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# Crop Modelling for Agriculture and Food Security under Global Change

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## POSTER

**SESSION 3 – SUSTAINABILITY, ECOSYSTEM SERVICES, AND BIODIVERSITY**

# Digital tool for accessible and comprehensive sustainability assessment: application in two cropping systems in the Mediterranean climate

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**Keywords:** Soil carbon, SOC, Performance indicators, Carbon trial, Cropping system.

## Introduction

Climate change severely threatens agriculture in Mediterranean regions, characterized by hot, dry summers and mild, wet winters (del Pozo, 2019). Yet, the Mediterranean agricultural soils are highly degraded and the fragmented agriculture leads to poor soil health strategies (Ferreira et al., 2022). Few accessible frameworks integrate process-based models for farm-level climate-mitigation assessments in the Mediterranean conditions. In response to this, Horta Srl created a tool that combines soil fertility and LCA approach assessments to assist the agri-food supply chain in the decision making and post-season evaluations. The tool was tested in a long-term field experiment comparing two cropping systems representative of Mediterranean agriculture.

## Materials and Methods

The tool calculates Life Cycle Assessment (LCA) indicators following ISO 14000 and Product Environmental Footprint (PEF) standards and simulates field level soil organic carbon (SOC) and nitrogen dynamics with a process-based model. Figure 1 illustrates the elements that constitute the tool and their connections. Inputs include field description, soil analysis, meteorological data from a chosen weather station, and crop operations with input materials. Material and energy flows are estimated to obtain updated LCA indicators. Sub-models and databases are linked to an agronomic decision support system (Horta DSS), which also provides agronomic recommendations.

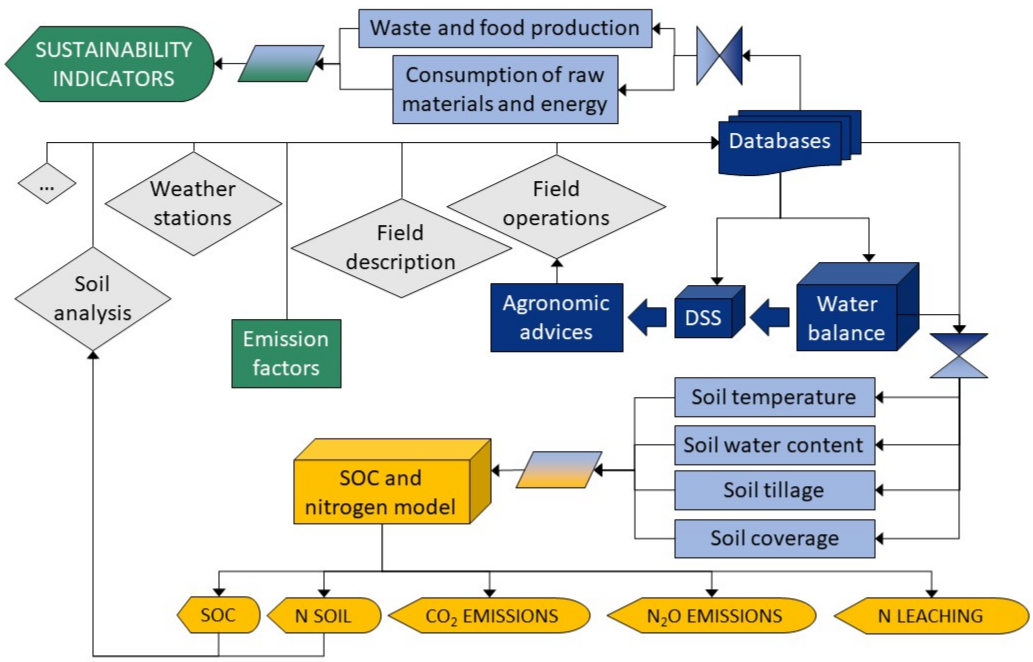


*Figure 1*. Data flow in Horta Srl tool for the sustainability assessment of agronomic activities.

SOC dynamics are based on the RothC model (Coleman and Jenkinson, 1996), adapted for Mediterranean conditions via RothC20_N (Farina et al., 2013) and for the inclusion of non-vegetation amendments (Mondini et al., 2017). The model is integrated in Horta DSS and sub-models and accounts for soil temperature, water content, vegetation cover, and tillage.

The tool was tested on a long-term rotational trial started in 2019 in two Italian sites (Ravenna and Foggia) with different climate and soil. Two cropping systems were tested with 4 replicates: Conventional Cropping System (CCS) recreated a common rotation for the area, and Efficient Cropping System (ECS) added legumes and cover crops in the rotations and DSS-based management.

Measurements included annual SOC and carbon in retained residues (all plots) and soil respiration (Rs; ECS and CCS, two plots per site) using eight permanent GHG emission chambers, allowing the calibration of soil carbon dynamics.

**Results and Discussion**

The trial duration is still not appropriated to detect significant changes in SOC, nevertheless ECS performed well compared to CCS in SOC measurements and LCA evaluations (Table 2). ECS reduced the sustainability impact maintaining the same food production, especially in Ravenna with an average of -11%; in Foggia sustainability was highly impacted by drought effects.

*Table 1*. Sustainability indicators produced by Horta's tool for Agrestic sites from 2020 to 2025, averaged between ECS and CCS plots.

| Site | System | Eco Tox Score | Water supply | Dose Area Index | Treatment Frequency Index | Human Tox Score | Water Footprint ($m^3$ $H_2O$ $t^{-1}$) | Carbon Footprint (t $CO_{2\,eq}$ $t^{-1}$) | Carbon Footprint (t $CO_{2\,eq}$ $ha^{-1}$) | Ecological Footprint (Global ha $t^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| Ravenna | ECS | 69.91 | 1.51 | 7.83 | 9.00 | 68.56 | 977 | 0.22 | 2.44 | 0.42 |
| Ravenna | CCS | 80.30 | 1.92 | 8.56 | 9.77 | 72.30 | 905 | 0.25 | 3.19 | 0.31 |
| Foggia | ECS | 34.11 | 1.14 | 3.75 | 4.68 | 38.49 | 3171 | 1.21 | 1.52 | 3.87 |
| Foggia | CCS | 46.77 | 1.09 | 5.00 | 5.98 | 59.67 | 1799 | 0.62 | 2.15 | 1.07 |

Soil respiration averaged 0.38 in Ravenna and 0.25 tC $ha^{-1}$ $month^{-1}$ in Foggia. Respiration was higher under CCS in Ravenna, but higher under ECS in Foggia. The calibrated carbon degradation rates deviated by only ~5% from default values, confirming good model performance in Mediterranean contexts.

**Conclusions**

Although the study duration limited SOC detection, the tool successfully quantified environmental performance with minimal data, distinguishing between contrasting management practices. A longer monitoring period is needed to assess SOC changes robustly. Future improvements should integrate soil health and biodiversity indicators for a more comprehensive sustainability evaluation, despite associated methodological challenges.

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## ACEA: an open-source global gridded crop model to simulate green and blue crop water use

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**Keywords: AquaCrop, crop modelling, crop water productivity, water footprint, climate change**

### Introduction

Water availability is a primary determinant of crop growth, and hence, accurately simulating how much water is available in the soil is essential for crop yield estimations. We can distinguish between two water sources: *green water*, which refers to soil moisture derived from precipitation, and *blue water*, which includes surface water and groundwater applied through irrigation or abstracted via capillary rise. Both sources play a critical role in global food production, but their dynamics differ substantially depending on local climate, crop and soil types, and field management practices.

Most crop models typically simulate total evapotranspiration (ET) without explicitly partitioning it into green and blue components as they do not trace the origin of water fluxes within the soil-plant-atmosphere continuum (Hoekstra 2019). Consequently, they cannot accurately quantify green ET and blue ET or, in other words, how much of the crop water consumption originates from rainfall versus irrigation. This distinction is particularly important under conditions of water scarcity and climate variability. In many regions, excessive reliance on green water availability (rainfed croplands) can result in high crop yield variability, whereas the excessive reliance on limited blue water resources for irrigation can lead to groundwater depletion, river flow reduction, and ecosystem degradation.

This work presents a recently developed global gridded crop model (GGCM) called ACEA (Mialyk et al. 2022), which can simulate crop-specific yields and daily green and blue ET at high spatial resolution. In the following section, we describe the model in detail, highlight recent applications, and implications for agricultural water management.

### Crop model description

AquaCrop-Earth@lternatives (ACEA) is a GGCM based on the latest version of AquaCrop-OSPy 7.1 (Kelly and Foster 2021). As shown in Figure 1 (left), crop growth is represented by dynamic rooting depth and canopy cover, both driven by growing degree days. Through canopy cover, a crop transpires the abstracted by roots water, which drives the above-ground biomass growth considering a CO2-adjusted water productivity. Water fluxes are traced daily allowing for precise estimation of green and blue water volumes consumed for transpiration and soil evaporation. Throughout the growing season, crop development is subjected to thermal and water deficit stresses, which may slow down crop development or even lead to crop failure (salinity is not considered).

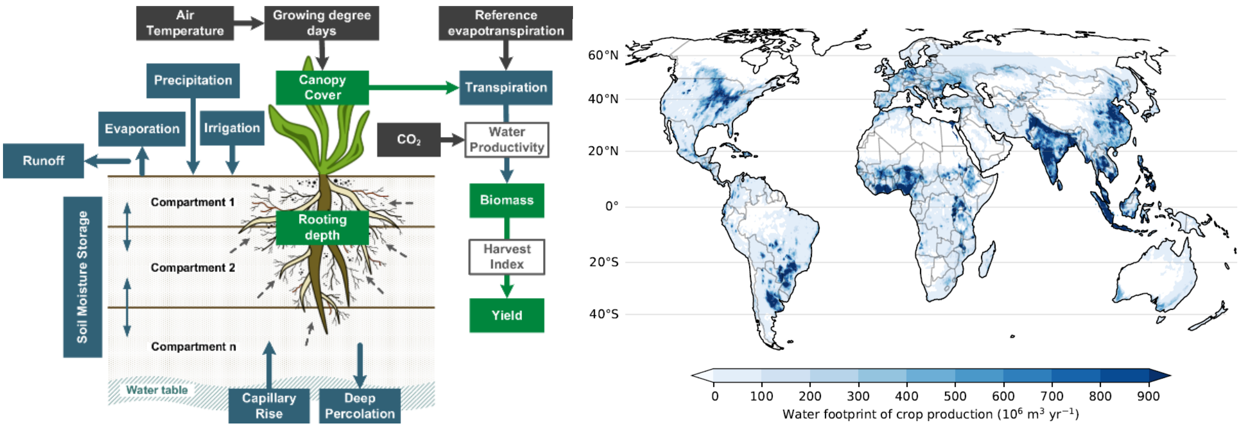


*Figure 1*. Considered water fluxes (blue boxes) and main plant growth processes (green boxes) in ACEA (left), adopted from Mialyk et al. (2024a). Global distribution of the total (green plus blue) water footprint of crop production in 2017–2019 (right), adopted from Mialyk et al. (2024b).

Currently, ACEA can run 50+ individual annual and perennial crops and there are both 5 and 30 arcmin versions available via GitHub, both based on the best-to-date input data for climate, soil characteristics, and field management practices (e.g. soil fertility, irrigation).

**Recent model applications**

The most recent global ACEA applications include studies by Mialyk et al. (2024b) and Su et al. (2025). Mialyk et al. used the model results to analyse historical changes in green and blue water footprints of 175 individual crops since 1990 (see Figure 1, right). In this study, ACEA was initally applied at 30 arcmin resolution (≈ 55 x 55 km at the equator) and the outputs were then allocated among 5 arcmin (≈ 9 x 9 km) grid cells based on crop distribution maps. A similar appoach was taken by Su et al. who looked into crop-water productivity of small- versus large-scale farmers. The authors further upgraded the model to include soil fertility stress. Currently, ACEA is also being used to assess global green water scarcity (or precipitation deficit) during both historial and future under climate change periods in order to identify the opportunies for irrigation development as an adoptation measure.

Beyond global applications, ACEA is presently applied at 5 arcmin resolution to study crop water footprints in Spain and Central Asia (https://weact-project.eu). In these regional cases, some model inputs are replaced with local datasets to better reflect regional characteristics. For example, in Spain, the availability of detailed irrigation statistics allows for improved calibration of irrigation parameters. On the contrary, in Central Asia, the absence of high-quality inputs requires adjustments to crop parameters and calendars using remote sensing data.

ACEA is also one of several GGCMs contributing to the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) and Global Gridded Crop Model Intercomparison Project (GGCMI).

**Conclusions**

Despite being recently developed, ACEA has already demonstrated its usefulness in providing robust crop water use estimates. The open-source code allows for project-specific model adjustments as demonstrated by the recent global and regional applications. More importantly, ACEA's ability to assess green and blue water contributions in crop production, can allow policymakers, farmers, and researchers better manage limited water resources and ensure food security under changing climate conditions.

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## Diagnostic vs. prognostic modelling approach to estimate ecosystem fluxes in grasslands

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**Keywords: biogeochemical cycle, crop modelling, grassland management, net ecosystem exchange**

### Introduction

Grasslands are worldwide terrestrial biomes, which provide multiple ecosystem services, including biodiversity protection, food production, and carbon storage (Bengtsson et al., 2019). In particular, these biomes act as carbon sink systems by playing a key role in mitigating climate change. However, grassland management practices (e.g. inappropriate nitrogen fertilization) can influence forage, soil and water production and quality as well as the net ecosystem $CO_2$ exchange (Guo et al., 2021). In this regard, existing biogeochemical models (e.g. DayCent, DNDC, PaSim, etc.) simulating water, carbon and nitrogen cycles have proven to be useful tools for assessing the impact of agronomic management on grasslands (Thentu et al., 2025). Despite the implementation of increasingly effective algorithms, an advantage for improving fluxes estimation could be provided by the integration of remote or proximal sensors data that currently play an important role in monitoring vegetation and ecosystem fluxes. The objective of this study is therefore to test the diagnostic (remote sensing data-driven model) and prognostic (non-driven model) approach of the GRASSVISTOCK model (Leolini et al., 2025) for estimating fluxes in grasslands.

### Materials and Methods

GRASSVISTOCK (Leolini et al., 2025) is a semi-mechanistic modelling approach which simulates grassland growth, water and carbon fluxes in agro-pastoral systems. The model was developed from the previous version of Bellini et al. (2023), in which the satellite-derived leaf area index (LAI) is used to estimate grass biomass accumulation (diagnostic approach). In its current version (Leolini et al., 2025), the model integrates the previous version with a prognostic approach, in which leaf life cycle and LAI are estimated based on temperatures and used to simulate grass biomass. The model is based on gross radiation use efficiency (RUE) approach for initially estimating gross primary production (GPP), then re-scaled to net primary production (NPP) by considering the autotrophic respiration. Water and thermal stresses are calculated for reducing initial RUE and convert potential to actual biomass. In this regard, soil water balance simulation is used to describe water dynamics and define the water stress that influences vegetation growth. Finally, the model is coupled with the soil organic carbon turnover module (RothC; Coleman & Jenkinson, 1996) to simulate litter decomposition and soil respiration. Currently, the implementation of the model with the nitrogen balance is in progress. The model is applied in two grasslands that are part of FLUXNET project: AT-Neu (47.12°N, 11.32°E, 970 m) and CH-Cha (47.21°N, 8.41°E, 393 m), characterized by different climates and management practices.

### Results and Discussion

The diagnostic version of the model was initially tested in a semi-natural pasture in the Alps chain (Torgnon), by obtaining good performances in NPP calibration ($R^2$> 0.94, RRMSE<25%) and validation ($R^2$> 0.84, RRMSE<27%). This approach was compared with the prognostic model version, which showed satisfactory but lower performances at simulating grass NPP ($R^2$ = 0.46, RRMSE=42%), when applied at the same site. These results indicate that the use of remote sensing derived information improves the NPP simulations compared to the modeled version. However, the prognostic version allowed to simulate NPP and ecosystem fluxes regardless of the need to acquire remote sensing data (Leolini et al., 2025). The prognostic model approach was applied to simulate water and C fluxes in AT-Neu and CH-Cha sites. The model obtained good performance at simulating fractional transpirable soil water in AT-Neu ($R^2$ = 0.82, RRMSE = 24%), while satisfactory model performances were also obtained at simulating GPP ($R^2$ =0.50, RRMSE = 73% vs $R^2$ =0.50, RRMSE = 58%) and RECO ($R^2$ = 0.32, RRMSE = 70% vs $R^2$ = 0.37, RRMSE = 61%) in AT-Neu and CH-Cha sites, respectively.

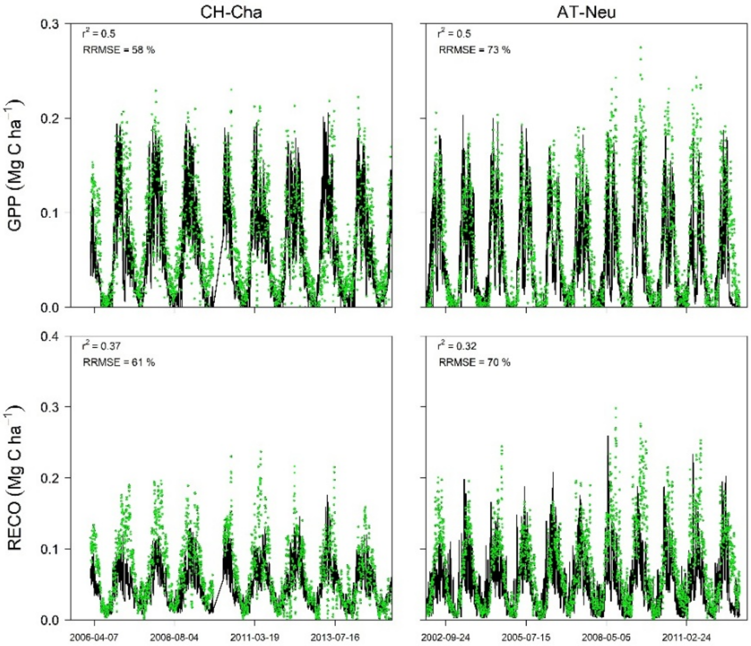


*Figure* 1. Comparison between observed (green points) and simulated (black lines) values of GPP and RECO (Mg C $ha^{-1}$) in AT-Neu and CH-Cha grasslands.

## Conclusions

The diagnostic approach of the GRASSVISTOCK model allows NPP and ecosystem fluxes to be estimated when high-precision data are available. This approach could be used to replace the state variables simulated by the model (e.g., LAI) and provide an alternative to the prognostic version when remote sensing data are available. Conversely, when well calibrated, the prognostic version of the model favors the application of the model in environmental conditions where external resources are not available.

## Acknowledgements

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Sustaining and enhancing food production is essential for reducing food insecurity across Africa (Abdi et al., 2024). In the Sudano-Sahelian zone, rainfed agriculture is predominant and serves as a major source of food and income for both rural and urban populations. In northern Cameroon, cotton and maize are commonly cultivated in rotation within cropping systems that employ improved cultivars, soil tillage, fertilizers, and pesticides. Despite such intensification, agricultural productivity is increasingly challenged by soil degradation, climate variability, and climate change.

Agroecological practices, particularly agroforestry, offer promising solutions to these challenges by improving sustainability (Raihan, 2023). For the past 40 years, agroforestry has been promoted in the region for its additional benefits, including enhanced crop resilience. To assess the sustainability of crop yields under climate variability and change, crop modeling is a valuable tool (Asseng et al., 2014). However, modeling agroforestry at the plot scale remains challenging, as it requires dynamic data on both tree and crop growth.

This studies and explores the feasibility and potential benefits of agroforestry using a simplified modeling approach. Crop models for cotton and maize were calibrated based on a two-year field experiment that tested different fertilization levels and sowing dates. Additional observations were conducted in 122 farmer-managed plots across three parkland systems in northern Cameroon. Measurements included microclimate (light, temperature, humidity), soil and nitrogen water content, crop growth, and yields. These data were used to adjust climate and soil input files for model evaluation. Subsequently, future climate scenarios were applied to assess the resilience of agroforestry systems.

The results highlight the benefits of agroforestry under rising temperatures, particularly on degraded or nutrient-poor soils. The study also demonstrates that even a simplified crop modeling approach can be effective in predicting phenology and yield outcomes in agroforestry systems under climate change.

**Keywords:** DSSAT, Faidherbia albida, climate change, Gossypium hirsutum (L.), Zea mays, crop-model.

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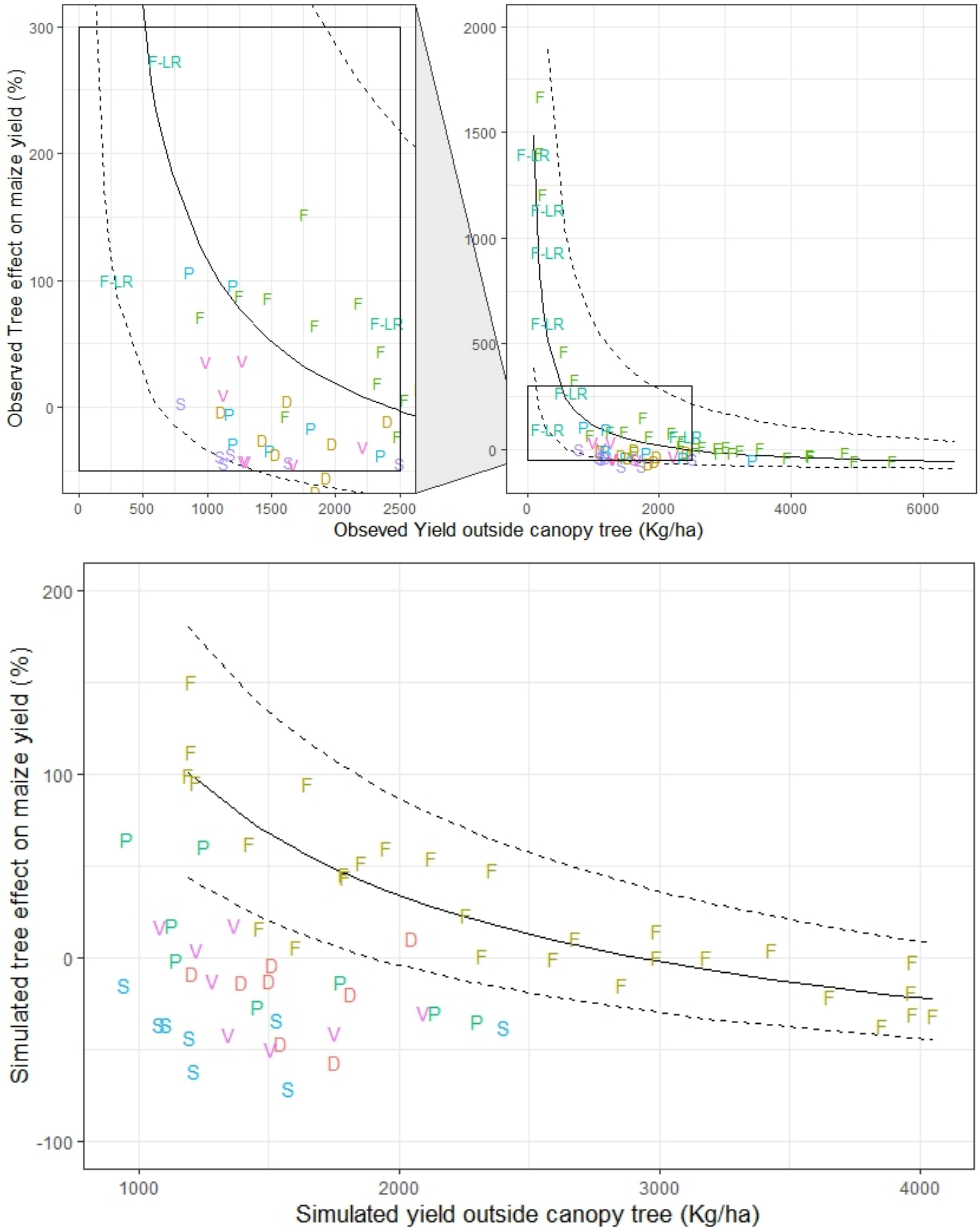


*Figure 1: Observed (with zoom subplot) and simulated effect of tree on maize yield below the canopy according to the simulated yield of the control plot. Letter are tree species (F Faidherbia albida, F-LR: references for Faidherbia, S: Senna siamea , P: Prosopis africana, V: Viteralaria paradoxa, D: Daniella oliveri). Regression (line) and confidence interval (dotted line) for Faidherbia albida.*

# MODELLING GHG EMISSIONS FROM A DOUBLE-RICE CROPPING SYSTEM IN TAIWAN USING DNDC AND DSSAT: EVALUATION WITH HIGH-FREQUENCY CHAMBER MEASUREMENTS

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Rice paddy systems are a significant source of agricultural greenhouse gas (GHG) emissions, particularly methane ($CH_4$) and nitrous oxide ($N_2O$). Accurately quantifying these emissions is essential for assessing mitigation strategies and informing climate-resilient agricultural policies. This study evaluates the performance of two process-based models, DNDC and DSSAT, in simulating $CH_4$ emissions from a double-rice cropping system in Taiwan during the growing seasons in 2024 and 2025.

Data collections were conducted in Ankang, northern Taiwan, using automated static chamber systems coupled with a laser-based gas analyzer to capture high-frequency (hourly) $CH_4$ and $N_2O$ fluxes. Two water management regimes were tested: conventional mid-season drainage (MSD) and alternate wetting and drying (AWD), with AWD water levels maintained between -5 cm and +5 cm. Fertilizer application and other agronomic practices were consistent with local farmer norms.

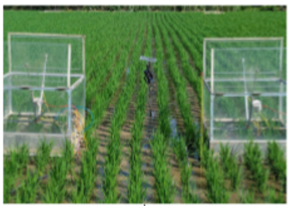
$CH_4$ fluxes showed a positive correlation to air temperature while $N_2O$ showed a mild negative correlation. Soil moisture content showed only a weak correlation with methane but was nevertheless a prerequisite for its production and a prolonged suppression effect to methane after drainage was observed. Diurnal change of methane was not always observed in all growing seasons, it had a higher chance to show under warm conditions.

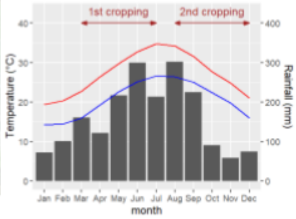
Both DNDC and DSSAT were calibrated using site-specific soil, weather, and management inputs. However, the models produced notably different outputs in both magnitude and temporal patterns of GHG emissions. Though both models captured the methane decline after mid-season drainage in the first season, the 'champagne effect' - a peak that happened during the drying period, however, was not captured by both models. The prolonged suppressive effect was not captured in both models, either. In the second season, DSSAT could better simulate the condition that the soil was not really drying during the drainage period due to precipitation. On the other hand, simulation of methane from DNDC dropped immediately after the drainage day.

Our findings highlight the importance of high-frequency field data for evaluating model performance in complex systems like double rice cropping under varying water regimes. The inter-model variability suggests structural differences in water and nitrogen submodels, as well as differing sensitivities to soil redox conditions. This study provides insights into the limitations and complementarities of current crop models for GHG simulation and suggests pathways for model refinement and ensemble approaches in future mitigation assessments.

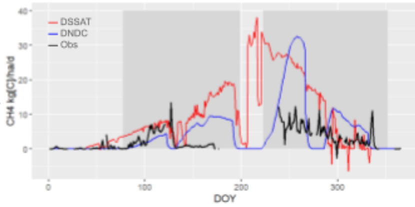
**Keywords:** Greenhouse gas emissions; DNDC; DSSAT; rice paddy; methane; alternate wetting and drying

Field data collection:
management, weather, soil and hourly GHG






Data process
and analysis


Conclusion:
DSSAT and DNDC could capture the trend of methane emission from paddy rice fields. However, the ability to simulate changes during transitions (drainage or drying periods) is still limited. The prolonged suppressive effect after effective drainage was also not captured in both models.

## Assessing Soil Health through Ecosystem Service Bundles Modelling

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**Keywords: soil ecosystem serivces, ARMOSA, crop-growth modelling**

### Introduction

Soil health is increasingly recognized as a key factor for agricultural productivity, environmental sustainability, and ecosystem resilience. However, its assessment remains challenging, as soil functions integrate multiple physical, chemical, and biological processes that interact across space and time (Sellami et al., 2025). To address this complexity, the study proposes an integrated approach based on process-based modelling and the analysis of ecosystem service bundles, using the FLOWS/ARMOSA model as the core tool.

### Materials and Methods

The primary objective of this work is to propose a methodology for assessing a bundle of key soil ecosystem services (SESs) as a foundation for evaluating the potential soil health status. To achieve this, we employ the ARMOSA model (Perego et al., 2013), which simulates various processes by performing balances of water, carbon, and nitrogen cycles within the soil-plant-atmosphere continuum. Figure 1 presents a step-by-step outline of the proposed methodology:

- Soil parameters: These parameters (either directly measured or indirectly derived) can be used in two ways: (i) combined into indicators for a direct assessment of proxi of SES and then of soil health status, or (ii) used as model inputs, together with climate data and management practices, as done in the present study.
- Function/processes: We adopted a process-based model that enables the investigation of crop production as well as water, carbon, and nitrogen cycles.
- Ecosystem services: The results of the modelling simulations can be aggregated at various levels to assess multiple ecosystem services soil, to establish a comprehensive understanding of its multifunctionality. In this study, we focused on four key ecosystem services (Food provisioning, Water Regulation, Carbon Sequestration & Climate Regulation, and Nutrient cycling) by deriving 9 indicators from the aggregation of model outputs across different temporal and spatial scales.
- Soil Health: Soil health represents the final step of the proposed methodology, grounded in the assessment of a bundle of soil ecosystem services.

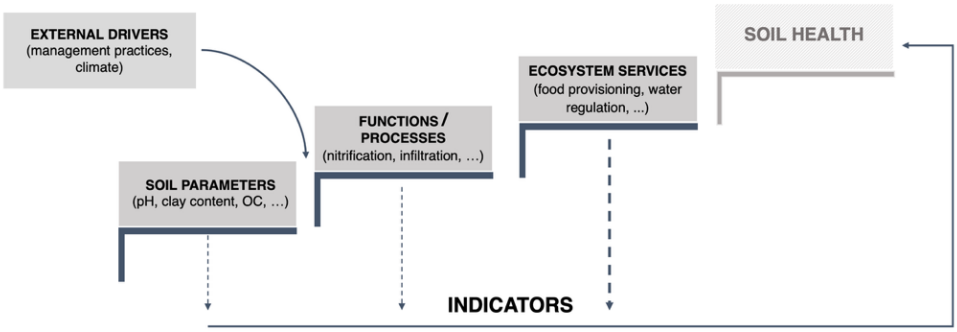


*Figure 1*. Schema of the proposed approach.

This methodological approach is illustrated through an application example in a large area cultivated with Durum wheat in the Campania Region, located in southern Italy.

**Results and Discussion**

The findings emphasize the critical need for employing multiple indicators to assess soil ecosystem services and then the potential soil health, integrating the approaches based on single-point measurements. Our results revealed significant spatial variability in soil ecosystem services, underscoring the necessity for localized strategies tailored to specific environmental and agricultural contexts.

**Conclusions**

Future applications will help identify key ecosystem processes and parameters, guide the selection of system-specific measurements, and explore long-term changes through 'what-if' simulations, fostering stakeholder engagement via geospatial decision support tools.

**Acknowledgements**

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# Modeling vegetables response to nitrogen and phosphorus in contrasting field environments using the DSSAT-CSM model

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**Keywords:** Cropping System Model, Specialty crops, Growth, Nitrogen, Phosphorus.

## Introduction

High-input field-grown vegetable crops grown in sandy, low nitrogen (N) retention or high-organic-matter, low phosphorus (P) retention soils under variable weather are highly vulnerable to nutrient losses. Therefore, Best Management Practices (BMP) are essential to balance yield, profit, and environmental harms (Scholberg et al., 2013). Combining field experiments with computer modeling systems analysis is a potential way to support nutrient management recommendations. One of the most widely used models is the Cropping System Model (CSM) of the Decision Support System for Agrotechnology Transfer (DSSAT) (Hoogenboom et al., 2019). In this context, the overarching goal of this modeling work is to evaluate and expand the capability of DSSAT-CSM to predict vegetable crop growth, yield and response to the environment and to N and P fertilization in order to support BMP development for vegetable production, particularly in Florida, United States (FL) where the abovementioned environments typically occur. Specifically, the project focused on model performance for potato (*Solanum tuberosum* L.; N), tomato (*Solanum lycopersicum* L.; N and P), bell pepper (*Capsicum annuum* L.; N) and green bean (*Phaseolus vulgaris* L.; N and P) using detailed growth and nutrient measurements of irrigated crops grown under contrasting environments across FL.

## Materials and Methods

Published field experimental data spanning from 1991 to 2022 for irrigated vegetable production systems from multiple locations in FL were modeled. Development, growth and nutrient (N or P) data for all crops came from comprehensive replicated experiments. Tomato and bell pepper were grown under raised bed, plastic mulch conditions. The DSSAT-CSM version v4.8.5 (Hoogenboom et al., 2024) was used, where the CROPGRO module (Boote et al., 1998), a core crop model in DSSAT-CSM, was employed for the simulations of all crops except potato for which the SUBSTOR module (Singh et al., 1998) was used. DSSAT default methods for the simulation of the soil water balance, potential evapotranspiration, and soil evaporation were adopted. Carbon and N (and P) dynamics were simulated with the soil organic matter CENTURY-Parton module, except for the potato experiment that was previously calibrated using the CERES-Godwin module. Model calibration and evaluation of crop development, growth and yield were individualized for each cultivar. Calibrations were needed for both plant N and P coefficients. In CROPGRO, plant N parameterization involved setting tissue composition, the relative rate of N mobilization and tissue senescence. P parameterization involved defining the optimum and minimal tissue composition over the crop cycle and empirical root traits for P uptake. Common statistical metrics were used to assess model performance.

**Results and Discussion**

Harvestable dry weight yield is presented in Figure 1 for each individual crop for the N experiments from different selected sites. The results showed that the CROPGRO model is robust enough to predict development, growth, and yield in response to different environments and N (tomato, bell pepper and green bean; Figure 1) and P (tomato and green bean; results not shown) fertilization after ensuring parameterizations were good. Similarly, the SUBSTOR model provided decent simulations for the response to the N rate and timing in potato grown in the most important growing region in FL. For future directions it is recommend to evaluate the model with new cultivars that are currently used by vegetable growers, as well as to evaluate the model for more contrasting environments beyond FL and its cropping systems, i.e. processing tomatoes, and more diverse P data from experiments in more environments.

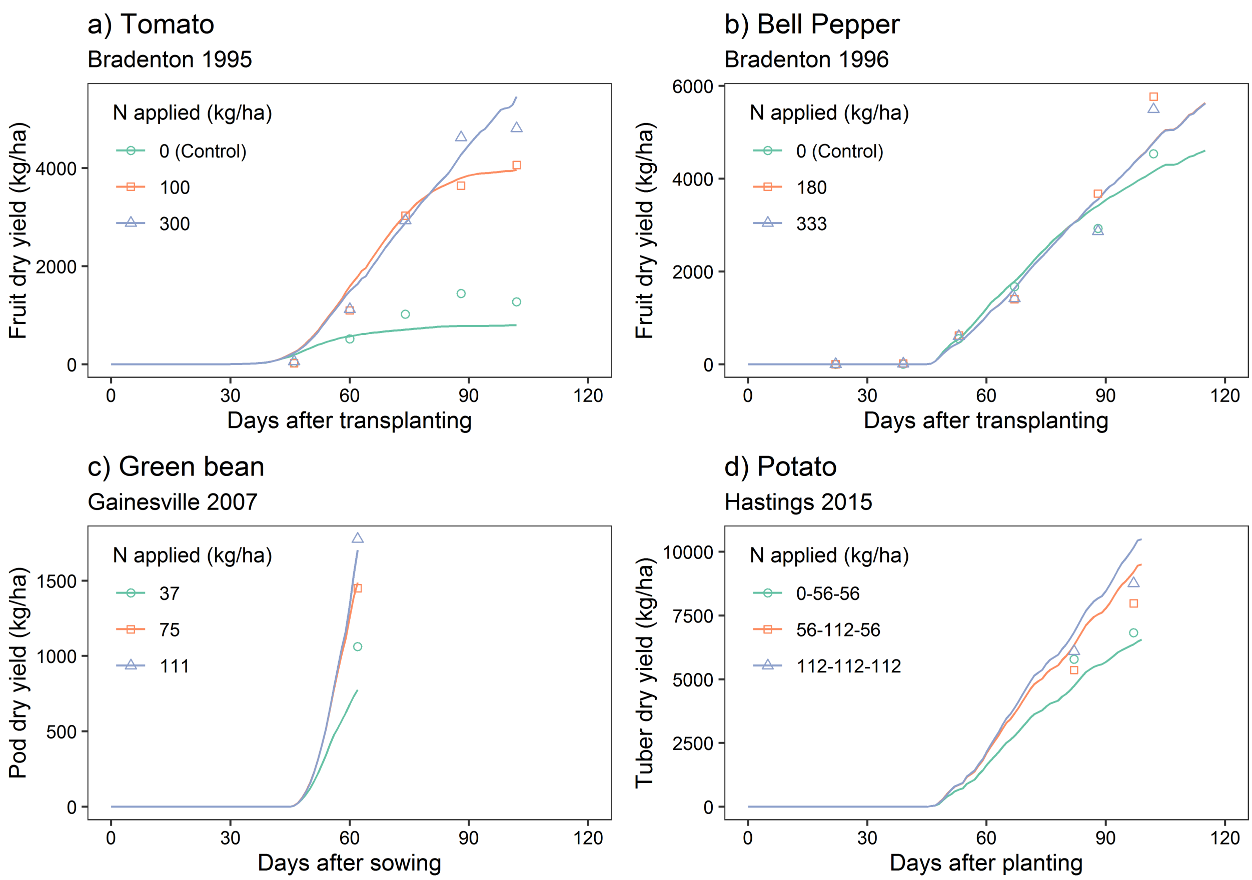


Figure 1. Examples of observed (symbols) and simulated (lines) harvestable dry weight yield over time tomato (a), bell pepper (b), green bean (c), and potato (d) as affected by nitrogen rates, grown under irrigated field conditions in varied locations in Florida.

**Conclusions**

The DSSAT-CSM was successfully parameterized, calibrated and evaluated for potato, tomato, bell pepper and green bean based on growth, nutrient and yield data from a range of N and P experiments spanning multiple sites in FL. The model provided good simulations for growth dynamics during different seasons, locations and in response to N and P fertilization. While further testing is appropriate, the CROPGRO and SUBSTOR models seem to be sufficiently ready to be used for various applications to evaluate management strategies and weather effects on the production of these fresh-market vegetable crops in FL and the southeastern USA, balancing productivity with environmental stewardship.

### Acknowledgements

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## Optimizing soil improvement and nitrogen management for sustainable crop production

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**Keywords: Soil organic matter, Nitrogen reduction, Carbon footprint, Cost-benefit**

### Introduction

Global food demand is projected to increase by 70% by 2050 (Cassman and Grassini, 2020). High-input agriculture meets this demand but causes nitrogen loss, greenhouse gas emissions and soil degradation, challenging alignment with UN Sustainable Development Goals. Soil quality, reflecting physical, chemical and biological traits, enhances crop yields, nutrient use efficiency and carbon storage (Ma et al., 2023). However, its quantitative relationship with nitrogen application and combined effects on productivity and emissions remain unclear globally. Existing nitrogen reduction strategies focus on short-term management, neglecting long-term soil enhancement. This study quantifies the interaction between soil quality and nitrogen application rate, optimizes management strategies, and evaluates sustainability to support resource-efficient, low-carbon agriculture and long-term food security.

### Materials and Methods

The soil quality index (SQI) was constructed using organic matter, bulk density, total nitrogen, and pH, and was used to classify soil quality into five grades (I–V). Based on this SQI, we used CERES-Rice, ORYZA v3, and RiceGrow to simulate rice yields from 1981 to 2020 at 290 meteorological stations across a wide range of soil quality and N application scenarios. For model calibration, we selected representative cultivars, one for each single rice subregion and two for double rice subregion (i.e., early and late rice). We then summarized yields as the 40-year multi-model mean. To evaluate environmental impacts alongside productivity, carbon footprints were estimated using life cycle assessment, incorporating emissions from agricultural inputs as well as $CH_4$ and $N_2O$. The scenario design included a baseline business-as-usual (BAU) case and soil quality improved by one to four grades, combined with N rates from 0 to 360 kg N ha$^{-1}$ in 20 kg increments. A sustainability index was established via the CRITIC-Entropy-weighted TOPSIS method with 12 criteria across socioeconomic, environmental, and cultivation return dimensions. Finally, we performed optimization targeting 5%-10% higher yield and benefit–cost ratio, 5%-10% lower carbon footprint, and a maximized sustainability index to identify optimal combinations of soil quality improvement and N application.

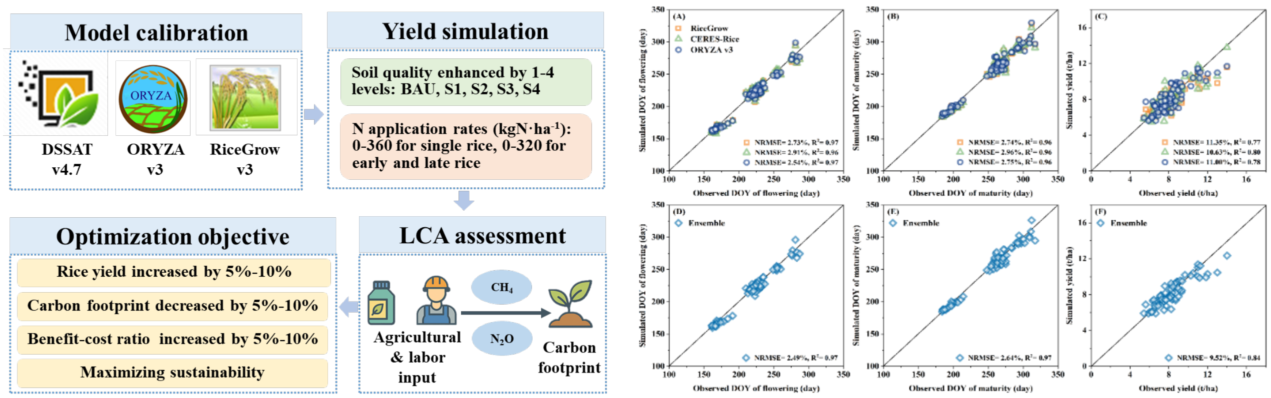


*Figure 1*. Research workflow and validation of crop model simulations for rice flowering, maturity, and grain yield

## Results and Discussion

Three crop models accurately captured phenology, with simulated flowering and maturity dates closely matching observations (Figure 1). Yield simulations showed moderate accuracy across models (NRMSE: 10.63–11.35%; $R^2$: 0.77–0.80), and consistent with Li et al. (2015), the multi-model ensemble improved performance (yield error: 9.52%; $R^2$: 0.84). This provides a solid foundation for subsequent management optimization.

Many rice N application optimization strategies overlook soil quality (Cai et al., 2023), yet aligning N rates with soil quality is critical. In low-quality soil regions, maintaining current N levels while improving soil quality is advisable. Conversely, high-quality soil regions can reduce N inputs, as excessive basal application causes high losses driven by farmers' risk aversion (Cai et al., 2023). Our results show soil quality index increases of 0.23–0.30 enable N reductions of 11–105 kgN $ha^{-1}$ for environmental and economic targets (Figure 2). However, policy support, including subsidies for advanced fertilizers and soil improvement as well as community-based services (Duan et al., 2024), is crucial to drive adoption, narrow regional gaps, and achieve global resource-efficient crop production.

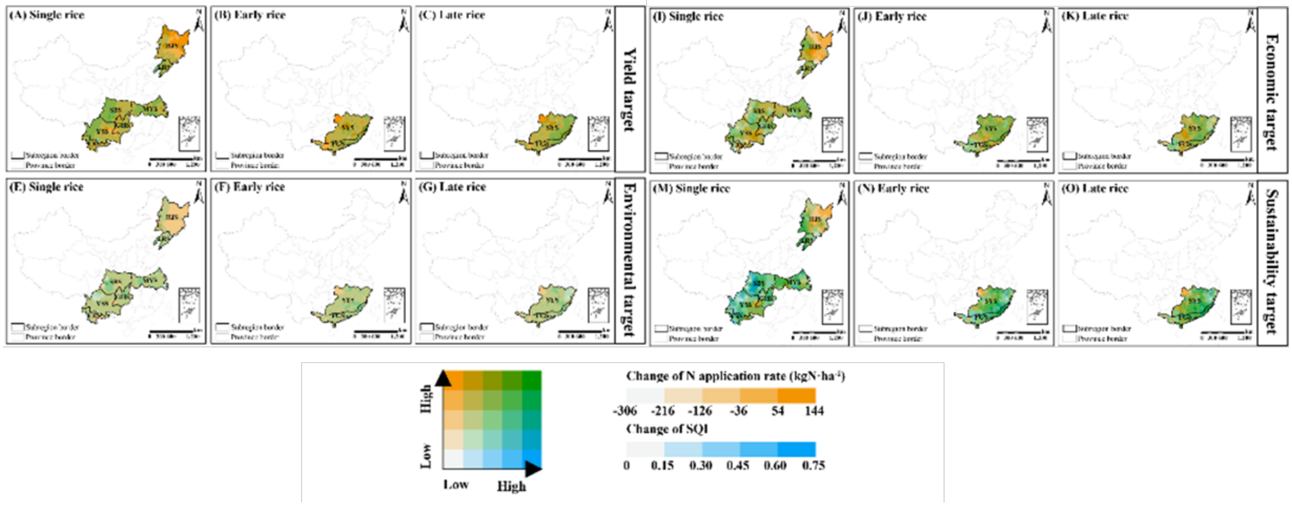


*Figure 2*. Change of N application rate and soil quality for achieving yield, environmental, economic and sustainability targets

## Conclusions

Low- to medium-quality soils account for approximately 80% of the cultivated farmland across China's major rice-growing regions. Our findings demonstrate that improving soil quality can increase rice yields by an average of 9% and reduce yield-scaled carbon emissions by 6%, with the most substantial yield gains observed in low-quality soils. Additionally, improved soil quality enables reductions in nitrogen input ranging from 20 to 116 kgN $ha^{-1}$ across rice subregions without compromising sustainability outcomes.

## Acknowledgements

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## Challenges in Agrivoltaics crop modeling

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**Keywords: Agri-PV, land use synergies, microclimate**

### Introduction

Agrivoltaics (AV) is an emerging land use system that combines agriculture and photovoltaic (PV) energy production on the same land. PV modules are mounted either above the crops or in rows allowing for agricultural cultivation in between. This simultaneous use has the potential to increase land use efficiency and to provide synergies along the food-water-energy nexus (Barron-Gafford et al. 2019). Whilst AV research sites have been established in various countries over the last few years, results remain limited: Due to differences in climate and soil conditions, selected cultivars, management practices and PV system parameters, transferability of results to other locations and setups is still lacking. Crop models have been widely used to estimate yields under different environmental conditions and could - once they are extended to AV - help to predict crop yields for future AV sites and scenarios. However, several challenges arise.

### State of research and common practices

As of now, in order to represent AV experiments in crop models, researchers face two options: either the use of a crop model *as is* with manipulation of its input data to account for AV effects e.g. on microclimate, or the detailed implementation of altered weather and growth equations under AV conditions within the crop model source code. Since the latter option is quite difficult as it requires in-depth process understanding and programming skills, attempts that rather modify crop model input data (see e.g. Bruhwyler et al. 2024, Ko et al. 2021) prevail in the AV community so far. Modeling approaches which simulate altered irradiance and wind speeds (without a crop model) for different AV setups are widely used by researchers and by the PV industry. Results from these simulations are then often used for crop model simulations. However, much less research is available about what happens to these modified inputs within the crop models. Whilst quantifying shading effects and their impacts on irradiance and simulating altered wind speeds in order to account for evapotranspiration and water distribution patterns also makes sense from a crop modeling perspective, the computation time and complexity of some widely used approaches may be questionable for use in crop modeling purposes - especially when considering how these modified data inputs are further processed and transformed in the crop model. Since assumptions and simplifications present in state-of-the-art crop models have typically not been made with AV in mind, caution is advised when combining these two separate steps.

### Discussion using the example of solar radiation

As an example to illustrate potential issues arising here, it is worth taking a closer look at irradiance and photosynthesis. Many state-of-the art crop models use global irradiance as an input and internally split this into direct and diffuse photosynthetically active radiation (PAR) based on sky clearness (Spitters et al. 1986, Ma Lu et al. 2024). With the addition of AV, irradiance is altered by PV modules blocking incoming direct light (direct shading) as well as obstructing part of the sky hemisphere, affecting diffuse irradiance. If the global irradiance input of a crop model is altered in AV preprocessing, the model receives less irradiance. When separating direct and diffuse irradiance based on sky clearness, the diffuse fraction is estimated based on clearness index, global irradiance, location and time. This estimate is then used to calculate $PAR_{direct}$ and $PAR_{diffuse}$, implicitly assuming that any kind of AV shading behaves similar to cloud cover. Whether this leads to acceptable results for the simulated AV system is unknown. Yet, cloud cover and AV shading are different processes and there is little reason to mix them. Even if $PAR_{direct}$ and $PAR_{diffuse}$ were to be used as crop model inputs directly, questions about the temporal resolution of the photosynthesis model within the crop model arise. In addition to these highlighted potential issues, it should be mentioned that many further challenges in AV crop modeling arise regarding the representation of sub-daily (temperature dependent) photosynthesis efficiency, soil, gas exchange and water distribution within these systems.

**Conclusions**

To accurately simulate AV effects in crop models, detailed understanding of microclimatic processes altered by the AV system is needed. However, since AV has emerged only recently, the quantity and quality of data is building up only slowly, as few sites have been equipped with the sensors needed for in-depth monitoring. To our best knowledge, there is no fully operational crop model available that directly simulates AV and its effects on microclimatic conditions. In order to achieve this, more detailed data as well as further methodic advances in crop modeling are needed. Our research addresses selected gaps here and aims to develop approaches capable of simulating altered irradiance and microclimate effects in AV systems.

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# A long-term simulation of organic fertilizer's effects on wheat, barley and potato production

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**Keywords: Organic farming, DSSAT, Wheat**

**Introduction**

Adapting to a rapidly changing climate is crucial, especially in the boreal region experiencing faster warming than the global average, and organic farming, has positive effects on soil properties, can play a vital role in building resilient agricultural systems. It is well known that compared with conventional fertilizer, organic fertilizer can increase microbial activity, improve aeration, raise the pH value in acidic soils and increase the cation exchange capacity when ageing. In addition, the stable long-term storage of carbon in the soil reduces the emissions of carbon dioxide to the atmosphere. The fertilizers are expected to be more effective than conventional fertilizers while significantly reducing negative effects such as nitrate leaching and water pollution. The development of a fertilizer based on available organic surplus residues will both increase resource use efficiency and offer economic returns to farmers (Gamage et al., 2023). This study is trying to simulate the effect of organic farming on the major crop production in Denmark from long-term perspective.

**Materials and Methods**

The three major crops (wheat, barley, and potato) in Denmark were calibrated based on the field experiment at Foulumgård experimental station, Aarhus University, Denmark (56◦30’N, 9◦35’E). For the calibration, we followed the protocol proposed by Wallach et al. (2024). The simulation was conducted using calibrated DSSAT parameters and weather data from both historical records and future projections, generated by Stefan L. and Matthias (2021). For conventional fertilizer application, we used an optimal nitrogen rate of 140 kg $ha^{-1}$, while for organic fertilizer, we applied 2 tons of animal manure per hectare, as described in Shah et al. (2017).

**Results and Discussion**

The results show the organic fertilizer has significant positive effects in the long run for all three crops ($p<0.001$; Fig. 1). while the conventional fertilizer has a negative effect for the barley and potato. The positive long-term effects of organic fertilizers on all three crops may be attributed to their ability to improve soil health, enhance nutrient availability gradually, and promote beneficial soil microbial activity, which collectively support sustainable crop growth. In contrast, conventional fertilizers often provide immediate nutrient boosts but can lead to soil degradation, nutrient imbalances, and reduced soil fertility over time, which may negatively impact crops like barley and potato. Additionally, the long-term use of conventional fertilizers, in comparison to organic fertilizers, can result in nutrient runoff and increased greenhouse gas emissions (Fig. 2), which further hinder crop development and negatively impact the environment. The simulation from DSSAT assessed the sustainability and efficiency of organic fertilization practices, optimized application strategies, and made informed decisions for improving soil fertility and crop yields while maintaining environmental health and guiding policy development. Ongoing regional-scale agricultural crop simulations will also be developed utilizing EU gridded weather data and the EU digital soil database.

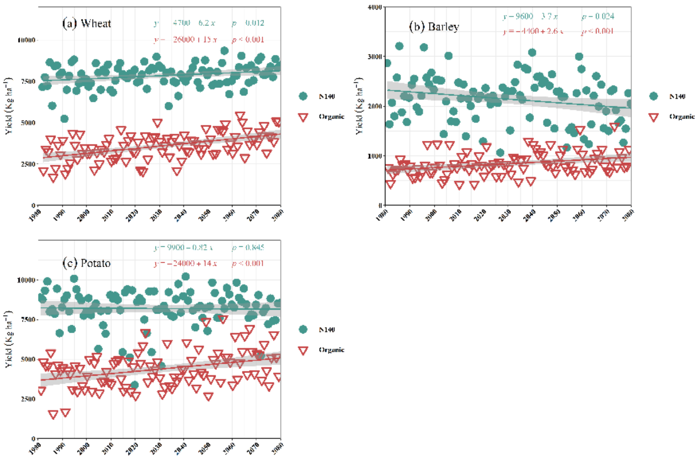


*Figure 1*. Simulated wheat, barley and potato yield under organic and optimal conventional fertilzer rate at long term conditions

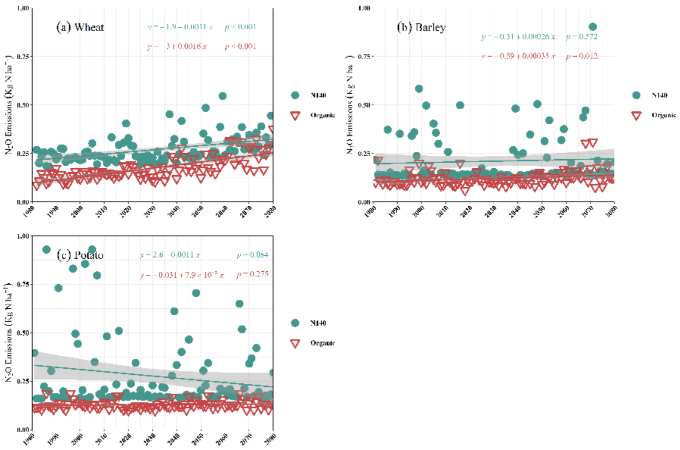


*Figure 2*. Simulated cumulative $N_2O$ emission of wheat, barley and potato fields under organic and optimal conventional fertilzer rate at long term conditions

## Conclusions

The long-term simulations conducted with DSSAT demonstrate that organic fertilizers yield positive effects on crop productivity over time, whereas conventional fertilizers tend to have a negative impact.

## Acknowledgements

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# Towards dynamic and integrated modelling of plant-microbe interactions for sustainable multispecies agroecosystems

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**Keywords: biogeochemical cycles; ecosystem resilience; modular frameworks; rhizosphere dynamics; trait-based metrics**

## Introduction

Biogeochemical models are essential for predicting agroecosystem responses to management and environmental changes. However, these models often oversimplify the roles of plant and microbial diversity. This limits their ability to capture the dynamics of complex systems like grasslands and intercropping, thus hindering the trade-offs evaluation between productivity and sustainability. Key feedback, such as rhizosphere priming and pathogen suppression, are frequently overlooked despite their importance for nutrient cycling, carbon (C) storage and ecosystem stability (Van Oijen et al., 2020). To address these issues, we propose a modular, trait-based modelling framework that balances mechanistic details with practical usability to support sustainable land management.

## Materials and Methods

To inform the development of such a framework and identify actionable pathways for model improvement, we reviewed over 150 peer-reviewed publications. We contrasted the limitations of traditional, homogeneous compartmental soil models (e.g. RothC; Mondini et al., 2017) with the enhanced ecological fidelity of microbially explicit models, which better simulate microbial functions. Assessing strategies for integrating biodiversity was a core objective of our review. We found that using functional traits and modular frameworks is crucial for balancing mechanistic detail with predictive power. We evaluated the utility of databases like TRY (https://www.try-db.org) for plant traits and BactoTraits (https://ordar.otelo.univ-lorraine.fr/record?id=10.24396/ORDAR-53) for microbial traits, which are essential for parameterising functional diversity. We also examined various biodiversity metrics, including taxonomic indices (e.g., Shannon) and functional measures (e.g., community-weighted mean), as tools for model calibration and assessment. These findings highlight the importance of incorporating specific microbial trade-offs, like those between copiotrophs and oligotrophs, to accurately represent nutrient cycling in agroecosystems.

**Results and Discussion**

Our review highlights three priorities for advancing biogeochemical models of plant-soil interactions: biodiversity metrics, microbial functional relationships and dynamic integration. Traditional models often rely on proxies like species richness, which inadequately reflect ecosystem functions. Trait-based metrics, such as community-weighted means, offer a more direct link between organismal functional traits and ecological processes. Indeed, plant traits - like root architecture, specific leaf area and exudation profiles - strongly influence microbial activity and nutrient cycling. Microbial communities should also be modelled beyond canonical homogeneous pools: incorporating functional guilds (e.g. copiotrophs and oligotrophs) enhances realism in simulating nutrient turnover, priming effects and soil organic matter (SOM) dynamics. Modular frameworks that connect plant and microbial traits to belowground processes are also key. We propose integrating vegetation (e.g. ModVege) and SOM modules (e.g. SYMPHONY), alongside diversity-focused tools like CoSMo and DYNAGRAM (Bellocchi, 2024). This approach allows us to test hypotheses on how biodiversity drives C stabilisation, either through environmental filtering or by capturing niche-driven community shifts, in response to resource competition. Despite progress, challenges remain - particularly in data availability, parameterisation and scaling. Addressing these requires interdisciplinary collaboration and emerging technologies. Machine learning (ML), digital twins and sensor-based calibration offer promising paths toward robust, flexible and predictive models. Our strategic roadmap (Table 1) outlines six key areas for development. Together, these form the foundation for next-generation models that bridge ecological theory and sustainable land management.

*Table 1*. Strategic roadmap for advancing biogeochemical model development of plant–soil interactions (ecological questions adapted from Sutherland et al., 2013, and Stokes et al., 2023).

| Key Area | Focus and objectives | Ecological question | Contribution of model development |
|---|---|---|---|
| Integrating plant diversity | Represent species composition, traits, and interactions | *What demographic traits determine the resilience of populations to disturbance?* | Improves predictions of how plant traits drive ecosystem stability |
| Incorporating microbial diversity | Represent microbial roles in nutrient cycling and stress responses | *How does below-ground biodiversity affect above-ground biodiversity?* | Enables quantification of soil–microbe–plant interactions |
| Accounting for temporal and spatial variability | Integrate short- and long-term dynamics; scale from rhizosphere to landscapes | *How do spatial and temporal heterogeneity influence diversity at different scales?* | Improves accuracy of biodiversity and ecosystem service predictions |
| Ensuring model accuracy and reproducibility | Clarify equations, test feedback, reassess assumptions | *Can biodiversity be effectively represented in models of ecosystem services to guide the design future agroecosystems?* | Test whether trait-based simplifications explain stability |
| Leveraging technological advances | Use sensors, computational tools, and ML for real-time calibration | *How can relationships between management practices and ecosystem services in agroecosystems be better investigated?* | Enables real-time tracking of management impacts on biodiversity |
| Promoting interdisciplinary collaboration | Foster cross-disciplinary integration and align terminology | *What can we learn from model communities of microorganisms about communities of macroorganisms?* | Bridges microbial and macroorganism ecology for ecosystem assessment |

**Conclusions**

This review provides a structured foundation for identifying priority areas in biogeochemical model development, linking biodiversity metrics, microbial explicitness, and dynamic integration to both ecological theory and applied agroecosystem management. Advancing agroecosystem models requires moving beyond simplified representations of biodiversity and static soil processes. Our analysis highlights three central priorities: (1) integrating trait-based biodiversity metrics, (2) incorporating microbial functional guilds, and (3) developing modular, dynamic frameworks that capture plant-soil-microbe interactions across spatial and temporal scales. Emerging tools - including trait databases, machine learning, digital twins and sensor networks - offer new opportunities for real-time calibration, model validation and hypothesis testing. By fostering interdisciplinary collaboration and embedding biodiversity into model design, next-generation frameworks can enhance the predictive capacity of agroecosystem models, supporting both fundamental ecological research and sustainable land management.

### Acknowledgements

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# HGS-DSSAT: Coupling a fully integrated surface-subsurface hydrological simulator with a cropping system for agro-hydrological simulations

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**Keywords: Coupling solution, Hydrogeology, Crop modelling, 3-D modelling, ISSHM**

## Introduction

Integrated surface-subsurface hydrological model (ISSHM) enable the simulation of fully coupled and variably saturated groundwater and surface water flow and transport solely based on defining the hydrological inputs from the catchment without the need to define internal stream-aquifer exchange fluxes or groundwater recharge. While ISSHMs like HydroGeoSphere (HGS) allow the simulation of vegetation processes such as evapotranspiration and root development, the relatively simple crop and evapotranspiration modules are not suited for the detailed simulation of cropping systems, fertilizer application and nutrient cycling (Schilling et al., 2017; Therrien et al., 2010). On the other hand, dynamic crop growth simulators like DSSAT (Hoogenboom et al., 2019), which allow the detailed simulation of the aforementioned agricultural components, are only based on 1-D water flow simulations and can thus not address spatially variable groundwater and surface water flow and transport processes. Using a coupled ISSHM-cropping system modelling framework such the here developed HGS-DSSAT can be a highly promising decision support tool that can be applied on an agricultural catchment scale and address hydrological complexity, environmental heterogeneity as well as various field and terrain configurations (You et al., 2024). Here we show the state of development of the coupled HGS-DSSAT framework and illustrate the performance of HGS-DSSAT versus stand-alone versions of DSSAT and HGS in a digital- twin experiment of the DSSAT wheat experiment SWSW75010. In addition, field simulations which show 3-D water flow dynamics within the HGS-DSSAT framework are demonstrated.

## Materials and Methods

For the comparison of the performance of HGS-DSSAT, 3 digital twins were prepared: **1)** A stand-alone DSSAT model of wheat experiment SWSW75010; **2)** A stand-alone HGS model setup as a twin of the DSSAT wheat experiment model (Fig. 1). Initial conditions for soil saturation and water table depth, as well as soil parameters (van Genuchten alpha and n parameters, hydraulic conductivity, pore size distribution), evapotranspiration properties (residual water content, drained lower limit, drained upper limit) and weather forcings (precipitation) were set to be identical to the DSSAT twin; **3)** A coupled HGS-DSSAT model of the wheat experiment, where water flow from layer to layer was simulated by the HGS and evapotranspiration (including all crop dynamics) was simulated by the DSSAT component. DSSAT flow routines (WatBal module, i.e., the infil and satflo Fortran subroutines) were turned off, as were the HGS evapotranspiration routines. The volumetric water content per layer was assigned to DSSAT based on the HGS water flow simulation, while ET from DSSAT was prescribed to the corresponding HGS model layers as nodal sinks. Rainfall was simulated to only occur in the HGS component (Fig. 1). All 3 model twins were simulated without considering runoff. Finally, to simulate a 3-D field lateral flow both on the surface (runoff) and in the subsurface (groundwater), a titled synthetic heterogenic field with a slope of 5% HGS-DSSAT and similar parametrization as the DSSAT wheat experiment was simulated.

**Results and Discussion**

The 3 models were compared in terms of total water balance and transpiration and evaporation components, volumetric water content in different layers of a root zone (Fig. 1), and amount of water that drained from layer to layer. In addition differences in crop growth parameters between DSSAT and coupled DSSAT where analysed. Comparison between the three models revealed similar changes in volumetric water content (which was desired) but also similar differences between the different model versions as had previously been shown in a comparison of DSSAT to Hydrus-1D (Shelia et al., 2018) (which was also desired). The presented results are the first step to our ultimate goal of creating a 3-D capable ISSHM-cropping systems modelling framework that can address realistic crop growth, evapotranspiration, and N- and P-species cycling and transport under robust and fully integrated surface-subsurface hydrological processes.

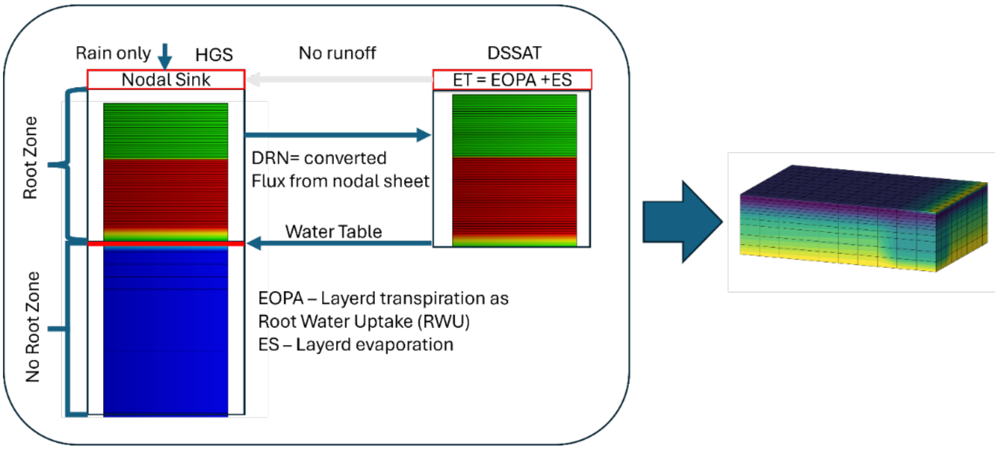


*Figure 1*. Concept information transfer in the root zone between HGS and DSSAT in copuled HGS-DSSAT

**Acknowledgements**

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# Coupling grazing and nutrient cycling for forage-based system simulation using the DSSAT-CSM-Perennial Forage Model

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**Keywords: beef cattle, *Brachiaria brizantha*, forage, pasture modeling.**

## Introduction

The Decision Support System for Agrotechnology Transfer (DSSAT; Hoogenboom et al. 2019) has been widely used to simulate forage growth, but mainly for cut-and-carry or rotational grazing management (Gomes et al., 2025; Brunetti et al., 2021; Pequeno et al., 2018). Continuous stocking systems are not well represented, as requires to quantify on a daily basis the amount of herbage biomass that animals remove. The existing MOW module within the Cropping System Model (CSM) of DSSAT specifies residual biomass after harvest, which is well suited for rotational management, but less flexible for continuous stocking systems. These systems require explicit estimation of daily herbage removal. Continuous stocking also involves nutrient cycling processes, including the return of nitrogen (N) excreted by animals to the soil, that should be more explicitly represented. Addressing these gaps requires the use of an automated mow functions to approximate daily herbage removal, and to account for organic carbon and N inputs from urine and feces. Therefore, the goal of this study was to enhance the CSM-CROPGRO-Perennial Forage Model (CROPGRO-PFM) by coupling it with a grazing module that integrates biomass removal and nutrient recycling. This modeling effort aims to improve the efficiency and accuracy of long-term simulations of livestock grazing systems.

## Materials and Methods

A three- year dataset was obtained from an experiment conducted at Embrapa Agrossilvipastoril, Sinop, Mato Grosso, Brazil (11°51″ S, 55°36″ W, 370m a.s.l.) for the calibration of CROPGRO-PFM. The experiment followed a randomized complete block design, with four paddocks of Marandu palisadegrass grazed by Nellore steers. Daily grazing was simulated using AutoMOW, a module that simulates mow events periodically during crop simulation, considering post-harvest biomass (HMMOW, kg $ha^{-1}$), leaf percentage (HRSPL, %), and vegetative stage (HMVS, unit) as parameters. A model in R was developed and coupled with CROPGRO-PFM to estimate N excretion from the simulated herbage biomass (HERB), (Figure 1A). Herbage availability per animal per day was calculated by dividing HERB by the stocking rate. A grazing efficiency of 65% was assumed to estimate dry matter intake (DMI). Total N intake was derived from DMI and herbage N content. N retention was estimated using net energy for growth and average daily gain, and N excretion was calculated as N intake minus N retention (IPCC, 2019). The model performance was evaluated using root mean square error (RMSE) and the Willmott index of agreement (d-stat).

## Results and Discussion

A sensitivity analysis indicated that the best performance was obtained with the following parameterization for AutoMOW: HMMOW = 2500, HRSPL = 30, and HMVS = 10. Considering continuous stocking without manure, RMSE was

28.89 kg $ha^{-1}$ and d-stat 0.654. Including manure slightly improved performance, with RMSE = 28.06 kg $ha^{-1}$ and d-stat = 0.684.

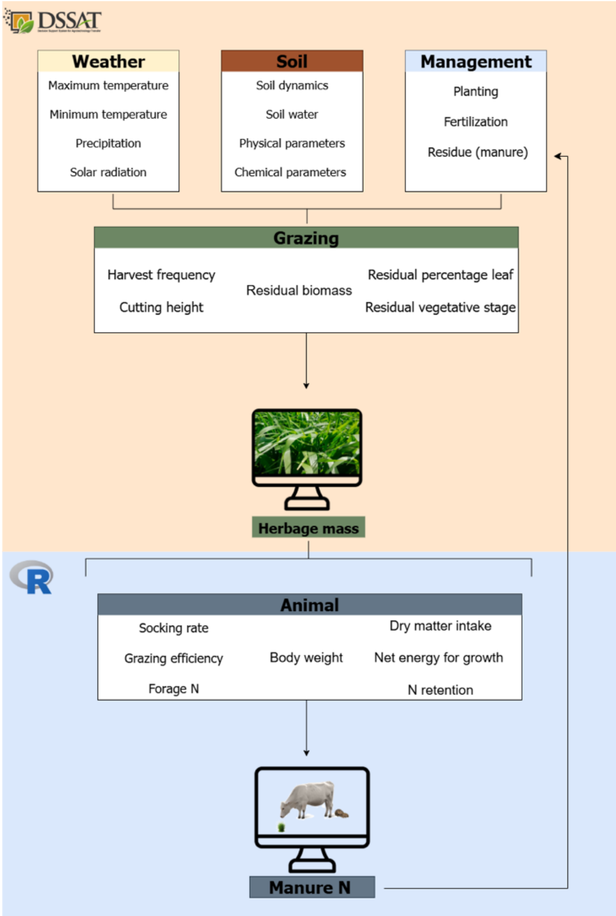


*Figure 1.* Framework of the crop model–grazing module integration

## Conclusions

Simulating grazing with the new R-model coupled with the CROPGRO-PFM model has demonstrated to be a promising approach. Incorporating daily biomass removal and N return to the soil is essential for improving model performance. However, further refinement of the methodology is still required. Ongoing work focuses on advancing this approach, with the next step being the integration of the Message Passing Interface (MPI) framework into DSSAT.

## Acknowledgements

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## Assessment of ARMOSA model performance in simulating nitrate leaching under digestate application

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**Keywords: Nitrate leaching; Digestate; Anaerobic digestion; N losses**

### Introduction

Digestate is the by-product of anaerobic digestion of biomass for bioenergy, mainly biogas. Its high nitrogen content poses risks: ammonia volatilization, nitrate leaching, and $N_2O$ emissions. The VIDEO project aims to define strategies under the principle of Maximum Sustainable Applicability (MAS), balancing productivity and environmental safety. It includes literature review, data collection, and modelling (with different models) to evaluate digestate use, nutrient efficiency, and impacts on cropping systems. Within this broader project, the present work aims to define the methodology for conducting a literature review and to analyze the state of the art of ARMOSA model (Perego et al., 2013) in simulate nitrate leaching.

### Materials and Methods

The state-of-the-art testing of ARMOSA was conducted through simulations on soils from the Lombardy region, using profiles that represent four soil textures, ranging from coarse to fine, according to a simplified version of the USDA soil texture classification system. Simulations were run with a 30-year weather dataset (1993–2023) from the Agri4cast database (Toreti, 2014), restricted to grid cells mainly used for arable land. A representative regional crop rotation (maize, wheat, soybean) was simulated under three nitrogen management scenarios involving progressive substitution of mineral N with organic N from digestate, in order to evaluate nutrient losses through nitrate leaching and to compare the performance of mineral fertilizers versus digestate: (i) Baseline scenario: mineral N fertilization only, cereal straw removal, and fallow periods; (ii) Ndig50: 50% of each crop's N requirement supplied as organic N, with the remainder as mineral N; (iii) Ndig100: maize receives 100% of its N requirement as organic N, while wheat and soybean receive 50% as organic N and the remainder as mineral N.

The objective of the present literature review was to synthesize current knowledge on the environmental impacts of digestate application, with particular emphasis on nitrate leaching and, secondarily, on nitrous oxide emissions and ammonia volatilization. The literature search was conducted in Scopus databases. In total, 368 documents were retrieved from 2020. These documents were subsequently analyzed using NotebookLM, an artificial intelligence tool commonly employed for extracting structured information from textual sources. The texts were processed using a pre-built query.

### Results and Discussion

The nitrate leaching amounts simulated by the ARMOSA model highlight its ability to distinguish nitrate leaching dynamics in response to different nitrogen sources used as inputs. The simulations show higher nitrate losses from the soil profile when fertilization relies entirely on mineral fertilizers, with a progressive reduction as mineral fertilizers are replaced by digestate ones. Moreover, the model allows the assessment of soil texture effects, revealing clear trends of decreasing nitrate losses when moving from coarse-textured soils to finer-textured soils.

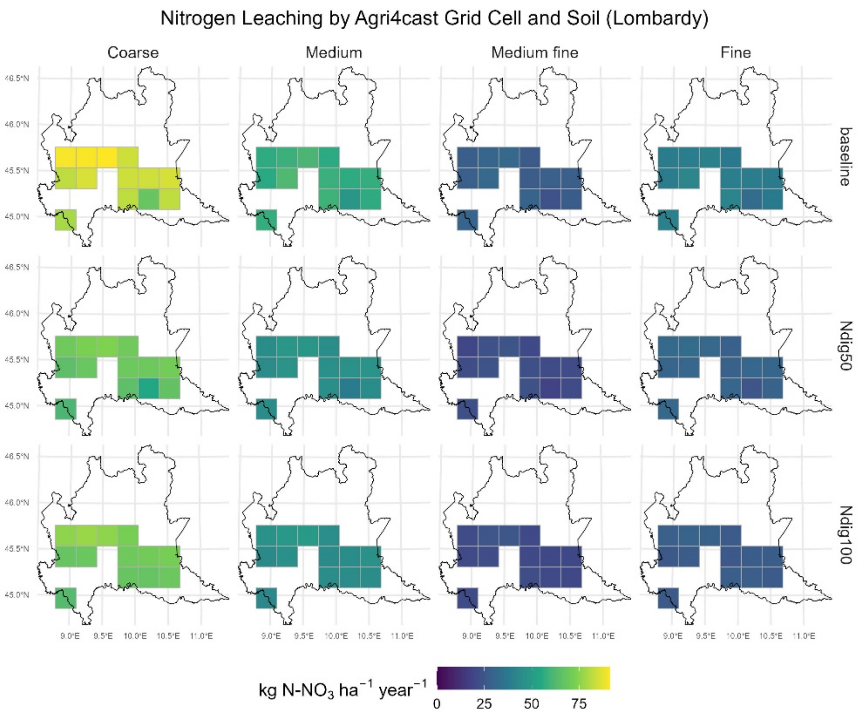


*Figure 1*. Simulated nitrate leaching in Agri4cast cells by nitrogen input and soil texture class.

## Conclusions

The study presented here constitutes the initial phase of a broader research project. The evaluation of the ARMOSA simulation model's capacity to discriminate nitrate leaching dynamics provides a robust foundation for subsequent developments. In the next phases, starting with an extensive literature review, the data collected will be employed to validate the model's performance. Furthermore, ARMOSA will be benchmarked against other models with comparable capabilities, with the aim of identifying the most appropriate tool for spatially assessing nitrate leaching losses following digestate application.

**Acknowledgements**

This research was carried out within the framework of the project *VIDEO – Valorizzazione innovativa del digestato per l'efficienza e l'ottimizzazione della nutrizione azotata*, funded by MASAF (Italian Ministry of Agriculture, Food Sovereignty and Forests). The work is conducted as part of the author's PhD project at the University of Ferrara.

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# An integrated modeling framework for assessing environmental and agronomic outcomes for farm typologies in Germany

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**Keywords: Agriculture, APSIMx, Crops, Impact Assessment, Management practices**

## Introduction

Agricultural systems worldwide face increasing pressure to enhance productivity while reducing environmental impacts related to soil degradation, nutrient losses, greenhouse gas emissions and biodiversity loss (Yang et al., 2024). Innovative farming methods such as agroforestry, conservation agriculture and diversified crop rotations are proposed to reconcile food production with environmental sustainability (Sims et al., 2009; Yang et al., 2024). Within the framework of the German Environment Agency-funded project "Food and Agriculture with a Future", this study proposes a model-based approach to evaluate the environmental effects of multiple innovative cropping concepts under regionally representative farm typologies. The key aim is to develop a robust and scalable simulation framework. It should quantify nitrogen dynamics, greenhouse gas emissions, soil organic matter changes and crop performance (yield modelling) across a range of management scenarios. Special attention is given to their potential for climate change adaptation. This approach facilitates an understanding of how agronomic measures can contribute to achieving environmental goals set by policy frameworks such as the EU Green Deal (EU-COM, 2019) and the Nitrates Directive (Council Directive 91/676/EEC 1991). At the same time, it fills the research gap on the limited evidence of farm-level modelling approaches in Europe.

## Materials and Methods

The process-based crop model APSIM Next Generation (APSIMx) was selected due to its modular design and ability to integrate crop growth, soil water and nutrient cycles, as well as management practices at daily resolution (Holzworth et al., 2018). APSIMx captures detailed crop physiology processes, nutrient dynamics and greenhouse gas fluxes including $N_2O$, $NH_3$ volatilization, as well as $NO_3$ leaching. Modeling at the field level allows the representation of various cultivation practices, such as crop rotation, intercropping and irrigation. In addition, its capacity to simulate various croptypes, such as cereals, legumes, oilseeds, and tubers, enables flexible scenario analysis (Keating et al., 2003).

Six Regional Farm Typologies were designed to capture the diversity of agricultural production systems across Germany (Figure 1). The regions were selected to represent both favorable and marginal sites and to cover different farming types such as arable, livestock, and mixed farms. The chosen regions reflect intensive arable production areas in Germany and locations experiencing specific environmental pressures, identified from the literature. The selected regions include typical arable regions with favorable soil and climate conditions in Schleswig-Holstein (Östliches Hügelland), Saxony (Leipziger Tieflandsbucht) and Hesse (Wetterau). In addition, a marginal site with low soil fertility and challenging weather in Brandenburg, intensive livestock farming and fodder production in Lower Saxony (Cloppenburg) and a mixed or forage-oriented system with organic components in Bavaria. This regional differentiation ensures that structural and site-specific conditions of diverse German farming systems (or farm typologies) are reflected. The prototype farms are parameterized with site specific detailed soil profiles as well as weather data provided by Germany's National Meteorological Service (DWD). In addition, input data on management practices were compiled from national agricultural statistics and farm surveys conducted by the Kuratorium für Technik und Bauwesen in der Landwirtschaft (KTBL). These include crop rotation, sowing and harvesting dates, fertilization practices (type, timing, amount, technology), tillage, irrigation amounts and yields over at least ten years. This data is used to test and calibrate APSIMx and to represent the current status quo of farm management and their environmental impacts (e.g., nitrate leaching).

*Figure 2.* Sites for prototype farms using APSIMx

On this basis, five management scenarios will be tested across all prototype farms. They have been selected due to their environmental relevance, their representation in the current literature as promising and near-future relevant practices, and their potential contribution to policy targets. The scenarios include: I) The concept of agroforestry, in which perennial elements are integrated into annual crops. This is expected to improve nutrient cycling, carbon sequestration and biodiversity (Plieninger et al., 2020). II) Patch cropping with spatial diversification with interspersed crops of differing rooting depths and nutrient demands to investigate the benefit of niche differentiation on resource use efficiencies (Hernández-Ochoa et al., 2022). III) Conservation and regenerative management with practices such as minimal tillage, residue retention, cover crops, and organic fertilization with expected effects on soil health and nutrient cycling (Biswas et al., 2024). IV) Vegan farming with organic fertilization based on animal manure and green manure and their effects on nutrient losses (Carr et al., 2019). V) Pesticide-free wheat cultivation and its effect on biomass and nutrient managements (Böcker et al., 2019). The integrated crop portfolio includes cereals (e.g., winter wheat, millet, winter and spring barley, silage and grain maize), legumes (soybean, chickpea, faba bean), root crops (potatoes), oilseeds (sunflower, linseed), forage crops (white clover, grassland) and others (fallow, mustard). Their incorporation into crop rotations not only diversifies production but also enhances the human diet (e.g. high-quality proteins) (Wittkop et al., 2009). In addition to assessing the status quo, the study also examines future scenarios for 2030 and 2045, with a particular focus on projected climate developments and their impact on the environmental performance.

**Results and Discussion**

This study is expected to provide region-specific insights into how different farm types and management strategies affect environmental outcomes such as nutrient balances. This research provides a robust basis for evaluating sustainable transformation pathways in the six German study regions. It can support regional and national agricultural decision makers and foster dialogue on environmentally necessary transformations of the conventional cropland sector. Furthermore, the detailed interregional farm-level analysis as presented in this study enables to explore the advantages and potential trade-offs that may arise from transitioning to alternative management scenarios in the specific regions. Beyond that, we are presenting an interregional farm-level management scenario analysis using APSIMx for the modelling community.

**Acknowledgements**

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## Scenario Analysis of Nitrate Leaching in German Cropping Systems

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**Keywords: APSIM, Crop Rotation, Nitrogen Fertilization Yield response, Calibration**

### Introduction

In some regions of Germany, agricultural nitrogen (N) inputs have caused nitrate contamination in groundwater, violating the European Nitrates Directive (91/676/EEC)Well designed and calibrated process-based models allow us to estimate the impact of different management scenarios on nitrate leaching and thus identify appropriate mitigation strategies.

### Materials and Methods

In this study, we use the agricultural systems model Agricultural Production Systems Simulator (APSIM), to investigate how changing the crop sequence and nitrogen input impacts on nitrate leaching potential. The APSIM model was calibrated using data from a three-year crop rotation of winter wheat (WW), winter barley (WB) and oilseed rape (OR). In the experiment, all crops were grown in each year, starting with one of the three crops in each case with two irrigation levels (I0: no irrigation, I1: 120-140 mm a-1) and three fertilization levels (N0: no fertilizer, N1: 75 % N demand, N2: 100 % N demand), summing up to 18 treatments. Data from 12 treatments over three years was used for calibration and data from 6 treatments for validation. Calibration was done in a stepwise approach following Wallach et al. (2024), focusing on simulating plant development, i.e. phenology, biomass, yield and nitrogen uptake first, then including soil water and mineral nitrogen content in soil.

### Results and Discussion

The parameter optimization substantially improved the fit of the model. In this rigorous calibration and validation exercise, phenology was predicted very well for all three crops, years and treatments (Fig. 1, top). Yield (Fig. 1, bottom) and biomass of crops as well as soil water contents were predicted satisfactorily. This is a good basis for further improving the model to accurately capture N uptake and nitrogen dynamics in the soil. Building on these refinements, scenario analyses on the validated model for the crop rotation trial will explore strategies to mitigate nitrate leaching with deeper insights on the nitrogen pathways. We will give insights into the role of crop rotation diversification and varying fertilization intensities in shaping the effectiveness of nitrate leaching reduction. Through the investigation of these approaches, the objective is to gain a deeper understanding of the trade-offs between agricultural productivity and environmental sustainability, thereby generating model- and data-driven insights optimising agronomic practices.

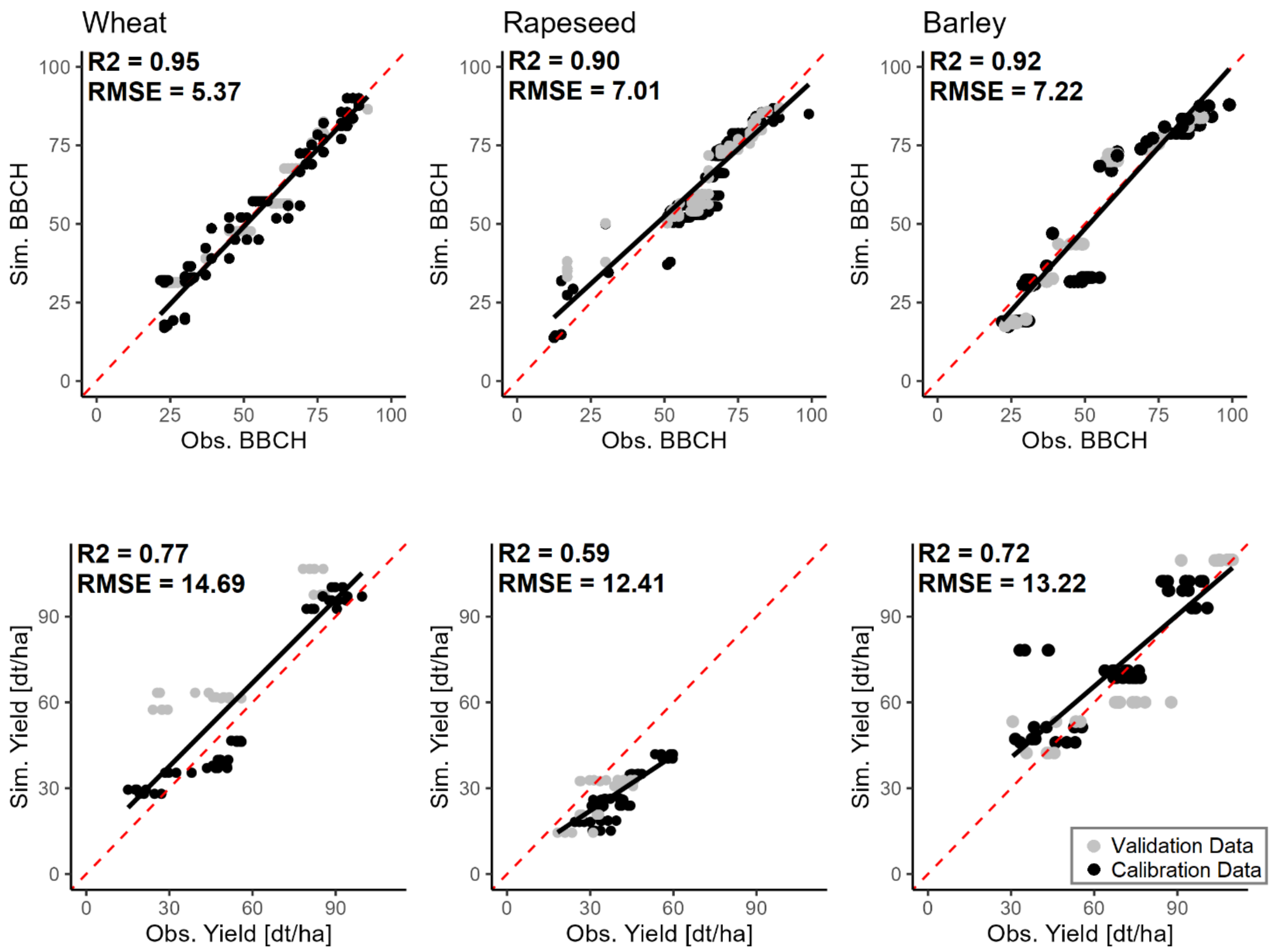


*Figure 1*

Observed vs. model simulated BBCH stages (top) and grain yield (bottom) for wheat, oilseed rape and barley (from left to right). 1:1-line is shown in red.

**Acknowledgements**

This work is supported by funds of the Federal Ministry of Agriculture, Food and Regional Identity (BMLEH), based on a decision of the Parliament of the Federal Republic of Germany via the Federal Office for Agriculture and Food (BLE), grant number 2823KLI001

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Journal article

Wallach, D.; Buis, S.; Seserman, D.-M., Palosuo, T.; Thorburn, P. et al. (2024): A calibration protocol for soil-crop models. Environ. Model. Softw. 180, p106147. DOI: 10.1016/j.envsoft.2024.106147.

## Simulating the effect of shading on crop growth in combined land use systems

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**Key words:** Agroforestry, Agrivoltaics, Coupled Soil-Vegetation Energy Balance, Expert-N

### Introduction

Establishing combined land use systems such as alley cropping agroforestry (AF) or agrivoltaic systems (APV) is considered a promising strategy to increase biodiversity and mitigate adverse impacts of climate change on agriculture. However, crop growth in such systems is influenced by shading and a change in vegetation and soil temperatures, wind speed, relative humidity. In order to assess the effects of shading and competition on growth of arable crops in agroforestry and agrivoltaic systems, the agroecosystem simulation software Expert-N (https://expert-n.uni-hohenheim.de/) was extended recently by two new modules to represent the effects of AF and APV on dynamic plant growth. In this study, we present simulated and measured effects of shading on the microclimate and the resulting impacts on plant development and growth at different test sites in SW Germany.

### Materials and Methods

In the new AF module, different instances of Expert-N run in parallel to simulate the interactions between rows of trees and arable crops. In one instance, the growth of the trees is simulated using the TREEMIX model, while in the other instances, the growth of the arable crop is simulated (SPASS, GECROS), in each instance with a different distances to the tree row. The shading of crops by the tree row (simplified by an opaque cuboid) is explicitly calculated from the position of the sun, the orientation of the tree strip and the geographical location (Fig. 1, left).
In the new APV module, incoming shortwave and longwave radiation are either simulated by a coupled model (e.g., Martinez et al., 2025) or must be predefined via an input file. The different positions on the field are again represented by separate crop model instances. In the coupled mode, simulated soil-vegetation temperatures feedback to photovoltaic panel temperature calculation and vice versa (Fig. 1, right; Martinez et al., 2025).

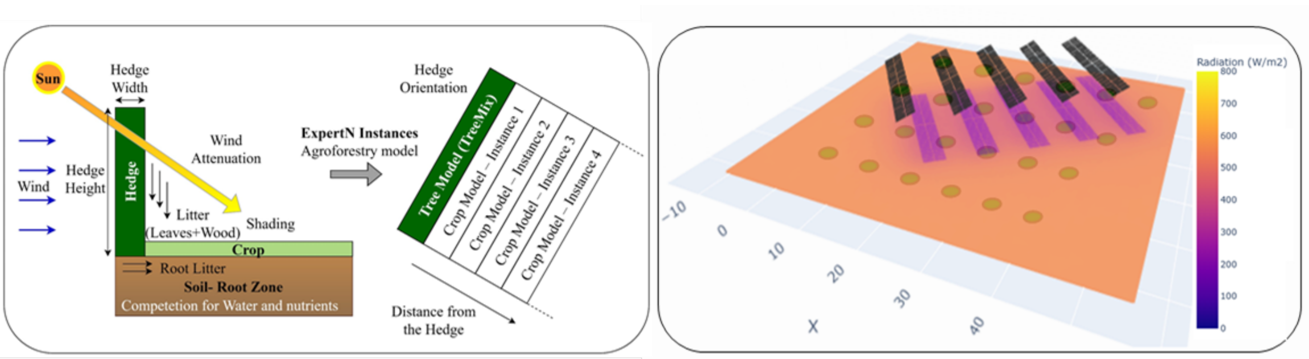


*Figure 1*. Model setups for crop growth simulations in alley-cropping agroforestry (left) and agrivoltaic systems (right). Green dots in the agrivoltaic system indicate different instances of Expert-N.

The temperatures in the vegetation layer and at the soil surface are calculated using the coupled solution of the respective energy balance equations in analogy to the NoahMP land surface model (He et al, 2023). Figure 1 shows setups for crop growth simulations in AF and APV systems. The data used to test the model originate from two agroforestry-like test sites in SW Germany, where rows of trees with heights of 10 and 20 meters shade the arable fields, as well as from an APV pilot facility near Lake Constance.

### Results and Discussion

At all test sites, measurements and simulations show clear effects of shading on the microclimate, which in turn affect simulated timing of phenological stages and predicted yields. The reduction in solar radiation in the simulated AF systems is well reproduced by the model (38 – 57 % less PAR at 4 m distance to trees). However, the model significantly overestimates yield losses in the shaded area (39 – 82% yield loss simulated vs. 2 – 37 % observed). Possibly, adaptation strategies of shaded plants, which are not taken into account in the model, are of crucial importance here. In contrast, shading is less pronounced in the simulated agrivoltaic system, and only minor yield losses are simulated. Vegetation temperatures that are simulated to be 0.6–1.1 °C cooler under PV panels during the main growth phase, led to an extension of the grain filling period by up to 5 days compared to the open field, which partly compensates yield losses due to reduced photosynthesis.

### Conclusions

Simulating plant growth in combined land use systems is challenging, as plant adaptation strategies need to be taken into account. However, still little data from agroforestry and agrivoltaic systems is currently available to further improve crop models in this regard.

### Acknowledgements

The study was financially supported by the Ministry of Economic Affairs, Labour and Tourism Baden-Württemberg (http://invest-bw.de/) and the Federal Ministry of Food and Agriculture (BMEL) of Germany via the Federal Office for Agriculture and Food (BLE) under the Federal Programme for Ecological Farming and Other Forms of Sustainable Agriculture.

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# Soil–vegetation–water interactions in Mediterranean silvopastoral agroforestry systems: effects of land abandonment and climate variability

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**Keywords: Hydrological modelling, land degradation, adaptive management, cork oak systems, agroforestry ecosystems.**

## Introduction

Silvopastoral ecosystems in southern Europe are becoming increasingly vulnerable to the combined pressures of land use changes, desertification, drought, and land degradation, driven by both biophysical and socio-economic factors. Understanding the hydrological consequences of interactions between soil and vegetation management and natural ecological processes is essential for promoting resilience and economic development in these socio-ecosystems. However, such interactions remain poorly characterized in Mediterranean silvopastoral systems under semiarid conditions, which face growing threats from land abandonment and climate change. This study hypothesized that land abandonment and climate variability significantly alter the hydrological balance of these systems, affecting water availability.

## Materials and Methods

Research was conducted in cork oak silvopastoral landscapes of northeastern Sardinia (aridity index = 0.57), encompassing three distinct land cover types representing large proportion of the agroforestry landscapes in the region: open grassland (OG), wooded grassland (WG), and woodland (WL), defined by increasing cork oak tree density, which was also considered a proxy for land abandonment processes. The main ecosystem components (e.g. tree and grass cover, productivity) and processes (e.g. throughfall, soil moisture) were analyzed through field observations and modelling approaches. In addition to direct sampling, the Agricultural Policy/Environmental eXtender (APEX) model (Gassman et al., 2010) was used to simulate broader hydrological dynamics. By integrating field-based measurements with model outputs, the study captured nuanced soil–vegetation–atmosphere interactions across the three land cover types. This approach enabled a comprehensive assessment of ecosystem responses under varying precipitation regimes.

## Results and Discussion

The results revealed distinct hydrological behaviors associated with land use and management practices, underscoring the pivotal role of rainfall patterns and tree cover in shaping water availability, productivity, and resilience of these ecosystems (Figure 1).

To explore future trajectories, the three land covers will be simulated under multiple climate scenarios, assessing the interactions between climate and land use and their impacts on the water cycle and water availability in silvopastoral systems. This work highlight the importance of integrated modelling and field-scale monitoring to inform adaptive land management strategies that enhance resilience and long-term sustainability of silvopastoral agroforestry systems in Mediterranean landscapes.

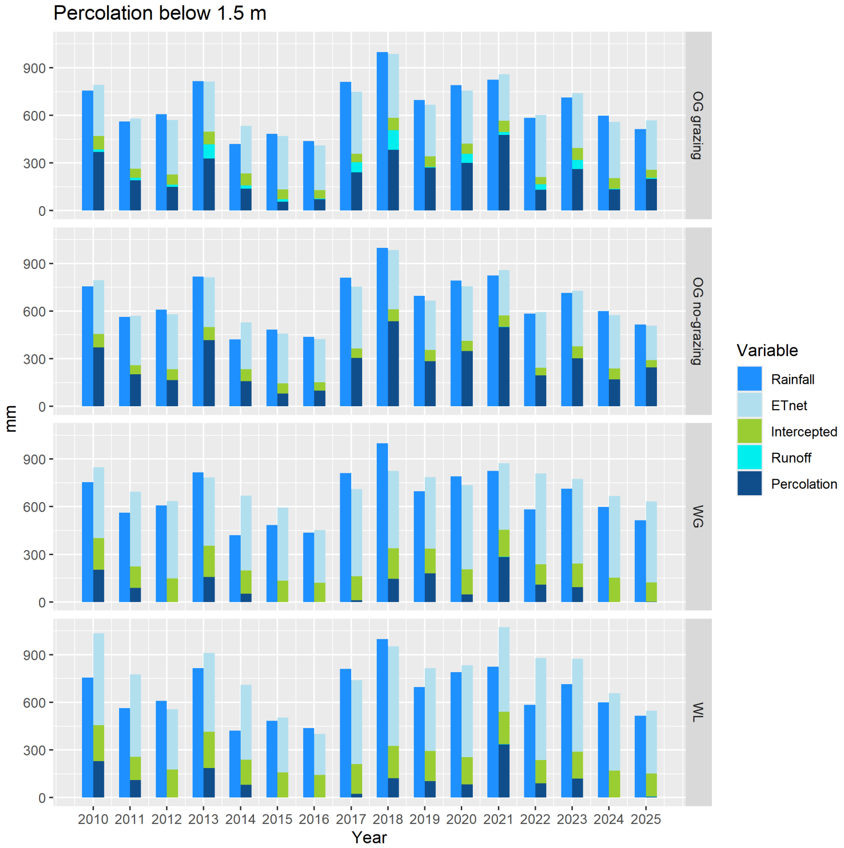


*Figure 1*. Water balance components for the three soil cover types (percolation is water flowing below 1.5 meters)

### Conclusions

This study provided preliminary valuable insights into how different land uses—characterized by increasing oak tree density—affect hydrology of agroforestry ecosystems, with specific reference to evapotranspiration (ET), surface runoff, water percolation, and rainfall interception by the tree canopy. These components are closely linked to soil water availability and groundwater recharge capacity. Consequently, land abandonment, represented by the transition from OG to WG to WL, may lead to a decline in soil water and groundwater recharge.

### Acknowledgements

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# Applicability of APSIM AgPasture for modelling yield and nitrogen content of timothy grass in boreal conditions

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**Keywords: grasslands, timothy grass, process-based modelling, APSIM, calibration**

## Introduction

In high-latitude regions, the short growing season and long day length result in vigorous early-season growth of perennial grasses but also create a narrow time window for harvesting. This increases the need for farmers to have accurate estimations of forage grass growth and quality development, which process-based models could provide. Timothy grass (*Phleum pratense* L.) is the dominant forage grass species in northern Europe, but accurate simulation of its growth dynamics and nutrient uptake remains challenging. Previous modelling studies (e.g. Korhonen et al. 2018) have shown that existing crop and grassland models often cannot reproduce seasonal biomass accumulation with high accuracy in northern climatic conditions. In practical applications on farms, where grass leys are grown as mixtures of plant species, this problem is exacerbated by the fact that most crop models do not adequately consider plant biodiversity (van Oijen et al. 2020). Other key limitations lie in the lack of process representations or adequate model parameterisations for cold climates, such as temperature-dependent nitrogen cycling and growth allocation, and winter damages. Many grassland models have also been developed to be used primarily for permanent pastures while production systems in most northern regions rely heavily on silage production on temporary grasslands with their own special characteristics the models are not able to capture.

In this study, we evaluated the performance of the APSIM AgPasture model (Li et al.,2011), originally developed for perennial ryegrass (*Lolium perenne* L.), for simulating biomass yield and nitrogen content of timothy grass in Finland. AgPasture differs from the standard crop modules in APSIM by representing perennial grasslands with repeated defoliation cycles and regrowth instead of simulating phenology and termination of growth at harvest. Our aim was to assess to what extent calibration improves this model's capability to replicate growth and N dynamics, and to identify critical limitations in model processes that need further development for reliable use in northern production conditions.

## Materials and Methods

AgPasture was calibrated following the standardized protocol proposed by Wallach et al. (2024). Parameters selected for the calibration were selected based on a sensitivity analysis. Overall, 11 plant parameters were involved. Calibration data were derived from a field experiment in Maaninka, Finland (63°09'N, 27°20'E) (Termonen et al. 2020). The experiment provided multi-year observations of biomass yield and nitrogen content of timothy grass (cultivars 'Grindstad' and 'Nuutti') under varying mineral nitrogen fertilization levels (0-450 kg N ha$^{-1}$). Model management setup replicated the field experiment, with harvest and fertilization events set to observed cutting and fertilization dates.

Model was set to leave 3000 kg DM ha$^{-1}$ residual biomass after harvest. An alternative of 1500 kg DM ha$^{-1}$ residual biomass was also analysed. Soil profile parameters were specified by layers based on soil measurements. Model initialisation was done applying spin-up runs of 700 years assuming grass rotation and applying 150 kg N ha$^{-1}$ year$^{-1}$ as mineral fertilisers. Alternative approaches for setting the soil temperature factor (soil temperature at which the model assumes mineralisation to proceed at its maximum potential rate), which influences organic matter decomposition and nitrogen mineralization, were tested for initialising soil nitrogen and organic carbon pools of the model and they were compared with total soil carbon and organic matter contents reported by Termonen et al. (2019). Weather data applied was ERA5 weather data for Maaninka from 1940 to 2022.

### Results and Discussion

Testing the AgPasture in boreal conditions is a critical test for a model that was originally developed in conditions very different from the test conditions. In particular, the soil temperature factor was shown to be important for nitrogen mineralisation and thereby for grass growth in applied conditions. The experiments with low nitrogen fertiliser rates made this impact particularly clear. This indicates the need for adjusting some key soil parameters when applying the model outside the range of its original application area. Calibration enhanced the model's ability to reproduce yield responses to fertilisation, but systematic biases remained, with a tendency to underestimate high yields and overestimate low yields. The amount of residual biomass left after each cut also affected results, as tests with 1500 vs. 3000 kg DM $ha^{-1}$ residual thresholds produced markedly different regrowth and plant N content dynamics. Overall, interannual variability in the observations was higher than in the simulations.

### Conclusions

While calibration improved APSIM AgPasture's simulation of timothy yield and nitrogen content, there were persistent errors indicating that applying the model beyond its original development context requires careful local parameterisation and even some process adjustments. In particular, adapting soil temperature factor for cooler climates is necessary to capture nitrogen cycling and yield responses.

### Acknowledgements

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# Assessing $N_2O$ and $CO_2$ emissions of Croplands in Berlin and Montpellier: Implications for Sustainable Food Systems

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**Keywords: Modelling, Winter Crops, Spring Crops, Nitrogen Cycle, Carbon Cycle**

## Introduction

A sustainable food system are at least the basic requirements demanded by the population and necessary to implement from an environmental, social and economic standpoint. Food production can involves environmental impacts such as land use, water consumption, and greenhouse gas (GHG) emissions.

The increment in cropland and intensification of agriculture production brought with it improvements in productivity, but also negative effects that have led release enormous amount of GHG (Stavi and Lal, 2013). Like the large rise of nitrous oxide ($N_2O$) emissions, due the intensification of agriculture cause the nitrogen-based mineral fertilizers (Tian et al., 2024), that can be also the cause of in the disequilibrium of the balance of carbon dioxide ($CO_2$) emissions. That processes can affect the Net Ecosystem Exchange (NEE), and these interactions highlight the dual role of agriculture as both a sink and a source of greenhouse gases (Moors et al., 2010).

To know the impact, it is essential to consider the origin of agricultural products and their final footprint. This gives particular importance to the role of local production in meeting food demand, especially in regards to nearby urban areas, where high population density increases both the diversity of food demanded and the complexity of distribution systems (e.g. Zasada, et al 2019). These dynamics make it even more challenging to quantify and manage the associated environmental impacts.

In this study, we analyze the variability of NEE and $N_2O$ emissions between 2007 and 2021 using simulation data for a set of representative crops that constitute the basis of regional food production over two Metropolitan areas in Europe. By examining both indicators together around metropolitan areas, this study aims to provide a more comprehensive understanding of the role of cropping systems in the overall GHG.

## Materials and Methods

For this study, we selected two metropolitan areas with contrasting geographical and climatic conditions: Berlin (Germany) and Montpellier (France). Around these metropolis we obtaining the Metropolitan Foodshed and Self-sufficiency Scenario (MFSS) (Zasada et al., 2019) based on the consumption and production requirements.

We calculated yearly values of greenhouse gas fluxes using the MOdel for NItrogen and Carbon in Agroecosystems (MONICA), a process-based agro-ecosystem model (Nendel et al., 2011). MONICA was calibrated for major spring and winter crops according to the local environmental conditions of both study regions. We simulated 11 crop types (including cereals, oilseeds, and tubers) between 14 to 18 year period (2005–2022) in the surrounding rural areas of Berlin and Montpellier, respectively.

**Results and Discussion**

We analyzed the conventional scenario, which includes a complete diet as well as all food waste and losses. Simulations provided estimates of $N_2O$ emissions and NEE on a seasonal basis for each crop (Figure 1). This allowed us to analyze the combined contribution of different cropping systems to the greenhouse gas balance at the regional scale. For $N_2O$ emissions both winter and spring crops displayed stronger variability in Brandenburg, with spring crops in particular showing higher magnitudes compared to winter crops. In terms of NEE, spring crops exhibited lower values in Montpellier compared to Brandenburg, highlighting likely the influence of local climatic conditions on carbon dynamics.

These findings emphasize the importance of considering both crop type and seasonal dynamics when assessing the GHG balance of regional agricultural systems in European level considering different climatic scenarios.

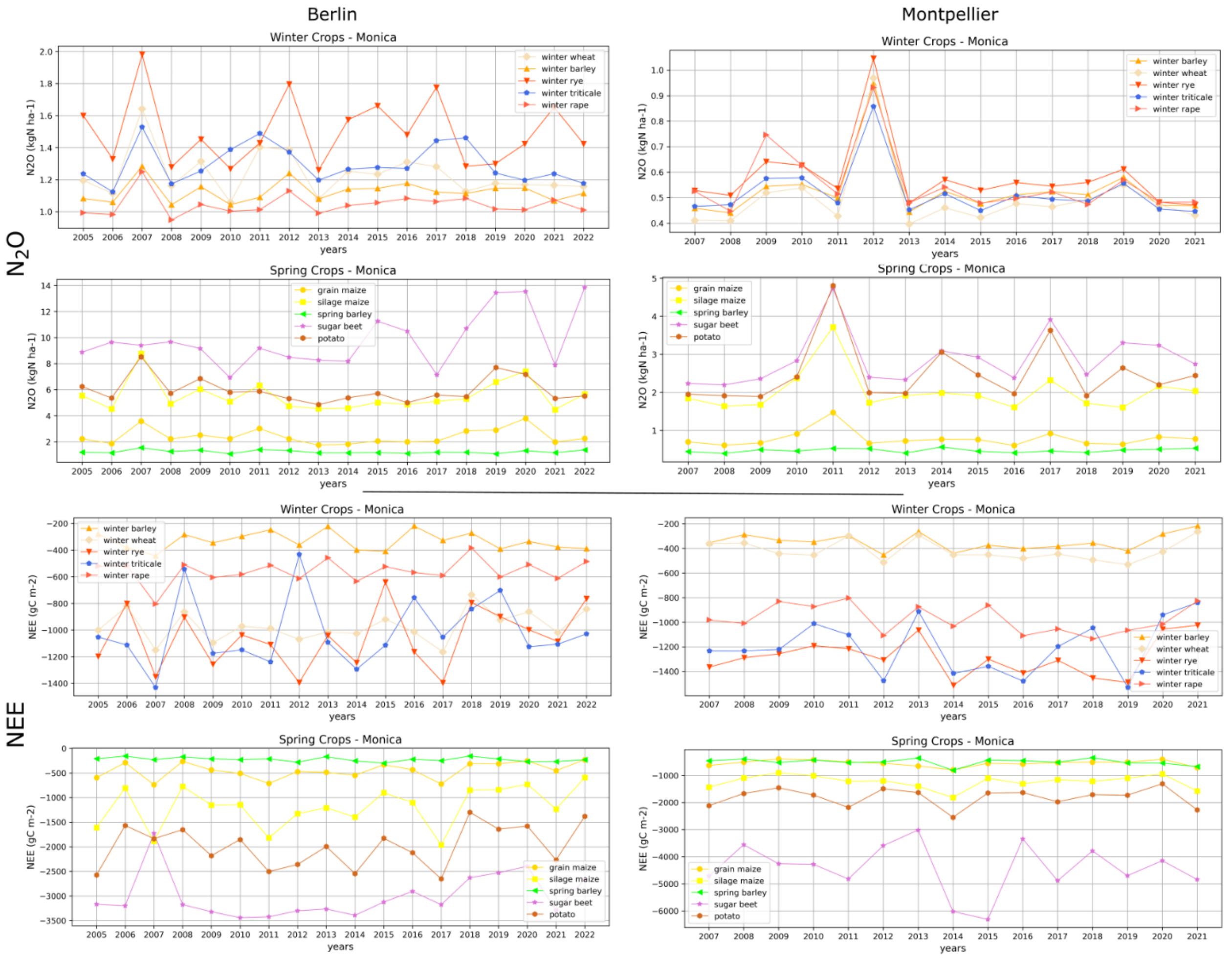


*Figure 1.* N2O emission and NEE, obtained using MONICA, for winter and spring crops in arable zone around the metropolis Berlin (Crops in Brandenburg) and Montpellier (Crops in Occitania), from 2005 to 2022 for Berlin and 2007 to 2021 for Montpellier.

## Conclusions

This analysis shows the trade-offs inherent to metropolitan food systems, while local production can help reduce transport-related emissions and strengthen regional self-sufficiency, it also involves important environmental costs through $N_2O$ emissions and altered $CO_2$ balances. It is crucial for designing sustainable food strategies that align with environmental and socio-economic objectives.

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## Challenges of simulating $N_2O$ emissions from a long-term experimental site

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**Keywords:** nitrous oxide, process-based modeling, long-term experiment, soil–climate interactions

### Introduction

Process-based agroecosystem models are widely used to analyze crop production and environmental trade-offs, supporting decision-making and scenario assessments such as climate change impacts. However, simulating nitrous oxide ($N_2O$) emissions remains a highly challenging task. Emissions are governed by microbial nitrification and denitrification processes, which are extremely sensitive to soil moisture, aeration, and substrate availability (Butterbach-Bahl et al., 2013). Long-term field experiments provide unique opportunities to study these dynamics, but modeling efforts face difficulties due to evolving soil properties, management shifts, and environmental variability.

### Materials and Methods

We present a case study using process-based models within the framework SIMPLACE <Lintul5, Slim, SoilCN> (Enders et al., 2023), applied to a long-term fertilizer trial established in 1904 at Dikopshof, Germany. The model was calibrated and validated with multi-decadal measurements of crop yields, soil nitrogen, and $N_2O$ fluxes under contrasting fertilizer and manure treatments. In addition, a literature meta-analysis was conducted to identify bottlenecks in representing event-driven emissions.

### Results and Discussion

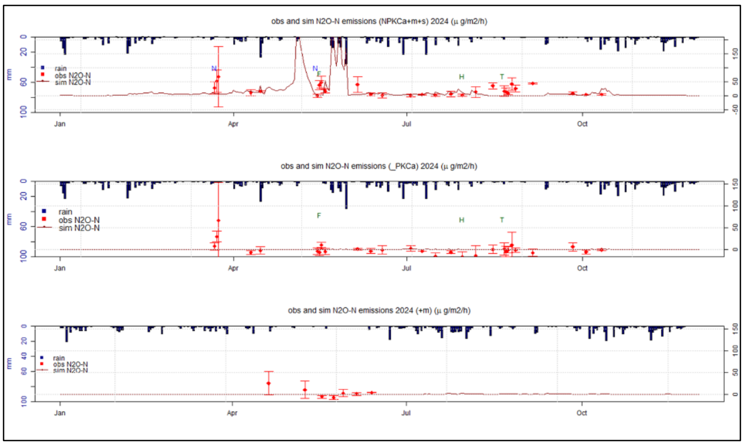


***Figure 1.*** *Observed and simulated $N_2O$ emissions from a long-term fertilizer trial at Dikopshof, Germany. Event markers: F = flowering; N = nitrogen fertilization; T = tillage; H = harvest. Treatments: NPKCa+m+s = full fertilization; PKCa = phosphorus, potassium, and calcium; +m = farmyard manure*

The model was able to reproduce many of the measured $N_2O$ emissions with good accuracy, particularly the background fluxes. However, it consistently underestimated short-term peak events, especially those associated with tillage operations and the spontaneous emissions observed in treatments with manure application. This underestimation reflects the challenges models face in capturing rapid, nonlinear microbial responses triggered by changes in soil moisture, aeration, and substrate availability (Smith et al., 2008). In particular, the effects of tillage remain poorly represented, despite their strong influence on soil structure and gas exchange. Ongoing efforts aim to implement tillage effects into the model to improve its representation of short-term dynamics and better fill gaps in the measurement series.

Freeze–thaw dynamics and winter fluxes were also underestimated (results not shown), although they can contribute disproportionately to annual $N_2O$ budgets (IPCC, 2019). Consistent with previous findings (Flessa et al., 2002), short-lived, high-magnitude emission pulses can significantly contribute to seasonal totals, underscoring the limitations of daily model validation against sparse measurements. While cumulative annual emissions were reproduced within acceptable error margins, daily and event-based fluxes were smoothed out, highlighting the need for improved parameterization of transient soil–climate interactions and management operations.

### Conclusions

Our results highlight the difficulty of simulating $N_2O$ emissions at high temporal resolution. Instead of focusing on daily agreement, model evaluation should emphasize seasonal or annual balances within reasonable error margins. Improving representations of microbial dynamics, stochastic weather–soil interactions, and event-based processes remains essential. More frequent field measurements are also required to better constrain models.

### Acknowledgements

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# Drivers of inter-annual variability in maize-cowpea intercropping performance along a climate gradient

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## Introduction

Cereal-legume intercropping is a promising sustainable intensification option for smallholder farmers in Sub-Saharan Africa under rainfed agriculture. Few studies have investigated the impact of climate variability on the Land Equivalent Ration (LER) of cereal-legume cropping systems in Sub-Saharan Africa (Kwenda et al., 2025). This study aims to assess the performance of intercropping along a climate gradient.

## Materials and Methods

The STICS soil-crop model was parameterised for maize-based cropping systems in Mutoko (semi-arid climate), then used to perform virtual experiments for Mutoko and Murewa (sub-humid climate) study sites. Soil characteristics and climate data corresponding to each site were used as input in the model. Observed historical climate from 1996 -2021 was also used as an input to the model. One maize (*Zea mays L.*), one cowpea (*Vigna unguiculata* (L.) Walp.) variety, two cropping systems (sole vs intercropping) were evaluated in the virtual experiment. The details of plant and soil calibration are reported in Kwenda et al. (2025). Sole and intercropped maize received 80 kg N $ha^{-1}$ in the simulations. The coefficient of variation (CV) was used to determine yield variability in the partial Land Equivalent Ratio and LER.

Simple linear regression analysis of intercropping performance (pLER and LER) against simulated water and N stress was performed to identify drivers of variability.

## Results and Discussion

Historical cumulative rainfall varied considerably between sites and growing seasons, with a mean and standard deviation of 933 ± 322 mm for Murehwa, and 757 ± 252 mm for Mutoko. Despite simulation of substantial water and N stress for maize and cowpea in intercropping system, the LER was always above one in Murewa, but below one for three growing seasons in Mutoko. The model simulated higher variability in maize pLER for aboveground biomass and grain yield in Mutoko compared to Murehwa (Figs. 1A and B). Wider variability in the maize pLER of aboveground biomass and grain yield was simulated in Mutoko (34.4% and 21.4% CV) compared to Murewa (8.7% and 4.7% CV). The model simulated strong water and N stress on the aboveground biomass and grain yield of maize, and very limited water and N stress for cowpea. The stronger the water and N stress for sole maize and cowpea, the larger pLER of aboveground biomass and grain yield.

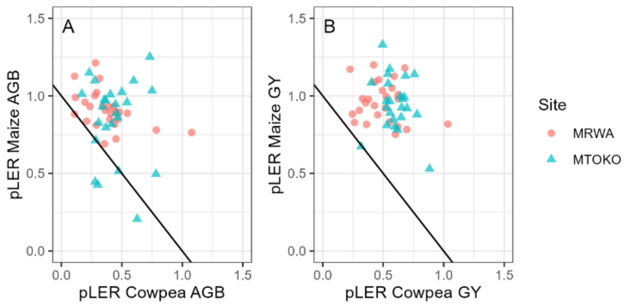


Figure 1. Maize and cowpea pLER for aboveground biomass (AGB)(A) and grain yield (B) as simulated by the STICS model for twenty-six historical growing seasons (1996-2021) for Murewa and Mutoko districts. In all subplots, the black solid line is LER = 1. Two outliers (> 1.5) were removed for the pLER of cowpea grain yield.

## Conclusions

Intercropping productivity is impacted by climate variability in all the sites. The performance of maize-cowpea intercropping varies with climate condition, and the average benefits are reduced under drier climate conditions, while risk of low benefits (LER<1) increase in drier climates.

## Acknowledgements

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## Modelling weed-crop interactions in tropical cropping systems: adaptation of the FLORSYS model

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**Keywords: tropical weeds; model parameterization; yield losses.**

### Introduction

Weeds may cause major yield losses in cropping systems, particularly in tropical environment (Oerke, 2006). Yet, the effect of weed-crop competition on cropping-system performances is rarely studied in these contexts. In Reunion Island, weeds are mainly managed with herbicides in sugarcane cropping systems. The development of alternative herbicide-sparse management practices is a critical challenge for sugarcane production. However, field experiments to address these questions are time-consuming and expensive, delaying actionable insights. The FLORSYS model, a 3D individual-based multi-species and multi-annual crop model, initially designed for arable cropping systems in temperate regions (Colbach et al., 2021), is a promising tool for overcoming this deadlock. The aim of this study is to assess the performance of the FLORSYS model under tropical conditions and its ability to account for the characteristics of semi-perennial sugarcane cropping systems and tropical weeds.

### Materials and Methods

So far, one sugarcane variety (R579) and 8 dominant tropical weed species were parameterized based on literature, measurements or expert knowledge. In addition, experiments were set up to characterize the early growth phase of sugarcane and to assess its morphological plasticity under light competition to estimate key parameters in weed-crop interactions. Weed species were chosen to be representative of the diversity observed in sugarcane cropping systems considering broad functional type – small dicotyledons, perennial weeds, lianas and tall grasses. The FLORSYS model, along with our parameterization, is currently being evaluated against experimental datasets to test its ability to accurately simulate weed competition effects on sugarcane yield. We test the model in weed-free and weedy cropping systems in which weed communities differed. We compare different approaches for weed parameterization and their impact on yield prediction: (i) clustering weeds into broad functional types and (ii) using average values to represent the weed flora without species discrimination.

### Results and Discussion

Results from experiments showed that sugarcane responded to shading by reducing the amount of biomass produced, and changing its morphology with a higher height and reduced width, which led to a greater distribution of leaves in the upper part (Table 1).

*Table 1*. Sugarcane response to different light conditions at two and four months after planting (mean ± standard error)

| | Two months after planting | | Four months after planting | |
|---|---|---|---|---|
| **Growth parameters** | **Full sun** | **50% shade** | **Full sun** | **50% shade** |
| Height / Biomass (cm $g^{-1}$) | 7 ± 2 | 16 ± 7 | 2 ± 1 | 6 ± 4 |
| Width / Biomass (cm $g^{-1}$) | 6 ± 1 | 10 ± 5 | 3 ± 1 | 4 ± 2 |
| Number of tillers | 5 ± 3 | 1 ± 1 | 8 ± 3 | 2 ± 1 |
| Leaf distribution | Evenly distributed | Top heavy | Evenly distributed | Top heavy |
| Biomass (g) | 17 ± 4 | 10 ± 5 | 76 ± 40 | 37 ± 23 |

First simulations with functional weed types showed that the model was able to rank correctly weed impacts under optimal growth conditions, *i.e,* with fertilization and irrigation. Yet, weed competition tended to be underestimated, particularly when weed communities were dominated by lianas. This may be due to the fact that the ability of these species to smother the crops is not currently taken into account in the model. In a context where quantitative data on tropical weeds is scarce, our results suggest that using functional weed types could be a relevant approach.

## Conclusions

This work is a first step towards the design of herbicide-sparse weed management strategies in sugarcane cropping systems. In the future, the FLORSYS model will be used to assess these strategies in relation to the objectives and constraints of different sugarcane farm types. This also paves the way for the use of this model in other tropical cropping systems.

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