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Rebalancing macronutrient supply in sub-Saharan Africa: Climate-smart optimization of cereal–legume systems

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Introduction: Malnutrition persists in sub-Saharan Africa (SSA), where diets rely heavily on rainfed cereals and legumes for the provision of calories and protein. Crop yields slowly increase in SSA (van Ittersum et al., 2025). Farmers' home-consumption highlights the critical role of local production in shaping food quality in SSA (de Haas and Giller, 2025). The aim of the study was to demonstrate: (i) how the local macronutrient balance is distributed across SSA; (ii) how yield intensification under climate change can help achieve both sufficient and nutritious food; (iii) the potential role of trade in supporting this process. The focus is on maize, millet, sorghum, wheat, soybean, groundnut, cowpea, and common bean.

Methods: This study introduces a spatial framework to optimize calorie-to-protein balance in cereal–legume systems across SSA, integrating crop modeling, machine learning (Alimagham et al., 2025), regression analysis, protein quality metrics, and climate scenarios (2050 time horizon, SSP370, SSP585, five GCMs). Nutrient supply was assessed from cereal–legume systems at continental to subnational scales, considering direct and by-product contributions (the latter via livestock). Calorie-to-protein ratios were benchmarked against a recommended value.

Results: Between 2005 and 2020, per capita production of calories and protein in SSA increased by 20%. Although SSA as a whole exhibited a favorable calorie-to-protein balance, substantial subregional disparities persisted, i.e., West Africa (WA) maintained a favorable ratio while Central, East, and Southern Africa showed signs of protein deficits. In 2020, SSA reached 89% calorie and 93% protein self-sufficiency. However, 66% of the population resided in deficit areas (Fig. 1). Imports were largely calorie-oriented and did not significantly enhance protein supply or food quality.

Climate change projections indicated potential yield gains for legumes but negative effects on cereals. By 2050, self-sufficiency could be achieved if 52% of the rainfed potential for cereals and 42% for legumes were realized at the SSA level. Nevertheless, only 38% of the population is expected to live in areas with balanced local calorie and protein supplies, underscoring the critical role of trade and distribution networks.

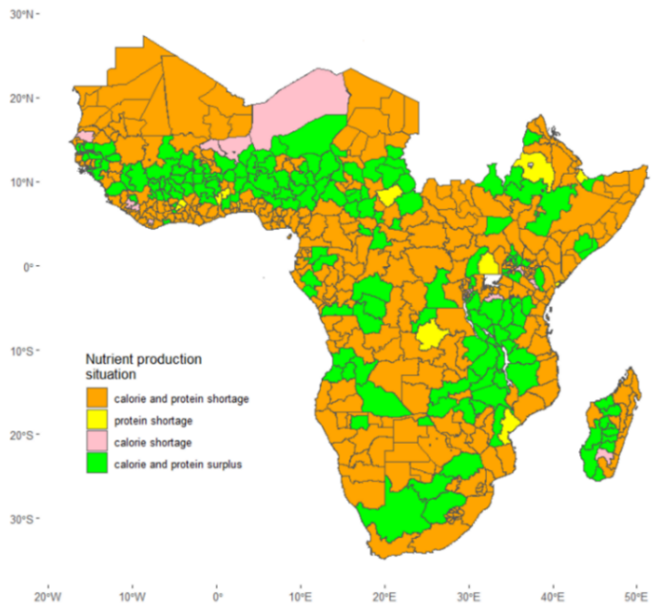

Figure. 1. The spatial distribution of calorie and protein shortage or surplus production in cereal-legume systems across SSA in 2020.

Discussion: Increasing the production and trading of legumes and cereals are occurring with limited attention to their nutritional value in SSA (de Haas and Giller, 2025). For instance, soybean expansion increased total protein availability, but much was diverted to feed and oil. Therefore, it does not translate into improved protein availability at consumer level. To optimize human nutrition, WA should prioritize cereals, while other regions need more legumes. Active, nutrition-sensitive national and international trade and storage systems are essential to bridge the mismatches between production zones and population (consumption) centers.

Conclusion: Balancing food quality with quantity is central to food security in SSA. Even if production increases to self-sufficiency levels at the level of SSA, spatial mismatches will still leave millions at risk of macronutrient deficits. Strategic adjustments in crop composition, combined with strengthened trade, can enhance resilience. The proposed framework provides a scalable tool for designing climate-resilient, nutrition-smart food systems across SSA and beyond.

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Sustainable intensification of grain legume production in sub-Saharan Africa and the impact of climate change

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Keywords: food security, protein production, water-limited potential yield, yield gap

Introduction

Sub-Saharan Africa's (SSA) population is increasing rapidly, leading to increased food demand. Food production must therefore be increased, but current yield improvements are slow, while climate change may further impose challenges (Van Ittersum et al., 2025). To address these challenges, sustainable intensification of food production is essential, as the current trend in SSA of increasing production through arable land area expansion is unsustainable.

The main aim of this study was to analyse how improved grain legume production in SSA, via narrowing yield gaps (i.e., the difference between the water-limited potential yield (Yw) and the farmers actual yield (Ya)), can contribute to sustainable intensification of food production under current climate (baseline) and climate change (2050) conditions. Our research focused on sole cropping of main cultivated grain legumes across SSA: common bean, cowpea, groundnut and soybean.

Materials and Methods

Geographically continuous gridded projections of Yw for the four grain legume crops across entire SSA were estimated for the baseline and 2050 conditions using the step-wise machine learning (ML) framework of Alimagham et al. (2025). Here ML and process-based eco-physiological model algorithms that account for crop phenology are combined. The ML model was trained using among others estimates of Yw for key production sites across a wide range of climates across SSA derived from a crop growth simulation model.

Total legume production is presented in terms of true digestible protein production. We estimated self-sufficiency in digestible protein of the four legumes for the years 2020 and 2050. For 2050 we considered increased demand, yield intensification and climate change.

Results and Discussion

Sustainable intensification increased digestible protein production by 141% when yields were increased until 80% of Yw at baseline, while cultivated areas remained the same (Fig. 1). Largest contribution came from West SSA (i.e., large area and small current relative yield [Ya/Yw]), and smallest from Southern SSA (i.e., small grain legume area and relatively high relative yield). However, current relative yields were only 33% on average and respectively 23%, 27% for cowpea and common bean and 40% for both groundnut and soybean. We projected that Yw in 2050 was generally positively affected (+11%), though there were distinct differences across crops and regions (Fig. 1).

In order to fulfil future increased demand for digestible protein delivered by the four grain legumes, a yield increase to 62% of Yw will be required. This is way exceeding the current slow yield growth rates of grain legumes. An increase in grain legume production is not only beneficial in order to meet food demand, but grain legumes also have a high nutritional quality.

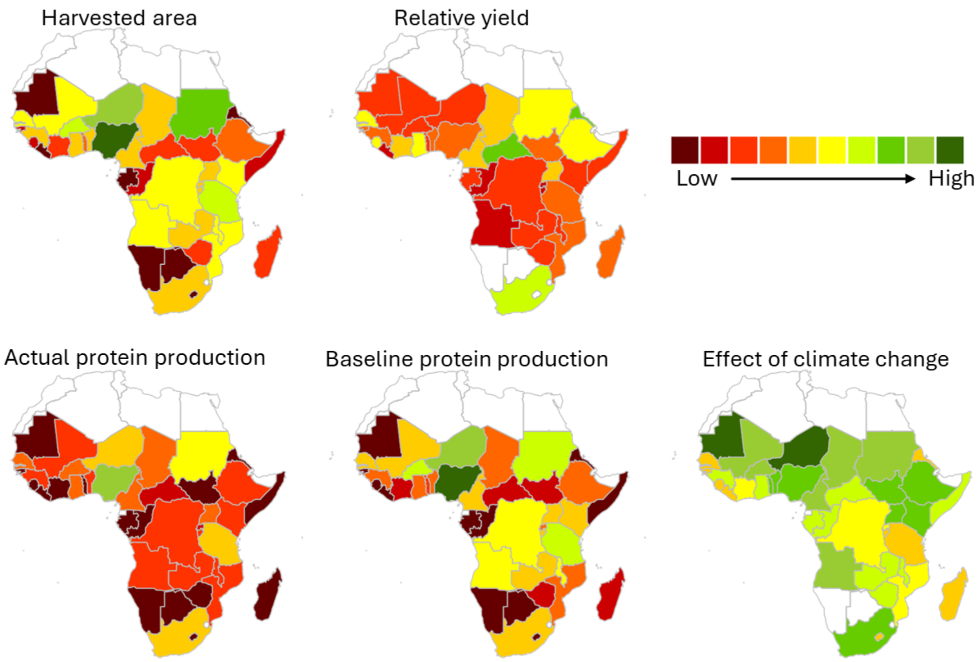

Fig. 2 Map of SSA showing actual harvested area, relative yield (Ya/Yw), protein production, as well as what the production could be under yield intensification to 80% Yw under baseline and the change under 2050 conditions.

Conclusions

Increasing grain legume yields could play an important role in sustainably enhancing food production. However, meeting this goal requires substantial increases in yields, from the current 33% of Yw to 62%. Though climate change is positively impacting grain legume production, still the current rate of yield improvement is insufficient to keep pace with the growing demand for food.

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Quantifying and analyzing planting date gaps in Sub-Saharan African maize systems: a hybrid approach

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Keywords : remote sensing, crop simulation model, machine learning, rainfed crop, smallholder farming

Introduction

Smallholder farmers in sub-Saharan Africa produce the majority of the region's food, yet for maize, the main staple and feed crop in the region, yields remain far below potential (van Ittersum et al., 2016). Planting date is one of the most critical decisions: early sowing risks poor germination and seedling establishment due to inadequate soil moisture, while late sowing exposes crops to rainfall deficits during sensitive growth stages. The divergence between optimal and actual sowing dates, planting date gaps, represents an important barrier to closing the yield gaps, and hence improving productivity and food security. This study introduces a hybrid approach that integrates remote sensing for actual planting dates, crop modelling for optimal planting dates, and machine learning to identify underlying drivers of planting dates gaps dynamics. This methodological advance enables consistent, large-scale assessment of planting date gap dynamics, addressing both spatial heterogeneity and long-term trends. We apply it to Kenya, Nigeria, and Rwanda for the period 2002-2022.

Materials and Methods

The analysis focused on the main maize-growing seasons in Kenyan Nigeria and Rwanda. Cropland extent was delineated using the ESA WorldCover product for the most recent available year. Actual planting dates were estimated from MODIS NDVI time series (250 m, 8-day) by detecting the first "green-up" signal, corrected for sowing-to-emergence lag using local field data. Calibration showed an average absolute difference of ~10 days. The optimal planting dates were derived from the DSSAT CERES-Maize model (0.5° grid), calibrated for local varieties and management. Maize yields were simulated for sowing every 7 days across the season, and the yield-maximizing date was defined as optimal (Mkulhani et al., 2024). The planting date gaps were calculated as the absolute difference between optimal and actual planting dates. Temporal trends were tested with Theil-Sen estimators, and clustered with AGNES hierarchical analysis. Eleven climatic, biophysical, and socio-economic variables derived from geospatial datasets were tested as potential drivers of planting date gaps dynamics. An interpretable machine learning approach based on Random Forest model with local-SHAP values was used to identify and mapped the local contribution of each driver.

Results and Discussion

Across the three countries, more than 90% of maize areas were planted outside the 7 days of the optimal date. Late planting was dominant, though interannual variability included occasional early sowing (Figure 1a). Most areas showed no significant long-term trend; where trends existed, three classes emerged: (i) stable gaps, (ii) shifts from early to late planting, and (iii) shifts from late to early planting (Figure 1b). Drivers varied: elevation dominated in Rwanda, while rainfall variability and rural population density were more influential in Kenya and Nigeria. These results highlight persistent but heterogeneous planting date gaps. The identification of both climatic and socio-economic drivers suggests that interventions need to be tailored, e.g., optimizing the amount of land to be planted in sparsely populated areas with limited labor availability or providing timely climate information where rainfall variability drives delays.

Conclusions

This study demonstrates the potential of combining remote sensing, crop modelling, and machine learning to assess planting date gaps at scale. Findings reveal widespread and persistent gaps across sub-Saharan maize systems, with spatially variable drivers. Such insights provide a foundation for targeting context-specific strategies to reduce planting date gaps and hence closing the yield gap and support improved food security.

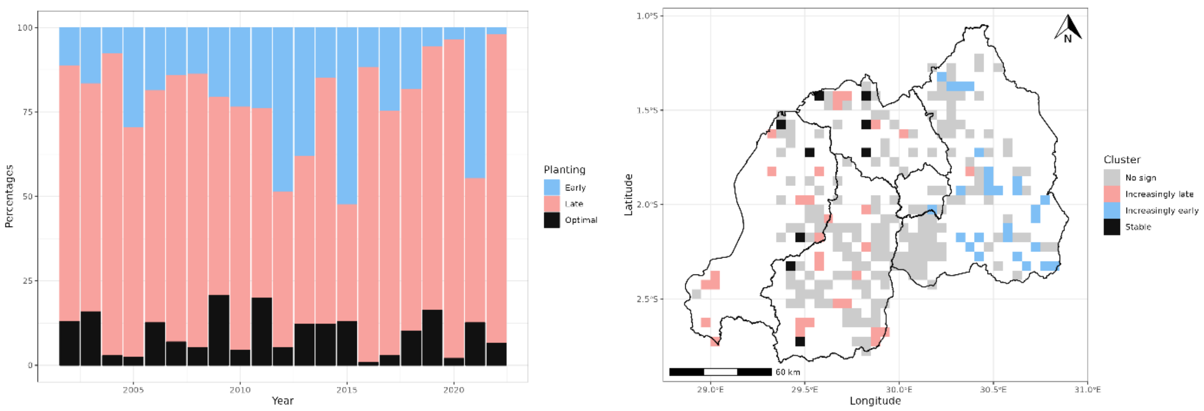

Figure 1. Illustration of the maize planting date gaps dynamics between 2002 and 2022 for the Rwanda use case. Left, interannual variability of the planting date gaps and right the maize planting date gaps trends derived from an AGNES clustering approach and a Theil-Sen estimator.

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Enhanced food security under global change requires a tritrophic perspective

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Keywords: invasive species, pest risk analysis, time-varying life tables, population dynamics, agroecology.

Introduction

Global change is altering the relationships between crops, pests, and natural enemies, and accelerating the spread of destructive invasive species. These changes pose a significant threat to agricultural production and food security worldwide (Cuthbert et al., 2022). Current risk assessment strategies often rely on correlative species distribution models (CSDMs) that lack the capacity to predict the complex, weather-driven population dynamics essential for informing robust management and policy development. To bridge this gap, a mechanistic framework using physiologically based demographic models (PBDMs) was proposed (Gutierrez and Baumgärtner, 1984). This framework posits that by capturing the fundamental, weather-driven biology of resource acquisition and allocation at each trophic level, we can develop powerful, predictive models of crop systems that are independent of time and place, providing a sound basis for proactive crop management. A web platform is proposed to assist non-experts in formulating PBDMs to help solve agroecological pest problems (Gutierrez et al., 2025).

Materials and Methods

To outline the development and demonstrate the utility of this framework as web platform software for non-experts, we utilize PBDMs for 13 invasive pest species of agroecological importance to Africa to predict their geographic distribution, relative abundance, and dynamics across the continent. The PBDM framework is based on the paradigm of time-varying life tables (TVLTs) (Gutierrez and Baumgärtner, 1984), which mathematically describes by analogy the developmental biology of all multicellular organisms (Fig. 1).

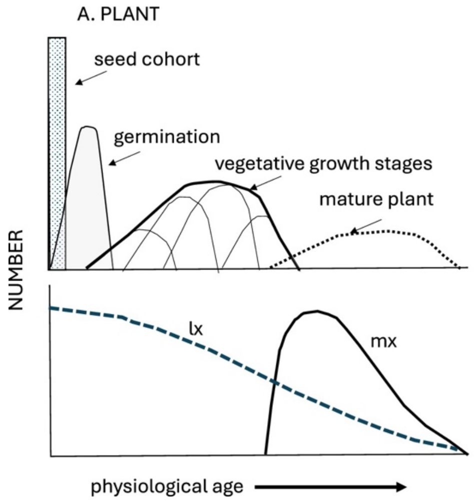

Figure 1. Analogous developmental stages of a plant and an insect, with the bottom panel characterizing survivorship (*lx*) and reproductive profiles (*mx*). Note that the developmental times of individuals initiated at the same time have distributed developmental rates (Gutierrez et al., 2025).

The models for all trophic levels are age-structured and parameterized using two related approaches: (1) a metabolic pool (MP) approach for resource acquisition and allocation, or (2) biodemographic functions (BDFs) fitted to vital rates (e.g., development, mortality, reproduction) from life-table studies (Gutierrez and Baumgärtner, 1984). By analogy, this unified structure allows the same modeling principles to be applied across taxonomically diverse species. A common modeling framework was employed to develop PBDMs for 13 invasive species systems of major agroecological importance to Africa, encompassing a total of 20 species, including crops, pests, natural enemies, diseases, vectors, and parasites. The underlying precepts of the approach are based on 1960-1970s crop plant modeling concepts of C.T. de Wit summarized for the WOFOST crop simulation model by A. de Wit et al. (2019).

Results and Discussion

In a GIS context, the PBDM framework successfully simulated the prospective geographic distribution and relative abundance of all 13 invasive species across Africa (Gutierrez et al., 2025). By focusing on the species' physiological responses to local weather, the models provided dynamic predictions that compared favorably to published data.

For example, the invasive pest South American tomato pinworm (*Tuta absoluta*), originally from Peru's cool highlands, spread to subtropical Brazil and was first detected in Europe (Spain) in 2006. Early assessments in 2010 and 2019 incorrectly predicted the pest would only survive in coastal southern Europe, due to its warm-climate expansion in South America. However, these predictions failed because researchers overlooked the pest's origins in the cold, semi-arid Andean highlands, which enabled it to survive in much broader climatic conditions. As a result, *T. absoluta* colonized far more of Europe than expected. By the time scientists recognized its full invasive potential, it had spread across large areas of Europe, with subsequent invasion of Africa and parts of Asia, where it poses a significant threat to food security. The prospective invasive distribution of *T. absoluta* in Africa includes the cooler climes of Senegal and Morocco, across coastal North Africa to Egypt and the Levant, with the highest populations found in sub-tropical and tropical Africa and decreasing levels in temperate regions of South Africa.

In contrast, PBDM analysis predicts that the highly destructive polyphagous pest Asian brown marmorated stink bug (*Halyomorpha halys*) would find most of sub-Saharan Africa unfavorable, with suitable niches restricted to coastal North Africa and the tip of South Africa. This analysis contradicts predictions from CSDM algorithms, including CLIMEX, which project a wide potential distribution in the region.

The PBDM framework routinely handled agroecological complexity that is intractable with CSDMs, including tritrophic daily dynamics of and interactions between the citrus crop, its pest *Diaphorina citri*, the natural enemy *Tamarixia radiata*, and the bacterial pathogen that causes citrus greening disease and is vectored by the pest. These and other examples highlight the critical importance of incorporating mechanistic biology to avoid potentially misleading risk assessments and more effectively target management strategies in cropping systems.

Conclusions

PBDMs provide a robust, mechanistic alternative to correlative methods for assessing the dynamics, distribution, and abundance of native and invasive pests interacting with their host crops under global change. In a multitrophic context, they hold high potential for examining the complex agroecology at the heart of crop production, integrated pest management, and biological control (see Tixier et al., 2013). By grounding predictions about the dynamics in the fundamental biology of the organisms, PBDMs deliver more reliable insights to safeguard food security. As with major cropping systems models, such as WOFOST (de Wit et al., 2019), which focus on crop growth and development, we advocate for the development of a web-based platform to make tritrophic demographic modeling approaches more accessible to non-experts, thereby fostering a global, proactive, and science-based pest management approach.

Acknowledgements

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Agronomy, not genetics nor climate change, explains wheat yield plateaus in high-yielding environments of Northwest Europe

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Keywords: Food security, WOFOST crop model, yield potential, N use efficiency

Introduction

Wheat yields in Northwest Europe increased at a rate of 120 kg ha^{-1} yr^{-1} between 1961 and the mid-1990s, after which a yield plateau was reached. Since then, wheat yields remained stagnant across most countries. Understanding this lack of yield progress is important to delineate the feasibility of yield increases in the future and requires unpacking the contribution of interactions between improved genetics, historical climate change and agronomic management (Rizzo et al., 2022). Previous studies estimated wheat yield gains due to genetic progress in the range of 55-130 kg ha^{-1} yr^{-1} in Northwest Europe (e.g., Rijk et al., 2013), partly explained by increases in thermal time from anthesis to maturity and slight increases in light use efficiency (Berghuijs et al., 2023). Based on literature, the contributions of climate trends and changes in agronomic management to wheat yield trends are less clear than that of improved genetics, and often conflict across studies, depending on whether crop models or statistical models are used. This study was thus devised to disentangle the relative importance of genetic improvement, historical climate change, and agronomic management to the wheat yield plateau in Northwest Europe in an integrated way.

Materials and Methods

Progress in actual farm yields depicts the full interaction between genotype, environment, and management and was estimated from official statistics using linear regression. *Yield gains due to genetic improvement* capture variety characteristics conferring higher yield potential and were estimated from variety trials using a two-step regression approach (Rijk et al., 2013). *Yield gains due to historical climate change* isolate the effects of growing season radiation, temperature, rainfall, evapotranspiration, and atmospheric CO_2 concentration on crop yield and were estimated through a combination of crop simulation modelling and linear regression. To do so, the WOFOST crop model (de Wit et al., 2019) was calibrated against field data and used to simulate the potential yield and the water-limited potential yield for wheat in the three Dutch case study regions. Lastly, *yield gains due to agronomic management* were estimated with the difference method and capture field and farm level factors affecting yield losses to water and nutrient availability and pest, disease, and weed pressure. A yield gap analysis was further conducted using farmer field data and crop model simulations to understand which agronomic factors explain the wheat yield plateau (Berghuijs et al., 2024).

Results and Discussion

Yield gains due to improved genetics amounted to 74-84 kg ha^{-1} yr^{-1} during the period 1994-2016 Netherlands, with wheat yields in variety trials conducted in the Netherlands reaching about 8.0 t ha^{-1} in the 1970s and 12.0 t ha^{-1} after 2010. Simulated yield gains due to historical climate change amounted to 26-60 kg ha^{-1} yr^{-1} over the period 1994-2016. This positive contribution of climatic factors to wheat yield trends was observed across regions, soil types and cultivars. The climatic factors associated with the positive impact of climate trends to wheat yields include increases in atmospheric CO_2 concentration and increases in solar radiation during grain filling period due to earlier anthesis leading to grain filling around the longest day of the year. Given the absence of genetic and climatic yield ceilings, we estimated that agronomic management is responsible for the wheat yield plateau in Northwest Europe and contributed to an unrealized potential yield gain of 67-114 kg ha^{-1} yr^{-1}. Water and nutrient management had a small contribution to yield gaps in farmers' fields (see also Silva et al. 2020 and 2021). Other factors associated with pests and diseases and with tactical management of crop rotations (e.g., a preference for root and tuber crops with higher economic value) are likely important causes of the wheat yield plateau in high-yielding environments of Northwest Europe.

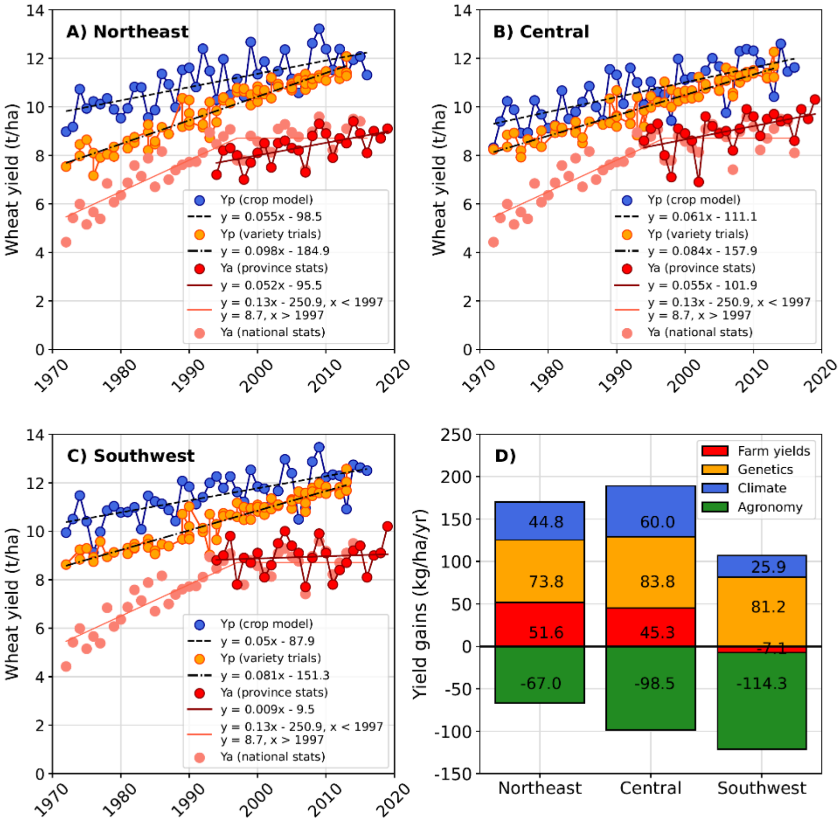

Figure 1. Yield gains due to genetic improvement, historical climate change, and agronomic management in high-yielding environments of the Netherlands. Key production regions include the Northeast, Central, and Southwest regions of the Netherlands. The actual yield (Ya) at regional and national levels was obtained from the National Statistics Bureau of the Netherlands (CBS in Dutch). Linear fits to the Best Linear Unbiased Estimates (BLUEs) for individual varieties in official variety trials provide a proxy for yield gains due to genetic improvement and linear fits to the potential yield (Yp) simulated with the crop model WOFOST for a modern wheat variety released in 2009 provide a proxy for yield gains due to historical climate change. Panel (D) presents the yield gains estimated for the 1994-2016 period. All directly estimated trends for the 1994-2016 period were statistically significant ($p \leq 0.05$), except for the actual yield trend in the Central region ($p \leq 0.10$) and the actual and climate yield trends in the Southwest region ($p > 0.10$).

Conclusions

Our results provide new evidence that no ceiling in genetic yield potential has been reached and that climatic conditions have not constrained wheat yields across high yielding environments of Northwest Europe thus far, hence sub-optimal agronomic management must be responsible for the observed wheat yield plateau. Breaking the yield plateau will require due attention to agronomic constraints from a farm level perspective and continued monitoring of genetic gains and climate change impacts on wheat yields.

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Scaling APSIM to Benchmark and Adapt US Maize Production Through Hydrology, Genetics, and Management Integration

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Keywords: yield prediction, genotype x management x environment, crop model calibration at scale

Introduction

Process-based simulation models are increasingly used to evaluate crop productivity and environmental outcomes, yet practical guidance on setting up, calibrating, and validating these models at scale remains limited. In this study, we (i) present a methodology for efficiently parameterizing and benchmarking APSIM across the US Corn Belt, assessing not only yield but also system-level processes (e.g., water balance, N cycling), and (ii) apply the calibrated model to explore the future of US maize production under two scenarios: business as usual (climate change only) and adaptation (concurrent advances in genetics, management, and environment).

Materials and Methods

APSIM model simulations were conducted at a 0.5° resolution (~25,000 grids across 12 USA states) for the period 1980–2020 (baseline) and were extended to 2060 (future). The US Corn Belt's diverse hydrological landscape was represented through region-specific bottom boundary conditions (shallow fluctuating water tables, drainage, irrigation). A 4-m soil profile was developed from SSURGO datasets, and management data were retrieved from USDA-NASS. APSIM maize hybrids were modified both spatially (relative maturity zones) and temporally (per decade) to capture breeding-driven trait changes (King et al., 2025). Benchmarking employed published water table data (Fan et al., 2013), USDA yield (Fig. 1), phenology, and soil moisture records, SSURGO rooting depths, and reported genetic gains in biomass and resource use efficiency traits. Future projections utilized nine CMIP6 datasets (three climate models × three scenarios). The adaptation scenario incorporated shifting planting dates based on modeling workable days (Huber et al., 2023) and continued historical rates of breeding and management change.

Results and Discussion

The model successfully reproduced historical maize yield trends from 1980 to 2020 across the US Corn Belt (Fig. 1). County-level yields, state-level phenology, and interannual variation in soil moisture and water tables were well captured. Simulated outputs revealed that all agricultural efficiencies increased (0.1 to 1% per year) from 1980 to 2020 and that poorly drained soils exhibited the greatest water and N losses. Projections indicated future yield increases under adaptation, though rates varied spatially.

Conclusions

Accurately representing hydrological heterogeneity and cultivar evolution enabled robust simulation of system dynamics at scale, validated by multiple indicators. Future projections suggest significant potential for increasing maize production in the US Corn Belt, provided breeding progress and improvement in agronomic management continue.

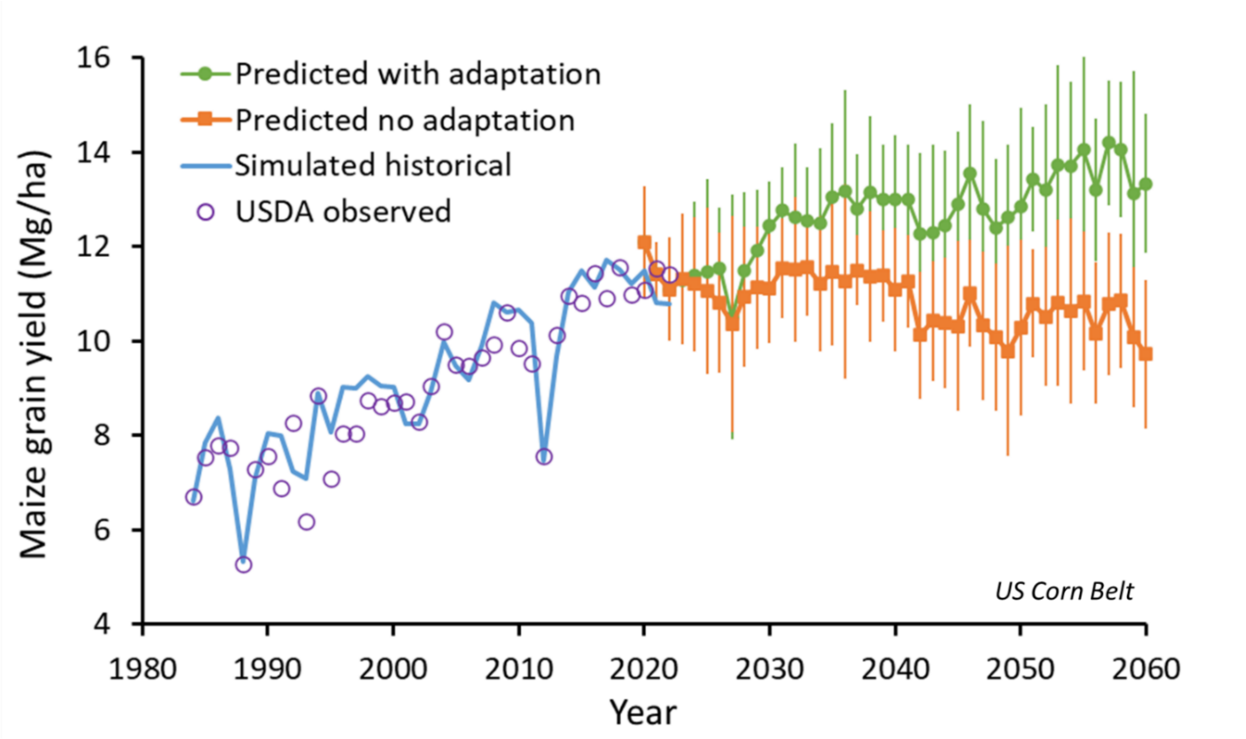

Fig 1: Observed (points) and APSIM model-simulated maize grain yields (lines) in the US Corn Belt for the historical and future conditions. The vertical bars in the future simulations indicate variability among the nine CMIP6 scenarios.

Acknowledgements

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Integrating agricultural and techno-economic models for optimising food supply chains: A concept study with plant proteins in New Zealand

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Keywords: APSIM; BeWhere; *Medicago sativa*, Modelling; Plant-protein; Optimization

Introduction

Contemporary Food Supply Chains (FSCs) are often characterized by substantial inefficiencies, largely due to fragmented development and the lack of integrated, sustainability-oriented planning (Gaupp et al., 2021). In this context, *in-silico* simulations for the *ex-ante* design and evaluation of FSCs provide a novel framework to anticipate system performance and guide innovation. In this paper, we describe a new approach to spatially optimize FSC's components by integrating existing agricultural and techno-economic models. The modelling framework is tested at country scale, across New Zealand, through a concept study in which lucerne (*Medicago sativa*), a high-protein crop mostly used for forage and fodder, is extended to human nutrition through the production of plant protein concentrates for the international market.

Materials and Methods

A hypothetical FSC for lucerne protein concentrate and its co-products was designed for New Zealand conditions (Figure 1a). Key FSC components (e.g., production, processing and logistics) were simulated through the soft coupling of two benchmark models. The Agricultural Production Systems sIMulator (APSIM; Holzworth et al., 2014) was applied to estimate protein productivity of irrigated lucerne across lands suitable for the cultivation of the crop (Teixeira et al., 2023). APSIM ran in response to daily weather inputs from historical climate (1971 to 2000) downscaled at 5 km resolution. The biophysical model outputs were processed by the techno-economic model BeWhere (BeWhere; Leduc, 2009) operating at 50 km grids (Figure 1b). BeWhere spatially minimised economic (NZ$/t) and environmental ($CO_2$ equivalent emissions, CO_2eq/t) costs of production, processing and transport across the hypothetical FSC. The model estimated potential locations and dimensions of production areas and industrial processing plants in relation to shipping ports.

Results and Discussion

Based on a preliminary parameterization set, results showed a large regional variability in protein yield in response to temperature and radiation profiles (Figure 1b). BeWhere identified multiple potential production areas and protein-processing plants across the North Island, and one at the Canterbury plains in the South Island. The method provided a flexible and transparent framework for evaluating trade-offs between productivity, costs, and greenhouse gas emissions. A key challenge lies in the need for multidisciplinary expertise to parameterize the interlinked biophysical, logistical, and economic dimensions of the approach. Sensitivity analysis across the data pipeline, and early engagement of different experts and stakeholders, is expected to minimise risks of misrepresenting FSC components.

(a) (b)

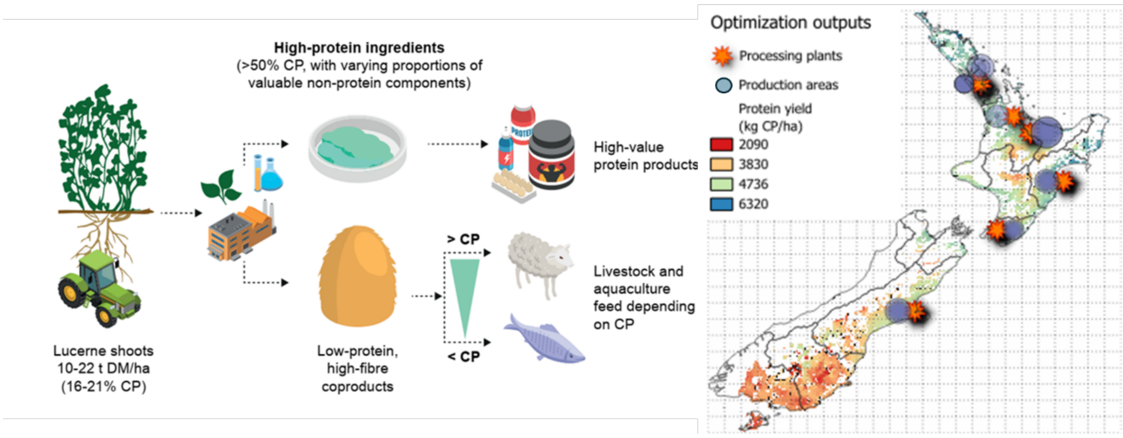

Figure 1. Conceptual representation of (*a*) a hypothetical lucerne protein supply chain in New Zealand and (b) simulated potential crude protein (CP) yields in relation to optimized locations for the production (blue circles) and processing (orange stars).

Conclusions

The newly developed approach was able to spatially optimize components of food supply chains through the soft coupling of well-established biophysical and techno-economic models. Beyond its immediate application, the methodology holds promise for broader use in guiding the design of more resilient and resource-efficient food supply chains.

Acknowledgements

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Ensemble Modeling and Multi-Criteria Analysis for Biofuel on Italian Marginal Lands

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Keywords: Double model analysis, Non-food crops, Castor bean, Safflower, MCA

Introduction

In Italy, road vehicles use 929 PJ of diesel, 66 PJ of biofuels, and 69 PJ for aviation/shipping (Antonella Bernetti et al., 2025). Most biofuels currently come from first-generation feedstocks such as wheat, rapeseed, corn, etc. (El-Araby, 2024). This reliance on food crops has raised the food-fuel debate, as it may increase food prices and reduce land for food production(Chakravorty et al., 2017; Rulli et al., 2016). Two solutions are proposed: using marginal lands and adopting non-food crops. Several underutilized crops, including safflower (*Carthamus tinctorius*), castor bean (*Ricinus communis*), and Ethiopian mustard (*Brassica carinata*), require low inputs and tolerate abiotic stress (Bressan et al., 2011; Russo et al., 2025). Our study used a double model analysis to estimate energy production from these three crops under two agronomic managements: minimum and low input.

Materials and Methods

Marginal lands were identified via a multi-criteria analysis using three clusters: pedo-climatic, geo-morphological, and socio-economic factors, with weights assigned by experts. DSSAT and ARMOSA were used in a double model analysis, calibrated with literature data and evaluated with open-field trials in Italy (2023-2024) and literature data for Ethiopian mustard. Trials were conducted at the University of Naples (Portici and Torre Lama) and on a private farm. The soil ranged from sandy to clay to sandy loam under a Mediterranean climate. Long-term simulations focused on the most marginal areas, using soil data from CREA database and weather data from MERIDA (2004-2023), totaling 50’000 unique combinations. Crops were simulated in rotation with fava bean under two managements: minimum (rainfed safflower and castor bean; unfertilized Ethiopian mustard) and low input (irrigated safflower and castor bean at 50% ETc; Ethiopian mustard with 50% N). Fava bean was chosen due to simulate a minimal management of the marginal lands, using it as a potential annual forage crop. An economic threshold at field level, based on input cost and yield return, was applied across four scenarios: 0.5, 0.6, 0.7, 0.8 (percentage of years with profit > 0).

Results and Discussion

Up to 38% of Italian agricultural land is classified as marginal, low (14%), medium (19%) and high (5%), with the highest concentration in Sardinia and Sicily, in alignments with the findings of Sallustio et al., (2018). In the North, both summer crops show a positive correlation with temperatures under rainfed and irrigated conditions (Table 1). In contrast, in central and southern regions, correlations between yield and maximum, minimum and mean temperatures during the growing season are negative, while correlations with rainfall are positive (Table 1). Simulations indicate that marginal lands could supply 16.07-50.07 PJ (Figure 1). This potential is relevant to current Italian biofuel consumption: Italy is a net importer, importing up 64% of biofuel demand. The energy from marginal lands could cover 17-52% of the energy required for aviation and shipping. In these sectors, energy density is crucial, and fossil fuel remains the dominant solution.

Table 1 Pearson correlation values between climatic variable as average temperature, maximum temperature and rainfall during growing seasons of the three crops (Safflower, Castor bean and Ethiopian mustard) divided between the three marco-regions (North, Centre, South and Islands)

Area	Crop	Management	Average Temp	Maximum Temp	Minimum Temp	Rainfall
North	Safflower	Minimum	0.30	0.27	0.31	-0.17
		Low	0.31	0.28	0.32	-0.26
	Castor bean	Minimum	0.35	0.10	0.31	0.37
		Low	0.61	-0.4	0.59	0.59
	Ethiopian mustard	Minimum	0.27	0.28	0.26	---
		Low	0.35	0.35	0.34	---
Centre	Safflower	Minimum	-0.29	-0.26	-0.25	0.26
		Low	-0.55	-0.47	-0.50	0.31
	Castor bean	Minimum	-0.39	-0.35	-0.32	0.51
		Low	-0.05	0.01	-0.11	-0.12
	Ethiopian mustard	Minimum	0.18	0.18	0.16	---
		Low	0.38	0.34	0.38	---
South and islands	Safflower	Minimum	-0.16	-0.25	0.009	0.28
		Low	-0.58	-0.49	-0.47	0.39
	Castor bean	Minimum	-0.32	-0.29	-0.24	0.55
		Low	-0.23	-0.21	-0.16	0.06
	Ethiopian mustard	Minimum	0.33	0.40	0.20	---
		Low	0.49	0.50	0.38	---

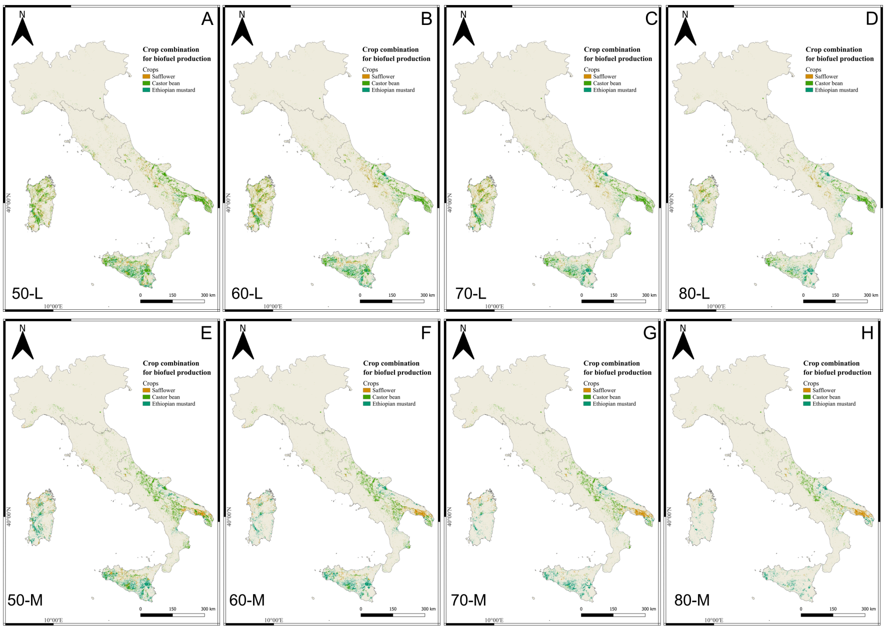

Figure 1. Optimal crop combination for biofuel production under different agronomical management, minimum (M) and low (L) input considering different threshold for viable years (50, 60, 70, 80 and more).

Conclusions

Second-generation feedstocks can be effectively cultivated on marginal lands for biofuel production. Weather variability is an important factor in selecting the most suitable crop to maximize returns. From this perspective, having access to more granular datasets would allow for more accurate simulations of crop performance, thereby improving productivity estimates.

Acknowledgements

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Crop-model informed economic analysis of nitrogen tax effects on food production

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Keywords: LPJmL, SIMPLE-G, planetary boundaries, spillover effect, agriculture

Introduction

Agricultural production systems are important elements in research around food systems, planetary boundaries or sustainability questions. However, these questions require a broad, interdisciplinary perspective that require combining crop models with other types of models, such as economic optimization models. However, the incompatible structures of economic optimization models and process-based crop models hinder their effective coupling so that feedback mechanisms are typically omitted in the analyses. Here, we investigate how a nitrogen (N) tax in highly N-polluting areas would affect N pollution levels and crop production, explicitly accounting for the market-mediated spillover effects to non-targeted regions and production systems. Given the non-linear nature of both yield and N pollution levels to N input, the modification of N inputs in agricultural production has great potential for achieving more sustainable crop production systems (Kahiluoto et al. 2024).

Materials and Methods

To circumvent iterative global crop model simulations with the dynamic global vegetation, hydrology and crop model LPJmL (von Bloh et al., 2018; Wirth et al. 2024) in the coupling to the spatially explicit global agricultural trade model SIMPLE-G (Haqiqi and Hertel, 2025), we created Gompertz-function based N input response curves for crop yield and N leaching. We fitted the Gompertz-function based response curves using a series of LPJmL simulations at different, globally uniform fertilizer levels from 0 to 300 kgN ha^{-1} (at intervals of 1 kgN ha^{-1}) for which crop- and location-specific N leaching rates and yields were recorded. These response functions were implemented into the global spatially explicit agricultural trade model SIMPLE-G. In this analysis framework, N tax rates were implemented to discourage highly polluting N input levels, which may be economically advantageous in the absence of a tax. Making use of the response curves this tax would directly impact fertilizer purchase and application, crop yields, and N pollution levels.

Results and Discussion

As a consequence of the N tax, N inputs were reduced in targeted regions, reducing N pollution much stronger than crop yields. Due to the reduced fertilizer use in targeted regions, the global price for N fertilizer fell, making it more tangible for farmers in non-targeted regions to increase yields through additional fertilizer purchase and application. Due to the non-linear nature of the response curves, reduced N input in targeted regions typically led to an overproportionally larger reduction in N pollution than in crop yield. Conversely, increasing N input in non-targeted regions typically led to an overproportionally larger increase in crop yield than in N pollution.

At the global aggregation, N fertilizer consumption fell in response to the tax and this could even lead to reduced food prices (lower input costs) and relatively stable global production levels. Results were most sensitive to the elasticity of N fertilizer production: reduced food prices occur if N fertilizer production was assumed to be inelastic (prices are reduced rather than production amounts in response to a reduced fertilizer demand), which is consistent with empirical evidence.

At local level, however, targeted farmers do experience reductions in farm income and agricultural production, while non-targeted farmers can experience increases in income and production shares.

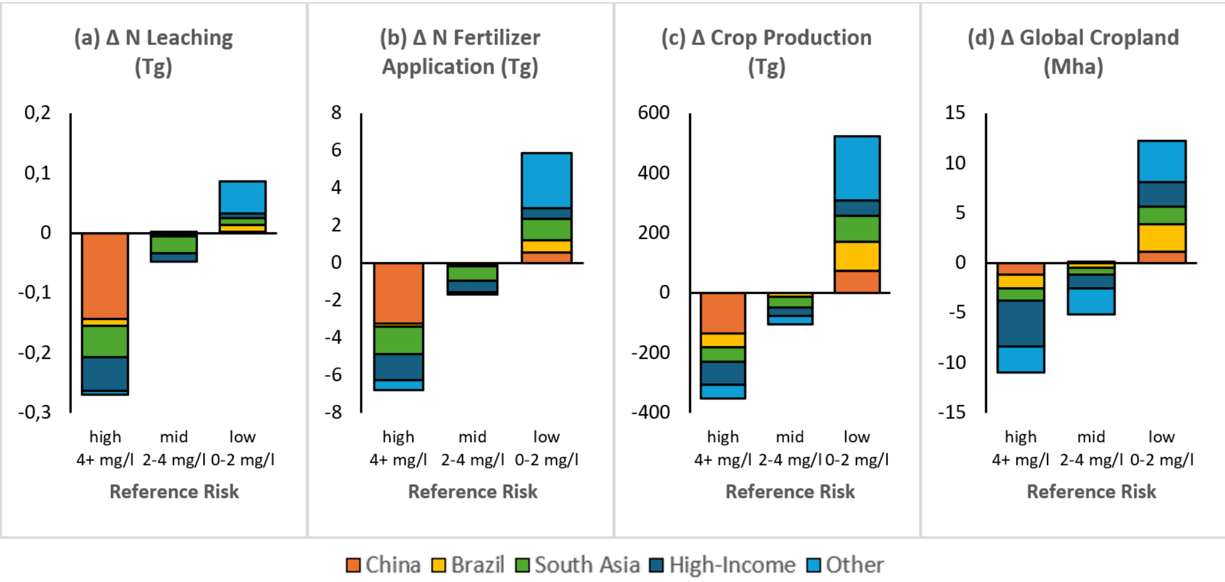

Figure 1. Effects of imposing an N tax in regions with N leaching rates over 5mg/l on total leaching losses (panel a), fertilizer application amounts (panel b), crop production (panel c) and cropland extent (panel d).

Conclusions

Crop models can be used in aggregate form to inform models of different structure and resolution. It is essential to combine bio-physical process understanding with economic rationale to capture the actual complexity of systems. The results challenge the conventional wisdom that additional taxes for environmental regulation necessarily lead to higher prices. However, they can be consistently explained by economic theory and plausible nitrogen (N) input response curves for yield and nitrogen pollution.

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Territorial food self-sufficiency under climate change through optimised crop rotations and STICS simulations

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Keywords

Food security; Optimisation; Land use; Soil crop modelling

Introduction

The globalisation of food systems has increased interdependence but also vulnerability to shocks such as wars, pandemics, and trade restrictions (Puma et al., 2015), a situation likely to worsen under climate change (Gregory et al., 2005). Ensuring regional food security requires agricultural systems that are both agronomically viable and resilient to climate change (Tilman et al., 2011). Wallonia (Belgium) was chosen as a case study to explore whether a highly industrialised region can achieve food self-sufficiency under future climatic conditions.

Materials and Methods

We developed a Mixed-Integer Linear Programming algorithm that designed crop rotations aligning local production with the nutritional needs of the population under the Eat-Lancet dietary scenario (Willett et al., 2019). The algorithm explicitly integrated pedo-climatic suitability, agronomic constraints (return times, exclusion rules), and regional land availability. These optimised rotations then served as input for the process-based STICS soil crop model (Brisson et al., 2003), which was run under IPCC climate scenarios corresponding to +2 °C, +3 °C, and +4 °C warming (mid- to late-21st century horizons) at high spatial resolution (50 m × 50 m soil data). STICS simulations were performed for major representative crops of each food group to quantify yield responses, water and nitrogen dynamics, and greenhouse gas emissions. The overall methodological framework is summarised in Fig. 1.

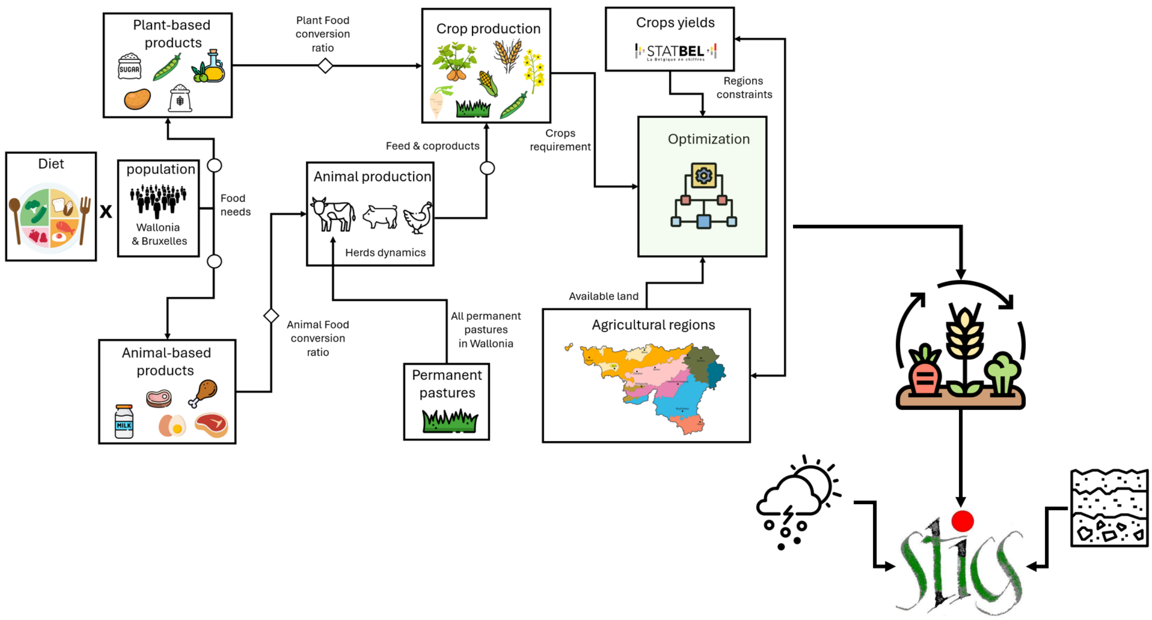

__Figure 1 : Schematic representation of the methodological framework__. Population dietary needs (Eat-Lancet scenario) were converted into crop and livestock requirements. Crop rotations were optimised under pedo-climatic and land-use constraints, then simulated with the STICS model to assess yields and environmental dynamics under climate change.

Results and Discussion

Preliminary optimisation showed that nutritionally balanced food self-sufficiency was theoretically possible with diversified four- to six-year rotations across Wallonia. STICS simulations revealed a heterogeneous climate impact: (i) cereals and oilseeds experienced gradual yield reductions under +2 °C, with more severe declines in shallow soils and under +3–4 °C; (ii) legumes displayed strong interannual variability due to drought stress, emerging as a limiting factor for robust rotations; (iii) sugar beet and maize benefited from longer growing seasons under warmer conditions, provided that water availability was not limiting. Territorial-scale outcomes suggested that food self-sufficiency remained achievable under +2 °C warming, but became increasingly fragile under higher scenarios, requiring adaptive strategies such as enhancing soil water retention, adjusting sowing dates, and broadening rotation diversity.

Conclusions

By coupling optimisation with a process-based crop model, this study goes beyond static feasibility analysis and provides dynamic insights into the resilience of food security strategies. The framework demonstrates that dietary transitions and optimised land use is necessary but insufficient without climate adaptation. Integrating rotation design with STICS projections allows policymakers and farmers to anticipate vulnerabilities, design resilient cropping systems, and sustain food security in a changing climate.

Acknowledgements

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Crop.MoniCast: A Global System for Crop Monitoring and Yield Forecasting

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Keywords: Yield forecasting; crop monitoring; early warning; global

Introduction

Ensuring stable crop production is a cornerstone of food security, yet agricultural systems remain highly vulnerable to weather extremes and climate change. For example, the 1993 rice production failure in Japan, caused by an unusually cool summer and reduced solar radiation, triggered a nationwide shortage with severe economic and social impacts. This event clearly demonstrated that timely early warning, early preparation, and early action are crucial for mitigating food crises.

To address these challenges, we have developed Crop.MoniCast, a global crop monitoring and forecasting system. Crop.MoniCast integrates long-range weather forecasting with process-based crop growth modeling, aiming to provide policymakers and farmers with actionable information several months in advance. By bridging the time gap between scientific information and practical decision-making, the system supports adaptation strategies to both inter-annual climate variability and long-term climate change.

Materials and Methods

The Crop.MoniCast system is built on two core components:

1. **CPS3**
   CPS3 is a state-of-the-art seasonal climate prediction system developed by the Japan Meteorological Research Institute (MRI). It is based on coupled atmosphere–ocean general circulation models and provides global forecasts of temperature and precipitation up to seven months in advance. The system has been widely evaluated and demonstrates high skill in reproducing large-scale climate variability, including El Niño–Southern Oscillation (ENSO) events. These forecasts form the climate input for Crop.MoniCast, enabling the translation of meteorological information into agricultural risk assessments.
2. **MATCRO**
   MATCRO is a process-based crop growth model developed at NIES (Masutomi et al., 2016a,b). It explicitly simulates the physiological processes of crops, including photosynthesis, stomatal conductance, respiration, biomass partitioning, and phenology. The model has been validated for major staple crops such as rice, soybeans, maize, and wheat. **Figure 1** shows the performance of rice yield simulation of MATCRO.

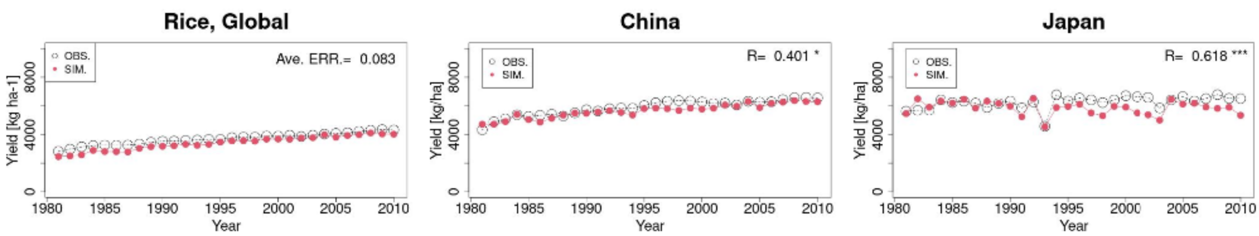

Figure 1. Yield comparison for rice between observations (FAOSTAT) and simulations with bias-corrected historical climate data

In addition to crop yield forecasting, Crop.MoniCast provides crop growth monitoring based on remote sensing data such as LAI and soil water content.

Results and Discussion

Figure 2. The user interface of Crop.MoniCast is shown (left: Yield Forecasting, right: Crop Monitoring). Four crops can be selected: rice, soybeans, maize, and wheat. The target region can be moved by dragging, and zooming in and out is also possible. In both panels, color differences indicate deviations from the climatological average.

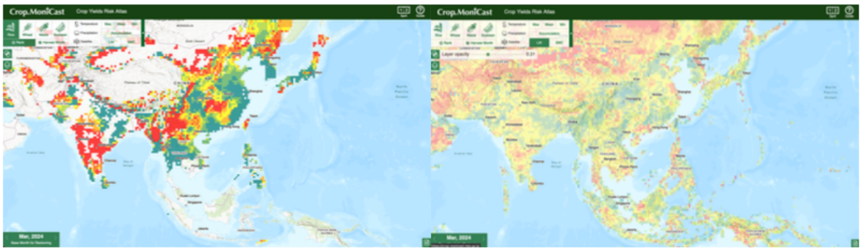

Figure 2. User interface of Crop.MoniCast (left: yield forecasting; right: crop Monitoring)

Figure 3. Forecasted rice yields in the Indochina Peninsula in 2017 (left, center, and right: forecasts issued in January, February, and March, respectively). A substantial yield reduction was predicted for the Mekong River Basin in Vietnam, where the harvest season occurs in March. In fact, a significant yield loss was observed in the Mekong River Basin of Vietnam in that year.

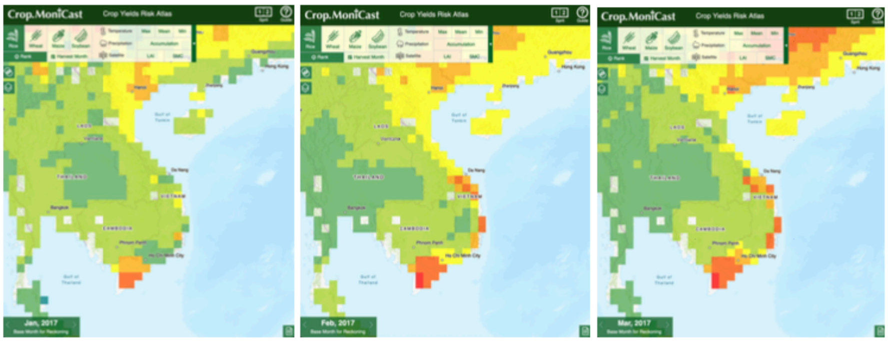

Figure 3. Forecasted rice yields in the Indochina Peninsula in 2017
(left: forecast issued in January; center: forecast issued in February; right: forecast issued in March)

Conclusions

Crop.MoniCast demonstrates strong forecasting skill for crop yields, offering a practical and science-based foundation for early warning systems. The global applicability of Crop.MoniCast makes it a promising tool for supporting food security, disaster risk reduction, and climate change adaptation worldwide.

Acknowledgements

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Capturing yield failure due to heat vs. drought in Germany

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Winter wheat, maize, heat stress, drought stress, yield

Introduction

Crop susceptibility to extreme events is becoming one of the main concerns of food stability of the future (Asseng et al., 2015; Baruth et al., 2022). Central Europe has seen large yield impacts over the past years stemming from the multiple weather extremes impacting agricultural production. 2018 saw one of the largest impacts, especially on grain cereals due to the precipitation deficit (Beillouin et al., 2020). Several studies have sought to disentangle the underlying causes of these yield reductions (Bogenreuther et al., 2025; Lüttger and Feike, 2018; Webber et al., 2020). In this work, we present a process-based model capable of accurately simulating both crop growth and yield outcomes, providing a comprehensive understanding of the key drivers behind interannual yield variability.

Materials and Methods

The model LandscapeDNDC was calibrated to accurately simulate crop yields in Germany in recent years, with a particular focus on the effect of extreme heat and drought. The yields of the two major crops - maize (*Zea maize*) and wheat (*Triticum aestivum*.) - were simulated at the district level by point sampling of 50 sites per district, thereby capturing the potentially diverse soil, climate and management conditions within districts. These were then compared to district level crop yield data, reported by Duden et al. (2024). Calibration was performed in a two step process. In the first step 5 districts were selected that showed no significant yield declines due to heat and drought stress, and crop parameters calibrated to reproduce reported yields. In the second step 5 different districts were selected that showed significant yield declines due to heat and drought stress, and the model parameters responsible for crop yield decline were calibrated. The model was validated by comparing simulated and reported yields across all 403 districts in Germany. To attribute yield declines to specific processes, drought stress, anthesis heat stress and generalised heat stress were selectively disabled in the model.

Results and Discussion

Our calibration results demonstrate strong agreement with reported district-level yields for winter wheat and maize, with standard errors below 0.2 t ha^{-1} and 0.3 t ha^{-1}, respectively, and average R^2 values of 0.3 (wheat) and 0.6 (maize). The model successfully reproduces both the magnitude and spatial patterns of yield variability, with comparable performance under stressed and non-stressed conditions. Moreover, the spatial distribution of simulated yields remains consistent across years and does not exhibit systematic regional biases.

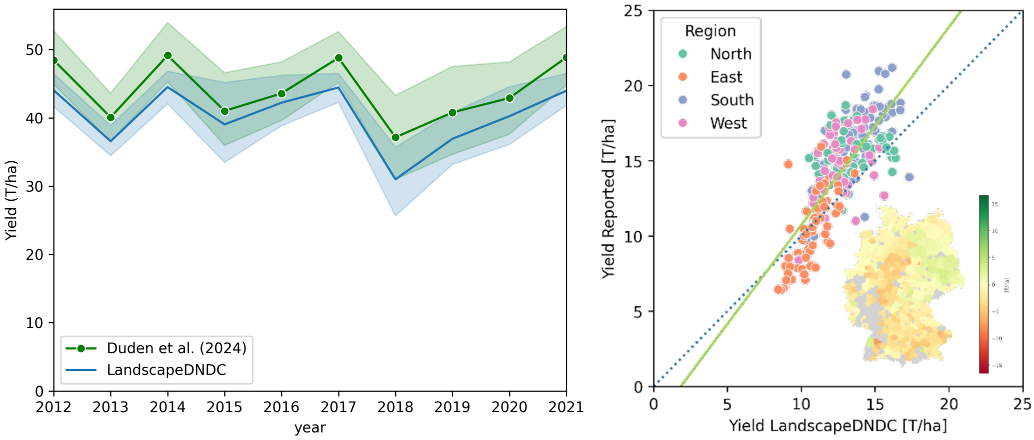

Figure 1: Comparison of reported (Duden et al 2024) and simulated (LandscapeDNDC) maize yields, averaged across Germany (left), and at the district level (right). Error bars show 0.95 percentile, the green line is a linear regression of all districts with a slope of 1.3 and an r-value of 0.75. The map shows the spatial pattern of yield differences.

Process attribution shows that drought was the main driver of yield losses in recent years, resulting in losses of up to 50% in some districts. At the German scale we show that drought decreased the yield by 27% in 2018. Heat stress played a much smaller role in decreasing yields, but may become more important in the future (Martin et al., 2025).

Conclusions

In recent years extreme heat and drought have significantly reduced German crop yields. The biogeochemical model LandscapeDNDC is now able to accurately simulate these losses and attribute them across multiple drivers. Our work provides a platform for studying how the likely increase in frequency and severity of weather extremes will affect crop yields in years to come, and how these yield losses will affect the biogeochemical cycling of carbon, nitrogen and water in German croplands.

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