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SESSION 3 – SUSTAINABILITY, ECOSYSTEM SERVICES, AND BIODIVERSITY

Sustainability, Ecosystem Services and Biodiversity

Modelling relay cropping in Germany

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Keywords: Agro-diversification; Drought; Irrigation; Climate change; Protein production

Introduction

Given that climate change poses threats to agriculture and food security, agro-diversification has been proposed as one of the adaptation and mitigation strategies to fulfill both food and sustainable needs (FAO, 2022; Mihrete & Mihretu, 2025). Relay cropping (RC), namely two crops growing in the same field with a partial overlapping growing period, is one of the agro-diversification approaches representing high temporal-spatial heterogeneity that benefits resource use efficiency and thus crop production (Lamichhane et al., 2023). The complexity resulting from the heterogeneous nature of RC leads to knowledge-intensive management, hindering its adoption. Crop models are promising tools for projecting crop growth under various environmental and management scenarios, but modelling for diversified cropping systems is not as common as that for sole crops (Hernández-Ochoa et al., 2022). To advance understanding of potential adaptation and mitigation strategies, a model is needed to capture the essential process of RC. Such a model would enable the evaluation of management scenarios and assessment of their potential under future climate conditions.

Materials and Methods

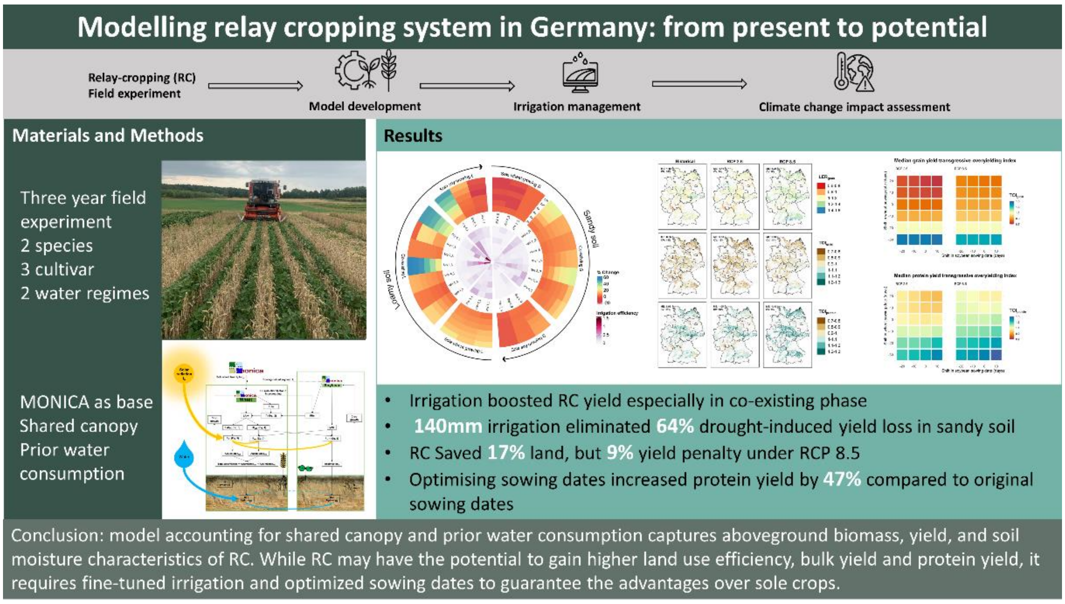
A three-year field experiment was conducted from 2021-2024 in Müncheberg, Germany, with winter wheat-soybean RC as the representative. Experiment includes three cropping systems (sole winter wheat, sole soybean and the RC), two water regimes (irrigated and rainfed), and two winter wheat cultivars (*Moschus* and *RGT Reform*). Leveraging the experiment data and the low calibration requirements of the agroecosystem model MONICA (Nendel et al., 2011), a simple routine was developed to simulate light competition in the RC system by assuming a shared canopy between two crops, while water competition was modeled by giving priority to the first crop. After calibration and validation on LAI, aboveground biomass, yield, and soil moisture, the model was also used to guide irrigation management in loamy and sandy soil based on the crop development stages in RC. A single application up to 140mm, and seven applications with dosage of 20mm applied to 7 critical stages were tested in two soil types for comparison in land use efficiency and irrigation efficiency. To understand RC's potential in yield and protein production under future climate, RC across whole Germany under low- (RCP 2.6) and high-emission (RCP 8.5) scenarios was simulated. As climate change may alter the suitable sowing window, we further simulated the RC with shifts in sowing date in both crops, comparing the land use efficiency, yield, and protein yield.

Results and Discussion

Irrigation during the co-existence of two crops significantly boosted the relayed-crop soybean and thus total yield production. 20 mm of irrigation in the soybean first pod stage increased the yield by 47% compared to rainfed. Soil texture influenced the optimal irrigation volume and timing at each growth stage. Loamy soil required high irrigation volume and generally achieved higher land use efficiency. Sandy soil benefits more from low-volume high-frequency irrigation, eliminating 64% drought-induced yield loss, compared to 48% in loamy soil. These findings stress the importance of a tailored irrigation strategy for RC on different soil textures. Follow-up large-scale simulations showed 9% yield penalty in RC at the current management level. However, when significant warming and climate change impacts are assumed in the future, RC produced 16% more protein with 17% land saving than sole cropping. When shifting the sowing dates for component crops, RC achieved up to 44% higher total yield production and 47% higher protein production compared to without shifting sowing dates under future climate scenarios.

Conclusions

Crop models that incorporate shared canopy and prioritised water consumption can capture the key characteristic of RC. But for designing a more diversified cropping system, crop models need to better represent phenotypes shaped by the environment and management conditions, and improve estimation accuracy across larger geographic area. Management of RC should be fine-tuned and site-specific. Agronomic practices like irrigation and shifting sowing dates should favour the relayed crop component to ensure the overall yield of the RC system. Winter wheat-soybean RC outperforms sole cropping in protein production and land use efficiency, compensating for stresses from climate change. More diversified cropping systems should be considered to support sustainable global food production under a changing climate.



Modelling relay cropping system in Germany: from present to potential

Materials and Methods

Three year field experiment
2 species
3 cultivar
2 water regimes

MONICA as base
Shared canopy
Prior water consumption

Results

- Irrigation boosted RC yield especially in co-existing phase
- 140mm irrigation eliminated 64% drought-induced yield loss in sandy soil
- RC Saved 17% land, but 9% yield penalty under RCP 8.5
- Optimising sowing dates increased protein yield by 47% compared to original sowing dates

Conclusion: model accounting for shared canopy and prior water consumption captures aboveground biomass, yield, and soil moisture characteristics of RC. While RC may have the potential to gain higher land use efficiency, bulk yield and protein yield, it requires fine-tuned irrigation and optimized sowing dates to guarantee the advantages over sole crops.

Figure 1. Graphical abstract of modelling relay cropping system in Germany

Acknowledgements

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Crop Modelling for Agriculture
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Simulating competition, facilitation, and yield dynamics in cereal-legume intercrops – The SSM-InterCrop model

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Keywords: cereal-legume intercrops, modelling, parameterization, grain yield

Introduction

Intercropping is gaining increasing interest in Europe due to mounting environmental and sustainability concerns in monoculture farming. The benefits of intercropping can be attributed to a more complete acquisition of resources (complementarity), and from beneficial neighbour interactions (facilitation). The productivity performance of intercropping systems is contingent on genotypic variation in genetic traits among the intercropped species and cultivars (G), environmental conditions (E), and management practices (M). The inherent complexity of these GxExM interactions poses a considerable challenge to the design of site-specific intercropping systems that optimise complementarity and facilitation, while minimising competition for resources. The objective of this study was to develop a mechanistic model for simulating competition, facilitation, and yield dynamics in cereal-legume intercrops, with a view to supporting decision-making for design and management of intercropping systems.

Materials and Methods

The SSM-InterCrop model was implemented in the existing SSM-iCrop modelling framework for monocultures (Soltani and Sinclair, 2012; Manschadi et al., 2022; Palka and Manschadi, 2024). The model accounts for competition and facilitation processes occurring between the intercrop species for above-ground (light) and below-ground resources (water and nitrogen(N)). The light interception submodel simulates the fraction of light intercepted by each intercrop, taking into account the planting configuration, plant height, leaf area index, and the light extinction coefficient. The model categorises the two intercrop species as tall and short daily and calculates the fraction of intercepted radiation for each crop. This is then used to calculate the potential daily dry matter production and the associated transpiration demand for each crop. Competition for water is simulated based on the rooting depth of the crops. For this purpose, the soil water content in each layer is multiplied by the ratio of the root depth of each crop to the total root depth of both crops within the layer. This factor allocates water between the two crops based on their rooting depth and transpiration demand. At the end of each simulation day, the total remaining water in each soil layer is calculated and then equally distributed to each intercrop species. This results in a daily horizontal movement of water from the crop species with the lower water uptake to the one with the higher water uptake. The same root depth ratio factors are used to allocate plant-available soil N in each layer to the intercrop species. However, while soil water is permitted to redistribute horizontally, soil N and the resulting quantity of soluble N in the soil solution are calculated separately for each crop species. This approach enables a crop-specific N balance to be calculated, whereby the intercrop species are fertilised differently. The SSM-InterCrop model simulates the N_2 fixation by the legume species and accounts for the facilitation of N transfer from legumes to cereals by specifying a user-defined N transfer factor. This factor can range from 0 to 100% of the daily amount of biologically fixed N by the legume crop.

The SSM-InterCrop model was parameterized and tested for intercrops of winter wheat-faba bean (WW-FB) and spring barley-field pea (SB-FP) using a dataset from two locations in Germany (Hof-Kautz, 2008) and another dataset including 37 field experiments carried out in 5 European countries (France, Denmark, Italy, Germany, England) (EU-dataset; Gaudio et al., 2023).

Results and Discussion

The experimental datasets exhibited substantial variation in sowing date, planting density, N fertilisation, irrigation, and weather conditions. Consequently, the observed grain yields in sole crops of WW-FB and SB-FP ranged from 198.6 to 695.0 and 137.5 to 620.0 g m^{-2}, respectively. The datasets provided periodic measurements of crop phenology, biomass, LAI, and N uptake, but not all variables were measured in every experiment. Furthermore, in some experiments, initial mineral soil N (Nmin) was not reported. No measurements of soil water content were recorded. For setting up the InterCrop model, these deficiencies were partly overcome by using the observed grain yield and N content from the N0 (no N fertilization) treatments to estimate the initial soil Nmin and water content. For most treatments, SSM-InterCrop simulated well the observed dynamics in crop phenology (BBCH), LAI, and plant height (data not shown). For the sole crops, the model was able to capture the observed variation in grain yields very well (Figure 1a and 1c). For WW-FB, the model achieved an R^2 of 0.76 and an RMSE of 55.76 g m^{-2}. The corresponding values for the SB-FP were 0.79 and 69.89 g m^{-2}, respectively. The model also performed well in simulating grain yield quantity (Figure 1b and 1d) and protein content (data not shown) in intercrops.

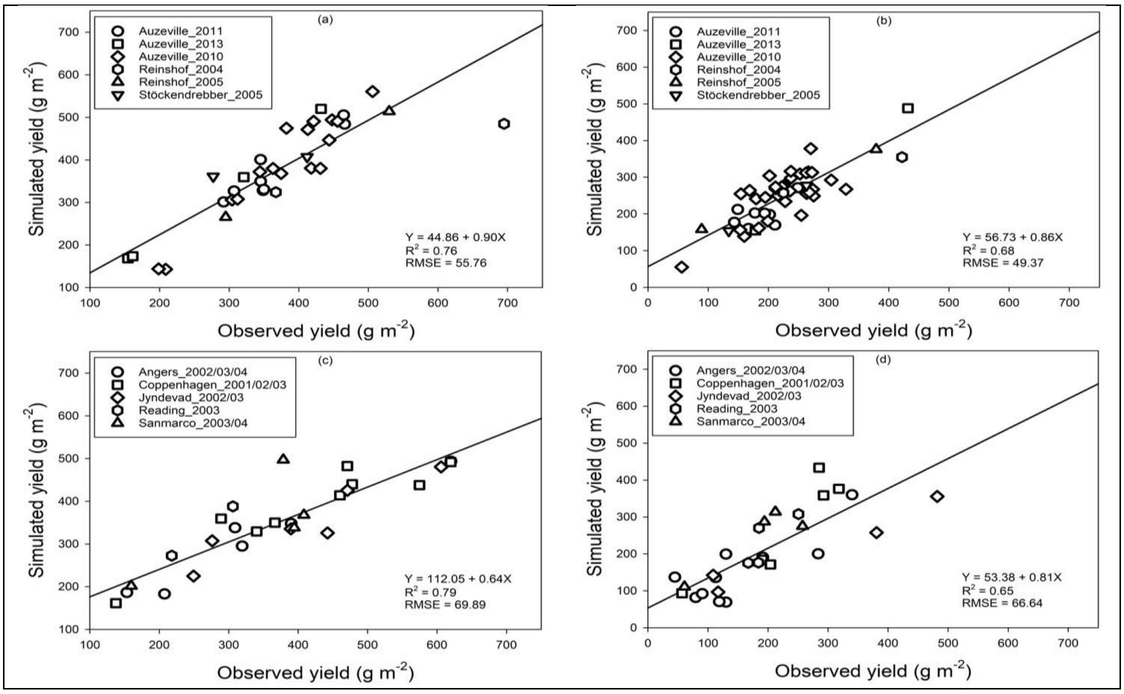

Figure 1. Observed versus simulated grain yields of sole crops (a, c) and intercrops (b, d) of winter wheat-faba bean (WW-FB; a, b) and spring barley-field pea (SB-FP; c, d); legends indicate the location name and year(s) of the field experiments.

Conclusions

SSM-InterCrop has been demonstrated to be a robust mechanistic model for simulating competition, facilitation, and yield dynamics in intercropping systems. The experimental datasets were found to be of considerable value for the modelling study, although they include only the mean values for each treatment and the details of management practices are not always provided. Following further evaluation using other datasets and methods, such as sensitivity analysis, the model would be a suitable component in a web-based platform for supporting decision-making in intercropping systems.

Acknowledgements

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DSSAT modelling of cover crop residues and tillage effects on N dynamics and maize productivity in Mediterranean climate

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Keywords: CERES-Maize, Century, crop growth, N mineralization

Introduction

The Decision Support System for Agrotechnology Transfer (DSSAT) is a group of simulation models with the capability to simulate the effect of tillage and surface crop residues on soil water content and organic matter turnover. Although simulating the effects of crop residue management on decomposition and nitrogen release is complex, process-based models can support the development of cropping systems with improved synchronization between nitrogen release and plant demand (Hasegawa et al., 2000). This study focuses on evaluating the response of the CERES-Maize model in terms of yield, biomass, grain nitrogen, and total nitrogen uptake in irrigated maize, following different cover crop (CC) residue treatments under conventional tillage (CT) and direct seeding (DS) using the Century module. The main objective is to accurately simulate soil nitrogen (N) mineralization dynamics and identify the phase during which most nitrogen from the cover crop residues is mineralized and becomes available to maize. Preliminary results after model calibration are presented.

Materials and Methods

This study was conducted in the Ebro River valley in Northeast of Spain, at the research station of CITA (Centro de Investigación y Tecnología Agroalimentaria de Aragón) in Zaragoza, on a 2 ha sprinkler-irrigated field. Data were collected during the 2024 maize growing season from 18 plots (each 45×6 m). The experiment included two soil management (DS and CT), three different cover crop treatments (common vetch, mixture of common vetch and oats, and a control without cover crop) and three replicates for each treatment. Before maize seeding, all the CC residues were left on the soil surface in the DS plots, while in the CT plots the CC residues were incorporated into the soil. Fertilization consisted of 50-100-120 kg of N-P$_2$O$_5$-K$_2$O before sowing and a side dress application of 100 kg N ha^{-1} just before the tasseling stage (V14 stage). The DSSAT v4.8.5 (Hoogenboom et al., 2024) model was calibrated to simulate grain yield, biomass, grain N, total plant N uptake, and soil inorganic N and water content. The calibration process was performed manually, and the soil fertility factor and CTCNP2 was also adjusted in order to minimize the RMSE (Malik et al., 2019, Liu et al., 2012). The CENTURY module within DSSAT was used to simulate nitrogen mineralization dynamics from the cover crop residues after first calibrating the fraction of stable carbon with data from winter fallow plots. The ongoing data from 2025 experiment will be used for model validation.

Results and Discussion

The RMSE after calibration was 541 kg ha^{-1} and 1841 kg ha^{-1} for grain yield and total biomass, respectively. These values can be considered good and are within the same range as those reported in other published studies performed under the same soil and climatic conditions (Malik et al., 2019; Salmeron et al., 2014). However, the model underestimated the grain yield by 3.3% (Fig. 1a), and overestimated total biomass by 7.5%, and total nitrogen content by 15.5% and 1.4% in grain and plant, respectively (Fig. 1b).

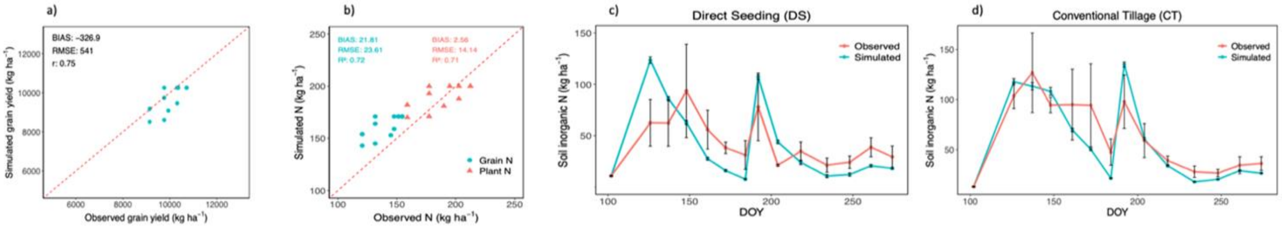

Figure 1. Relationship between simulated and observed values of (a) grain yield (kg ha^{-1}), (b) grain N and plant N content and soil inorganic nitrogen content within the 0–30 cm soil layer of vetch and oats treatment under (c) no tillage and (d) conventional tillage.

The best model performance for simulation of soil N mineralization and the resulting soil inorganic N were achieved under CC with a mixture of common vetch and oats, with RMSE of 25.7 and 19.8 kg soil inorganic N ha^{-1} within the 0–30 cm soil layer under DS and CT, respectively (Table 1). In general, results indicated more precise predictions under CT compared to DS, possibly due to residue incorporation and faster early-season residue decomposition (Fig. 1cd).

Table 1. Bias, RMSE and r resulted from model calibration of soil inorganic N (kg N ha^{-1}) and volumetric water content (cm^3 cm^{-3}) within the 0–30 cm soil layer.

Treatments	**Soil inorganic N**			**Volumetric water content**		
	Bias	RMSE (kg N ha^{-1})	r	Bias	RMSE (cm^3 cm^{-3})	r
DS control	-1.99	27.62	0.73	-0.02	0.03	0.84
CT control	-14.05	42.09	0.67	-0.04	0.05	0.81
DS common vetch	-16.19	26.47	0.88	-0.02	0.03	0.85
CT common vetch	-0.39	23.69	0.87	-0.02	0.03	0.83
DS common vetch and oats	-2.25	25.69	0.74	-0.02	0.04	0.80
CT common vetch and oats	-5.63	19.79	0.89	-0.03	0.05	0.76

In all treatments, both soil inorganic and water content within the 0–30 cm soil layer presented a negative BIAS, indicating that the model slightly underestimated the actual values of both variables (Table 1). Simulation of nitrogen dynamics was the most accurate in the treatments under CT, while simulation of volumetric water content was more accurate under DS management.

Conclusions

After the calibration of genetic and soil parameters, and soil stable carbon, acceptable model performance simulating the effect of cover crop residues and tillage on N dynamics and maize productivity were obtained when compared to other studies. Yet, additional research is required to better simulate nitrogen dynamics under no-till management.

Acknowledgements

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The drivers of water use efficiency in aerobic rice under tropical south Indian conditions

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Climate change and increased population demands are increasing pressure on freshwater resources. Rice is the most cultivated crop worldwide, and also consumes the most water. In southern Indian systems, it is still grown in paddy conditions, but this is unsustainable due to rising population demand for freshwater and the erratic changes in weather due to climate change. Hence, growing rice under drier conditions is imperative. To do that, we need to understand what enables rice to grow under lower soil moisture, what drives rice water use and how can we increase its water use efficiency. And most importantly whether we can maintain high yields without high water use? To answer these questions, we used data from phenotyping trials of 225 rice genotypes in Bangalore, India to build a narrative of what the best performing rice under well-watered conditions are like, and what traits underpin rice water use. We found that rice genotypes that display produce many tillers and leaves, but with lower leaf width and thickness, tend to have higher transpiration rates and yield (Fig. 1a). We hypothesize that this is due to improved light interception across the canopy and equitable nitrogen distribution (Fig. 1b). To test these theories under tropical south Indian conditions, we used the crop model GECROS to simulate the response of rice varieties to environmental change across the past 35 years in 4 key sites (Bangalore, Mandya, Aduthurai and Chandrapur). We are also conducting a GWAS to find significant QTLs that drive differences in water use and underlying traits, and formulate QTL-based model parameters to infer the effect of genetic variation on water and yield. Initial results suggest an important contribution of reduced leaf width and longer crop duration as key indicators of improve yield and water use efficiency in the different sites (Fig. 1c), with these traits showing significant correlations specifically at Aduthurai and Mandya, likely due to higher radiation availability. These simulations are currently being run under water deficit and the results are under analysis.

Compared to taller, less bushy genotypes, the shorter, bushy plants have :

- More tillers,
- High LAI,
- Many Panicles,
- High Yield,
- More EvapoTranspiration,
- More canopy photosynthesis....
- but more equitable leaf nitrogen distribution and higher SLA? (Fig. b)

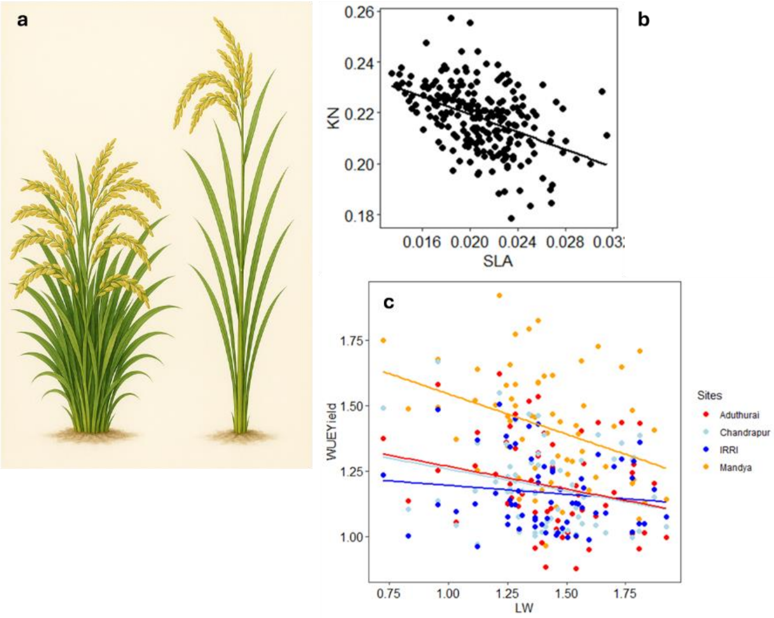

Fig 1. Preliminary results showing the two identified phenotypes (a), the response of nitrogen extinction coefficient (KN) to changes in specific leaf area (SLA, m2 g-1) in the GECROS model (b), and the response of yield water use efficiency (g m-2 ml-1) grain yield divided by cumulative water transpired) in the different simulated sites in response to leaf width (LW, cm).

From Long-Term Experiments to Models: Evaluating Set-Aside as a Strategy to Reduce N Leaching in Intensive Cropping Systems

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Keywords: Winter Wheat, APSIM modelling, Grass, Biodiversity,

Introduction

Set-aside land, agricultural land withdrawn from production, is increasingly promoted in Europe and supported through the EU Common Agricultural Policy (CAP), the EU Biodiversity Strategy for 2030 and the Nitrates Directive. Set-aside practices include fallowing, afforestation, and wetland restoration, with the aim to restore soil health, enhance habitat diversity, reduce nitrogen (N) losses, and increase carbon sequestration.

However, there is a lack of understanding on potential benefits and long-term effects of set-aside land and how it should be managed. Here we explore different types of set-aside crops following continuous winter wheat production systems, and how this effect nitrate (NO_3) leaching. To broaden the scope and implications beyond the experimental evidence, we employed the APSIM model to simulate management scenarios and long-term outcomes under varying conditions.

Materials and Methods

Field experiments with different set-aside land were set up in autumn 2021 in Flakkebjerg, Denmark after 7 years of winter wheat cropping with different N fertilisation rates (Vogeler et al., 2021). Set-aside included (T1) pure grass, (T2) grass/legumes, (T3) weeds and volunteers, (T4) flowers, and (T5) flowers and crucifers. Treatments 1 to 3 were established after harvest of winter wheat in autumn 2021, and these were cut once a year. Treatments 5 and 6 were established in spring 2022 and not cut. The set aside was monitored over a period of three years, via collection of dry matter (DM) production, DM-N and NO_3 leaching via suction cups. The Agricultural Production Systems sIMulator (APSIM) was first calibrated using the experimental data and then used to simulate various set-aside practices under different pedo-climatic conditions and evaluate their effectiveness in reducing N leaching by including set-aside land in intensive cropping systems. Simulations were so far only done for grass and grass/clover set aside.

Results and Discussion

Average grain yield over the 7 years of the continuous winter wheat cultivation increased with increasing levels of N fertilisation rate, with an economic optimum at a rate of 185 kg N/ha. NO_3 leaching increased exponentially with increasing N fertilisation rate and was on average 58 kg N/ha at the economic optimum N rate. This is above the critical N concentration of 34 kg N/ha with an annual drainage of 300 mm and highlights that mitigation measures are needed to adhere to European regulations.

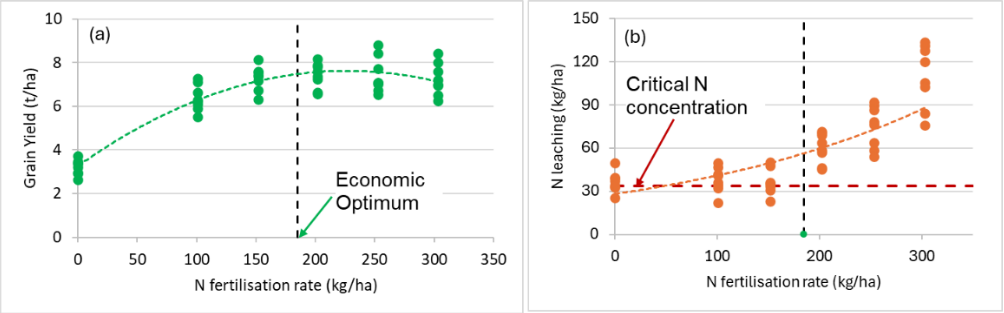

Figure 1. Average (a) grain yield and (b) N leaching from 7 year continuous winter wheat cultivation at different N fertilisaiton rates.

In the first drainage period (2021/2022) NO_3 leaching was significantly lower under the volunteer treatments compared with the grass set-aside. This is due to the slow establishment of the grass after sowing at the end of August. In the following two years, only the pure grass treatment had consistently lower N leaching compared to the other set-aside treatments. The spring barley with catch crop had low leaching similar to pure grass in only one of the years. The grass/legume mixture, volunteers and flower treatments had generally high leaching. After the establishment year, the mean N leaching over the following two years followed the order of: grass < spring barley/catch crop < volunteers (cut) < grass clover < flowers < flowers with crucifers. The poor performance of the flower treatments was due to die off over the winter with likely subsequent residue mineralisation, which increased N leaching. Weeds and volunteers showed very different N leaching levels across the years due to un-controlled seed banks and species pools.

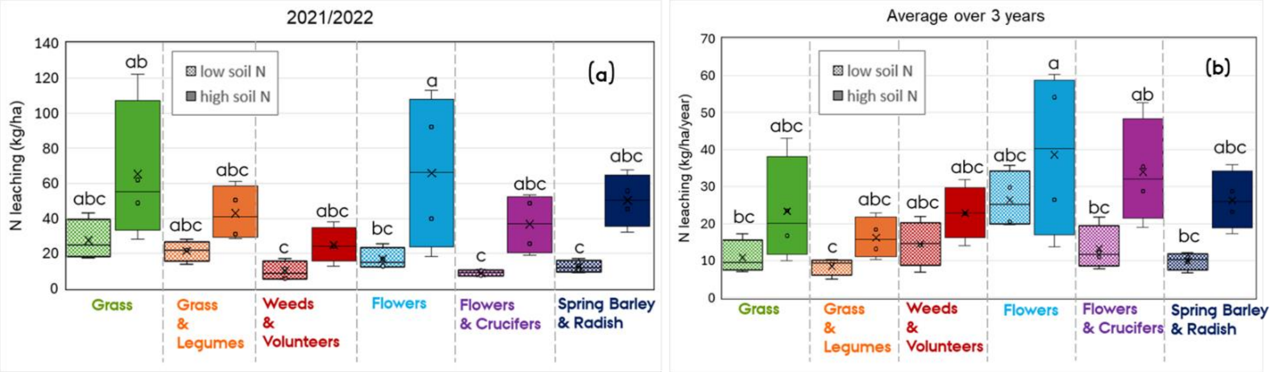

Figure 2. N leaching under set-aside land, with (a) showing leaching in the first year, and b) average over three years after establishment

APSIM simulations well prediced the grain yield of winter wheat over the 6 years and 6 different N fertilisaiton rates. N leaching under the winter wheat was, however underpredicted, which could be due to carry over effects (Vogeler et al., 2020) or mineralisation of degradable organic matter that has previosuly been build up in the soil (Zhao et al., 2022). The APSIM simulated biomass production of the grass set-aside agreed well with the measurements, and while there was a good correlation between the measured and predicted N leaching under the grass set-aside, the simulaitons underpredicted N leaching in all three years. This is likely due ot the overestimation in the N uptake of the set aside grass. Improvements in model parameters to overcome these shortcomings are underway.

Conclusions

The use of set-aside land is a promising way for reducing N leaching from intensive agricultural systems. However economic and social aspects also need to be considered, and further studies are required to design sustainable systems, including assessments of long-term productivity, biodiversity benefits, and policy incentives to ensure farmer adoption."

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Crop Modelling for Agriculture
and Food Security under Global Change

Disease regulation in intercropping systems depends on spatial arrangement – a modelling study

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Keywords: crop diversification, field design, pathogens, STICS soil-crop model

Introduction

Cultural diversification is considered an effective method to increase the resilience of agrosystems in the face of climate change and to reduce reliance on artificial inputs (Deguine et al., 2023; Vialatte et al., 2021). In particular, there is growing interest in understanding how diversified cultures can help in reducing pesticide use. In the case of intercropping, specific mechanisms have been identified which impact disease development: dilution and barrier effects as well as changes in canopy microclimate, but they are hardly characterised (Boudreau, 2013).

Materials and Methods crops

We used a process-based, mechanistic modelling approach (Caubel et al., 2012; Vezy et al., 2023) to study a wheat/pea intercrop with a brown rust epidemic using averages over 30 reference years, to quantify the effect of regulation mechanisms and their sensitivity to changes in spatial arrangement (plant density, row spacing and species proportion).

Disease intensity, quantified by the AUDPC (Area Under the Disease Progression Curve), was compared in the wheat sole crop (SC) versus the wheat/pea Intercrop (IC). It highlighted the weight of the dilution, barrier and microclimate mechanisms and as well as the disease processes (spore interception, infection) at play during the crop cycle.

Results and Discussion

The impact of IC on disease intensity is significant but nuanced according to spatial arrangements, i.e. combinations of row spacings, sowing densities and species proportions.

Overall, fewer spores were intercepted throughout the crop cycle in IC compared to SC, leading to a reduction in disease intensity, with the main benefit coming from the barrier effect. This is most notable in the delayed start of the epidemic (Figure 1.A). IC could therefore protect photosynthetic capacity of wheat for longer during the crop cycle, hence facilitating grain filling.

Even though the IC system created microclimates more conducive to pathogen proliferation, particularly in the later stages of the crop cycle; the beneficial effects of the early disruption in spore interception remained stronger. Spatial arrangement variables—such as plant density, row spacing, and species proportion— either mitigated or exacerbated these mechanisms (Figure 1.B). In particular, increasing the distance between rows was the most influential agronomic lever. This underscores the potential of mobilising these agronomic levers, which can be adjusted to enhance disease control in intercrop systems. In this context, modelling makes it possible to assess and sort many different possible scenarios offered by diversification in the field.

Conclusions

The *in silico* experiment detailed in this paper demonstrated that our model allows the quantification the primary mechanisms and processes involved in disease regulation in intercrops, along with their dynamics.

Combining the dynamics of the pathogen, host plant and non-host plant from a mechanistic perspective highlights phenomena which other modelling approaches cannot describe. For example, competition mechanisms between the two crop species reduce the surface available for infection, disrupt the interception of spores and consequently delay the start of the epidemics. This facilitates the barrier effect translating into an AUDCP generally lower in IC compared to SC. Additionally, it emphasised which species arrangement in the mix promotes disease regulation.

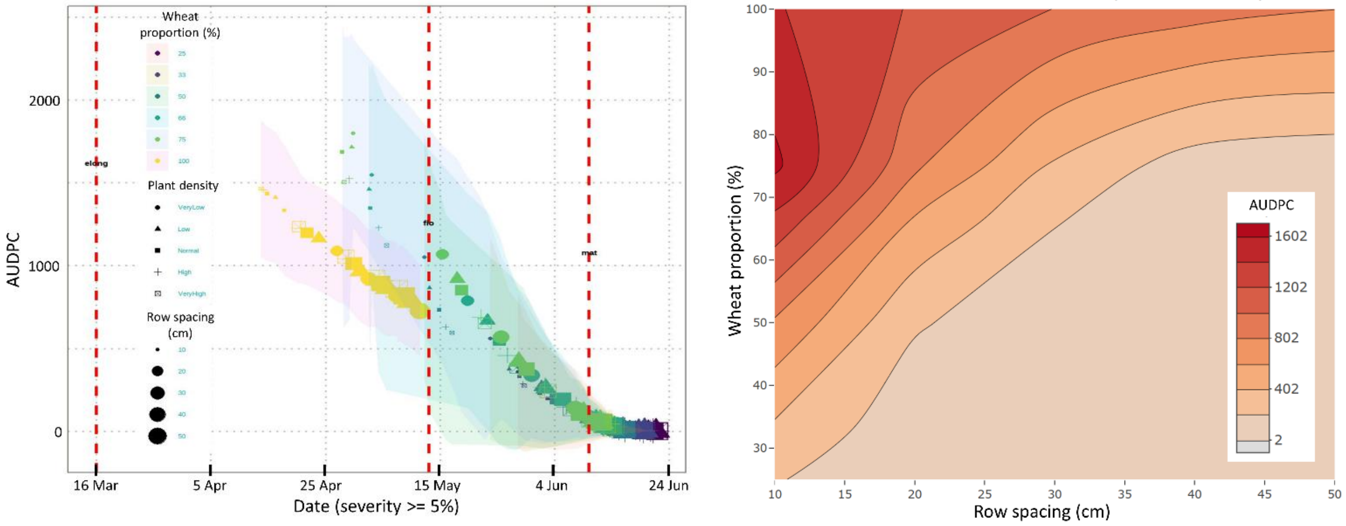

Figure 1. A) Disease intensity (AUDPC value reached at maturity) as a function of disease precocity (date when the severity reaches 5%, considered the start of the epidemics). The colours represent wheat proportion in the species mix, shapes the level of total plant density and size of the shapes the distance between rows. The ribbons represent standard deviations for each level of species proportion. B) contour graph of mean AUDPC at physiological maturity over 30 years averaged for plant densities. The x axis represents distance between rows and the y axis represents proportion of wheat in the mix.

Acknowledgements

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Developing 2-D and 3-D variants of the Cycles agroecosystem model for farm practice optimization and landscape design

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Keywords: spatially distributed modeling, agroecosystem modeling, Cycles agroecosystem model

Introduction

Agroecosystem models have become knowledge repositories and essential tools for understanding soil physics, biogeochemistry, and crop ecophysiology. They form the backbone of planning and decision-support systems in agriculture, helping to optimize farm practices across multiple spatial scales.

Traditional one-dimensional (1-D) agroecosystem models cannot capture highly nonlinear processes controlled by spatial heterogeneity within subareas because of their 1-D structure and lack of lateral water and nutrient transport between grids. In contrast, spatially distributed three-dimensional (3-D) agroecosystem models are valuable for landscape design and precision agriculture at watershed scales, as they can simulate processes influenced by topography, soil heterogeneity, and management practices. However, their application at larger scales is limited by challenges in collecting spatial data and by high computational costs.

Two-dimensional (2-D) agroecosystem models provide a middle ground between 1-D and 3-D approaches. They balance spatial detail relevant for crop management (e.g., banding of fertilizer) with manageable computational complexity. These models can efficiently represent spatial heterogeneity along long field slopes, support finer spatial resolutions for subsurface hydrology and transport, and incorporate more complex agroecosystem processes than 3-D models, all while maintaining computational efficiency.

Materials and Methods

We present a 3-D variant of the Cycles agroecosystem model (Cycles-L, L for landscape; Shi et al., 2023) and a 2-D variant (Cycles-S, S for slope), designed for *in silico* testing of farm practices that account for spatial heterogeneity due to topography, soil, and management. Cycles-L couples Flux-PIHM (Shi et al., 2013), a 3-D land surface hydrologic model, with the agroecosystem processes of the 1-D Cycles model. Cycles-S adds a two-dimensional soil discretization with variably saturated subsurface hydrology to the 1-D Cycles model. Both variants simulate solute transport with water, with each subsurface grid cell two-way coupled to a 1-D Cycles model. Each vertical grid can be assigned distinct surface elevation, soil type, and management practice. Hydrology as well as solute and gas transport are solved using the CVODE ordinary differential equation solver (Hindmarsh et al., 2005). Together, the 1-D, 2-D, and 3-D versions of Cycles provide a flexible suite of models capable of handling simulations across locations and spatial scales.

Results and Discussion

We demonstrate Cycles-L using a 730-ha experimental watershed in Pennsylvania, USA. The model performs well in simulating streamflow and mineral nitrogen discharge (NSE 0.55 and 0.60, respectively) and grain yield (RMSE 1.2 Mg ha^{-1}). It also predicts spatial patterns of nitrogen fluxes, illustrating the combined influence of crop management and topography (*Figure 1*). A test case with the 2-D variant will also be presented, highlighting its capability of simulating topographic effects on hydrology and agroecosystem processes.

Conclusions

As among the first next-generation spatially distributed agroecosystem models, Cycles-S and Cycles-L enable explicit representation of hillslope- and landscape-scale processes. Their design positions them to support applications in climate change analysis, precision agriculture, precision conservation, and AI-driven decision making.

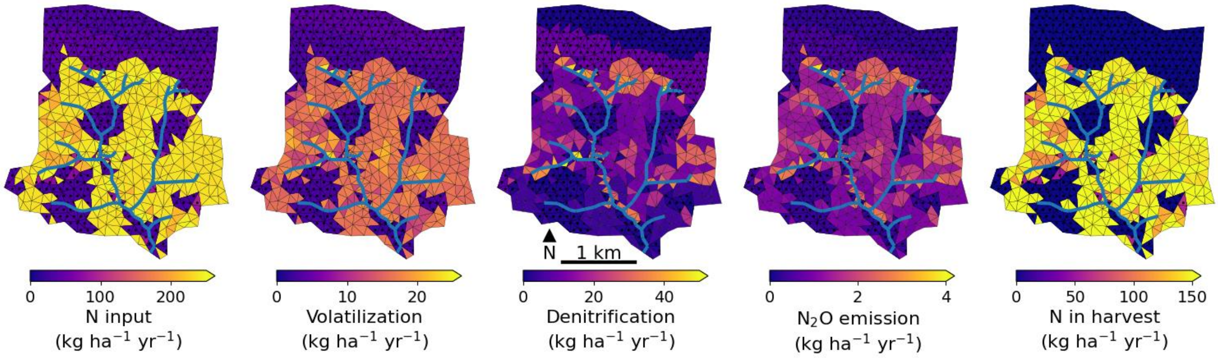

Figure 1. Spatial patterns of nitrogen fluxes estimated by Cycles-L at the 730-ha WE-38 experimental watershed.

Acknowledgements

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Crop Modelling for Agriculture
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Multi-model predictive analysis of apple scab for apple tree pest management

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Keywords: Predictive models, DEXi, Sensitivity analysis, Orchard, Integrated Pest Management

Introduction

Apple scab caused by *Venturia inaequalis* leads to yield losses through quality defects. Its development is influenced by complex interactions between weather, orchard design and practices. Developing pesticide-free control strategies requires predictive modeling tools that can integrate and assess the effects of multiple levers under varying environmental conditions. Among these tools, IPSIM (Injury Profile SIMulator), based on the DEX (Decision EXpert) method (Bohanec & Zupan, 2002), is a generic, qualitative and hierarchical model simulating crop injuries from weather, cropping and environmental factors (Aubertot & Robin, 2013). An apple scab-specific version has already been developed in the context of southern France (Memah et al., 2025), providing a framework to explore interactions between agroecological levers. This study aims to enhance the predictive capability of the apple scab version of IPSIM in northern contexts and to improve our understanding of how agroecological practices influence disease risk.

Materials and Methods

Model predictions were first compared with data from northern orchards (n = 52). Sensitivity analyses were then conducted on the apple scab IPSIM model to identify the key factors, with Shapley-Shapiro indices. These indices quantify each variable's contribution for all possible interactions, providing a detailed view of model sensitivity. Logistic regression (LR) and Classification and Regression Trees (CART) approaches were also applied to real orchard data and IPSIM outputs. LR provided a probabilistic framework for assessing relationships between explanatory variables and disease risk, while CART produced explicit decision rules highlighting variable hierarchies and interactions. Variable importance was compared across approaches: LR and CART on orchard data, LR and CART on IPSIM outputs, and Shapley-Shapiro indices from sensitivity analysis.

Results and Discussion

Sensitivity analyses of the IPSIM model identified cultivar resistance and preventive fungicide use as the most influential factors for disease prediction, reflected by high Shapley-Shapiro indices. Machine learning analysis of IPSIM outputs revealed that the model underestimates the effects of some agronomic levers, such as inoculum management and hedgerows. Logistic regression applied to the orchard data highlighted the strong influence of weather-related variable on disease risk. CART analysis enabled the identification of decision rules combining weather conditions with management practices, including fungicide application, landscape features and inoculum management. Based on these findings, IPSIM decision rules were refined by down-weighting weakly informative criteria and enhancing those with stronger predictive influence. Comparison of confusion matrices showed that model refinement substantially improved prediction of scab intensity, with a higher agreement between observed and predicted values (fig. 1).

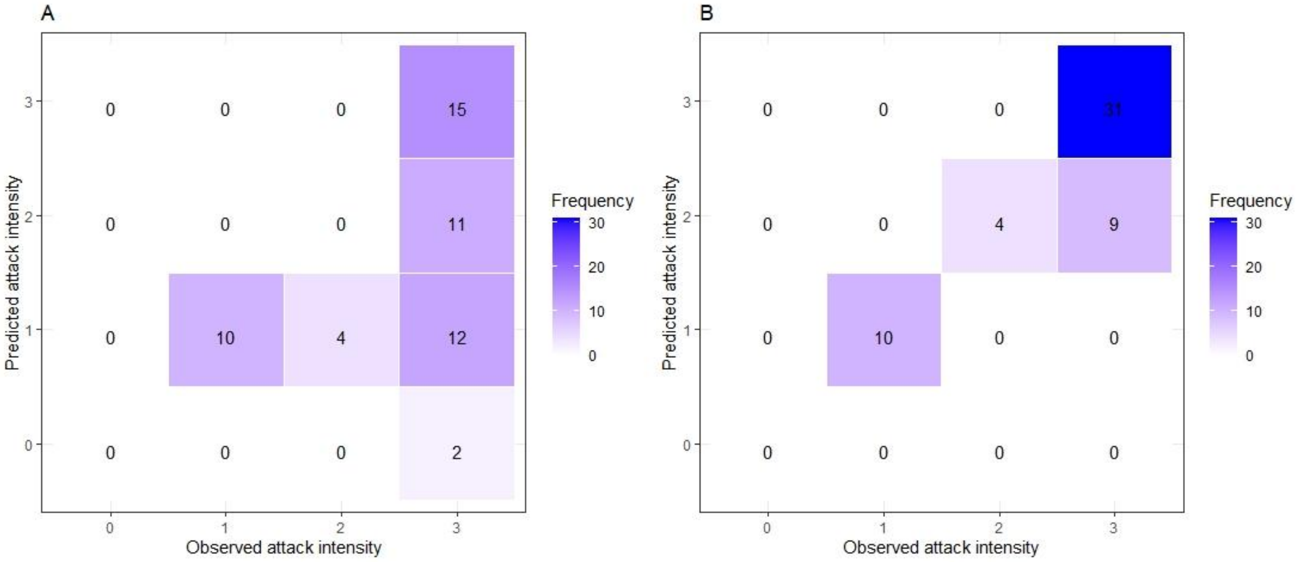

Figure 1. Confusion matrices comparing predicted versus observed scab attack intensities before (A) and after (B) modification of the apple scab IPSIM model.

Conclusions

This study highlights the importance of continuously refining predictive models to improve their accuracy. The integration of multiple analytical methods offers a holistic perspective on the factors driving pest outbreaks, paving the way for more effective, targeted, and environmentally responsible management strategies. Future work will aim to expand the dataset to include more orchards and conditions to enhance the IPSIM model for more robust and generalizable predictions.

Acknowledgements

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Crop Modelling for Agriculture
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Continental-scale differences in winter wheat transpiration between historic and modern cultivars

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Keywords: breeding, water use efficiency, upscaling, crop model

Introduction

Wheat is among the most dominant land cover types in Europe, covering approximately 4.3% of its land surface. In the past decades however, wheat yields in Europe increased significantly, caused by improved management strategies and breeding of new varieties. A recent multi environment study with 191 German winter wheat cultivars grown in several locations and under 9 different management scenarios, showed that 48% of the grain yield improvements can be explained by breeding progress alone (Wang et al. 2025).

While a lot of research has been attributed to how advances in breeding have improved wheat yields, relatively little attention has been paid to the understanding of how this affected water fluxes between the land surface and the atmosphere. Other management interventions, like consideration of irrigation in land surface models, have previously been reported to increase transpiration rates over land areas, resulting in significant changes in near surface temperatures and evapotranspiration (Sacks et al. 2009).

While only a small percentage of agricultural land area in the EU is equipped for irrigation, all wheat grown areas were affected by physiological changes in cultivars from prior the green revolution until today. This resulted in modern varieties with a smaller leaf area index (LAI), a shorter growing season and a larger harvest index. Until now however, most simulations of continental water fluxes do not consider differences between cultivars on the simulation of transpiration in space and time.

To test the relevance of accurate crop physiology parameters for the simulation of transpiration, we calibrated our crop model SIMPLACE<LintulCC2> with experimental data from a historic and a modern winter wheat cultivar and upscaled it to the European domain for the period of 1991-2020 with the following research questions: (1) Do physiological differences between winter wheat cultivars affect crop transpiration on a continental scale? (2) Were cultivar differences in transpiration constant over time and are they affected by the climate zone? (3) What are the main reasons for cultivar differences at EU scale and in different climate zones?

Materials and Methods

Crop model calibration was performed using experimental data of a modern German winter wheat cultivar that was popular within the period of the simulation (Tommi – released 2002) and a historic cultivar released before the green revolution (S. Dickkopf – released 1895). The model was calibrated using data of destructively measured LAI, phenology, biomass and biomass partitioning between leaf, stem, grain and roots, measured several times throughout the growing season, and grain and straw yield measured at harvest. Canopy transpiration rates were further calibrated using measurements of sap flow sensors.

The model was upscaled to the European domain on a 3 by 3 km grid, using hourly weather data from the ERA5-reanalysis dataset for the years 1990-2020 and soil data from the SoilGrids 2.0 database. Location specific sowing dates of both cultivars and phenological requirements of temperature sums from sowing to anthesis and harvest for the modern cultivar were obtained from the dataset of Ceglar et al. (2019). As temperature sum requirements of the historic cultivar differed from the requirements of the modern cultivar in the field experiment, requirements suggested by Ceglar et al. (2019) were adapted by adding percentual differences measured in the field.

Results and Discussion

Results of the simulations showed that, similarly to the observations in the field, the historic cultivar consistently transpires more water over its growing season than the modern cultivar. Over all years and locations, the modern cultivar transpired 17% less water [266.5 ±41.2 vs. 320.2 ±32.4 (mm m^{-2} growing $season^{-1}$)] than the historic cultivar (Figure 1).

Cultivar differences were compared to results of Sacks et al. (2009), who implemented irrigation in a land surface model and reported increased mean daily canopy transpiration sums by 0.579%. By considering that wheat covers 4.3% of the land surface of the EU and the average simulated growing season, the consideration of cultivar specific model parameters changed yearly transpiration sums by 0.53% according to our simulation.

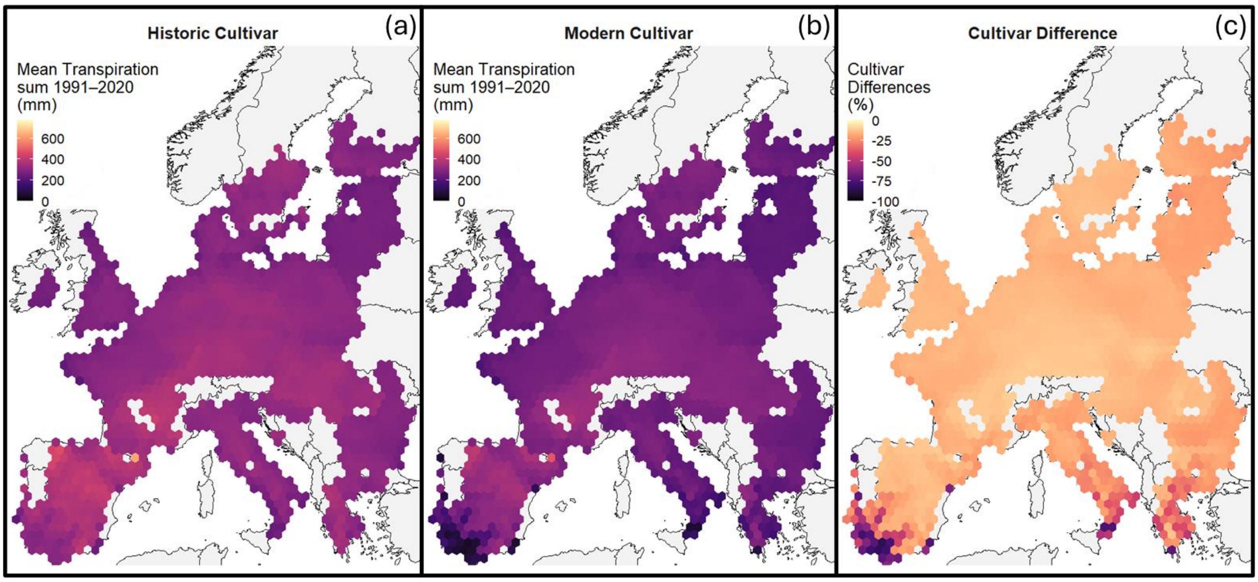

Figure 1. Mean seasonal transpiration (mm 1991-2020; sowing to harvest) simulated with a crop model for a historic winter wheat cultivar (a), a modern cultivar (b), and their relative differences (c) across major wheat-growing areas of the European Union.

Differences between cultivars in yearly transpiration sums were larger in southern Europe and water limited environments. Which were likely caused by the observed and calibrated differences in the cultivars reactions towards water stress, due to the higher root biomass and root length observed in the historic cultivar. Throughout the simulated period, transpiration rates of both cultivars increased significantly, because of increasing CO_2 concentrations, temperature and radiation. Separated into different climatic zones, transpiration rates seemed to increase faster in southern regions.

Although the modern cultivar transpired less than the historic cultivar, it produced similar amounts of biomass and therefore showed a higher water use efficiency in most locations.

Conclusions

Our findings emphasize the need to integrate crop genetic diversity into land surface modelling, as breeding-induced changes in winter wheat physiology might have not only affected yields but also water fluxes between croplands and the atmosphere and therefore should not be neglected in land surface models.

Acknowledgements

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Crop Modelling for Agriculture
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Process-based regional assessment of nitrogen dynamics in arable farms under increasing organic fertilisation

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nitrogen losses, sustainable crop management, cropping system model

Introduction

The increasing intensification of crop and livestock production, along with the resulting farming specialization and high livestock density, presents growing challenges in achieving an optimal balance between economic profitability and environmental sustainability. In this context, an integrated system has been developed, combining a software tool (ReturN, Gabbrielli et al., 2025) for optimising manure redistribution between farms with a process-based dynamic model (ARMOSA, Perego et al., 2013), which evaluates the effects of such redistribution on crop productivity, as well as on C and N cycling. This system enables stakeholders to identify feasible solutions that maintain yields while reducing environmental impacts at local and regional scales.

Materials and Methods

ReturN was applied in three European regions—Lombardy (Italy), Nordjylland (Denmark), and Catalonia (Spain)—to assess the potential for substituting part of mineral N with organic N through the redistribution of manure from livestock to arable farms, where crops are mainly fertilised with mineral N.

ARMOSA was used to assess crop productivity and N recovery, SOC stocks accumulation and N losses (NO_3 leaching, N_2O and NH_4 emissions) in arable farms before and after manure application.

The modelling analysis was performed at the Agri4Cast weather cell scale, on 10–15 weather cells per region having a substantial proportion of arable land, with each scenario simulated over a 30-year period (1993–2023). Simulations included a baseline with only mineral N fertilization and a set of alternative scenarios with increasing levels of organic N replacing baseline mineral N (25–100% of crop N requirements) across four soil textures, two manure-N rate limits (NVZ vs non-NVZ) and two representative crop rotations per region (non-feed crops). Each crop's N requirement was set to the region-specific maximum total N application allowed under the EU Nitrate Directive (91/676/EEC). Improved management practices (straw incorporation, cover cropping, minimum tillage) were simulated on top of maximum organic N substitution scenarios.

Results and Discussion

Replacing mineral N with organic N had variable effects on long-term average N losses and C sequestration. For many soil–weather cell combinations, scenarios with improved practices consistently resulted in higher leaching and N_2O emission, particularly at higher N input levels (i.e., Norg50imp. and Norg100imp.). This indicates that while such strategies enhance SOC accumulation, they tend to increase N losses.

Compared to the baselines, the alternative scenarios resulted in both increased, unchanged, or decreased leaching rates, depending on regional precipitation patterns and their interactions with soil texture and crop rotations (Figure 1). In Lombardy, the lowest leaching occurred under the Norg50 scenario without improvements, especially in medium fine and fine soils (< 35 kg N ha^{-1} $year^{-1}$). In Nordjylland, the lowest leaching was observed under the Norg50imp. scenario in medium fine and fine soils (< 5 kg N ha^{-1} $year^{-1}$). In Catalonia, leaching losses under these scenarios were similar to baseline conditions, with lowest leaching below 30 N ha^{-1} $year^{-1}$ for coarse (Norg50imp.) and medium soils (Norg50), and below 5 N ha^{-1} $year^{-1}$ for medium fine and fine soils (Norg25).

The integrated C–N modelling framework highlights that intermediate organic N substitution may offer a balance between agronomic performance and environmental outcomes, and emphasizes the need for context-specific, integrated N fertilisation and soil management strategies to optimize SOC retention and minimize environmental impacts across diverse pedoclimatic conditions and cropping systems.

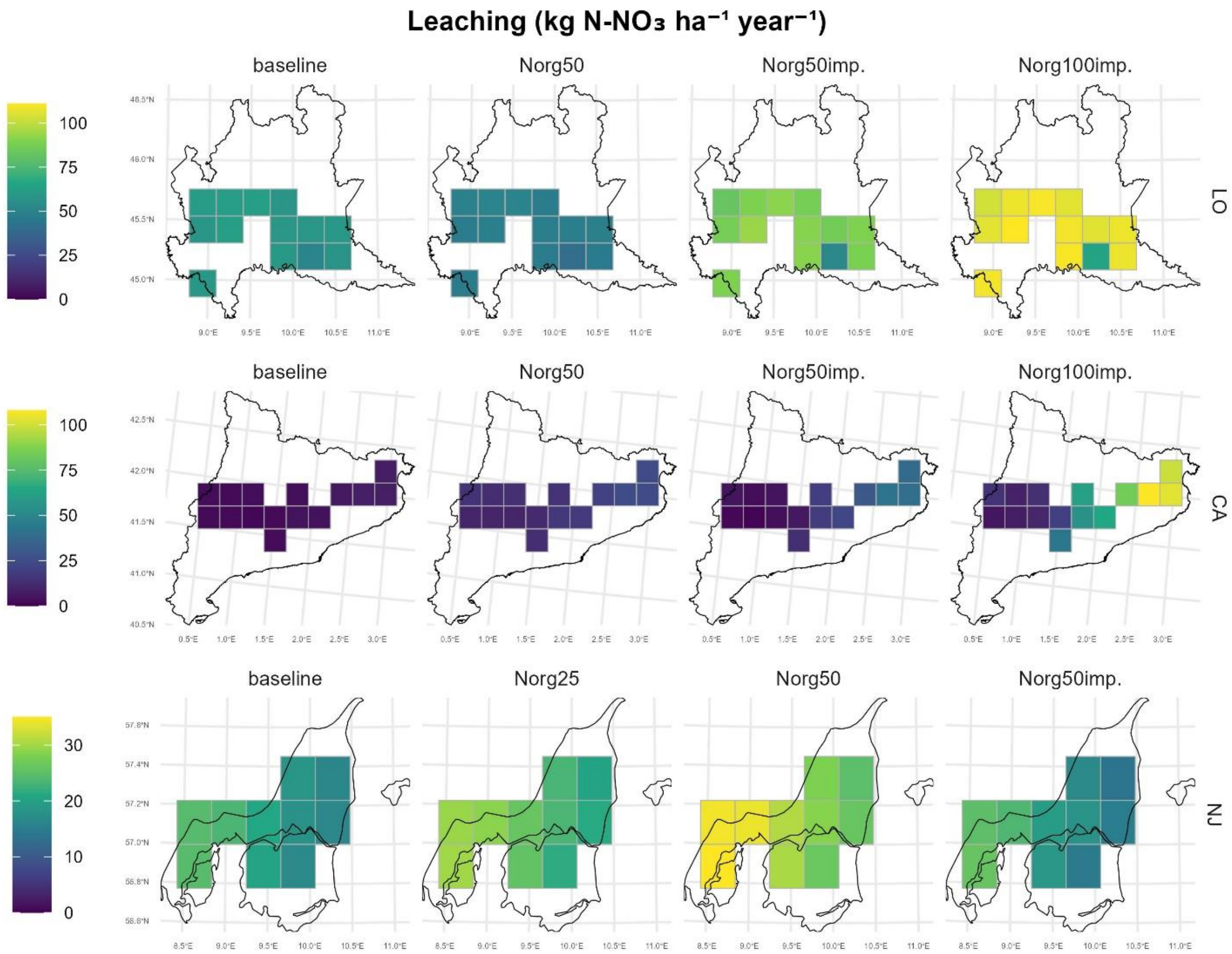

Figure 1. Simulated average annual nitrate leaching under baseline, 25 and 50% organic N substitution (Norg25, Norg50), 50 and 100% substitution with improved management (Norg50imp., Norg100imp.) in Lombardy (LO), Nordjylland (NJ) and Catalonia (CA)

Conclusions

This integrated system demonstrated its suitability for application to data available Europe-wide, enabling the a-priori evaluation, at multiple scales (local, regional, territorial), of the effects of redistributing manure from livestock to arable farms on N use efficiency and SOC dynamics within the framework of collaborative agreements for manure management.

Acknowledgements

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Crop Modelling for Agriculture
and Food Security under Global Change

Assessing the performance of DayCent and STICS in simulating soil carbon and maize yield responses to contrasting organic resources in sub-Saharan Africa

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Keywords: Model intercomparison; Integrated soil fertility management; Kenya; Long-term experiments

Introduction

In many regions of sub-Saharan Africa (SSA), soil fertility decline is the major constraint to crop productivity, with maize yields remaining among the lowest worldwide (Van Ittersum et al., 2016). Integrated Soil Fertility Management (ISFM), which combines the use of mineral fertilizers with locally available organic resources, is increasingly promoted as a pathway to improve yields while maintaining soil organic carbon (SOC) (Vanlauwe et al., 2010). Soil–crop models are valuable tools to test ISFM strategies under contrasting soils, climates, and management scenarios. Yet, most soil–crop models were developed and validated in temperate regions, and their accuracy in tropical agroecosystems remains uncertain. Improving the reliability of these models in SSA is critical for guiding sustainable intensification. In this study, we evaluate the performance of two widely used models, STICS and DayCent, for their ability to simulate maize yields and SOC dynamics across long-term experiments with contrasting organic amendments in tropical Kenya.

Materials and Methods

We used data from four long-term experiments established in central and western Kenya, spanning contrasting pedo-climatic conditions (mean annual temperatures 20–24 °C, rainfall 800–1700 mm, and soils ranging from sandy to clay-rich) (Laub et al., 2023b, 2023a). Treatments included organic resources of varying quality—high-quality (farmyard manure, *Tithonia diversifolia, Calliandra calothyrsus*) versus low-quality (maize stover, sawdust)—applied at two rates (1.2 and 4 t C ha^{-1} yr^{-1}), with or without mineral nitrogen fertilizer. Uncropped subplots allowed a unique independent calibration of soil processes. Altogether, the dataset represented 3384 site × season × treatment combinations. Both models were calibrated using a unique stepwise approach: (i) soil organic matter (SOM) turnover based on uncropped soils without organic resources, (ii) microbial carbon use efficiency with uncropped soils receiving organic resources, and (iii) maize growth and yield in cropped plots. Evaluation was carried out on independent treatments at lower organic resource input levels (1.2 t C ha^{-1} yr^{-1}).

Results and Discussion

Both STICS and DayCent reproduced SOC and yield dynamics with comparable accuracy (Figure 1) despite their structural differences. Changes in SOC were captured well in clay-rich soils (nRMSE < 30%) but poorly in sandy soils, where both models underestimated SOC losses—likely due to erosion, a process not represented in either model. Importantly, both models differentiated the impacts of high- versus low-quality organic resources, reproducing higher SOC maintenance and yields under high-quality inputs, especially when combined with mineral N (Figure 1.A). For maize yields, the models successfully simulated average responses to mineral fertilizer and organic resource quality across most sites (Figure 1.B). They captured the yield benefits of high-quality inputs and the synergistic effect of combining them with mineral N. However, they systematically underestimated yield variability under conditions of poor-quality inputs and no mineral N, indicating that processes such as soil N mineralization, microbial priming, and short-term water–nutrient interactions are insufficiently represented. The stepwise calibration proved valuable in highlighting model strengths and weaknesses. Both models relied on conceptual SOM pools that do not directly correspond to measurable fractions, complicating calibration and interpretation. Their similar performance suggests that structural complexity does not automatically translate into higher accuracy without sufficient supporting measured data (Castañeda-Vera et al., 2015). Detailed in-season crop and soil measurements (leaf area index, N uptake, soil moisture) would be essential to fully exploit model capabilities.

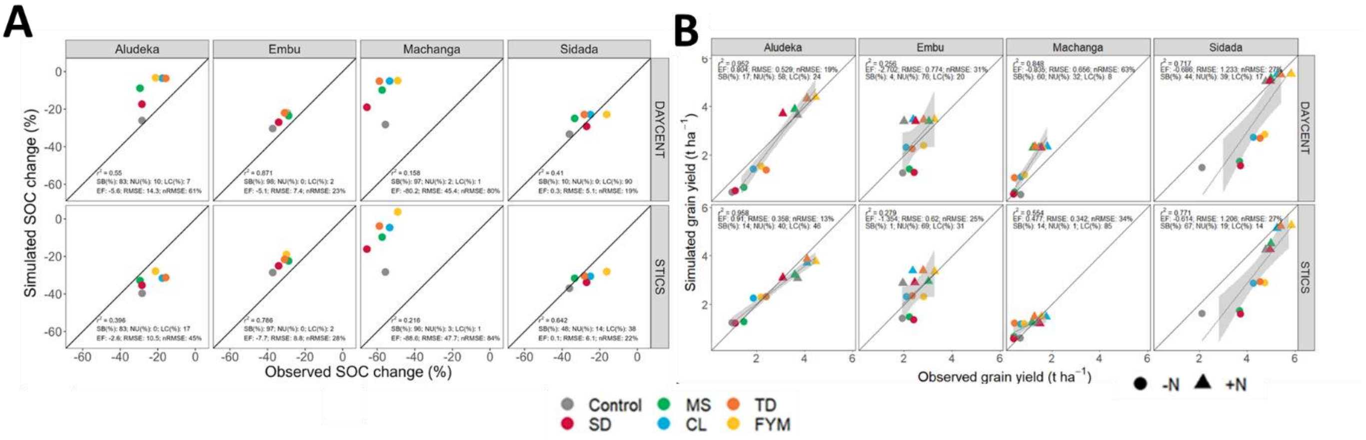

Figure 1. Model evaluations of DayCent and STICS. (A) Observed versus simulated SOC change (%) in the 0–20 cm layer at the end of the experiments. (B) Simulated versus observed maize grain yield under five organic resources (1.2 t C ha^{-1} yr^{-1}, ±240 kg N ha^{-1} yr^{-1}). Data are from four sites in Kenya. Control = no input; CL = Calliandra; FYM = farmyard manure; MS = maize stover; SD = sawdust; TD = Tithonia. Grey shading indicates 95% confidence intervals.

Conclusions

This study provides the first systematic comparison of STICS and DayCent for contrasting organic resource amendments under tropical conditions. Both models showed potential for exploring management scenarios with high-quality organic resources, but their limitations in sandy soils and under low-input conditions underline the need for further model refinement. Future improvements should include the integration of erosion processes, microbial-driven SOM decomposition, and the use of measurable SOM pools (e.g., particulate versus mineral-associated organic matter). Our results highlight the value of long-term tropical experiments not only for agricultural development but also for improving global soil–crop modeling.

Acknowledgements

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A credible crop model ensemble to simulate maize response to intensification and climate variability in sub-Saharan Africa

Crop Modelling for Agriculture
and Food Security under Global Change

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Keywords: model uncertainty, calibration, fertilizer, profitability, risk

Introduction

Understanding how climate and soils drive maize response to nutrient addition is critical to target risk management interventions in the context of sub-Saharan Africa (SSA). Crop models are great tools to unravel how climate and soil drive the variability in maize response to fertilizer. Yet, uncalibrated approaches incorporate uncertainties that can undermine the recommendation generated with modelling outcomes. The objective of this study is to i) provide a set of generic species, cultivar, and soil parameters for three crop models that allow accurate simulation of maize growth and response to nitrogen (N) input, for the contrasting climates and soils in SSA, and ii) illustrate the skills of the model ensemble in identifying and understanding risk of intensification at contrasting sites.

Materials and Methods

We selected three crop models that can simulate potential, water-limited and water- and N-limited cereal growth in tropical conditions, namely CELSIUS (Ricome et al., 2017), STICS (Brisson et al., 2002), and DSSAT (Jones et al., 2003). This study relied on detailed observations on maize growth at seven experimental sites in SSA (Falconnier et al., 2020) for two growing seasons and contrasting water and N availability, to set generic soil and plant model parameters. The model ensemble (mean of the three models) was then evaluated against observation of maize response to fertilizer at four sites with long-term trials (Couëdel et al., 2024). Creation of model inputs, model runs, and aggregation of models outputs was automated into ACME (Agile Crop Model Ensemble), an operational workflow that facilitates calibration, evaluation and virtual experiments with model ensembles (Giner et al., 2024).

Results and Discussion

The calibrated model ensemble reproduced variations in observed maize grain yield in the calibration experiments with Root Mean Square Error (RMSE) of 2.1 t/ha (for observed yields varying from 1.3 to 13.7 t/ha) and coefficient of determination (R^2) of 0.88. Model accuracy was similar in the evaluation dataset with and RMSE of 1.9 t/ha, yet with a smaller R^2 of 0.52 (Figure 1). The model ensemble was able to explain a fourth of the observed variability in maize response to N input (nitrogen agronomic efficiency) in the four long-term experiments (R^2=0.25). Ensemble simulations with historical climate (1980-2010) at the calibration/evaluation sites showed contrasts across sites in the risk of unprofitable nitrogen fertilizer investment. The ensemble classified with high-confidence this risk as ‘low’ at seven sites, and ‘high’ at one site, while for four sites model uncertainty precluded a robust risk assessment. We discuss avenues to improve model calibration with additional observations related to N balance and water stress, and opportunities for spatial upscaling to understand how risk of intensification varies across SSA.

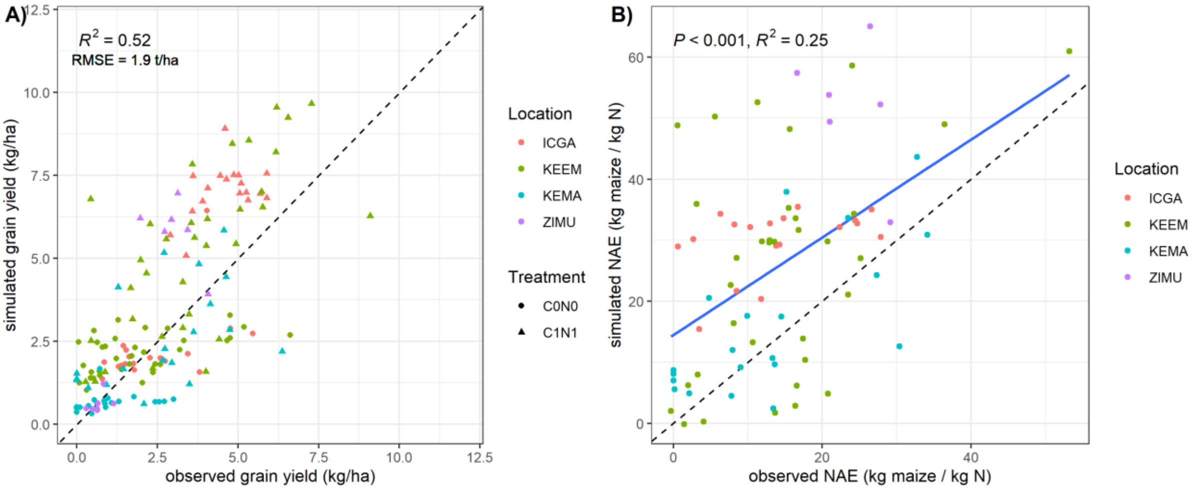

Figure 1. A) Observed and ensemble-simulated maize grain yield for the evaluation dataset for the treatment without nutrient input (C0N0) and with a combination of mineral and organic fertiliser (C1N1); B) Observed and simulated nitrogen agronomic efficiency (NAE) in the four long-term experiments of Couëdel et al. (2024). Dotted lines are 1:1 lines. The blue line in B) is the regression line of simulated against observed values. ICGA = Ivory Coast – Gagnoa, KEEM = Kenya – Embu, KEMA = Kenya – Machenga, ZIMU = Zimbabwe – Murehwa.

Conclusions

A thorough quality-check of the crop models used to derive information on fertilizer response is required – if meaningful and credible information is to be generated. This study shows that a locally calibrated crop model ensemble, evaluated on independent experimental sites, can be useful and credible to inform the targeting of interventions around mineral N fertilizer for maize intensification in SSA. There is still a large scope to improve the prediction skill of the model ensemble. Generating and compiling experimental datasets on the water and N balances of maize cropping systems remains a priority to improve current crop models.

Acknowledgements

We are thankful to the Climate-KIC/European Institute of Innovation and Technology (ARISE project) and EU-DESIRA program under Grant Agreement No 424-933, project RAIZ (Promoting agroecological intensification for resilience building in Zimbabwe).

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Crop Modelling for Agriculture
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Increasing grass-clover ley duration and proportion in dairy crop rotations increases SOC but also increases N leaching

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Keywords: Agroecological modelling; Daisy; Carbon sequestration; Nitrogen turnover

Introduction

Intensive dairy production systems are associated with high greenhouse gas emissions, primarily due to the enteric methane emissions from cattle. Solutions and strategies that can offset these emissions are sought after, and one of such potential solutions is perennial grass-clover ley, which is already an important source of roughage in dairy farming systems. Grass-clover leys are potential carbon (C) sinks due to their enhancement of soil organic carbon (SOC) through more permanent rooting system and rhizodeposition, and, in the case of dairy production systems, from slurry-derived inputs. Increasing the proportion or duration of leys in crop rotations could be a potential strategy to offset the negative climate emissions. However, the residual effects of leys and responses of succeeding crops are variables that ultimately determine whether the net effect of leys is positive. The aim of the study was to analyze the short- and long-term consequences for crop productivity, SOC accrual, and N leaching from changing the duration or the proportion of grass-clover ley in dairy crop rotations, under the limitation that the dairy cow roughage ration should be maintained. Studying these tradeoffs is challenging due to the long-term nature of SOC dynamics. Developments in advanced agroecological modelling have made it possible to simulate these systems, providing an initial identification of potentially successful strategies. One of such models that has recently been calibrated on several larger datasets is Daisy. Daisy simulates C and N dynamics in the soil-plant-atmosphere continuum and has been widely used to quantify C and N losses in agricultural systems.

Materials and Methods

Using the agroecological model Daisy, three crop rotation scenarios were developed to reflect realistic practices of two representative Danish dairy production systems, a conventional low stocking density (LS) and a conventional high stocking density (HS). Each production system was modeled with a total of 100 ha. The baseline 'Now' crop rotation scenario was constructed using typical crop combinations and feed rations. In the 'More' scenario, the duration of the ley was extended, increasing the total ley area. The 'Even' scenario maintained the same total ley area as the 'Now' scenario but extended the duration of ley to four years. Each scenario was designed to align with feed requirements, ensuring consistent dry matter intake across scenarios. All simulations were conducted on the dominant Danish soil type, fine loamy sand. The scenarios were run for a total of 100 years, excluding model spin-up time of 30 years. To account for climatic variation, two regional weather conditions were applied using actual weather from 2012-2024, repeated over the 100 years.

Results and Discussion

Our results showed that altering ley duration and proportion had negligible effects on crop yield but strongly influenced soil C and N dynamics. Rotations with longer duration and higher proportion of ley increased SOC the most (+0.6 Mg C ha^{-1} year^{-1}), with the HS systems consistently producing higher SOC accrual. However, high ley proportions and stocking densities also increased N leaching (Fig. 1). The 'More' scenarios increased SOC by 25–37% vs. 'Now' but also increased N leaching by 5–26%. The 'Even' scenarios reduced SOC by 25–41% while also decreasing leaching by 8–34%. There was some effect of climate, in which West, with higher precipitation, had both higher SOC accrual and N leaching.

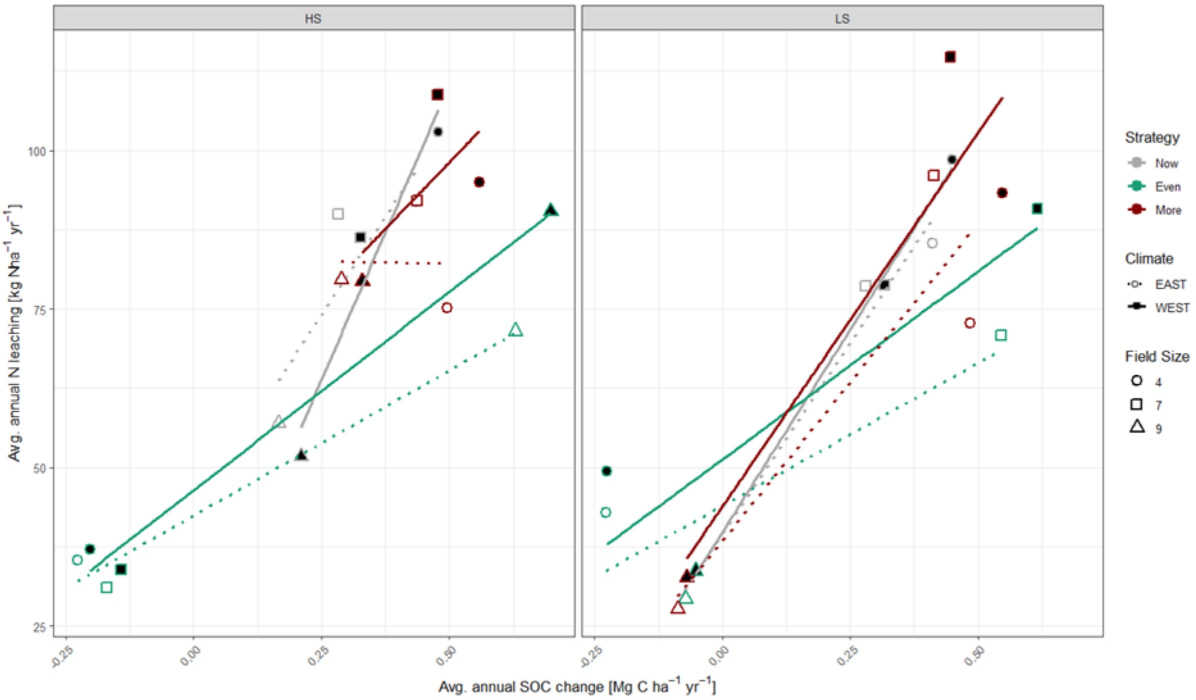

Figure 1. Mean annual soil organic carbon (SOC) change (accrual rate) [Mg C ha^{-1} yr^{-1}] in 0-300 cm against mean annual nitrogen (N) leaching [kg N ha^{-1} yr^{-1}] at 100 cm for the 'Now', 'Even' and 'More' scenarios and West and East climate by High (HS) and Low (LS) stocking systems. Each point is value for specific sub-rotation and line is trendline for entire scenario/strategy.

Conclusions

The trade-off between SOC accrual and N leaching reflects a prioritization in short-term versus long-term environmental impacts.

Integrated Hydrologic Modeling to Quantify Hydrologic Impacts of Natural Small Water Retention Measures

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Keywords: nature-based solutions, soil water, groundwater, infiltration

Introduction

Switzerland is experiencing both more frequent and more severe droughts and more frequent major precipitation events as a result of climate change, leading to issues with runoff, erosion, agricultural drought, and increased demand for irrigation water in agricultural watersheds (FOEN, 2021). Agricultural operations and resource managers are increasingly interested in Natural Small Water Retention Measures (NSWRM) as a potential mitigation activity due to their low cost and minimal permitting needs, but currently lack science-based tools to help them answer questions like 1) whether NSWRM are likely to improve water retention on a farm based on farm catchment characteristics (slope, soil type, hydrogeology, climate), 2) which types of measures are likely to be the most effective on their farm, and 3) what measure design aspects should be considered in the planning and construction of a NSWRM. Generally, quantitative evidence of measure impacts is limited in the scientific literature, and what does exist is from single field or modeling experiments and thus not broadly applicable to a wide range of agricultural conditions (Lalonde et al., 2024). In the Swiss Federal Office of Agriculture FOAG funded research project "Slow Water", we address this knowledge gap with an integrated hydrologic modeling study aimed at creating a catalog of how a variety of NSWRM impact a variety of hydrologic variables in a variety of catchment conditions, providing the most comprehensive and broadly-applicable dataset of quantitative NSWRM impacts available to date and enabling apples-to-apples comparisons of different measure classes and designs that would not be possible in a field study (Cornelis et al., 2021).

Materials and Methods

We leverage the three-dimensional, physically-based integrated surface-subsurface hydrologic model HydroGeoSphere (Aquanty, Inc.) and high-performance computing resources to create a synthetic modeling framework that enables modeling experiments for testing measure- and field-scale impacts of several NSWRM classes across more than 5,000 catchment conditions scenarios. The synthetic model consists of a half-space Tilted V type model domain measuring 120 by 110 meters and with a thickness of 29 meters. We simulate different catchment conditions scenarios by varying parameters catchment slope, soil depth, soil type, soil porosity, bedrock transmissivity, field cover, long-term climate, and antecedent drying. Using output from a spin-up model with long-term climate followed by an antecedent drying period as initial conditions, we run several hot-start water retention stress test models for each catchment conditions and NSWRM implementation scenario. Hot-start models simulate representative 1-hour precipitation events for different return periods for northwest Switzerland followed by a longer period of representative summer potential evapotranspiration with no precipitation. NSWRM are implemented with changes to topography and/or physically measurable parameter values.

Results and Discussion

Synthetic modeling experiments produced with this framework prove to be effective in highlighting differences in impacts of implementations stemming from 1) different measure types, 2) different measure designs, 3) different catchment conditions, and 4) different precipitation event magnitudes. The HydroGeoSphere model is computationally intensive, and simulating a single measure design for the entire range of over 5,000 catchment conditions scenarios requires tens of thousands of core hours, indicating that a synthetic modeling study of this scope is only possible with access to high-performance computing resources. However, owing to its physical consistency, the results obtained from this integrated surface-subsurface hydrological model are robust and although computationally intensive, enable transferrable insights beyond those achievable from single farm analyses.

Conclusions

The synthetic modeling framework developed for this study proves to be an effective tool to carry out numerical experiments to evaluate quantitative NSWRM impacts at the measure- and field-scale. The catalog of results derived from this study will be used to develop insights about which NSWRM implementations work in which agricultural settings, and be used in the development of broadly-applicable NSWRM selection guidance for agricultural resource managers. Additionally, results provide validation information for parameterization of NSWRM implementations in larger models used for catchment-scale impacts. Beyond enabling an experimental design that would not be possible with traditional field studies, another key advantage of using models in this study is shown to be the ability to measure hydrologic variables that would be difficult to measure in the field, like infiltration, flux across the soil-bedrock interface, and model-wide plant available water.

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Crop Modelling for Agriculture
and Food Security under Global Change

Global hotspots of future cropland expansion vs. intensification and impacts on biodiversity

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Keywords:

integrated assessment; land-use change; biodiversity; computable general equilibrium (CGE) model; land use model; crop growth model

Introduction

The global demand for agricultural products rose by 27% from 2010–2023 and is projected to grow by 1.2% annually (OECD/FAO 2024–2033). Meeting this demand risks accelerating terrestrial biodiversity loss, to which agriculture is a leading contributor via land-use change. Declining biodiversity and associated ecosystem services may also undermine agricultural productivity. We map globally where cropland expansion and intensification are likely to happen under future climate and socio-economic scenarios and estimate the consequences for biodiversity intactness, addressing gaps in prior work that examined only one strategy, lacked spatial explicitness, or neglected feasibility constraints (Zabel et al. 2019).

Materials and Methods

We applied the integrative land allocation model (iLANCE) to identify globally the most profitable areas for cropland expansion and cropland intensification at the same production target to meet expected future demand. iLANCE allocates cropland based on the principle of profit maximization, thereby taking into account regional socio-economic conditions coming from the CGE-model DART and combining it with spatial information of yields coming from the mechanistic crop growth model PROMET and limitations on physical land availability (Schneider et al. 2024). Expansion hotspots arise by increasing land endowments in DART and then iteratively rank areas by profitability. Areas are physically in alignment with spatially available areas suitable for expansion (Schneider et al. 2022). Intensification pixels are iteratively identified by selecting pixels which generate the highest added profit under intensification. In the model this intensification process is initialized by closing the yield gap by 80%. The coupled system then iteratively reaches an equilibrium considering expansion and intensification areas. Scenarios target a 30% production increase relative to 2010, consistent with FAO projections. Biodiversity effects are assessed with the Biodiversity Intactness Index (BII) (De Palma et al., 2021).

Results and Discussion

Preliminary results indicate clear contrasts between possible future expansion and intensification areas. Expansion clusters occur along tropical/subtropical frontiers in Central Africa, parts of Central and South America, India and China. Intensification follows existing production belts (e.g. Brazilian Highlands/Paraná and Pampa, the Indo-Gangetic Basin, the North China Plain, and parts of West and East Africa) with large current cropland areas and sizable yield gaps. These patterns imply different biodiversity risks: expansion overlaps several high-value natural ecosystems, whereas intensification concentrates pressure in existing cropland. We will present trade-off analysis with biodiversity by quantification of BII for both, intensification and expansion. Conservation policies are not yet considered. BII is informative but simplified and may miss time-lag effects and obscure biodiversity hotspots.

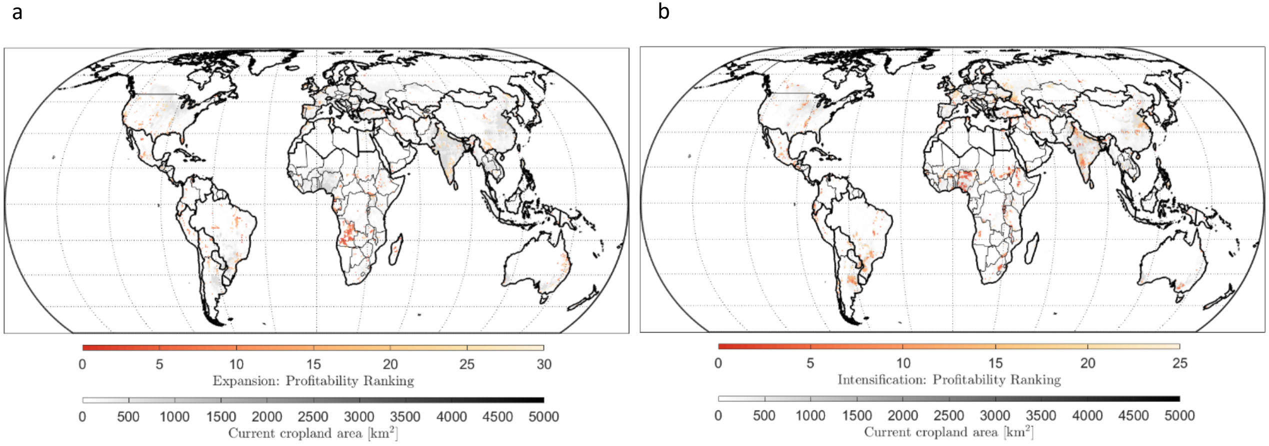

Figure 1: Areas under expansion and intensification pressure up to a potential increase of crop production of 30% without conservation policies. (a) Profitability ranking of expansion areas, indicating under which global cropland expansion a pixel is among the globally most profitable ones to be transformed into cropland. (b) The profitability ranking of intensification areas indicates under which global cropland intensification a pixel is among the most profitable areas for intensification. Grey areas display current cropland.

Conclusions

Our approach enables the quantification and comparison of biodiversity effects for both, agricultural expansion and intensification and thus could help to mitigate trade-offs by guiding policy and land-use planning for a sustainable agricultural production increase.

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A conceptual intercomparison of intercropping models: Insights from model developers and expert users

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Keywords: agroecological modelling, model comparison, ensemble modelling, agroforestry systems, diversified systems

Introduction

In recent decades, growing interest in intercropping systems has been driven by the push toward sustainable agriculture. However, the complex ecological and management interactions inherent in these systems have limited their large-scale adoption across diverse global environments. An alternative approach to addressing these complex interactions and supporting the scaling of intercropping systems lies in the application of crop models. Crop models have been successfully used for decades to optimize production in conventional agricultural practices or monocultures (Boote et al., 1998). Notably, the number of crop models capable of simulating intercropping has grown rapidly in recent years. Notably, the number of crop models capable of simulating intercropping has grown rapidly in recent years. However, to effectively use these models for simulating various intercropping forms, a proper understanding of their capabilities and limitations is required, as they are often adapted from single-crop models. Despite advances in modelling intercropping, it is still largely unknown how these models conceptually represent interspecies interactions (including their similarities and differences) and how well they simulate different types of intercrops. To address these challenges, our study provides a state-of-the-art overview of crop models with intercropping capabilities that is grounded based on the insights from model developers and expert users.

Materials and Methods

This study utilized the Agricultural Model Intercomparison and Improvement Project (AgMIP) platform (https://agmip.org) to engage with crop modelling teams. representing nine prominent models: APSIM, DayCent, DSSAT, LandscapeDNDC, LUCIA, MONICA, SIMPLACE Lintul5, STICS, and WaNuLCAS. For three of these models (APSIM, DSSAT, and STICS), two distinct subtypes were identified based on their approaches to simulating intercropping systems, resulting in a total of 12 participating models. Each participating modelling group was asked to provide detailed descriptions of the core concepts and model structure, underlying assumptions, key equations, and driving variables influencing interspecies interactions using online survey questionnaire.

Results and Discussion

We have seen that the number of crop models that can handle intercropping has grown significantly in recent years (Fig. 1). These models are now used globally, across Asia, Africa, Europe, and North America (Fig. 2), demonstrating a growing interest in designing sustainable and productive cropping systems for the future. We identified six (6) major approaches that current intercrop models use to simulate how species share light: uniform canopy, two-layer canopy, three-layer canopy with four spatial horizontal zone, multi layered canopy, strip-planted canopy, and shading-centric methods. Modelers simulated below-ground competition for water and nutrients using four main approaches: alternating or sequential uptake, partial interspecific competition, resource allocation based on root growth, and the use of sole crop routines.

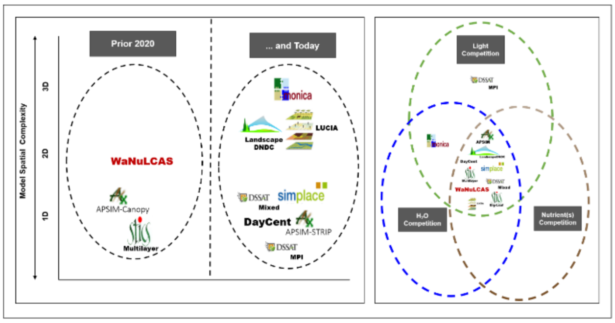

Figure 2. Advances in modelling intercropping systems over time (right) and in complexity (left). The green dotted circle represents the incorporation of light competition routines, the blue dotted circle signifies water competition routines, and the brown

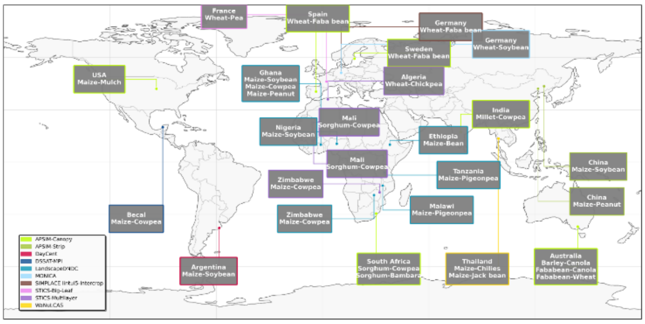

Figure 3.Example application of intercrop models across different geography and species combination globally. Note: DSSAT-Mixed and LUCIA were omitted as they are yet to be formally published in the scientific literature.

Conclusions

In summary, our results demonstrate that crop models with intercropping routines are evolving toward a better capabilities to simulate interspecies dynamics across diverse environments. Crucially, the study confirmed that each model conceptualizes these interactions uniquely. While some models are suited to simpler systems, others can represent more complex interactions. Consequently, understanding these differences is essential for selecting the most appropriate model for specific applications, such as scenario analysis or uncertainty quantification.

Acknowledgements

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Crop Modelling for Agriculture
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Modeling strip intercropping systems in APSIM Next Generation: The importance of strip width specification and intercrop traits

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Keywords: maize-soybean strip intercropping, composite canopy, light interception, biomass, grain yield

Introduction

Intercropping, the practice of growing multiple crops simultaneously in proximity, can enhance productivity and resource use efficiency. Cereal-legume systems like maize-soybean strip intercropping are particularly common, leveraging complementary traits for resource use, biodiversity, and climate resilience (Wu et al., 2023). However, modeling such systems is complex due to the spatial heterogeneity of the canopy. The strip crop light interception model (Gou et al, 2017) calculates light capture for each crop in strip intercropping and has been integrated in the APSIM NG model. However, it ignores the physiological and morphological changes of the intercrops due to altered environment in the composite canopy. This study evaluates the performance of the APSIM NG strip intercropping model and discuss the need for improved modelling of intercrop physiology.

Materials and Methods

One field experiment was conducted in 2022 at Baotou city, Inner Mongolia, China, to investigate mono- and intercropping systems of maize and soybean. Both the mono- and intercropping treatments included maize at three densities (6, 7.5, and 9 plants/m²) and soybean at a single density (15 plants/m²). The intercropping system featured two rows of maize alternated with three, four, or five rows of soybean, creating nine treatments with a constant maize strip width but varying soybean strip width to manipulate interspecific competition. All plant densities were calculated on a whole-field basis, leading to higher densities within the individual crop strips. The row spacing was 40 cm for maize and 30 cm for soybean, with a 60 cm gap between maize and soybean rows. For both crops, we measured phenological stages, leaf area index (LAI), biomass, and grain yield. Radiation use efficiency (RUE) was derived from intercepted solar radiation and dry matter accumulation.

The strip crop light interception model, initially tested in APSIM Classic model (Wu et al., 2021), and has been implemented in APSIM NG (Holzworth et al, 2014). It calculates the light capture for intercrops based on leaf area index (LAI), crop height, and strip width. We first calibrated the model by deriving phenology and height parameters for sole maize and soybean crops, using a trial-and-error approach to minimize the root mean square error (RMSE) between observed and simulated values (height, flowering & maturity dates). Subsequently, we adjusted cultivar-specific parameters for leaf size, radiation use efficiency (RUE), grain size, and grain number for maize, and leaf size for soybean, based on observed data. For the intercropping simulations, we defined the maize strip width as 100cm (40 + 2x60/2) and the corresponding soybean strip widths in each treatment, by allocating half of the space between the two crops for each crop. The calibrated model was used to simulate the dynamics of LAI, biomass, and grain yield for both sole and strip-intercropping systems.

Results and Discussion

After calibration, APSIM NG accurately simulated monoculture soybean and captured maize responses to density, though it overestimated maize LAImax and yield (Fig. 1). In intercropping simulations, the model correctly captured trends but overestimated soybean growth and underestimated maize growth. We attributed this to an inaccurate canopy structure. Observing that maize leaves extended further into the shared space than modeled, we adjusted the strip widths, widening maize to 120 cm and narrowing soybean strips accordingly. This refinement significantly improved the model's accuracy for the intercropping system (Fig. 1). Across all the treatments, the model explained 76-95% of the variance in LAImax, biomass and yields. Two key deviations were noted: first, a general overestimation of soybean LAImax, and second, a weaker fit for intercropped soybean biomass. In the latter case, the low R^2 is attributed to the inherently small range of observed data, as indicated by the low RMSE (0.18 t/ha) (Fig. 1b).

Our results yield several key implications: 1) APSIM NG's strip crop model was able to simulate maize and soybean growth responses to strip width and plant density; 2) Model accuracy depends on defining strip width by canopy cover, not merely land area; 3) The overestimation of soybean LAImax, coupled with correct biomass and yield, implies a shift towards smaller leaves with higher radiation use efficiency in intercropped soybean—a hypothesis consistent with our field data (Wu et al., 2025); 4) Conversely, the overestimation of monoculture maize yield suggests a lower harvest index in intercropped maize, contradicts our observations. However, the intercropped maize did receive more light by the middle and lower leaves due to border row effect, which delayed the senescence of these leaves (Yang et al., 2025) – a phenomenon needs to be captured by the model. These findings underscore the need to consider intercrop-specific physiological traits to improve simulations.

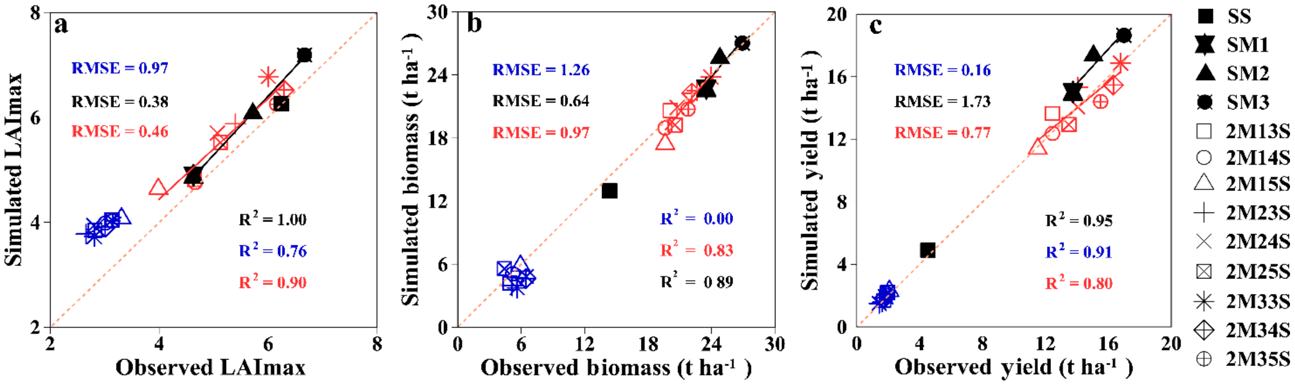

Figure 1. Performance of APSIM-NG model to simulate maximum LAI (LAImax) (a), biomass at start grain filling stage (b) and grain yield (c) of mono- and intercropped maize and soybean. Symbols in black color represents mono-cropping, in red intercropped maize, in blue intercropped soybean. SS represents monocrop soybean. SM1, SM2, SM3 represent monocrop maize with 3 densities. 2M13S, 2M14S, 2M15S represent 2 maize rows intercropped with 3, 4, 5 rows of soybean with the first maize density (6 plants/m^2), the rest with the 2nd and 3rd maize densities (7.5 & 9 plants/m^2)

Conclusions

APSIM NG was able to simulate LAI, biomass and yield of the maize-soybean strip intercropping systems in response to variations in strip width and plant density. Accurate simulation required defining strip widths by actual canopy cover rather than planted area. The model's overestimation of soybean leaf area, despite correct yield prediction, suggests intercropped soybean develops smaller, more efficient leaves. Conversely, discrepancies in maize yield point to differences in grain partitioning between monoculture and intercropping systems. These findings underscore the need to integrate intercrop-specific physiological traits to improve model accuracy.

Acknowledgements

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Crop Modelling for Agriculture
and Food Security under Global Change

The effect of using different pedotransfer functions on modelling crop yield, water and N fluxes

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Keywords: agroecosystem modelling, crop growth, nitrate leaching, N2O emission, evapotranspiration.

Introduction

Modelling agroecosystem processes at larger scales often lack of detailed soil data. To overcome the problem of missing hydrological parameters, so-called pedotransfer functions (PTF) are employed by modelers to derive hydrological soil characteristics from readily available soil information such as texture and soil organic matter. Several formulas have been developed and tested for different regions of the world. Pedotransfer functions can significantly differ in their resulting parameters (Rosso et al., 2025). Since soil hydrology has a strong impact on several processes such as crop growth, C and N turnover, nitrate leaching, denitrification including N_2O emissions we investigated the effects of using different pedotransfer functions on the output of the HEMES2Go model. At the plot level, we compared model results for crop yields, evapotranspiration, soil moisture with observed values. To show the effects for a larger area we used high-resolutions data of two districts in Czechia using data from SoilGrids (Poggio et al., 2021) and some common pedotransfer functions to show their effects additionally for simulated N leaching and N_2O emissions.

Materials and Methods

The model HERMES2Go was used, which simulates soil water and nitrogen dynamics, and crop growth. On the plot level we used data from a site at Polkovice, in Czechia to simulate a continuous crop rotation from 2019-2023 with the crops winter oilseed rape, winter wheat, sugar beet, grain maize, and spring barley. The crop rotation was cultivated in parallel with an annual shift, to obtain data on crop yields for each crop in each year. The soil was a silty loam. For the simulation we used local weather data, cultivation data and soil texture, soil organic matter and bulk density from corresponding grid cells of SoilGrids 500x500 m resolution (Poggio et al., 2021) to derive the soil hydraulic parameters of field capacity wilting point, and total pore space. We used four different parametrisations derived from three different PTFs (Toth et al., 2015; Batjes, 1996 at pF 1.8 and 2.5, Rawls et al., 2003). Model results are compared to observed crop yields and soil water content in the upper soil layer (0-30 cm). The uncertainty of simulated fluxes such as nitrate leaching, actual ET, and N_2O emissions are assessed from the range of outputs. To show the effect on a regional scale we performed the simulations for the same crop rotation for two districts in Czechia using texture, bulk density and soil organic matter of the SoilGrids data base (Poggio et al., 2021) at a 500x500 m resolution.

Results and Discussion

For the Polkovice grids, the use of different PTFs resulted in relatively small differences of yield production, while the outputs for N leaching and N_2O emissions showed a stronger variance among the different PTFs. However, the tabulated parameters for texture classes increased the variation significantly. The comparison of PTFs for winter wheat and spring barley highlights clear differences in variability between yield and N_2O emissions (Table 1).

For winter wheat yield, the coefficient of variation (CV%) across years remained relatively low (4.8-13.2) indicating a more robust reaction on inter-annual weather variability and the high buffer capacity of the site. Among the PTF there was nearly no difference in wetter years, and a CV% of 6-7 % in dryer years.

In contrast, spring barley and grain maize yields showed much higher inter-annual variability, with CV values exceeding 30% and 17%, respectively. This indicates a stronger sensitivity to inter-annual precipitation variability. However, differences among PTFs are low (Table 1). Generally, spring crops, due to their shorter growing period and shallower root system, are more susceptible to water stress, which is reflected in the higher spread among these results of PTF simulations.

The results for N_2O emissions showed generally higher variation among PTFs for all crops than crop yield (Table 1). Inter-annual variability was greater for winter wheat and spring barley than for maize, indicating that the coincidence of partly anaerobic conditions and higher nitrate content in soils are more probable than for the late sown maize. Wet years tend to increase absolute emissions but also reduce the relative spread among PTFs.

Table 1. Simulated crop yields (t/ha) and annual N_2O emissions (kg N/ha) and coefficient of variation (CV%) across four pedotransfer parametrisations. Annual calculations are from October 1st to September 30th, *precipitation crops from April 1st to August 31st.

Year	**2019**	**2020**	**2021**	**2023**	**2023**	**2018/19**	**2019/20**	**2020/21**	**2021/22**	**2022/23**
Precipitation	**444***	**370***	**333***	**316***	**371***	**620**	**645**	**594**	**481**	**522**
Crop	**Yield (CV%)**					**N_2O (CV%)**				
W. wheat	9.4	9.5	7.8	8.1	8.0	15.4 (6.4)	13.9	10.8	9.2	12.6
	(0)	(0)	(4.9)	(6.2)	(7.1)		(4.5)	(4.6)	(5.3)	(4.6)
Spring barley	7.5	7.9	6.6	4.4	3.6	15.5	16.9	13.4	8.7	13.8
	(0)	(0)	(5.2)	(2.9)	(1.0)	(6.3)	(6.0)	(6.6)	(7.3)	(5.5)
Grain maize	13.1	12.2	11.6	7.7	11.2	12.0	13.0	9.8	10.8	10.8)
	(0.4)	(3.3)	(1.8)	(1.0)	(0.6)	(10.6)	(9.4)	(10.6)	(12.0)	(12.3)

Conclusions

The first results at a more favourable site showed that high precipitation years cause lower yield variability across PTFs, but relatively higher variability in N_2O emissions. On the other hand, low precipitation years cause higher yield variability (particularly in spring barley), whereas N_2O emissions may show reduced variation across PTFs. Generally, the silty loam buffered the inter-annual variability for yields. Within the regional simulations grid cells with more sandy soils are expected to show a higher effect of the selected PTF on crop yield and leaching losses, but moderate effects on N_2O emissions.

Acknowledgements

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Crop Modelling for Agriculture
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Modelling the Impact of Animal Stocking Rate and Crop Diversity on N circularity of European Dairy Cattle Systems

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Keywords: circularity indicators; nitrogen use efficiency; cropping system model; livestock nutrition model

Introduction

Circularity in agri-food systems enables the optimization of resource use, the closure of nutrient loops, the reduction of external inputs, decreased reliance on non-renewable resources, and an overall enhancement of system resilience. However, defining and quantifying circularity remains both conceptually and methodologically challenging. Dairy production represents a cornerstone of global agri-food systems. Dairy cows can convert human-inedible biomass into high-value, animal-sourced food, contributing to protein security, while also producing valuable organic fertilizer that returns nutrients to the soil. This study aims to assess the level of nitrogen (N) circularity in 22 case-study dairy cattle farms across six EU countries. The assessment integrates the cropping system simulation model ARMOSA (Gabbrielli et al., 2015) with a livestock nutrition model (NASEM, 2021), in order to explore the long-term variability of the Cycle Count indicator, CyCt (van Loon et al., 2024). This analysis considers key factors such as meteorological patterns, land use and crop diversification, nitrogen management strategies, and animal stocking rates.

Materials and Methods

A modelling framework was developed by integrating a process-based cropping system model with a livestock nutrition model to simulate nitrogen flows under both baseline and alternative scenarios. These scenarios varied in animal stocking rate (LU ha^{-1}), farm land use, and N fertilization strategies. The NASEM and ARMOSA models were interactively used for estimating the N flows within the crop-livestock systems. Data on crop management practices and livestock diets were collected within the DairMix project, via questionnaires administered to 22 representative European farms. Soil profiles data were obtained from the European Soil Database provided by the European Soil Data Centre (ESDAC). Synthetic series (1979-2022) of daily meteorological data were obtained from AGRI4CAST of the JRC MARS Meteorological Database. ARMOSA was calibrated against average yield data per crop as provided by the farmers, and its behavior was assessed simulating the cropping system response to increasing N fertilization rates, from 0 to excess levels. Then, ARMOSA simulated crop rotations under a baseline scenario and 10 what-if scenarios which combined 5 different levels of animal stoking rate with 2 levels of N management for each farm. The models' outputs were scaled up to the farm level, using one representative hectare as functional unit, and used to estimate the annual N circularity at farm level by computing the CyCt. To assess the relative importance of predictors in explaining CyCt, a Random Forest regression model was fitted using the randomForest R package.

Results and Discussion

Results (Figure 1) showed that moderate stocking rates (1.5–2.5 LU ha^{-1}), combined with increased crop diversity—especially the inclusion of legumes—allow to enhance both crop NUE and N farm circularity. Excessively high or low stocking rates undermine circularity, either by overloading soil-crop N capacity or reducing manure availability. The findings suggest that strategic integration of crop and livestock management, rather than isolated technological fixes, is essential for enhancing circularity in European dairy systems.

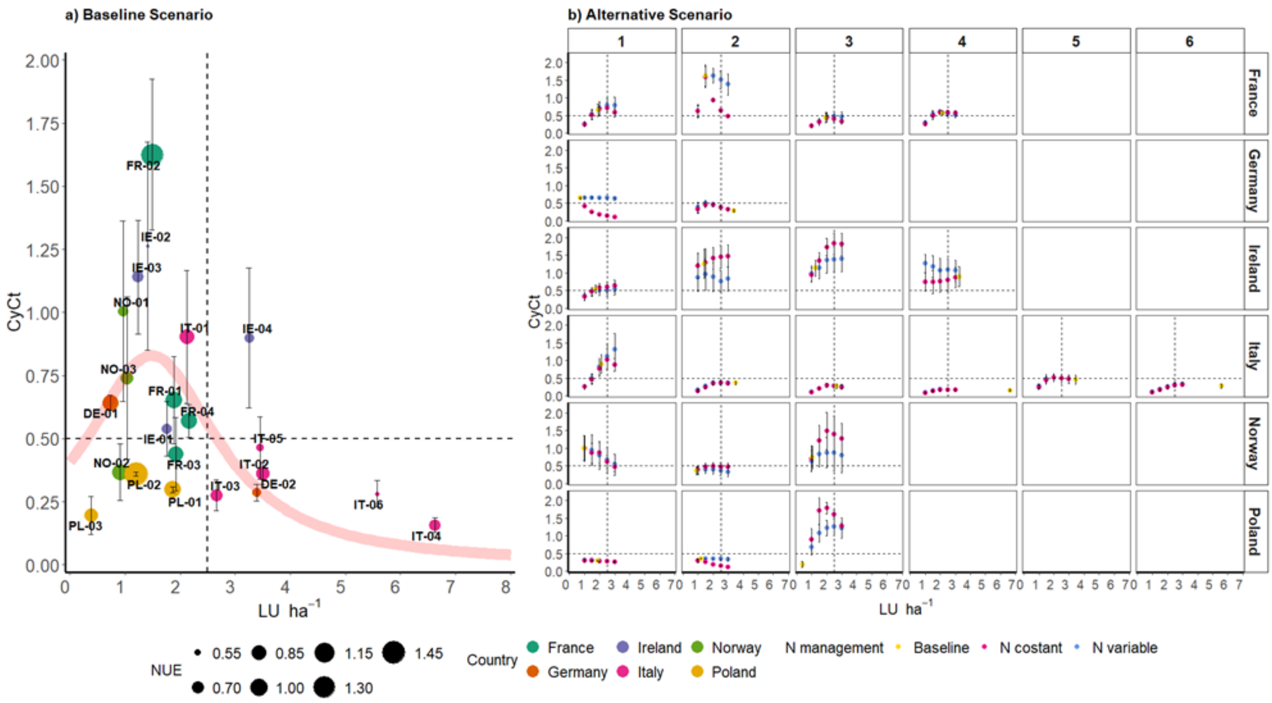

Figure 1. Cycle Count (CyCt) variation according to anaimal stoking rate in 22 case studies of European dairy cattle farms. A) each dot represents a case study, coloured according to country (France, Germany, Ireland, Italy, Norway, Poland). The size of the dot is proportional to the crop nitrogen use efficiency (NUE). B) effect of different nitrogen management scenarios on CyCt as a function of stocking rate for each case study (rows per country, columns per case). The dots represent the scenarios: baseline (yellow), constant N (fuchsia), variable N (light blue).

Conclusions

The approach adopted overcame the limitations of annual assessments by expanding the temporal and management perspective through 44 years of simulations, allowing to extend the range of explored management and environmental combinations. Our results show that improving nitrogen circularity in dairy systems requires integrated strategies that prioritize the optimization of stocking rates. A lower stocking rate reduces the nitrogen circularity potential due to insufficient organic nitrogen sources, which can result in reduced crop yields or a greater reliance on mineral fertilizers. The integration of modelling solution and farm data can be an effective approach for assessing the transition to more sustainable crop-livestock production systems.

Acknowledgements

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Crop Modelling for Agriculture
and Food Security under Global Change

Optimizing crop allocation to improve field productivity and resilience under heterogenous soil conditions.

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Keywords: spatial diversification, crop modelling, grain yield.

Introduction

Agricultural production faces the challenge to reduce environmental risk while improving system sustainability and resilience in the face of climatic change. Crop diversification represents a promising strategy to improve the delivery of ecosystems services, to support biodiversity as well as resilience. Heterogeneous soil conditions can affect crop productivity patterns but, they are barely considered in crop diversification strategies Therefore, the main goal of the current study, was to explore to which extent spatially diversified fields improve crop performance and resilience under heterogenous field conditions.

Materials and Methods

The input data for the current study was collected from the patchCROP landscape laboratory, in Brandenburg, Germany. The area is part of a young moraine undulated landscape with heterogeneous soil characteristics, leading to considerable spatial patterns in crop growth and yield productivity (Grahmann et al., 2021). Based on this data, we conducted a modelling experiment for eight winter and summer crops currently grown at the experimental site. For this, we used a validated process-based crop growth model within the SIMPLACE modelling framework (Enders et al., 2023; Hernandez-Ochoa et al., 2023). Crop management by crop was based on the 2020-2024 data and fixed every year. As for soil input data, we used a cluster map with top and subsoil information based on soil electromagnetic induction and soil augers from Dogar et al., (2025). Each cluster was represented by one 2 m soil profile with 3 layers with varying characteristics in top and subsoil. Each crop was simulated for a 30-year period (1980-2020) and for each soil cluster. To better understand the effect of crop allocation in heterogeneous field conditions, we tested different forms of field arrangements including a 9 m and 18 strip cropping and irregular polygons formed by the 5 clusters. Strip direction was paralell to the current tractor lines. To optimize the spatial allocation for maximum field productivity, we used the absolute weighted yield and attained yield (fraction of simulated yield obtained under water and nitrogen stress relative to the potential yield, under optimum non-stress conditions). Crop stability was measured as the coefficient of variation.

Results and Discussion

Simulated results showed an interaction of crop-cluster allocation, where in average, winter crops performed best in terms of attained and absolute grain yield in clusters 1 to 3, while barley, rapeseed, soybean, and rye performed best in clusters 4 to 5 (Figure 1). Optimizing field productivity resulted in low spatial diversification. We observed differences also on simulated crop productivity during extreme wet or dry years. Crop resilience of simulated crop yield varied by crop.

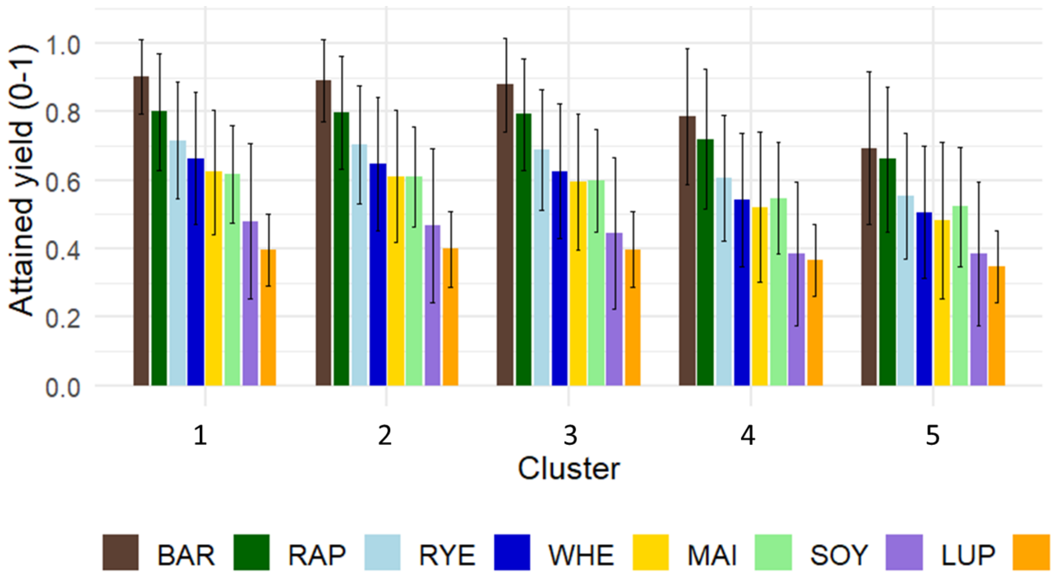

Figure 1. Simulated average attained grain yield fraction (0 to 1) by crop and cluster for winter (barley-BAR, rapeseed-RAP, rye-RYE, wheat-WHE) and summer (maize-MAI, soybean-SOY, lupine-LUP, and sunflower-SUN) crops growing at the patchCROP lab for a 30-year period (1990-2020). Error bars represent the standard deviation of weighted grain yields over the 30-year period.

Conclusions

We conclude, that while optimizing crop allocation had only a small effect on field productivity, it may offer enhanced resilience of the diversified field. Effects of diversified systems to supporting biodiversity and additional delivery of ESS is likely but has not been simulated yet. We also did not consider crop rotation, and border effects, which may have caused some underestimation of land use productivity in the present study. However, our study is indicative on some selected effects of crop diversification and the relevance of site-specific crop allocation.

Acknowledgements

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Crop Modelling for Agriculture
and Food Security under Global Change

Simulation of the interspecific dynamics of Mediterranean annual sown grasslands.

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Keywords: Forage mixes, Botanical composition, Grazing, CoSMo model, Monoculture parameters.

Introduction

In Mediterranean regions, growing season is limited to few months, forage production is sensible to climate change and natural grasslands are often poor. To address this challenge, farmers usually sow annual forage mixes. The botanical composition of these mixes evolves in response to environmental drivers. Changes in botanical composition directly affect key ecosystem services such as forage production.

In this context, the availability of decision support tools is essential (Soussana et al., 2012). Among the existing models, CoSMo dynamically estimates the botanical composition of the grasslands with good agreement and low complexity (Confalonieri 2014; Movedi et al., 2019). The model does not provide the states and rates of each simulated species, but it uses changes in relative abundance of the different species to estimates at each time step a weighted average of the species parameters in monoculture, which is then used for the simulation.

The aim of this project is to adapt CoSMo to simulate Mediterranean sown forage mixes.

Materials and Methods

The adopted modelling solution link CropSyst crop model (Stöckle et al., 2003) to CoSMo.

This solution was already tested in other context (Movedi et al., 2019, Movedi et al., 2023) and for this reason the parametiraztions of some speces was available.

The field trial was carried out in Sardinia, in the 2024/2025 growing season, in four experimental sown fields: one with species in monocultures and three adopting commercial mixes. The aim of field trials was twofold: collecting the CropSyst parameters in monoculture and generating a dataset of state variables to test the model with the species in competition and with and without grazing.

The collected dataset had 4 variables: botanical composition, above ground biomass (AGB), plant height and leaf area index (LAI), it included data collected pre grazing, post grazing and never grazed.

Model was parametrized using: the value collected in the experimental field, the existing parametrization for three species and the trial-and-error method for the other species. The dataset was divided into calibration (2 field) and validation (1 field).

Weather, soil and management information were available for the trial fields.

Results and Discussion

Model state variables, after the parameterization, agreed with the observed ones and there was no change of model behaviour or loss of agreement while shifting from calibration to evaluation (Fig. 1).

In detail for LAI, the absolute error (MAE) was around 0.75 m^2 m^{-2}, relative root mean square error (RRMSE) was close to 31% and the model efficiency (EF) ranged from 0.37 in calibration to 0.51 in validation. For botanical composition, MAE ranged from 5% in validation to 7% in calibration, RRMSE ranged from 38% in validation to 55% in calibration, EF ranged from 0.81 in calibration to 0.92 in validation. For AGB, MAE was close to 1 t ha^{-1}, RRMSE ranged from 33% in validation to 57% in calibration, EF ranged from 0.14 in calibration to 0.58 in validation; for plant height the agreement was worse than for the other variables: MAE was round 0.2 m, RRMSE was closed to 60%, EF ranged to 0.56 in validation to 0.62 in calibration.

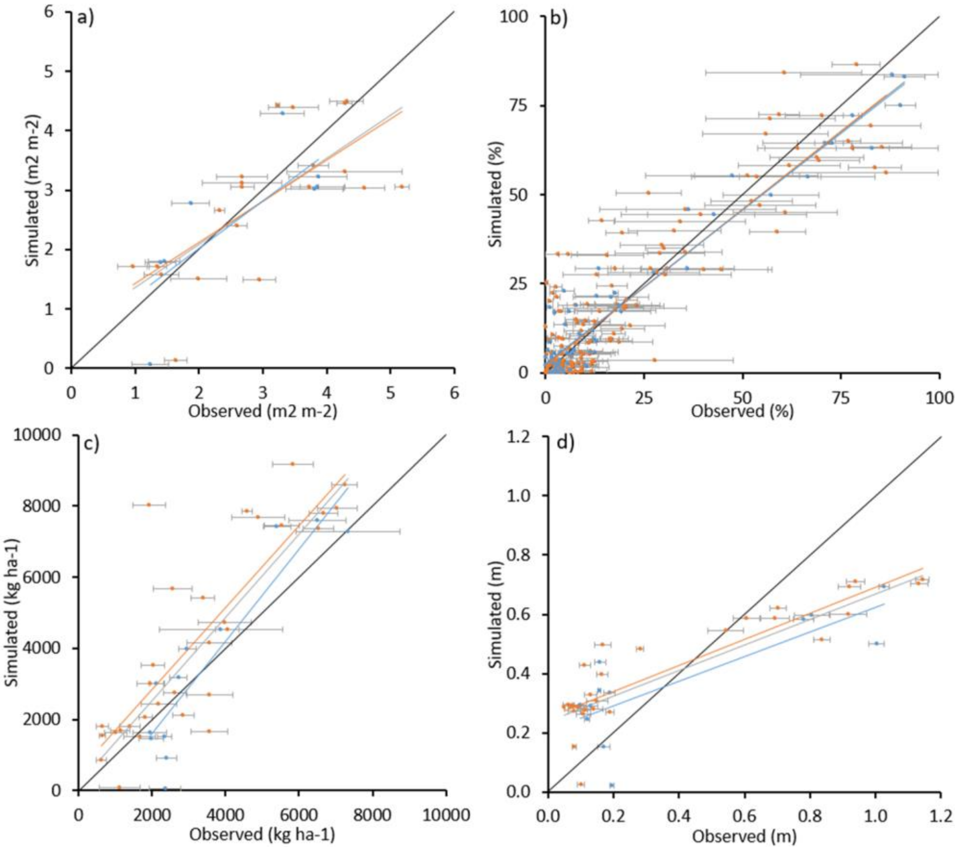

Figure 1. Comparison between observed and simulated variables: a) LAI; b) botanical composition; c) AGB; d) plant height. Red dots: couples of observed *vis* simulated data in calibration; blue dots: couples of observed *vis* simulated data in validation; black line: $y = x$; gray line: regression line of the overall data; red line: regression line of calibration; blue line: regression data of validation; grey bar around observed points: ½ standard error left and ½ standard error right.

Conclusions

In conclusion, considering the good agreement achieved, CoSMo was considerable ready to be adapted as decision support tool for the Mediterranean pasture. For example, model can be used to select mixes composition that optimize the forage production or adjust the grazing timing.

Acknowledgements

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Crop Modelling for Agriculture
and Food Security under Global Change

New European datasets on agricultural land use and farming practices from Earth Observation, survey, administrative sources, and model applications

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Keywords: Farm Structure Survey, Copernicus High Resolution Layers, CAPRI, LUCAS, EMBAL, CAP declarations.

Introduction

Recent developments are improving our capacity to represent the spatial, temporal, and thematic detail of European agricultural activities. These developments include but are not limited to the recently published Copernicus High Resolution Layers, the Farm Structure Survey, European-Union wide in-situ monitoring schemes, and increasingly available farmers' declarations. Together these provide a new and comprehensive view on European agriculture and farming. This covers geospatial data on agricultural land use including annual crop type maps, livestock numbers, information on farming practices, including crop rotation, grassland mowing, as well as organic farming and tillage, nutrient budgets, biodiversity, as well as socio-economic variables such economic farm size and the age and gender of farm managers. Here we illustrate these datasets and highlight their large potential to enrich baselines, assessments, and scenario development, with implications for indicator design and model applications.

Materials and Methods

Recently published datasets and model outputs that will be discussed include:

- High Resolution Layers on Cropland and Grassland (Claverie et al., 2026)
- Geospatial layers from the Agricultural Census / Farm Structure Survey (Skoien et al., 2025, Lampach et al., 2025) and see Geospatial data from agricultural census - Experimental statistics - Eurostat
- Disaggregated CAPRI model layers (Koeble et al., 2026)
- LUCAS and EMBAL in-situ land monitoring schemes (e.g. d'Andrimont et al., 2024 and European Commission, Joint Research Centre (JRC) (2025)) and see EMBAL_anon
- Harmonized and publicly available farmers' declarations (e.g. Schneider et al., 2024)
- JRC Farming practices dashboard (Schievano et al., 2024 and 2025) and see JRC - Farming Practices Evidence library

Furthermore, the various methodological developments behind these different datasets that allowed publishing these European Union wide datasets are presented, including implementing legal rules on confidentiality and privacy for statistical disclosure control, knowledge synthesis, rapid survey approaches, semantic harmonization of crop code lists, and interoperability procedures to cross-linking these datasets overcoming bureaucratic and technical barriers.

Results and Discussion

Several applications are presented to illustrate the value of these different sources of information. Furthermore, we show how combining these datasets with information on the impact of farming practices can lead to new insights.

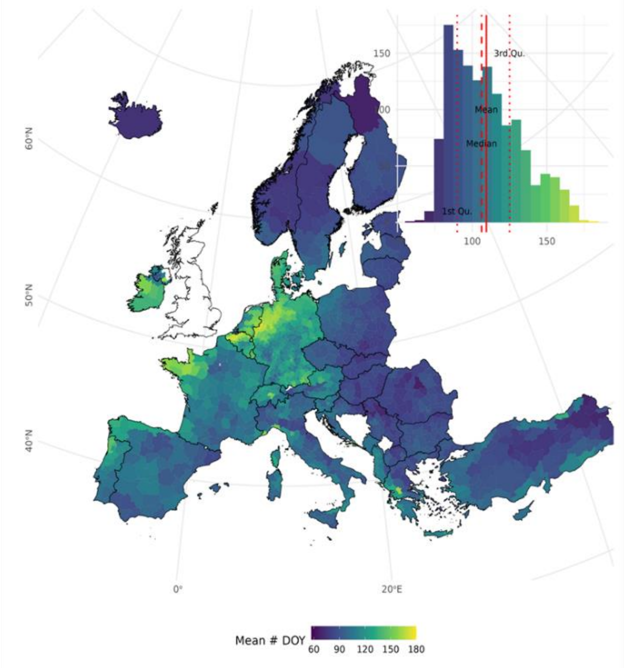

Figure 1. Secondary crop presence (mean number of days)

We illustrate how farm typologies can be characterized better, how we can benchmark and understand organic farming uptake, and how we can provide detailed data on farm practices, for instance on secondary crop presence as derived from the Copernicus High Resolution Layer. Finally, we highlight how farm and crop system models can be enriched by incorporating this information.

Conclusions

There is a need to strengthen European Union wide datasets that are consistent, harmonized, and continuous. We reach out to the crop modelling community so these datasets can find more uptake and improve scientific assessments to ultimately enable better EU decision making.

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