainfed. Nitrogen fertilization: NLF = baseline –10%, NBL = baseline, NHF = baseline +10%. Stability is expressed as the standard deviation of BLUPs (Best Linear Unbiased Predictors) across years (lower = more stable).

Stability analysis of irrigation × fertilization combinations (Figure 1) showed that a 30% PAWC threshold improved yield stability, albeit at the cost of lower absolute yields. Conversely, irrigation at 70% PAWC produced higher yields but reduced stability due to elevated nutrient leaching risks in sandy soils. At Bollberg, with low SQR but reduced sand content, the combination of irrigation and increased nitrogen fertilization resulted in both high yields and high yield stability.

Overall, these findings highlight the necessity of tailoring management strategies to site-specific conditions in order to optimize yield outcomes while minimizing environmental impacts.

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Climate change impact assessment on spring barley production across European environmental zones: Model-based projections using CMIP6

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Keywords: Crop model, Agro-climatic indicators, Climate change, Impact assessment, CO2 fertilisation

Abstract

Original: Breeding of climate-resilient barley cultivars requires knowledge about shifts in climate hazards and potential yield impacts. This Europe-wide study aims to provide such information by using the latest (CMIP6) climate scenarios (six Global Climate Models x two emission scenarios SSP1 2.6 & SSP5 8.5 x two time slices, 2050s and 2080s) for crop model-based yield projections and generation of agroclimatic indicators to characterize climate-induced hazards and likely impacts on spring barley production conditions across environments within Europe. The results from analyses of 19 different sites were aggregated over eight environmental zones across Europe. For all zones, we found elevated growing season temperatures, which were associated with increased likelihoods of heat hazards across most zones. Phenological development was consequently accelerated, resulting in yield penalties across the majority of zones, with up to 31 % yield reduction in the Mediterranean south under high emission scenarios for the 2080s. Such simulated losses were found to be compensated by CO_2 fertilisation effects under high emission scenarios (at 868 ppm CO_2). However, the fertilization effect was not uniform across zones and might mask production losses that are related to an increased exposure to extreme growing conditions not captured by the crop model. Based on our results, it can be concluded that rainfed barley production in Europe will very likely face more climate-related hazards, especially related to heat. This emphasizes the need for designing adaptation strategies that combine climate-resilient crop cultivars tailored to evolving climatic hazard combinations with suitable management practices that are adapted to local conditions.

Paraphrased: Developing barley cultivars which can withstand changing climate conditions requires comprehensive insight into evolving climate risks and their effects on crop yields. This European-wide study utilizes the latest CMIP6 climate projections—including six global climate models, two emission scenarios (SSP1-2.6 and SSP5-8.5), and two future periods (2050s and 2080s)—to simulate barley yields and generate agroclimatic indicators that assess climate-related threats and their potential consequences for spring barley cultivation across diverse European environments. Outcomes from analyses at 19 sites were summarized within eight environmental zones. For all zones, we found elevated

growing season temperatures, which were associated with increased likelihoods of heat hazards across most zones. This accelerated the phenological developmental of barley, leading to yield reductions in most zones, with up to a 31% decline projected in the Mediterranean region under high emissions by the 2080s. While increased CO2 levels partially offset these losses under high emissions (868 ppm CO2), this fertilization effect varied by zone and may mask production declines caused by extreme growing conditions not captured in the crop model. The findings indicate that rainfed barley farming in Europe will likely face increased climate hazards, predominantly heat stress, underscoring the urgent need for adaptation strategies that combine climate-resilient barley varieties with locally tailored management practices.

Climate Impact Analysis of the full Nitrogen Balance with the LandscapeDNDC Model and EURO-CORDEX Ensembles for Greece

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Keywords: Climate impact, Euro Cordex ensemble, LandscapeDNDC, nitrogen fluxes

Introduction

In this study, we aim to present national-scale assessments of the full nitrogen and carbon balance, including all associated fluxes of the cropland cultivation for Greece on a national scale. We propagated the EURO-CORDEX ensemble under the mid-impact and high-impact Representative Concentration Pathway scenarios (RCP4.5 and RCP8.5) through the LandscapeDNDC model to compile result ensembles of detailed inventory simulations.

Research questions addressed in the study:

a) Assessment of the full nitrogen balance for present conditions as demanded by UN FCCC reporting
b) Climate change impact analysis on agricultural production on a national scale
c) Assessment of the full soil carbon balance for present conditions and climate change projections
d) Climate change impact analysis on the carbon and nitrogen cycle and fluxes towards 2100

Materials and Methods

We used the bio-geochemical model LandscapeDNDC to simulate carbon and nitrogen cycling in cropland soils in Greece on a 0.25° lat x 0.25° lon resolution (430 arable grid cells). Soil physical and chemical initialization data were based on the European Soil Database data. Agricultural management data was available for the period 1990 – 2100. We used the first 15 years as a prerun period to achieve equilibrium for the soil carbon and nitrogen pools, and the evaluation period 2005 – 2100 was used for the climate impact assessment.

In this study we used 46 regional climate change datasets from the EURO-CORDEX data repositories, combining 6 GCMs with 8 RCMs, comprising structural variability/uncertainty of the climate change projections RCP4.5 and RCP8.5.

Results and Discussion

The analysis of the climate change ensembles shows for the arable land in Greece an average temperature increase of 1.37°C for RCP4.5, and of 3.21°C for RCP8.5. For precipitation we see a decrease of 17.96 mm for RCP4.5 and a decrease of 102.52 mm for RCP8.5.

Arable production under RCP4.5 remains constant until 2045, followed by a clear decrease towards 2100 on average of 144 kg C ha^{-1} yr^{-1} (decline of approx. 9.5% compared to present conditions, medians of 111 kg C ha^{-1} yr^{-1}). Under RCP8.5, arable production dynamics show similar behavior with a much stronger decline after 2045, resulting in yield reductions of 484 kg C ha^{-1} yr^{-1} (median of 544 kg C ha^{-1} yr^{-1}) corresponding to lower values of approx. 29% and 31% respectively, comparing future to present conditions.

The soil organic carbon (SOC) show from 2050 onwards a steady decrease in SOC by approx. 11.1 kg-C ha^{-1} yr^{-1} for RCP 4.5 and 26.7 kg-C ha^{-1} yr^{-1} for RCP 8.5, respectively.

The ensemble simulations for present show N_2O emissions of 0.494 or 0.476 kg N_2O–N ha^{-1} yr^{-1}, NO emissions of 0.031 kg NO–N ha^{-1} yr^{-1}, N_2 emissions of 4.806 or 4.252 kg N_2–N ha^{-1} yr^{-1} and NH_3 emissions of 24.662 or 28.829 kg NH_3–N ha^{-1} yr^{-1} comparing ensemble means versus medians in the case of RCP 4.5 scenario. For the future time slice, we see stronger differences in ammonia volatilization, increase from 24.353 to 35.040 kg NH_3–N ha^{-1} yr^{-1} comparing present to future conditions under RCP8.5. Nitrate leaching is together with nitrogen removal via agricultural yields and straw the largest nitrogen flux within the system (see Figure 1). The ensemble simulations show an increase in nitrate leaching losses (comparing present to future time slices) for the mean from 50.752 to 58.213 kg NO_3-N ha^{-1} yr^{-1} under RCP8.5.

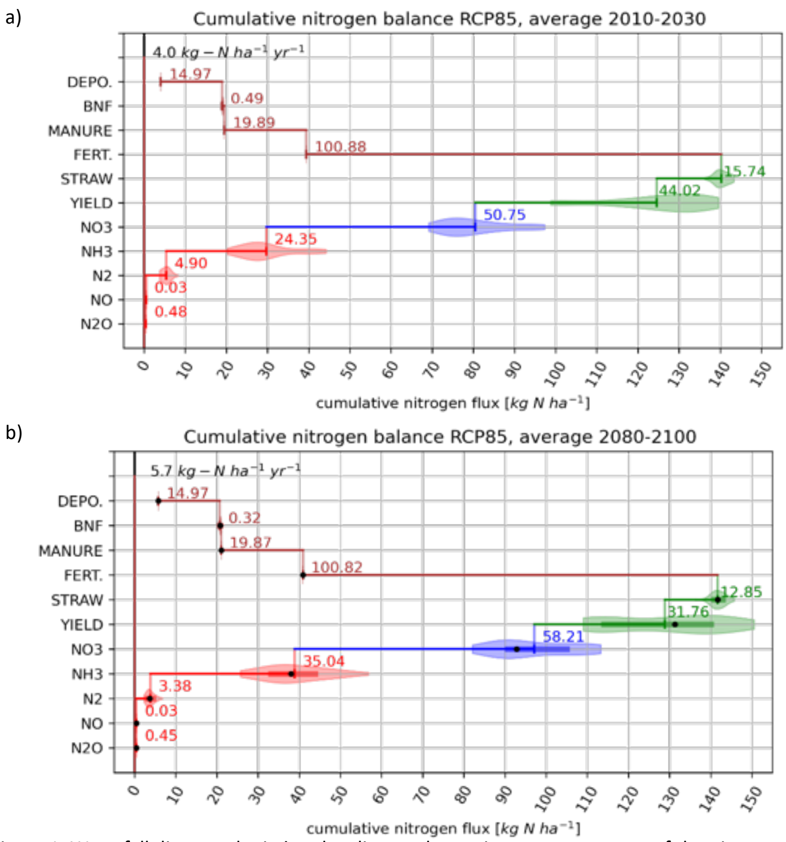

Figure 1. Waterfall diagram depicting the climate change impact assessment of the nitrogen balance (NB) for current (a) versus future (b) conditions under RCP 4.5 and RCP 8.5. The violin plots span the entire range, the vertical line indicates the median and the point indicates the mean values.

Conclusions

The projected changes in the carbon and nitrogen balance were relatively small. Simulated soil carbon stocks remained stable wile NH_3 volatilization increases towards 2100.

Some aspects may have to be considered in future assessments:

a) The EURO-Cordex ensembles show a large variance for the historic time span and therefore demonstrate the necessity of a general bias correction.
b) The use of identical GCM / RCM downscaled climate change projections in the ensembles for RCP4.5 and RCP8.5 is strongly advised for detailed climate change impact analysis to avoid the influence of additional model structural uncertainty only present in one of the scenarios.
c) Projections of irrigation management (spatial and temporal availability of irrigation water) need to be derived from individual climate change scenario results in advance of the simulations.
d) Climate change projections offer perspectives on the derivation of future crop cultivation strategies and timelines, such as shifts in crop calendars, double cropping potentials and replacements of winter crops due to failing vernalization.
e) Nutrient supply and fertilization need to be dynamically calibrated/optimized towards the future to fulfill crop demands and respect soil nutrient availability.

The model lacks capabilities to simulate impacts of severe heat stress conditions (e.g., anthesis stress) and needs to be improved in this respect for climate change impact analysis.

Assessing Climate-Smartness of Agronomic Practices in Oil Palm Production Under Climate Change

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Keywords: Climate impact, Carbon balance, Uncertainty, Irrigation

Introduction

Assessing climate–food interactions is vital for sustainable production. Climate-smart practices which seek to simultaneously increase productivity, enhance resilience and reduce greenhouse gas (GHG) emissions have been explored for many agricultural systems, yet few studies address oil palm (OP), which contributes to 58% of global vegetable oil and 1.4% of anthropogenic emissions. Most studies have assessed the climate impact of OP practices on yield or emissions separately (e.g. Watson-Hernández et al., 2022), but none have simultaneously assessed productivity, mitigation, and adaptation; and few have quantified uncertainty. Accordingly, we assessed which practices are most climate-smart under climate change, and how site-specific soil and management conditions and climate projections affect the uncertainty of the projected climate-smartness.

Materials and Methods

We assessed the climate-smartness of irrigation and empty fruit bunch (EFB) application (a type of organic residue management practice that is used to improve soil fertility and reduce fertiliser use) in combination with standard and reduced nitrogen (N) fertiliser. Five agronomic scenarios were selected, including business as usual (BAU) and combinations of irrigation and EFB application: Irrigation with standard N, EFB with reduced N, Irrigation + EFB with standard N, and Irrigation + EFB with reduced N.

Climate-smartness was assessed by examining yield change (%), carbon balance change (t C eq. ha^{-1} yr^{-1}), and two integrated climate-smartness indices—one combining water use and emissions (Climate-Smartness Index, CSI), and the other combining yield and soil organic carbon, called the Soil-based Climate-Smartness Index (SCSI) (Arenas-Calle et al., 2019, 2021).

The Agricultural Production SIMulator (APSIM) model was used to simulate yield, carbon balance components and water use over a 25-year plantation cycle by incorporating ten different sites, five GCMs (IPSL, GFDL, MPI, MRI, UKESM1), two emission scenarios (SSP1-2.6 and SSP5-8.5) and three periods (baseline: 1998–2022; mid-century: 2041–2065; end-century: 2071–2095). The model was calibrated and tested against observed yields (R^2 is 0.003 to 0.79 and RMSE is 3.12 to 7.51 t $ha^{-1}yr^{-1}$) and bunch number (R^2 is 0.42 to 0.89 and RMSE is 0.83 to 2.88 bunches $palms^{-1}$ yr^{-1}).

Results and Discussion

The mean values of all climate-smart metrics under each agronomic practice scenario across sites, climate models, emission scenarios and periods are summarised in Fig 1 so that the most climate-smart agronomic practices under climate change can be easily assessed. A higher value indicates a better performance for all metrics, except for carbon balance change, in which a lower value represents less emissions, indicating better performance.

Across all conditions, irrigation with standard N emerges as the most climate-smart practice under climate change. This scenario increases yields relative to BAU, produces the lowest mean carbon balance change (indicating potential as a carbon sink), and achieves the highest mean CSI scores, reflecting efficient water use and low GHG intensity. However, it ranks second lowest for SCSI, suggesting limited yield and SOC improvement.

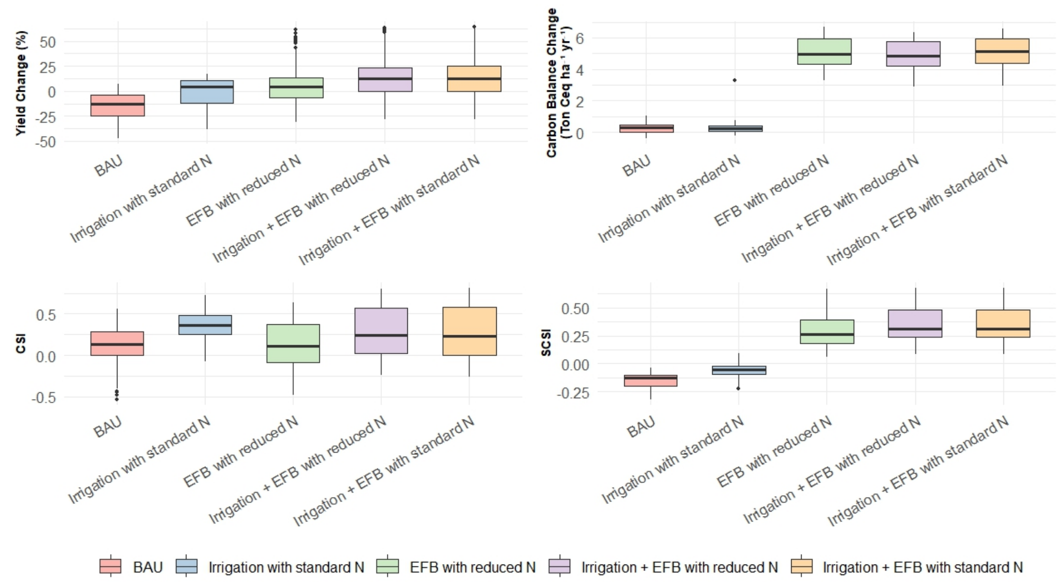

Figure 1 Summary of the mean values all climate-smart metrics under each agronomic practice scenario across sites, climate models, emission scenarios and periods.

In contrast, scenarios incorporating EFB application achieve greater yield and SOC gains as indicated by higher yield change and SCSI scores but show higher carbon balance changes, implying a shift from carbon sink to carbon source.

The results also show that climate models with higher projected temperatures and higher emission scenarios reduce production and increase GHGs, further lowering climate-smartness, especially in the latter half of the century. However,

this study indicates that site-specific management conditions have a larger uncertainty in projected climate-smartness than climate models through a higher variation of GHG emissions and yields across OP sites.

Conclusions

This study demonstrates that climate-smartness assessment using crop model simulations can identify the trade-offs between productivity, mitigation, and adaptation among agronomic practices under climate change. Our results also show that uncertainty in climate-smartness is strongly influenced by site-specific management conditions (e.g., fertiliser application and plant density), highlighting the need to incorporate local variability in assessments. We conclude that this approach provides a transferable and quantitative framework to guide industry and policy makers toward sustainable production strategies that support climate goals and global food security.

Acknowledgements

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Biophysical assessment of sustainable intensification in Northern Ghana under current and +2 °c conditions

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Keywords: crop modeling, ISFM, yield stability, production risk, climate adaptation.

Introduction

Climate shocks and soil degradation pose major threats to food security and agricultural sustainability in Sub-Saharan Africa, with Ghana being particularly vulnerable (Sultan and Gaetani, 2016; Thornton et al., 2018). Smallholder farmers in Northern Ghana face growing challenges in sustaining maize production, the country's staple crop, under conditions of increasing climatic stress and declining soil fertility. Integrated Soil Fertility Management (ISFM) has been promoted as a promising pathway for sustainable intensification, as it combines organic and inorganic inputs to improve nutrient use efficiency, soil health, and crop yields (Vanlauwe et al., 2015). Despite its potential, little quantitative evidence exists on how ISFM influences yield stability, sustainability, and production risks in specific agroecological contexts under current and future climates. This study addresses this gap by evaluating the performance of ISFM options in maize systems of Northern Ghana using the SIMPLACE (Anders et al., 2023) modeling platform under a wide range of plausible weather conditions for present climate conditions and a scenario climate of 2 °C global warming.

Materials and Methods

Twenty-three sites across the Northern, Upper East, and Upper West regions were analyzed, covering the mono-modal rainfall agroecology (mean annual rainfall ~955 mm; monthly temperatures: 25–38 °C). Soil characteristics were retrieved from SoilGrids (Hengl et al., 2017). The open-pollinated Obatanpa maize variety, widely cultivated in Ghana, was used for all simulations (Nguyen et al., unpublished). Ten fertility treatments (ranging from unfertilized control to organic-only inputs, inorganic nitrogen rates of 30–90 kg N/ha, and integrated organic–inorganic combinations) were simulated across seven sowing dates at 10-day intervals from June to July. Biophysical sustainability was assessed using five indicators: grain and biomass yield, nitrogen leaching, soil organic carbon (SOC) to 30 cm, and nitrogen use efficiency (NUE). These indicators were standardized into a composite sustainability index. Climate risk analysis was based on 325 ensemble members of daily climate realizations from HAPPI datasets (ECHAM6, MIROC5, NorESM1), under current climate (2006–2015) and +2 °C scenarios (Mitchell et al., 2017).

Results and Discussion

The biophysical assessment revealed substantial yield variability across fertility and climate treatments, with fertilizer management emerging as the dominant driver of maize productivity in Northern Ghana. Under current climate conditions, higher maize yields were strongly associated with increased inorganic fertilizer application, with the 90 kg N ha^{-1} rate producing the highest grain yields and significantly outperforming all other treatments. However, under a

+2 °C warming scenario, combined organic–inorganic inputs outperformed sole inorganic applications in terms of yield magnitude but displayed increased variability. This aligns with earlier findings that integration of organic amendments with mineral fertilizers can enhance resilience while moderating long-term soil fertility decline (Vanlauwe et al., 2015).

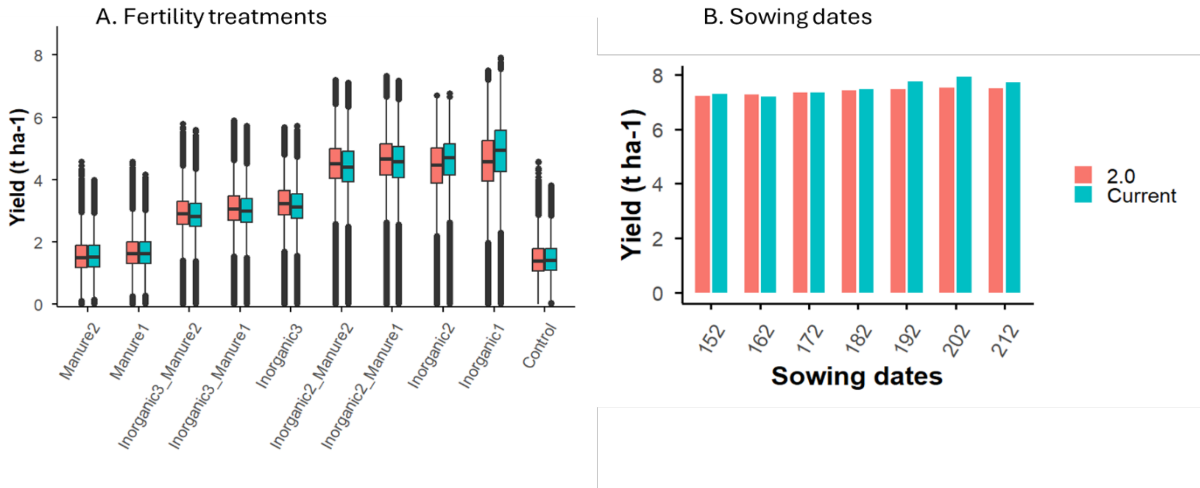

Figure 1. Effects of ISFM practices on maize yield under current and +2 °C scenarios. A. Compares maize yield performance under the ten fertility treatments (Control: No inputs applied; Inorganic1: 90 kg N/ha; Inorganic2: 60 kg N/ha; Inorganic2 + Manure1: 5 t/ha of manure and 60 kg N/ha; Inorganic2 + Manure2: 2.5 t/ha of manure and 60 kg N/ha; Inorganic3: 30 kg N/ha; Inorganic3 + Manure1 5 t/ha of manure and 30 kg N/ha; Inorganic3 + Manure2: 2.5 t/ha of manure and 30 kg N/ha; Manure1: Application of 5 t/ha of manure; Manure2: Application of 2.5 t/ha of manure). B. Indicates the sowing days in Day of Year on the X-axis.

Median yields under sole organic treatments and control plots did not differ significantly between current and warmer climates, though yield variability increased with warming. The risk of yield loss was highest under no-input conditions (~45%) and remained high under manure-only systems (~43%), underscoring nutrients as essential for stabilizing productivity. In contrast, inorganic fertilizer alone reduced yield loss probability (~32%), corroborating evidence that mineral inputs remain indispensable for achieving food security goals under climate stress (Frelat et al., 2016, Faye et al., 2018).

Sowing date exerted a smaller effect relative to fertility. Early sowing buffered climate impacts, with yields showing no significant differences across scenarios, while late sowing magnified yield losses under warming. Integrated treatments combining 5 t ha^{-1} manure with 60 kg N ha^{-1} enhanced biomass production and soil organic carbon accumulation, thereby boosting a sustainability index (2.8 vs. 2.0 under current and warming climates, respectively), though grain yields trailed behind sole inorganic treatments. This demonstrates a classic trade-off between immediate yield maximization and long-term sustainability (Tittonell and Giller, 2013). Overall, balanced organic–inorganic strategies appear most promising for climate-smart sustainable intensification in Northern Ghana.

Conclusions

This study demonstrates that ISFM offers a pathway to balance productivity, resilience, and ecological outcomes in maize systems of Northern Ghana. While high inorganic inputs maximize yields, they increase risks of nitrogen losses and are less stable under warming scenarios. Integrated organic–inorganic strategies, though yielding slightly less, enhanced yield stability, SOC, and resilience during dry years. These findings underscore the need for context-specific ISFM recommendations that align productivity gains with climate adaptation and sustainable land management goals in West African smallholder systems.

Acknowledgements

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Addressing near-term climate impacts in agriculture – comparing decadal predictions with scenario-based projections

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Keywords: near-future climate impacts, Europe, pDSSAT, ECMWF, CMIP6

Long-term climate impact assessments, such as IPCC-style end-of-century projections often provide less relevant information for farmers and decision makers in the field than shorter-term outlooks. Many of the on-farm management decisions that need to be made today – including seed procurement, rotation planning, irrigation investments, machinery purchases, etc. – are based on a 5 to 15 years planning horizon. However, established strategies for assessing long-term climate change, i.e., scenario-based climate modeling used as inputs in impact models, are not designed for near-future analyses and are sensitive to the bias-adjustment of the underlying climate model. CMIP6 climate model simulations have been released almost 10 years ago, meaning that 5-15 years outlooks from today are well past the initialization of the CMIP6 models. Decadal weather predictions, e.g., operationally provided by ECMWF, can provide an alternative approach to estimating near-term climatic trends and impacts, even though predictive skill may still remain limited.

Here we evaluate crop model simulations with the pDSSAT model based on both ECMWF decadal predictions and CMIP6-based climate model simulations, bias-adjusted and down-scaled for the European continent. We compare changes in weather variables, quantify skill and lead time in the decadal predictions, and quantify differences in maize and wheat yield responses. This project funded by the European Climate Foundation has only recently launched and results are not yet available. By the time of the conference, first results will be ready to present.

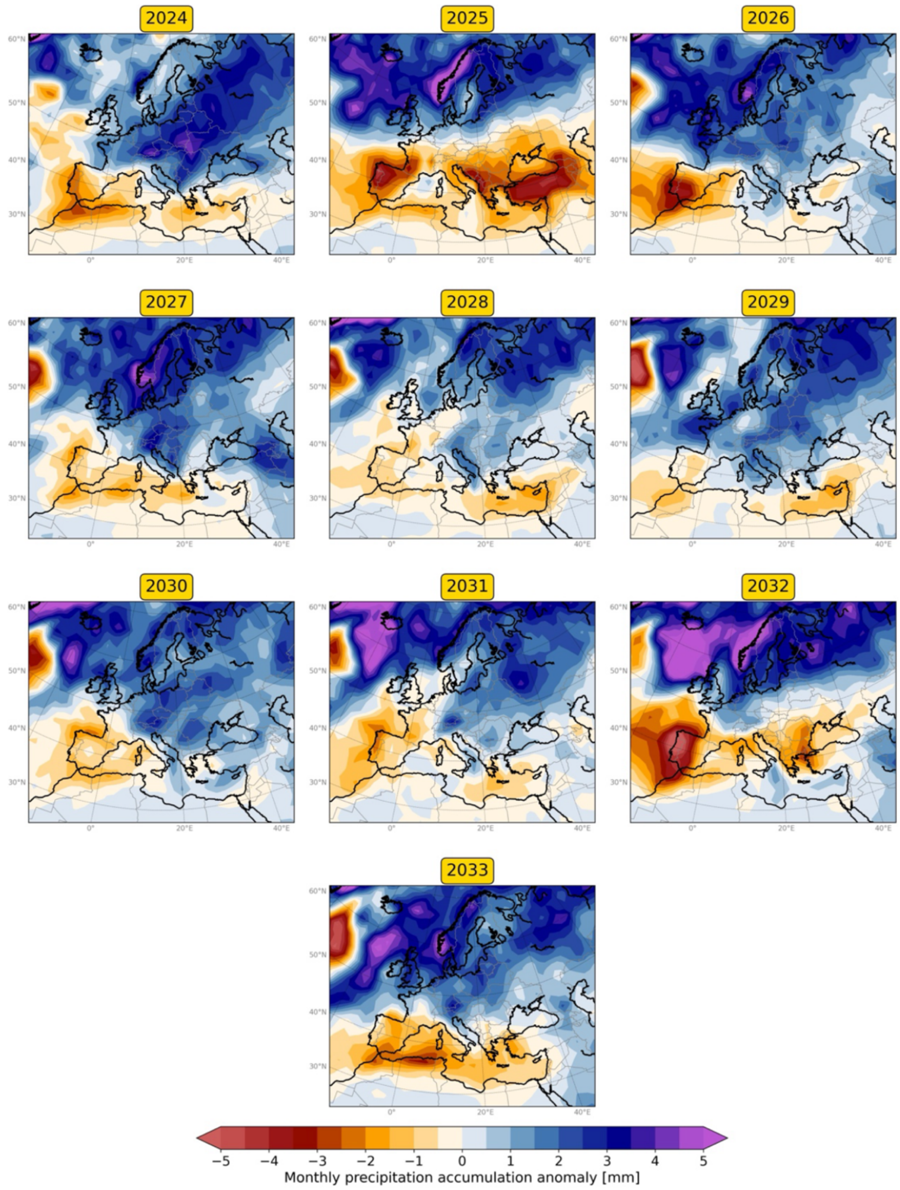

Fig. 1: Multimodel-mean annual precipitation anomalies for 2024-2033 from the 11/2023 ECMWF decadal prediction.

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Climate risk and suitability for European hazelnut (*Corylus avellana* L.) from expert knowledge, climate indicators, and process-based modelling

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Keywords: climate change; crop modeling; climate indicators; hazelnut suitability; E-OBS; phenology; indicators; European scale.

Introduction

European hazelnut (*Corylus avellana* L.) has served as a basic food since prehistoric Europe and nowadays it is indispensable to confectionery and chocolate production, where its sensory and processing traits drive product quality. Hazelnut plants thrive in mild Mediterranean climates and, being highly sensitive to summer water scarcity, tend to avoid the hottest, most arid zones. Water deficits depress photosynthetic efficiency, vegetative growth, yield, and nut quality, while late winter and spring cold spells can injure flowers. In recent years, brief but intense late frosts in major production areas have markedly reduced global output. Hazelnut is also vulnerable to elevated temperatures and high vapor-pressure deficit during ripening, conditions that suppress photosynthesis and ultimately yields. Adding to these climate risks is the species' alternate-bearing habit, which makes industrial planning, logistics, and stock management even more difficult.. At present, roughly 60-70% of global production is concentrated along Turkey's Black Sea coast, with Italy, the USA, Chile, Azerbaijan, and Georgia among the leading producers. Such geographic concentration magnifies systemic risk when frost or heat waves strike key zones, with repercussions for global stocks and prices. Identifying emerging cultivation areas is therefore strategic to diversify supply and buffer climate shocks. In this context, closer collaboration between industry and science is enabling new climate services to characterize evolving hazards and opportunities. To anticipate how climate change could reshape hazelnut suitability and risk across Europe, we integrated expert knowledge, climate-risk indicators, and process-based crop modeling into a unified workflow to identify past and future trends of hazelnut suitability at European scale.

Materials and Methods

We co-designed the study with managers, agronomists, data analysts and scientists through iterative workshops to define decision-relevant indicators and reporting formats. A structured survey of hazelnut specialists and growers prioritized phenological stages at risk, and elicited expert thresholds for critical climate risks (i.e. cold, heat, and drought stress). These results informed a tailored suite of climate indicators covering thermal requirements, damaging frost/heat spells, and seasonal water stress (Materia et al. 2022). Piedmont (Italy), a long-standing hazelnut growing region of high socio-cultural relevance, served as the calibration and validation baseline. Historical climate observation was derived with E-OBS dataset; climate projections used a large Euro-Mediterranean CORDEX ensemble at 0.11° (~12 km). Core variables included near-surface temperature, precipitation, wind, radiation, and potential/actual evapotranspiration (Zomer et al., 2025). Hazards were characterized using climate indices consistent with WMO CLIMPACT practice, including heatwave/cold-spell frequency and duration, annual temperature extremes, tropical nights, early-spring frost days, heavy and very heavy precipitation thresholds, consecutive dry/wet days, and radiation metrics. We tailored these indices via recursive, participatory meetings with agronomic experts. Climate modelling bias was assessed against E-OBS observation for temporal consistency. The crop-modeling component builds on the HADES yield forecasting system (Bregaglio et al., 2021), refined with the SWELL phenology module (Bajocco et al., 2025) calibrated using ground observations and remotely sensed vegetation indices (MODIS NDVI) from 91 Piedmont orchards. Simulations at hourly-daily resolution resolve light interception, stomatal conductance, photosynthesis and respiration, assimilate partitioning, chilling/forcing dynamics, and frost, heat and drought sensitivity of reproductive stages. A resource-budget scheme captures alternate bearing by modulating fruit allocation across years. Outputs were aggregated by decade to derive climate normal environmental response surfaces and suitability classes. We then applied the climate indicators and the calibrated crop model across Europe to map historical and future suitability.

Results and Discussion

The average historical March minimum temperature map (Figure 1a) highlights strong spatial gradients in early-spring cold and frost exposure across Europe, critical for flowering stage. In Piedmont, the probability distribution of peak summer temperature (Figure 1b) has shifted toward higher values over recent decades, indicating an increased likelihood of heat extremes.

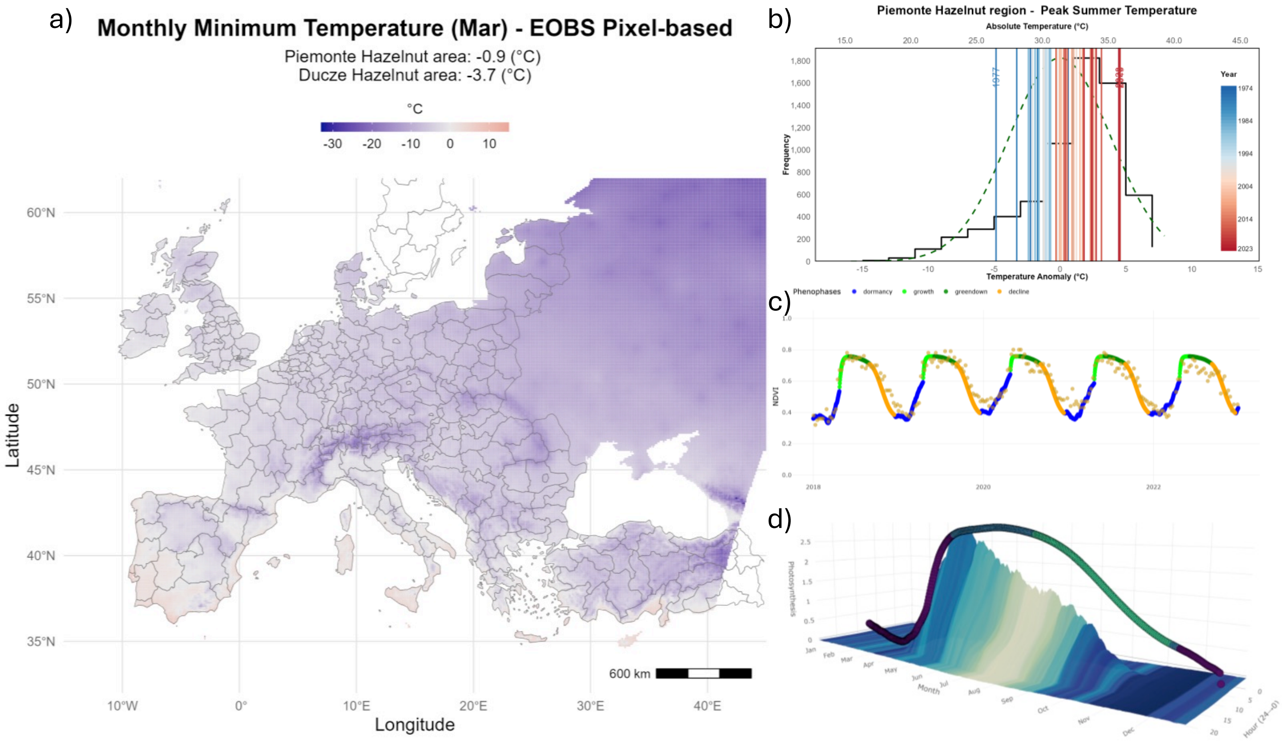

Figure 1. March minimum temperature (E-OBS) as a frost-risk indicator (a), distribution of peak summer temperature in Piedmont (b), NDVI phenology calibration (c), and 3-D view of photosynthetic activity modulated by water availability in Alessandria province (d).

The NDVI calibration shows close agreement between MODIS observations and SWELL simulations across phenophases (Figure 1c), validating the model's ability to reproduce seasonal canopy dynamics. The 3-D surface for Alessandria province (Piedmont) links photosynthetic activity with water availability (2000–2010), revealing clear depressions in plant activity during dry periods (Figure 1d). These preliminary results identify late-winter frost and summer heat-drought as dominant hazards for hazelnut, while modelling phenology-productivity enables site-specific assessment of suitability patterns. This approach will be extended to evaluate agro-management options with short- and medium-term climate projections to quantify future suitability and guide adaptation in major hazelnut producing areas.

Acknowledgements

This work was carried out within the HazelnUt Research on Resilient Areas for future Yields (HURRAY!) project. We are grateful to the agronomists, technicians, and scientists who participated to the expert survey and to the partners for their support throughout data sharing and methodology preparation.

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