

XIVth STICS Seminar - Conference Proceedings

Benjamin Dumont, Samuel Buis, Marie Launay, Christine Le Bas

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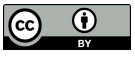
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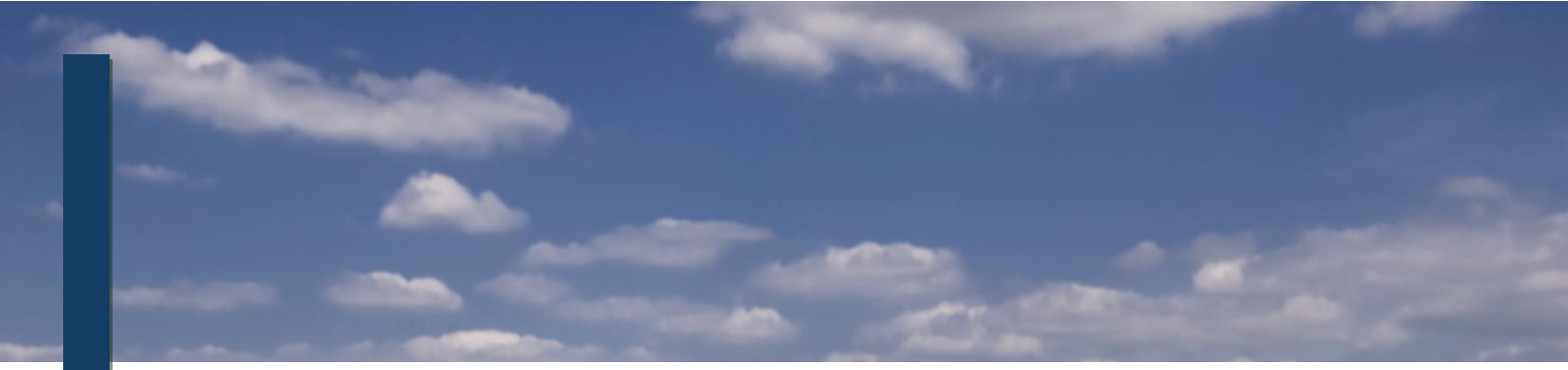
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XIVth STICS SEMINAR

Conference Proceedings

March 17-19, 2026

Organized by the University of Liege, Belgium



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Welcome

On behalf of the Organizing Committee, it is my great pleasure to welcome you to the 14th STICS seminar 2026. I am delighted to gather this audience for three days of scientific exchanges and discussions. Agriculture is facing unprecedented challenges ! While it must keep ensuring food security for all, it has to face the threat of climate change, lower the pressure it puts on the environment, stop biodiversity erosion and contribute to its restoration. In this context, I'm convinced that crop modelling can play a key role in advancing our knowledge of agro-ecosystem functioning and in designing innovative cropping systems, able to support the unquestionable required agroecological transition towards a sustainable and resilient future.

The aim of the seminar is to bring together the designers, the developers and the users of the STICS crop model - and associated tools - to present the latest technical and scientific advances around the model, illustrated by relevant case studies. The seminar should also provide us with the opportunity to share ideas and insights, and further discuss strategies for deploying and developing the model to meet the nowadays' and tomorrow's challenges.

The scientific program is structured around five themes that are important to me :

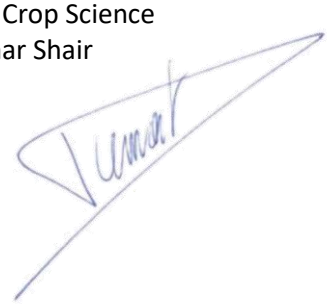
- Agroecology: Assessing ecosystem services and supporting the agroecological transition using the model
- From seed to harvested organ, from variety choice to crop sequence design, from a practice to its effect on biogeochemical cycles: the model as a tool to understand systems
- Climate change: Using the model as a tool to explore adaptation and/or mitigation strategies
- New formalisms, parameterization of new species and development of tools around the STICS model
- STICS & friends: interfacing the model with databases and coupling with other models

I hope the best for this event to be a stimulating conferences. I wish you a productive, inspiring, and enjoyable seminar, and I look forward meeting and discussing with you during this meeting.

Welcome to Belgium, welcome to ULiege-GxABT,

Prof. Benjamin Dumont

University of Liege – Gembloux Agro-Bio Tech
Plant Sciences – Crop Science
14th STICS Seminar Shair



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Philippe Baret	UCLouvain – Earth and Life Institute, Belgium
Xavier Draye	UCLouvain – Earth and Life Institute, Belgium
Guillaume Lobet	UCLouvain – Earth and Life Institute, Belgium

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They have supported us

On behalf of the Organizing Committee, we wish to express our sincere thanks to the partners who have supported us in the seminar's organization

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Keynote Speech I

Agroecology : from plant to systems

Prof. Philippe Baret[1]

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Who is he ?

Philippe Baret is an agricultural engineer specialized in tropical systems (1986) and holds a PhD in quantitative genetics (1995). He is Professor at UCLouvain, where he has been lecturing systems analysis, genetics, and agroecology since 1997. From 2016 to 2021, he served as Dean of the Faculty of Bioscience Engineering.

He has supervised numerous doctoral theses on agricultural and food systems and leads the Sytra research team, which focuses on understanding diversity in farming systems, innovation processes, and pathways for systemic transitions in agriculture and food. His work places strong emphasis on inclusivity, interdisciplinarity, and systemic thinking.

Philippe Baret is an active member of several scientific boards and research bodies, including the Académie Royale de Belgique, the Académie d'Agriculture de France, and the Accademia dei Georgofili.

Agroecology : from plant to systems

Agroecology is not a set of practices. Agroecology is delineate by a set of principles as a guide to pilot agricultural and food systems. When working on plants and farmers, this specifity of the agroecological framework is a challenge. From a technical point of view, the integration of different scales implies a specific attention to emergence effect and to the limitation of indicator upscaling. In a impact driven perspective, a specific attention to the diversities of actors and pathways is key to contribute to a real agroecological transition.

Keynote Speech II

Plant roots within crop models: why are they important and how should they be managed?

Prof. Guillaume Lobet[1], Prof Xavier Draye[1]

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Who are they ?

Guillaume Lobet and Xavier Draye are professors at the Earth and Life Institute of the Faculty of Bioengineering, UCLouvain. Their research aims to understand how cultivated plants can better adapt to variations in water availability during their growth cycle. To do this, they study roots, their structure, and their organization. In a broader context, they want to contribute to the creation of sustainable agrosystems that are resilient to drought and water shortages.

Plant roots within crop models: why are they important and how should they be managed?

During this conference, we will discuss the role of roots in agrosystems. In particular, we will look at how their complexity and multi-scale nature make them difficult to quantify, especially within the field. We will see how we can combine and exploit the latest computational tools to quantify relevant functions, despite this complexity. We will talk about roots, their anatomy, their architecture, and also the role played by soils.

Session I

Agroecology: Assessing ecosystem services and supporting the agroecological transition using the model

Assessing Low-Input Crops and Crop Rotations to Reduce Nitrate Leaching in Water Catchment Area with the STICS model

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Keywords: STICS, agronomical diagnosis, low-input crops and rotations, nitrate leaching, Miscanthus.

Introduction

Water catchment areas (WCA) are vulnerable to pollution from agricultural, industrial, and domestic sources. Between 1994 and 2013, 7,716 WCAs used for drinking water supply were abandoned in France, 39% due to nitrate and pesticide contamination. Despite regulations promoting “good agricultural practices”, water quality often remains unsatisfactory. This study aimed to perform an agronomic diagnosis of agricultural practices affecting water quality and to assess the potential of alternative crop rotations including low-input (LI) crops to mitigate nitrate leaching.

Material and methods

Simulations were carried out at the scale of the Mérobert WCA (3,670 ha), located near Chartres (France). The area is 93% cropland, dominated by arable farming. Climatic data for the WCA centroid were derived of Météo-France datasets from physical meteorological stations (2000–2022). Soil types were identified from the 1:250,000 soil database of the Eure-et-Loir department, and six main soil types were selected for the simulations: Luvisol, Truncated Luvisol, Eutric Cambisol, Colluvic Regosol (with or without pebbles), and Hydromorphic Planosol (WRB classification, FAO, 2022). Crop rotations were derived from the land parcel identification system (LPIS, 2015–2023). Fifteen rotations, representing 60% of arable land, were identified. Nitrogen fertilization was calculated using the COMIFER balance-sheet method and applied according to technical institute recommendations. Automatic irrigation was calibrated to reproduce biomass production and irrigation amounts observed in the WCA. The simulations complied with the legal minimum soil cover requirements set by the administration regulation. These simulations, considered as the reference scenario, were used for agronomical diagnosis and model outputs validation at the WCA scale (yield, N fertilization, irrigation, nitrate content in drained water).

The low-input (LI) scenario involved keeping the share of current spring crops unchanged while replacing one wheat–wheat succession in three-year winter cereal sequences with a sunflower–wheat succession, converting 1% of arable land to organic farming and 10% to Miscanthus production. The objective was to decrease mineral N fertilization (with 0 kg N ha^{-1} y^{-1} in organic farming and for miscanthus production and 26 kg N ha^{-1} y^{-1} on average for sunflower). Simulations covered the 2000–2022 period and the first two years were used for model initialization.

Results and discussions

The model satisfactorily reproduced irrigation, fertilization, and yields at the WCA scale (data not shown). The average simulated nitrate concentration in drained water over 20 years was 35.3 ±

18.4 mg L^{-1} in the reference scenario and 31.4 ± 15.0 mg L^{-1} in the LI scenario, corresponding to an 11% reduction of nitrate concentration associated with a 2.4% decrease in drainage volume. Soil type and crop rotation significantly affected these variables ($p < 0.01$). It appears that nitrate content of drained water simulated by the model was lower than observed value in the groundwater which is stabilized around 44 mg L^{-1} from 2005 to 2017. This underestimation can be linked to several limitations that we cannot address in this study: N fertilization was adapted yearly, which is a better practice than in reality; yield objectives were assigned to the different soil types assuming homogeneous soil conditions within fields, which is wrong; simulated farmers' agricultural practices follow technical institute recommendations as the administration regulation, whereas actual practices vary and regulations are not always respected (DREAL Centre-Val de Loir, 2022); simplifications which were necessary to perform simulations at the WCA scale.

Agronomic analysis of model outputs showed that nitrate concentration in drainage water increases with the frequency of winter cereals (due to low N needs of these crops in autumn and winter) or with the presence of spring pea in crop rotations (in accordance with Plaza-Bonilla et al., 2015). Conversely, increasing the frequency of rapeseed in rotations or including spring crops preceded by catch crops tends to decrease nitrate concentrations in drainage water (as also reported by Justes et al., 1999; Schnebelen et al., 2004; Jégo et al., 2008; Constantin et al. 2010). In the LI scenario, the organic farming rotation resulted in a low nitrate concentration (26.4 mg L^{-1}; -39 to -62% compared to replaced rotations), consistent with Rakotovololona 2018. Replacing wheat–wheat sequences in the targeted rotations with sunflower-wheat reduced nitrate concentration by 19 to 32%. The lowest nitrate concentration was observed under Miscanthus (20.2 mg L^{-1}; -53 to -69% compared to replaced rotations), in agreement with McIsaac et al. (2010) and Thomas et al. (2014).

Conclusion

Implementing low-input crops showed strong potential for reducing nitrate leaching in the WCA while maintaining agricultural production. These results highlight the importance of diversifying crop rotations to improve water quality in vulnerable catchment areas, as well as the usefulness of the STICS model for conducting agronomic diagnoses and evaluating scenarios.

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

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

Introduction

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

Material and methods

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

Results and discussions

The calibration of the STICS model was both accurate and robust in simulating cereal-cowpea intercropping, see Table 1 (de Freitas et al., *under review at FCR*).

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

in WA.

Table 1: Accuracy of the STICS simulations of millet, sorghum and cowpea with the calibration dataset (sole crops) and the evaluation dataset (intercrops) in four West African sites. Statistical description of model performance is displayed: rRMSE in % and bias have no unit (de Freitas et al., *under review FCR*).

		Millet		Sorghum		Cowpea	
Variable	Statistical indicator	Calibration - Sole cropping	Evaluation - Intercropping	Calibration - Sole cropping	Evaluation - Intercropping	Calibration - Sole cropping	Evaluation - Intercropping
Cycle duration	rRMSE	17	15	9	25	6	17
	Bias	7	10	-8	3	1.4	8
AGB at maturity	rRMSE	44	29	27	29	38	76
	Bias	0.5	-1	0	-0.2	0	0.2
Plant N at maturity	rRMSE	55	21	20	30	32	71
	Bias	22	6	-6	-17	14	7
Grain yield	rRMSE	41	34	38	40	38	111
	Bias	0.1	-0.2	0.2	0.2	0.1	0.1

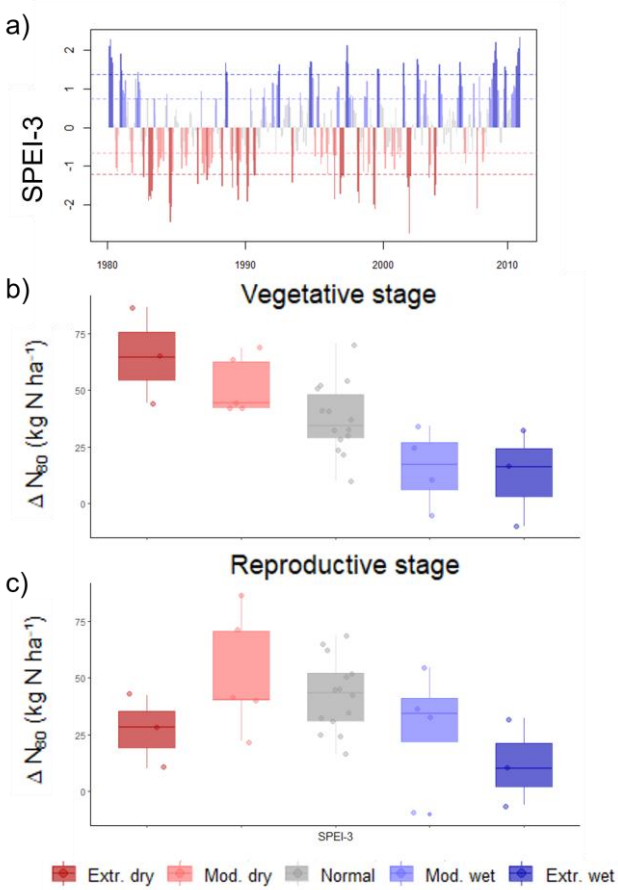


Figure 1: a) SPEI-3 index (expressing the dryness/wetness, computed monthly from the water balance over the current and the two-preceding months), of the historical period 1980–2009 in the station N'tarla in Mali. The colours designate the category of climatic events (extremely/moderately dry/wet). Dashed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

Conclusion

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

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

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Keywords : Food security; Optimisation; Land use; Soil crop modelling

Introduction

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

Material and methods

We developed a mixed-integer linear programming algorithm that designed crop rotations aligning local production with the nutritional needs of the population under the EAT-Lancet dietary scenario (Willett et al., 2019). The algorithm explicitly integrated pedo-climatic suitability, agronomic constraints (return times, exclusion rules), and regional land availability. These optimised rotations then served as input for the process-based STICS soil crop model (Brisson et al., 2003), which was run under IPCC climate scenarios corresponding to +2 °C, +3 °C, and +4 °C warming (mid- to late-21st century horizons) at high spatial resolution (50 m × 50 m soil data, derived from the Walloon regional soil database WalOnMap). STICS simulations were performed for major representative crops of each food group, selected based on both their regional importance and their availability in the STICS crop library. Food groups not explicitly represented (e.g. fruits from orchards) were excluded, while vegetables were represented by proxy crops (e.g. carrot) assuming similar functional responses. We assessed yield responses, water and nitrogen dynamics, and greenhouse gas emissions simulated by STICS. The overall methodological framework is summarised in Fig. 1.

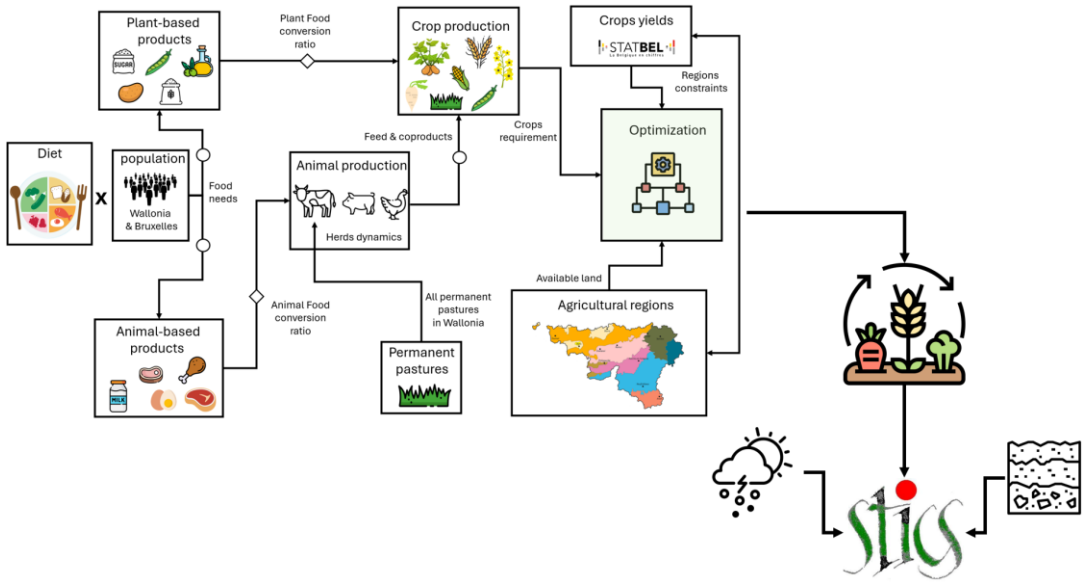


Figure 1: Schematic representation of the methodological framework. Population dietary needs (EAT-Lancet scenario) were converted into crop and livestock requirements. Crop rotations were optimised under pedo-climatic and land-use constraints, then simulated with the STICS model to assess yields and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

Results and discussion

Crop rotation optimisation showed that nutritionally balanced food self-sufficiency was theoretically possible with diversified four- to six-year rotations across Wallonia. STICS simulations revealed a heterogeneous climate impact: (i) cereals and oilseeds experienced gradual yield reductions under +2 °C, with more severe declines in shallow soils and under +3–4 °C; (ii) legumes displayed strong interannual variability due to drought stress, emerging as a limiting factor for robust rotations; (iii) sugar beet and maize benefited from longer growing seasons under warmer conditions, provided that water availability was not limiting. Territorial-scale outcomes suggested that food self-sufficiency remained achievable under +2 °C warming, but became increasingly fragile under higher scenarios, requiring adaptive strategies such as enhancing soil water retention, adjusting sowing dates, selecting better-adapted crop varieties, and broadening rotation diversity. The study also highlighted several limitations, including the limited number of crop species that can currently be simulated within STICS, uncertainties in varietal parameterisation under extreme climates, and the absence of explicit biotic stress simulations. These results point to the need for improved crop parameter libraries, better representation of perennial systems, and closer coupling with varietal and pest-pressure scenarios.

Conclusion

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

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Large-scale Multi-criteria Evaluation of Agroecological Strategies with the STICS Model

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Keywords: Agroecology; Climate change; Ecosystem services; Resistance; Integrated crop-livestock systems; Crop diversification

Introduction

Agriculture is under mounting pressure to supply an ever-increasing demand for food, feed, and fiber, all while drastically cutting its ecological footprint. This task is made even more difficult by the accelerating impacts of climate change, which both disrupt and are amplified by agricultural practices – forming a feedback loop of vulnerability (Yang et al., 2024). In response, a range of agroecological approaches are being explored within crop rotation systems. These approaches span from improving input efficiency, such as reducing nitrogen fertilization, to more transformative redesigns, such as crop diversification or pastures and integrated crop-livestock systems (ICLS).

However, considerable uncertainty persists about the actual impacts of these strategies. Their performance varies widely depending on factors such as soil and climate conditions, as well as specific agronomic contexts, where complex trade-offs and synergies can arise among the ecosystem services agriculture provides. Research that bridges broad spatial and temporal scales remains scarce – most studies being limited to specific sites or short periods – leaving a gap in our understanding of fundamental aspects like soil fertility, system stability, and resistance to climate change.

Material and methods

In a PhD thesis entitled '*Soil-crop modelling of ecosystem services in diversified and integrated crop-livestock systems for climate change adaptation and mitigation*' (Delandmeter et al., 2025), we investigated the impacts of three main agroecological levers: reduced nitrogen fertilization, crop diversification, and crop-livestock integration. These levers were analyzed across multiple crop rotations, under diverse present and future pedoclimatic conditions, using different climate change scenarios and climate models. All these rotations were simulated with the STICS model (Beaudoin et al., 2023).

The impacts of agroecological strategies were evaluated through a broad range of indicators, each associated with ecosystem services, specifically provisioning services (e.g., productivity, profitability, and the stability and resistance of yields to extreme climatic events), supporting services (e.g., soil carbon sequestration and reduced nitrate leaching), and regulating services (e.g., greenhouse gas emissions reduction).

In Wallonia (Southern Belgium), both *single-site* – simulating different crop rotations under different climate scenarios in a single location – and *large-scale* – analyzing cropping systems over large territories – studies were conducted. In a first time, based on De Clerck et al. (under review), three circularity scenarios were compared. These scenarios were designed to provide a diet to a local population which would fulfill the requirements of the EAT-Lancet diet – being healthy and environmentally-friendly (Willett et al., 2019), but under different constraints. A business-as-usual scenario serves as the baseline for Belgium, involving the import of manure in exchange for exported

wheat straw; a Vegan scenario models an agricultural system without any livestock, to investigate if such system is realistic; and a third scenario envisions a farm-level integration of crop and livestock production (ICLS). These three scenarios were first compared in a single-site study in Gembloux (Belgium), to study how soil-crop feedbacks influence crop resistance to extreme climate events (Delandmeter et al., 2026). In a second time, they were investigated over the whole region of Wallonia – which represents 11,515 distinct locations covering 541,800 hectares – and under ten climate change scenarios, involving three global warming scenarios (+2, +3, and +4°C) with three distinct Earth System Models (MPI, CMCC and MIR). Then, in a second time, starting from a traditional, high-intensity crop rotation, we evaluated the effects of gradually implementing a range of agroecological practices across eight distinct crop rotation systems, still at the scale of Wallonia. For all scenarios, the variety of ecosystem services mentioned above were compared.

Then, we also investigated the impacts of grazing intensity within ICLS in the contrasting context of soybean-pastures systems in Brazil, based on a single-site study conducted in São Miguel (Delandmeter et al., 2024). Pastures were grazed by beef cattle with four increasing grazing intensities, plus an ungrazed treatment. The grazing process was simulated through regular cuts in sward, and the return of residues to simulate feces and urine. The different treatments were simulated over an 18-year period under historical climatic conditions – allowing the validation of the model on yields, total herbage productivity and beef live weight gain – and in 2040-2070 (RCP8.5). Productivity levels – along with their stability and resistance to extreme climatic events – were compared, as were soil organic carbon dynamics within the 0-30 cm layer and across the entire soil profile.

Results and discussions

Results show that, across studies and contexts, crop diversification — and even more so, ICLS — decrease productivity compared to business-as-usual scenarios favoring cash crops, but provide significant opportunities to improve climate change adaptation by increasing the stability and resistance of agricultural production under extreme weather conditions. These approaches also help reduce environmental issues such as nitrate leaching and greenhouse gas emissions, and increase soil carbon sequestration. Reducing nitrogen fertilizer use proves to be an effective way to lessen both impacts, while having only a minor effect on overall productivity. Finally, ICLS performances are highly dependent on grazing intensity, with benefits maximized under moderate grazing intensities which balance the trade-off between maximizing carbon uptake through cattle grazing for live weight gain and maximizing the amount of carbon returned to the soil.

Conclusion

These studies illustrate how process-based soil-crop models can be harnessed to evaluate agroecological transition strategies across the efficiency, substitution, and redesign spectrum. The computational resources available today make it possible to carry out such analyses across extensive spatial and temporal scales, thereby reducing the biases that can arise from narrowly focused evaluations. By combining these models with innovative methods for designing cropping systems, it becomes possible to generate tailored scenarios that promote diverse and balanced human diets while reducing dependence on food and feed trade. Moreover, when integrated with an innovative framework for assessing system stability and resistance to extreme climatic events, soil-crop models emerge as powerful tools for analyzing how agricultural systems can both adapt to and mitigate the impacts of climate change.

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Experimentating with farmers: understanding perceptions and assessing agro-environmental performance of occitan cereal systems through crop modelling

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Keywords: Beliefs, Co-conception, Cropping system, Practices changes

Introduction

In the Occitanie region (France), where 1/3 of the used agricultural area is dedicated to cash crops, several factors affect the sustainability of agroecosystems. In this context, modeling tools may provide a useful interface to support farmers' agroecological adaptation (Blanc et al., 2024). In particular, the impact of cover crops raises questions among farmers. Cover crops are often promoted to reduce erosion and nitrate leaching, or to enhance carbon sequestration and soil quality, or to reduce mineral fertilizer requirement. But some effects can be much more variable such as nutrient and water competition with cash crops, changes in GHG balance, management obstacles or financial returns (Rivière et al., 2022). The long-term change in farming practices implies changing the way farmers perceive their productive environment which is anchored in a social and institutional environment (Hodgson, 2006), and a personal context which influences his beliefs and values (Peirce, 2000). Multi-criteria assessment based on simulation of specific farmers' practices can act as a mediating artifact that may trigger a change of beliefs (Sutherland et al., 2012). This change is expected to depend on farmers' initial perception since it would drive the extent to which farmers may take ownership of the multi-criteria assessment.

Material and methods

The model STICS - Simulateur mulTIdisciplinaire pour les Cultures Standard (Brisson et al., 2003) is used in this research as a mediation tool. STICS assesses the effects of climate, soil and agricultural practices to inform farmers' choices. STICS has been chosen as a generic and robust model allowing calculation of a large and "invisible for farmers" range of agro-environmental variables at the crop plot scale, such as component of water, carbon and nitrogen soil budgets, as well as yields. STICS was calibrated and validated in Southwestern France.

A community of 11 farmers who belong to a network of farmers engaged in increasing soil quality (Groupement d'Agriculteurs de la Gascogne Toulousaine - GAGT) volunteered for this research. This network of 90 farmers aims to 'Develop a Sustainable, High-Performance Agriculture that respects the environment, while preserving farmer's income'.

The research strategy is to characterize their perception of their agricultural practices and its potential evolution, through semi-structured interviews and collective workshops to redesign their cropping systems. STICS simulations are run on two plots for each farm over past years, based on farmers recent practices, to supply multi-criteria assessments of crop plot performance including agro-environmental indicators. Farmers engage with the multi-criteria assessment during collective workshops that aim to make new practices emerge. The upcoming workshops will allow the design of new cropping systems, including more or less cover crops among others agroecological practices.

The interpretation of these changes will stem from an abductive approach.

Results and discussions

Multicriteria assessment

We focus on (1) potential soil organic carbon (COS) storage in different cropping systemsin recent years and in cropping systems scenarios involving agricultural practices such as cover crops that are supposed to modify water storage dynamics and increase COS, (2) GHG balance (N2O, CO2) of these cropping systems, (3) identifying limiting agronomic factors and meteorological variability and (4) yield (in quantity and quality).

Farmers' typology and expectations

The interviews have been conducted before workshops. Collected data allowed characterizing 3 plots groups structured by agricultural practices involved in the multicriteria assessment. The interviews show that farmers are interested in understanding processes at work in their plots. Above all, they want to increase soil organic carbon, and soil fertility. They are aware that some factors considered in the assessment might enhance their decision-making, and that engagement with diversified practices might be inspiring.

Conclusion

The adopted research strategy is expected to improve ways to work and experiment with farmers using modeling, thanks to their reflexive approach on their practices and capacity to change. It is in line with research on the presence of digital technology in agriculture (Schnebelin, 2022), the use of companion models (Hossard et al., 2022), and the use of simulated data to co-design adaptation strategies (Blanc et al., 2024). The originality is to investigate the interactions between the modelling results, farmers believes and practices at the plot level. This co-research study should lead to the co-production of new knowledge about the benefits, the barriers to the adoption of agroecological practices in Occitan context, and to the identification of necessary trade-offs to meet both environmental and socio-economic needs.

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Building on a process-based modelling framework to assess CO_2 exchanges in a grazed grassland–maize rotation

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Keywords: Grassland management, Carbon fluxes, STICS model, Eddy covariance, Net ecosystem exchange

Introduction

Grasslands play a crucial role in the carbon (C) balance of agricultural systems, mainly acting as sinks of CO_2. The evolution of their soil organic C depends on soil and climate conditions and how they are managed (Bai et Cotrufo 2022). In intensively grazed grasslands, C fluxes vary due to cutting and grazing activities, which cause abrupt changes in canopy structure and soil biological activity. In particular, animals play on C dynamics through herbage removal, excreta return which in turn depend on variations in the quantity and quality of feeds ingested during grazing and in barn, and finally through animal respiration. This further influences C exchanges at the ecosystem scale and increase the complexity of CO_2 flux modelling. Process-based models, such as the soil-crop model STICS, provide a detailed representation of soil–plant interactions and can be used to simulate key C processes such as vegetation net primary production (NPP) and heterotrophic soil respiration (HR). (Delandmeter et al. 2023) proposed a methodology for assessing ecosystem CO_2 fluxes from STICS outputs in arable crop rotations, with good results. The present study aims to adapt and apply this framework to rotations including intensively grazed grasslands, and to evaluate its relevance against continuous eddy covariance (EC) observations.

Material and methods

The study was conducted at the Integrated Carbon Observation System (ICOS) FR-Mej station (https://meta.icos-cp.eu/resources/stations/ES_FR-Mej), located at the Méjusseaume dairy experimental research facility of the French National Research Institute for Agriculture, Food and Environment (INRAE, IEPL, 35650 Le Rheu, France; https://doi.org/10.15454/yk9q-pf68). The field is managed as a pasture sown with perennial ryegrass (*Lolium perenne* L.), alternating every 5 to 6 years with a silage maize crop grown from May to September. For rotational grazing management, the field is divided into two subplots, the north-west (Plot A) and south-east (Plot B) sections, which are grazed alternately by the dairy herd. Livestock typically graze each subplot 4 to 6 times per year, with 2 to 4 grazing phases concentrated in spring when grass growth is most vigorous. The herd consists of Holstein cows that usually graze 18–20 hours per day, with feed supplementation provided during milking hours. This study focused on Plot A, where eddy covariance (EC) measurements of CO_2 fluxes are available for 2020–2024, while STICS simulations were performed for 2019–2024 using onsite soil analyses together with local climate and management data. The animal's herbage removal and associated C returns on the ground during grazing were simulated according to (Graux et al. 2020).

Following the approach of Delandmeter et al. (2023) completed with root biomass simulations allowed by STICS V10.0, we simulated the Net Ecosystem Exchange (NEE) of the FR-Mej site based on simulated NPP, HR and animal respiration (CR). The estimate of the NPP of the grassland was modified by considering the above-ground and root growth simulated and by adjusting the carbon contents used. Prior comparison, the observed NEE values from the flux tower were post-processed in order to filter those that actually correspond to the plot under study due to wind direction, then to fill in the gaps. A preliminary comparison of the NEE estimated by the model with that measured by the flux tower was made. We then broke down the simulated NEE between gross primary productivity (GPP) and total ecosystem respiration (RECO), adapting the equations of Delandmeter et al. (2023) for calculating growth and maintenance respiration to grasslands after Johnson et Thornley (1983). We also accounted for animal feces decomposition and animal respiration after Faverdin et al. (2007), assuming that all cows are distributed evenly across the plot. We also broke down the observed NEE between GPP and RECO according to Reichstein et al. (2005) in order to compare them with the simulated fluxes.

Results and discussions

Preliminary analyses indicate that STICS-based preliminary estimation of CO_2 fluxes reproduce the main seasonal pattern of observed NEE, including periods of net uptake during herbage growth and net release following cutting. The simulated fluxes exhibit however a lower amplitude than observations. Discrepancies between simulated and observed NEE varied across seasons, and tended to increase under warm and dry conditions, suggesting a possibly attenuated model response to soil temperature and moisture variations. In addition, short-term increases in CO_2 release were observed after cutting or grazing events, whereas these pulses were not reproduced by the simulation. Overall, this tendency indicates that management effects may play a significant role in explaining short-term mismatches between simulated and observed NEE.

Conclusion

This work illustrates the feasibility of adapting the generic soil-crop model-derived framework proposed by Delandmeter et al. (2023) to estimate CO_2 exchanges in rotations including intensively grazed grasslands. Future work will focus on improving the calibration and the modelling of respiration fluxes, integrating grazing events more explicitly, and testing the transferability of this framework to other grassland ICOS sites such as the second plot B of the site (with different soil conditions). Such developments will contribute to a better understanding of C fluxes in grassland-based dairy systems and enhance the use of process-based models for climate mitigation assessments in agriculture.

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Modeling and assessment of the sustainability of bioeconomy scenarios in contrasting large-scale territories in France and Europe

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Keywords: bioeconomy scenarios, modeling framework, agro-environmental impacts, N autonomy

Introduction

France and the European Union's ambitions to achieve carbon (C) neutrality by 2050 are based on reducing greenhouse gas (GHG) emissions and increasing C sinks. Agriculture, which is a source of GHG emissions and can partly act as a sink of GHG through soil C storage, is at the heart of strategies that aim to replace fossil-based resources with renewable resources such as agricultural residues (Bentsen et al., 2014) to fuel various bioeconomy sectors (*e.g.* energy production, molecules, materials), storing C in the soil (C farming) (Petersson et al., 2025), and adopting practices that limit the use of fossil-based inputs (particularly nitrogen) and reduce GHG emissions (Ruml et al., 2025).

As part of the SLAM-B project (www.slamb.fr, FairCarboN program), our objective will be to apply STICS to evaluate different bioeconomy scenarios in contrasting regions of France and Europe by 2050. To this aim, we are (i) developing a generic modeling framework across Europe based on high resolution data on climate, soils, crop rotations and agricultural practices, and (ii) planning to simulate and evaluate the sustainability of different prospective bioeconomy scenarios. Beyond simulations across Europe, we are also considering performing simulations at higher spatial resolution for contrasting regions (to be selected) to evaluate scenarios at continental and regional levels and to confront conclusions obtained on these different spatial resolutions.

Material and methods

The general method consists in (i) comparing and selecting databases for soil, climate and cropping systems available at the European scale, (ii) sampling data when necessary to achieve a reasonable number of final simulation points (*i.e.* agro-pedo-climatic units) for the simulated scenarios, (iii) determining crop management through decision rules, (iv) using a modeling chain based on the 4 models “STICS - N ferti - ALFAM2 - SYS-Metha” and scale change methods (*e.g.* interpolation) to provide results across Europe for the baseline scenario, (v) designing, simulating and assessing alternative prospective scenarios including firstly energy cover crops and crop residue mobilization, before considering potentially more significant changes in cropping systems and/or land uses. In the modeling chain, N ferti is used to better adapt N mineral fertilization in our scenarios, considering organic or mineral fertilizer use (COMIFER 2013) ; anaerobic digestion model SYS-Metha (Bareha et al., 2021) allows to transform a cover crop harvest into biogas and digestate which can be spread in the crop succession as fertilizer ; ALFAM2 model allows to refined estimates of ammonia volatilization given the poor results of STICS on this process (Moinard 2021).

Results and discussion

For building the information system, we compared different sources of climate data, distinguishing between historical data and future data based on different pairs of climate models (Senges et al., 2025a). We first selected climate data from Agri4Cast (JRC), with daily data by 25 km^2 grid cell, that have a better sensitivity to heat wave events, precipitation, or strong winds than other

worldwide datasets. The Corine Land Cover data were used to filter area covered by arable croplands. For soils, the SoilGrids dataset was selected because it produces maps of soil properties for the entire globe at a fine spatial resolution (250 m cell size) using state-of-the-art machine learning methods, it is also one of soil European scale information system for soil horizons below 30 cm. JRC's Lucas program was used to complete data on soil $CaCO_3$ content which is needed as input of STICS. Combined soil data were used to produced new soil mapping units for Europe (**Figure 1**). Data preparation on cropping systems and agricultural practices is still under consideration and progress.

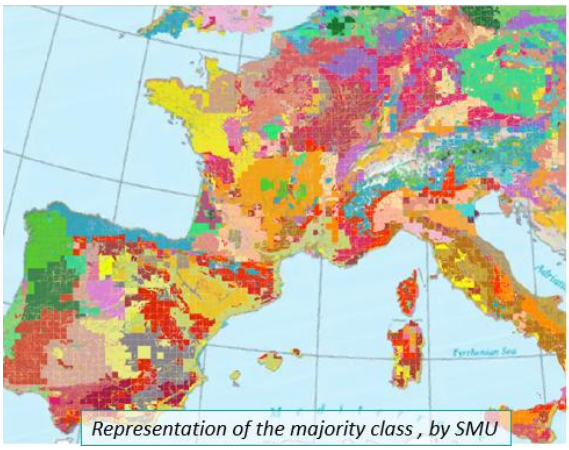


Figure 1: Newly produced soil mapping units by k-means clustering based on soil texture, structure and composition data (80 classes) (Senges et al., 2025b)

For the multi-criteria assessment of baseline and prospective scenarios, the considered criteria will relate to (i) feed, food and energy biomass production, (ii) agro-environmental performances: soil C storage and soil fertility, nitrogen losses (NO_3 leaching, NH_3 volatilization and N_2O emissions) and GHG balance, and (iii) nitrogen self-sufficiency of the investigated territories.

We expect to quantify, using a detailed modeling approach applied at the European level, different production potentials and their short- and long-term impacts, and to evaluate and identify scenarios and associated trade-offs (*e.g.* C storage *vs* N losses: Zhang et al., 2024 ; residue management *vs* soil health: Turmel et al., 2015) that would enable the agricultural sector to cope with various food, energy, and environmental production issues. We also hope to provide a generic information system and a modeling framework that could be reused or adapted for further research or decision support projects.

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Session II

From seed to harvested organ, from variety choice to crop sequence design, from a practice to its effect on biogeochemical cycles: the model as a tool to understand systems

Use of the STICS model to evaluate nitrogen leaching in perennial forage- and annual crop-based rotations

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Keywords : Nitrogen leaching, perennial forages, crop rotations, fertilizer, lucerne-grass

Introduction

In eastern Canada, dairy farms are shifting from perennial forages to annual crops like silage maize (*Zea mays* L.), which requires high N inputs (120–180 kg N ha^{-1}) that increase risks of N leaching, especially in cool and humid climates (Kokulan et al., 2022). Perennial forages typically reduce leaching risks (Ferchaud & Mary, 2016), but it is unclear if this is due to crop type or fertilizer source. The effect of ending perennial stands on N leaching remains also poorly understood due to limited data. This study examines five years (2016–2020) of N leaching across six crop rotations with varying crops and N sources, followed by a two-year (2021–2022) legacy phase evaluating the impact of terminating perennial forages.

Material and methods

The experiment was conducted as part of the Permanence project (Khechine et al., 2025), initiated in 2016 near Quebec City, Quebec, Canada (46°43'41" N; 71°30'44" W). The study compared six crop rotations that differed in both crop type and N source over the first five years (Fig. 1).

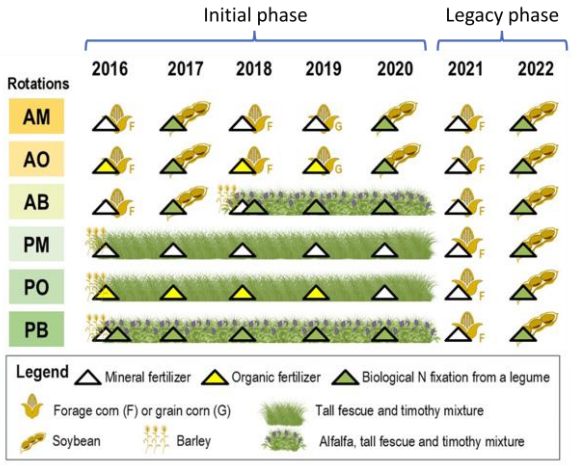


Figure 1: Illustration of the 7-year rotation cycle of the PERenniality and MANure (PERMANENCE) project (2016–2022), which includes six crop rotations with different cropping sequences and N sources. Rotations: AM) annual crops with mineral N; AO) annual crops with cattle slurry; AB) annual crops with a 3-year short sequence of a perennial forage mixture relying on biological N fixation by alfalfa; PM) perennial grasses with mineral N; PO) perennial grasses with cattle slurry; and PB) perennial forage mixture relying on biological N fixation by alfalfa. Figure adapted from Khechine et al. (2025)

Zero-tension lysimeters were installed at a 30-cm depth in each plot, just above a low-permeability shale layer located at 30 to 45 cm depth that limits water flow and root growth. From 2016 to 2022, leachate samples (~150) were regularly collected and analyzed for volume and N-NO_3 concentration. Lysimeter capacity was sometimes exceeded, leading to inaccurate drainage measurements. Therefore, the STICS model was used to estimate drainage for the entire crop rotation. First, the performance of the model in predicting seasonal drainage (spring, summer, fall, and winter) and soil water content was evaluated by comparing simulation results with measurements for all rotations. Then, N leaching (kg N-NO_3 ha^{-1}) was calculated by combining estimated water volumes with measured nitrate concentrations. Statistical analyses were performed to test the effects of crop type, forage duration, stand composition, and N source on cumulative N leaching across rotations.

Results and discussions

The performance of the STICS model in predicting seasonal drainage at a 30-cm depth was good for all treatments and years with no bias (<1%), a Normalized Root Mean Square Error (NRMSE) of 49.8%, and a model efficiency (EF) of 0.58 (Fig. 2). There was, however, a tendency of the model to underestimate the high drainage values (> 300 mm), particularly in spring, and to overestimate the low values (< 50mm), particularly in winter. The soil water content was also well predicted by the model with a very small bias (+0.7%) and NRMSE (11.4%) along with a positive EF (0.18).

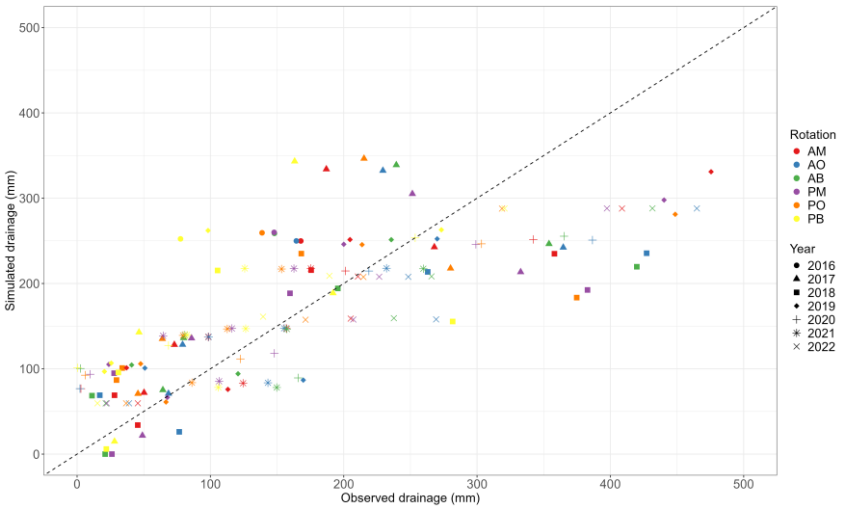


Figure 2: Observed versus simulated drainage in the six treatments from 2016-2022. The dashed lines are the 1:1 lines between simulated and observed values. See descriptions of the rotations (AM, AO, AB, PM, PO, and PB) at Fig. 1. From Nyaga et al., submitted.

Perennial-based rotations (PM, PO, PB) resulted in significantly lower N leaching than annual-based rotations (AM, AO), by 86% during the initial 5-year phase and 50% over the entire 7-year rotation. The longer growing season and deeper roots of perennial crops enhance continuous soil N uptake, reducing leaching (Ferchaud & Mary, 2016). A 5-year lucerne-grass sequence (rotation PB) reduce N leaching by 54% compared to a 3-year sequence (rotation AB) in the initial 5-year phase. However, lucerne-grass mixtures caused greater N leaching than grass-only mixtures (+172% in the initial 5-year phase, +65% in the 2-year legacy phase, and +79% over the entire 7-year rotation), likely due to increased soil N from lucerne growth and residue release after termination. Lucerne taproot decay may also form biopores that facilitate leaching. Lastly, the N source (mineral vs. organic) had no impact on N leaching across all phases.

Conclusion

This study is one of the first to evaluate the performance of the STICS model in predicting seasonal drainage under a cold and humid continental climate including long periods of snow cover. The overall model performance was good, although slightly better during the growing season than during the rest of the year.

Regardless of the N source, perennial forages reduced N leaching during the initial 5-year phase and over the entire 7-year rotation compared to annual crops. However, lucerne-grass mixtures caused more leaching than grass-only mixtures during the initial 5-year phase, with this difference increasing in the 2-year legacy phase. Therefore, careful management of the termination of lucerne-grass stands is essential to maximize the benefits of perennial forages.

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Upscaling STICS to management zones: a way to enhance N fertilization?

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Keywords: STICS, Remote sensing, N fertilization

Introduction

Improving nitrogen (N) management in European agriculture remains a key lever for enhancing the environmental sustainability of farming systems (Zhang et al., 2015). Most strategies focus on matching N supply to temporal crop demand, but few consider both spatial and temporal variability within fields (Machet et al., 2017).

Remote sensing enables delineation of Management Zones (MZ) using sentinel-2 imagery, reflecting within-field yield levels and stability (Lenoir et al., 2024). The framework distinguishes high stable (HS), low stable (LS) and unstable (U) zones, which can guide N fertilization to improve N use efficiency (NUE) and optimize sub-field management (Basso et al., 2019). Crop models such as STICS are valuable for assessing and adapting N fertilization to crop dynamics (Dumont et al., 2015). However, evidence of the benefits of MZ-based N management in European contexts remains limited compared with studies from the United States (Basso et al., 2019).

This study uses the STICS model to assess differences in N fertilization performance among HS, LS and U zones across several fields in Wallonia (Belgium).

Material and methods

The study was conducted in Wallonia (Belgium) from 2016 to 2021. MZ were delineated following Lenoir et al. (2024) using Sentinel-2 imagery. Only fields cultivated with wheat for at least three years during the period were retained, as the approach was calibrated specifically for this crop. Soil properties were extracted from the Aardewerk database (n = 3,867; Legrain et al., 2011) for soils whose depth ranges from 50 to 200 cm. Parameters included texture, organic carbon, and pH. Pedotransfer functions estimated bulk density, gravimetric water content at field capacity and wilting point and plant-available water content. Eighteen weather stations were associated with fields based on proximity. Simulations were conducted for each soil, and only fields with at least two soil samples located in different MZs were retained to ensure comparability between zones. STICS was calibrated using N-fertilization trials conducted from 2008 to 2014 in Gembloux Agro-Bio Tech using the R package "CroptimizR". Simulations used winter wheat variety "Barok", a common variety in experiments in this context, sown mid-October at 250 seeds m^{-2} and harvested at physiological maturity. N was applied in three equal doses at tillering, stem elongation and flag leaf, from 0 to 90 kg ha^{-1} per stage (10 kg ha^{-1} step).

NUE was calculated as the difference in N uptake between fertilized and non-fertilized crop, divided by the N supplied. Kruskal-Wallis tests assessed (1) the yield variation among the years per field and (2) NUE differences among MZ over time.

Results and discussions

Combining delineation and soil maps enabled comparison of MZ across 10 fields (Figure 1). The fertilization strategy was identical across zones to detect performance differences.

For each field, interannual yield differences were significant over the 2016–2021 period, with yield gaps ranging from 0 to 5 t ha^{-1}. However, yield differences between management zones were not consistent over time and were not always significant. Moreover, yields simulated in HS zones were systematically lower than those in LS zones in some fields (i.e., “F1”, “F2”, “F3”).

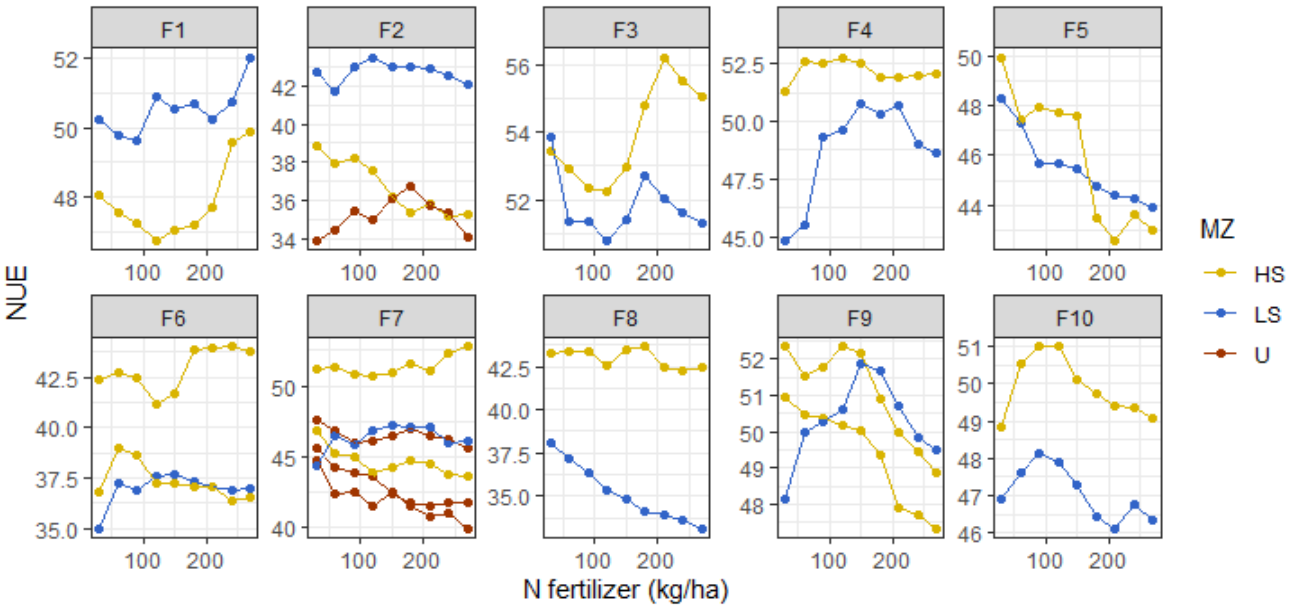


Figure 1 : NUE calculated on MZ (colors) from each soil sample over the 2016:2021 period for different N fertilization levels

In terms of NUE, differences between management zones ranged from 0 to 10% and were significant for three fields regardless of the year (i.e., “F2”, “F4”, “F8”) (Figure 1). At the annual scale, significant but inconsistent NUE differences were simulated across all fields. NUE was not systematically higher in HS zones, suggesting that applying higher nitrogen rates in these areas could lead to degraded environmental performance. These results should be further supported by analyzing the influence of N application dynamics during the fertilization period while N inputs were equivalent at each application date across zones.

Conclusion

The delineation of MZ within agricultural fields represents a promising lever for improving N fertilization practices. However, the yield differences observed between MZ reflect a complex set of mechanisms that can only be comprehensively analyzed on large scale through crop modeling. This study highlights the value of coupling these two approaches to strengthen agronomic reasoning and decision-making.

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Simulation of the nitrogen effect of legumes as a tool to unravel their non-nitrogen benefits

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Keywords : legumes, N mineralisation and non-nitrogen effect

Introduction

Grain legumes play an important role in the transition to more sustainable agroecological cropping systems. Incorporating them into traditional crop rotations can offer a wide range of benefits. Both direct and indirect ecosystem services are associated with the introduction of legumes into current cropping systems, commonly described as the 'nitrogen effect' and the 'non-nitrogen effect'. The 'nitrogen effect' refers to the fact that legumes increase N availability through biological N fixation, thereby decreasing the reliance on synthetic N fertilisers and potentially increasing the yield of subsequent crops through the mineralisation of their N-rich residues (Ditzler et al., 2021). The 'non-nitrogen effect' encompasses all non-N related benefits, such as an improved soil water retention and penetrability through their deep root systems (Angus et al., 2015) and an altered soil microbial community (Borrell et al., 2017).

Understanding and quantifying the N effect is a crucial first step towards comprehending the additional benefits arising from the non-N effects of legumes, which remain comparatively less studied. Therefore, the crop growth model STICS is used in this study to simulate the amount of belowground crop residues that remain in the field after legume cultivation, as well as their contribution to N mineralisation and availability over time for the following crop.

Material and methods

The STICS model (Brisson *et al.,* 1998) was parameterised using data from a field experiment between 2024-2025 where three legumes (red kidney bean (*Phaseolus vulgaris*), yellow pea (*Pisum sativum*), faba bean (*Vicia faba*)) and three cereals (spring wheat (*Triticum aestivum*), spring durum wheat (*Triticum durum*) and spring barley (*Hordeum vulgare*)) were installed as precrops for winter barley.

As preliminary simulation, the mineralisation of legume crop residues was modelled on bare soil for the winter barley season. Initial soil water content and nitrate and ammonium content were determined from soil samples at harvest of the precrops. The amount of root residues was estimated from aboveground biomass measurements at precrop harvest, applying a root:shoot ratio of 0.15, and C:N ratios of residues were estimated from literature (Table 1). The area under the curve (AUC) for total mineral nitrate and ammonium content was calculated to estimate the cumulative N release over time, which was then compared to observed yield responses in the winter barley crop.

Table 1: Root C:N ratio and average mass of root residues of precrops sown in 2024.

Crop	C:N ratio	Residues (ton ha^{-1})	Source
Spring wheat	48	2028	(Soon & Arshad, 2002)
Spring barley	48	1814	(Soon & Arshad, 2002)
Spring durum wheat	48	2024	(Soon & Arshad, 2002)
Faba bean	26.8	1109	(Guinet et al., 2023)
Yellow pea	18.7	686	(Guinet et al., 2023)
Kidney bean	17.5	684	(Guinet et al., 2023)

Further simulations are planned to more accurately represent the two-year crop rotation, integrating crop N uptake and soil–plant interactions. Additionally, simulated N dynamics will be validated against observed N data collected at both precrop and winter barley harvests. The AUC of simulated soil mineral N content during winter barley cultivation will serve as an estimate of the nitrogen effect of the precrops, and will be compared against measured winter barley yields to identify discrepancies and hence the non-nitrogen effect.

Results and discussions

Preliminary results indicate that simulated residue mineralisation differs only slightly among precrops, with legume residues releasing more N than cereal residues (Figure 1). The main differences for N availability after precrops are, however, attributable to the measured soil nitrate content after harvest of the precrops, which was significantly lower for kidney bean compared to faba bean and pea. The enhanced N availability after legumes partially explains the observed yield advantage of winter barley following legumes, which averaged approximately +0.9 ton ha^{-1} compared with cereal precrops. However, a significant amount of variation in yield is still explained by the precrop species, suggesting that observed yield increases are not solely attributable to the N effect and that additional factors beyond N availability contribute to the precrop effect.

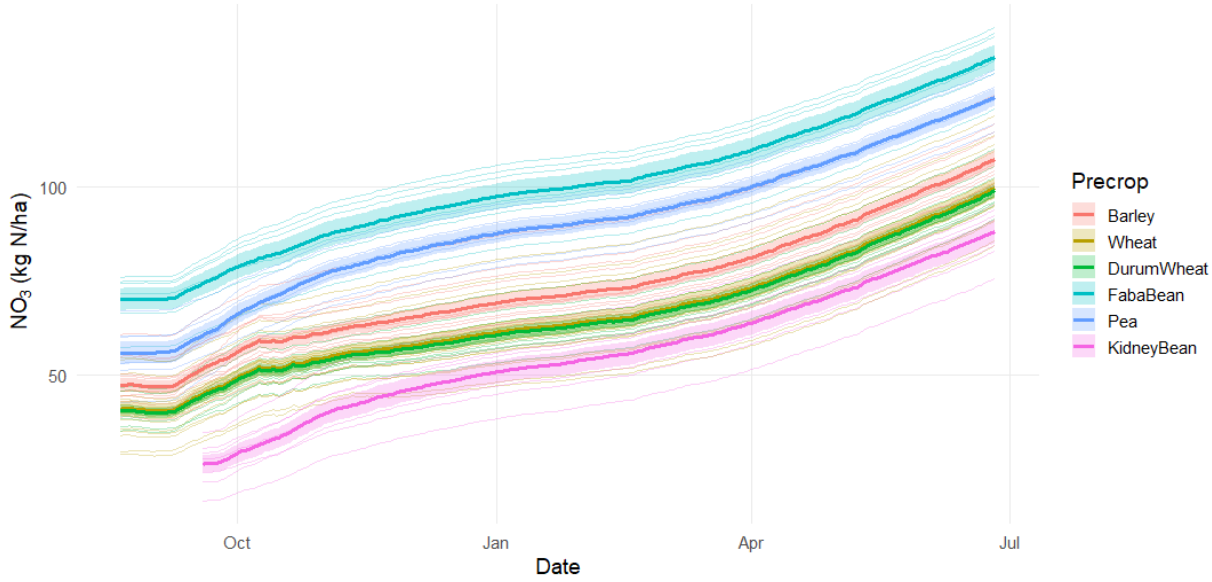


Figure 1: Simulated NO_3 availability for a bare soil between September 2024 and July 2025.

Conclusion

In this experiment, a preliminary analysis was performed to explore N mineralisation in a bare soil. The next step is to model the whole crop rotation using STICS. Simulated residue mineralisation will be used to represent the N effect of the precrops. Its contribution to the variation in observed yields will be analysed to determine whether yield differences due to precrops persist beyond the N effect, indicating the existence of a non-N effect of leguminous precrops. Understanding the relative importance of these N and non-N mechanisms will support the refinement of legume-based crop rotations and their integration into more sustainable and resilient agricultural systems.

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Evaluating the STICS research branch for intercrops and its coupling with an epidemiological model: case study on winter wheat-pea with brown rust

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Keywords: intercropping, fungal disease, wheat, pea, brown (leaf) rust

Introduction

To reduce, or even eliminate, the use of synthetic inputs, the agroecological transition involves spatial and temporal diversification of agricultural crops. The strategy of sowing a mixture of cereals and legumes in the same field (intercropping) has many advantages, both in terms of limiting diseases (Boudreau, 2013) and improving the use of soil resources (Jensen et al., 2020). The varieties currently used in such mixtures have been selected only in a monovarietal context, despite evidence for significant genotype x cropping type interactions (Demie et al., 2022). However, breeding for mixing ability is confronted with an explosion in the number of possible combinations, compounded by the multiplicity of environments. A strategy to tackle this challenge would consist in calibrating a process-based model on monovarietal data (Demie et al., 2025), and use it to predict the response of unobserved mixtures to various management x environment scenarios. Gaudio et al. (2021) analyzed the complementarities of several modeling approaches, but did not consider the genetic aspect we were interested in. Even though individual plant models have many advantages to decipher the processes underlying plant-plant interactions in mixture, crop models still are the approach of choice to incorporate genetic information. We hence chose to initiate the assessment of this approach using the STICS research branch on intercropping (Vezy et al., 2023) and the previously coupled disease model MILA (Caubel et al., 2017).

Material and methods

A field trial was conducted in Saclay (France) in 2021-2022 and 2022-2023, with two winter wheat varieties, two winter pea varieties, and all four possible binary intercrops. The wheat cultivars were chosen for their contrast in competitive ability and disease resistance (Bergamo being less competitive and resistant than Titlis). The pea cultivars were chosen so that one, Flambo, was sensitive to photoperiod (Hr type) contrary to the other, Aviron (hr type). The field comprised three blocks according to a randomized complete block design, two of which were designated to yield assessment, and the third for plant sampling.

Three phenological stages were recorded for wheat (ear 1cm, heading, maturity), as well as the beginning and end of pea flowering. Yield and its components were assessed per species (at the scale of microplots of 5.31 m^2), as well as aboveground biomass (at the scale of three sowing rows, A, B and C, of 0.13 m^2 each) at each of the three wheat phenological stages. Biomass sampling was preceded by flights of uncrewed aircraft systems (UAV) to take RGB images from which vegetation indices can be derived. Abundances of nitrogen and carbon isotopes were assessed after drying and grinding the biomass samples. During the second season, incidence and severity were visually scored, once a week, for three wheat diseases (yellow rust, brown rust and septoria).

The STICS research branch, corresponding to the integration of improvements from Vezy et al.

(2023) into STICS v10, is mobilized, as well as an updated coupling between STICS and MILA for brown rust.

Expected results and discussions

The data on biomass dynamics, e.g., in Figure 1 for Bergamo the second season, show that this weakly competitive cultivar reached a similar biomass at harvest when cultivated in a monovarietal stand as in mixture with the Hr pea cultivar (Flambo), but a much lower one when mixed with the hr pea cultivar (Aviron). As can be also seen on the figure, STICS simulation for Bergamo in monovarietal provided a good fit of the observations in this case. For the final poster, we will adapt available wheat and pea calibrations to the three other varieties used in the trial, so that the fit of the model to the monovarietal data is maximized. Predictions of the intercrops will then be compared with the corresponding field data. A similar strategy will be used for the coupling with the disease model.

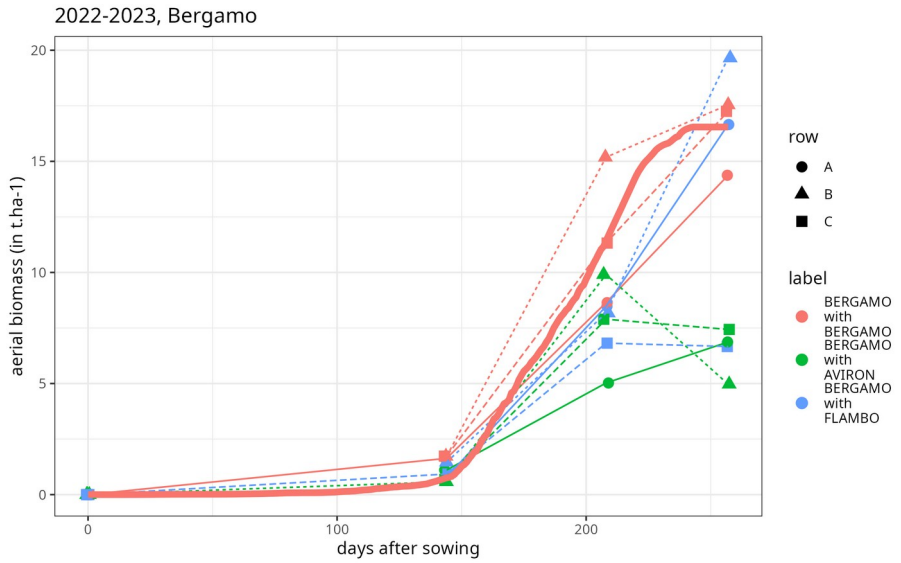


Figure 1: Dynamics of aboveground biomass for the wheat variety Bergamo in the second trial season, in monovarietal (red), or in intercrop with either Aviron (green) or Flambo (blue). Points connected by narrow lines are observations along three sowing rows (A, B and C), whereas the wide, red line corresponds to the STICS simulation.

Conclusion

This work will contribute to showing the usefulness of STICS in the agroecological transition, and likely initiate future improvements with respect to the coupling with disease models and the calibration of genotypes in breeding programs.

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Monitoring water, carbon and nitrogen cycles in the Champagne vineyards through a decision support tool

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Keywords: Champagne vineyard, soil, climate, viticultural practices, Decision Support Tool

Introduction

The Champagne vineyard is facing increasing climatic variability, with some years marked by drought episodes starting in early spring or summer, and others marked by periods of intense rainfall. These climatic fluctuations have direct impacts on the vine, generally resulting in a decline in vigor, depending on soil type and viticultural practices. Furthermore, must nitrogen content—a direct indicator of the vine's nitrogen status—has decreased considerably since the 2000s, potentially leading to sluggish fermentations during the winemaking process. Therefore, nitrogen management remains a key lever for achieving production objectives. However, it is particularly challenging for perennial crops such as grapevines, where reserve organs play a critical role in the remobilization of nutrients from one year to the next. The Champagne industry, wine growers and houses, is thus seeking tools to analyze and anticipate imbalances related to water, carbon and nitrogen dynamics, to support sustainable management of the Champagne vineyard. To address these challenges, the VITICYCLE project aims to 1) simulate key indicators accounting for Champagne's specific conditions, 2) automate simulations at the regional scale, and 3) provide access to indicators through a decision-support tool (DST) for the Champagne industry.

Material and methods

The choice of the model focused on selecting a tool capable of accounting for vine physiology in terms of carbon and nitrogen dynamics. The model also had to incorporate the specific characteristics of the environment, soil, climate and vineyard management practices. The STICS model (Brisson et al., 1998) was therefore selected, as previous work had already started to integrate grapevine in this model (Garcia de Cortázar-Atauri, 2006).

Adaptation to Champagne's viticultural conditions involved considering the main grape varieties of the area (Chardonnay, Pinot noir, Meunier) and the different pruning methods (Chablis, Guyot, Cordon, Vallée de la Marne), as well as the characteristics of Champagne chalky soils. The procedure included three main steps: 1) calibration of the STICS v10 model using field data (including calibration of capillary rise, trimming practices, and yield estimation) and evaluation on independent variables including soil and plant nitrogen as well as wine growth variables ; 2) automation and large-scale deployment of simulations across the entire Champagne vineyard area; 3) integration of simulated outputs into a decision-support tool for wine growers, accessible through the Comité Champagne website.

Results and discussions

The STICS v10 model was calibrated and validated using field data from Champagne vineyards to account for capillary rise in chalk soils (Figure 1) and trimming practices, leading to accurate yield estimations for the three main grape varieties according to pruning type. This validation resulted in eight calibrated variety × pruning type configurations.

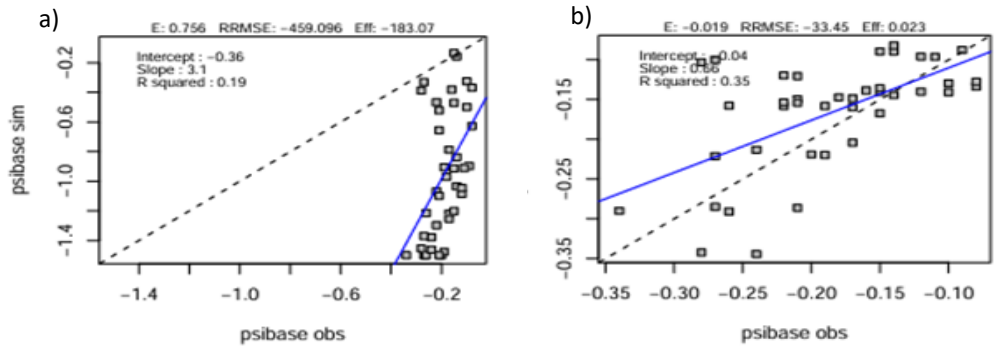


Figure 1: Comparison between observed and simulated predawn water potential (psibase) without capillary rise (a) and with capillary rise (b) on chalky soils

Based on the soil analyses database maintained by the Comité Champagne, a soil typology was developed considering substrate nature, texture, limestone content and soil depth. This classification resulted in 15 soil types, each associated with three potential mineralization levels (*i.e,*. 45 soil files) to integrate soil nitrogen and carbon functioning. These soil types were combined with a 1 km²-resolution weather data grid and the eight plant files (variety × pruning), producing a total of 114,912 simulation combinations, in addition to the automated technical itinerary and initialization files integrated into the workflow. All simulated data are integrated into a decision-support tool available to winegrowers through the Comité Champagne online platform (Figure 2).

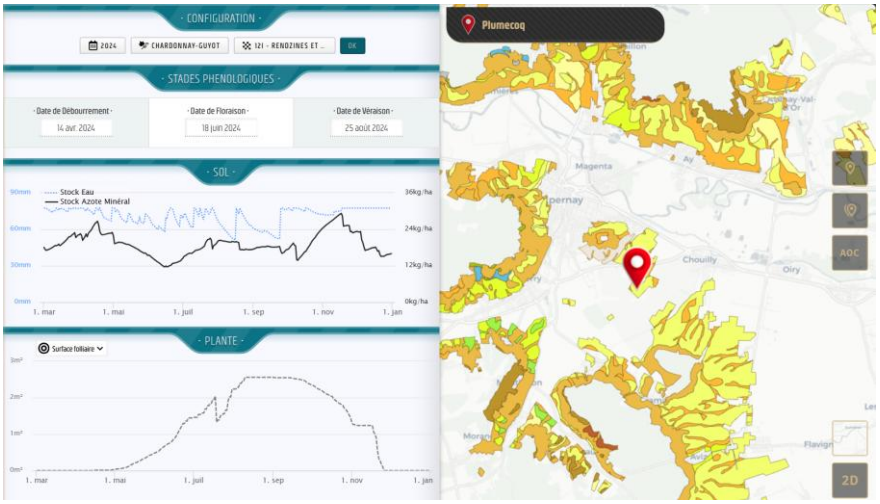


Figure 2: Example of visualization of the DST outputs by selecting a plot on the map and choosing a configuration (year, grape variety *pruning, soil)

Conclusion

This project has enabled the STICS model to be adapted to vines in the specific context of Champagne vineyards, using a bottom-up approach from plots to the Champagne area. Cooperation between researchers, developers and the Champagne industry has made it possible to combine the benefits of modelling with a user-friendly tool for the Champagne industry. Subsequently, user feedback will be considered to further develop the tool, both in its form and in the selection of outputs. Furthermore, data from Champagne's observation networks will be compared with simulation data to validate the change of scale. Nevertheless, long-term data would be useful to confirm the model's accuracy in simulating vine vigour and to validate the model's simulations of changes in soil organic carbon and nitrogen storage.

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Session III

STICS & friends: interfacing the model with databases and coupling with other models

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

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Keywords : crop diversification, field design, pathogens, plant density, interrow, species proportion

Introduction

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

Material and methods

We used the STICS Intercrop branch (Vezy et al., 2023) coupled with the epidemiological model MILA (Caubel et al., 2012;) to study a wheat/pea intercrop with a brown rust epidemic using averages over 30 reference years (SAFRAN 1991-2020), to quantify the effect of regulation mechanisms and their sensitivity to changes in spatial arrangement. Three factors were considered to design a variety of virtual fields , i.e. species proportion, total plant density and row spacing. Accordingly, the parameter *densitesem* was set to values indicated in table 1. This unique parameter enables us to manage two factors (proportion and density). We repeated this design for five levels of row spacing (parameter *interrang*): 10, 20, 30, 40 and 50 cm, at each of the previous total densities and proportions. This resulted in a full factorial experiment with 150 combinations (5 row spacing(s) x 6 species proportions x 5 densities) representing a mix between substitutive (at a same total density) and additive (across total densities) designs.

Table 1: values for the sowing density of each crop (plants.m-2) to reflect the different levels of total densities (from very low to very high) and species proportion, repeated for the five levels of row spacing.

field density level	**wheat/pea proportions (%)**					
	25/75	**33/66**	**50/50**	**66/33**	**75/25**	**100/0**
very low	35/27	46/24	70/18	93/12	105/9	140/0
low	53/43	70/38	105/27	140/18	158/14	210/0
normal	70/54	93/48	140/36	186/24	210/18	280/0
high	88/68	116/60	175/45	231/30	263/24	340/0
very high	105/85	140/71	210/54	277/36	315/27	420/0

Disease intensity, quantified by the AUDPC (Area Under the Disease Progression Curve), was compared in the wheat Sole Crop (SC) versus the wheat/pea InterCrop (IC).

Results and discussions

Our *in silico* experiment highlighted the weight of the dilution, barrier and microclimate mechanisms, as well as the disease processes (spore interception, infection) at play during the crop cycle. The impact of IC on disease intensity is significant but nuanced according to spatial arrangements, i.e. combinations of row spacings, sowing densities and species proportions. Overall,

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

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

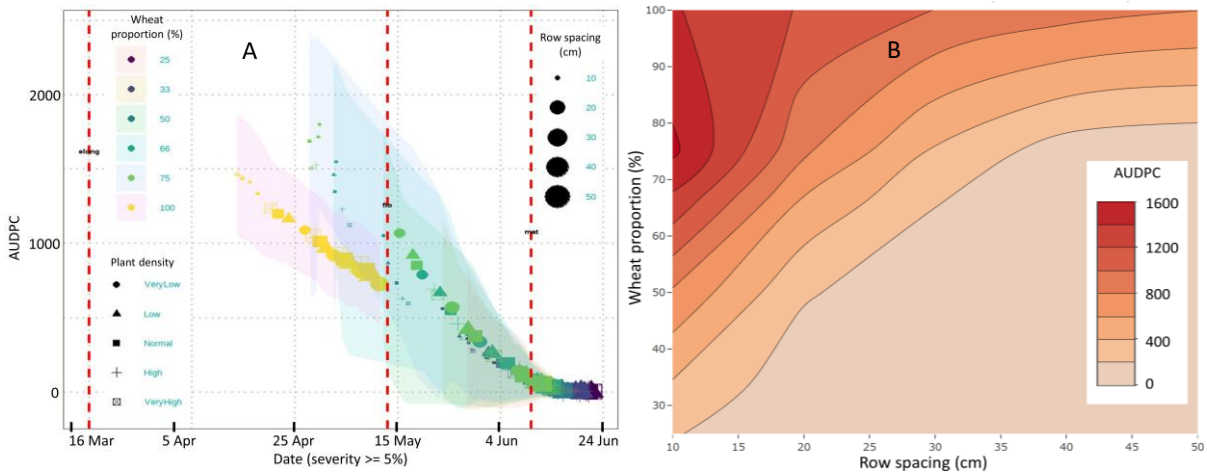


Figure 1: A) Disease intensity (AUDPC value reached at maturity) as a function of disease precocity (date when the severity reaches 5%, considered the start of the epidemics). The colours represent wheat proportion in the species mix, shapes the level of total plant density and size of the shapes the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

Conclusion

The *in silico* experiment detailed in this paper demonstrated that our model allows the quantification of the primary mechanisms and processes involved in disease regulation in intercrops, along with their dynamics. Combining the dynamics of the pathogen, host plant and non-host plant from a mechanistic perspective highlights phenomena which other modelling approaches cannot describe. For example, competition mechanisms between the two crop species reduce the surface available for infection, disrupt the interception of spores and consequently delay the start of the epidemics. This facilitates the barrier effect translating into an AUDPC generally lower in IC compared to SC. Additionally, it emphasised which species arrangement in the mix promotes disease regulation.

Acknowledgements

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Special thanks to Timothée De Decker for his support with climatic data, and Rémi Vézy for his help with the STICS-IC research branch.

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The contribution of STICS to modelling the impacts of weeds and climate change on crop production and biodiversity in FLORSYS

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Keywords: weed, FLORSYS model, biological regulation, climate change, cropping system

Introduction

Arable weeds are essential for biodiversity, highly damaging to crop production and usually controlled with herbicides. The latter are harmful for the environment and human health but so far, no non-chemical curative weed-control option used alone is as efficient as herbicides. Because their seeds survive for several years in the soil, weeds must be managed at the rotation scale to limit damage to the current and following crops. Non-chemical weed management must thus be based on a multi-annual combination of multiple, partially efficient, and interacting techniques, whose effects depend on weather and soil conditions, and evolve with climate change. Because of this complexity, models are essential to design herbicide-scarce climate-change-resilient weed management strategies. Mechanistic models can be used in diverse situations without reestimating parameters but need many equations and parameters. The objective of this paper was to show (1) how the crop-weed model FLORSYS (Colbach et al., 2021) benefitted from the STICS crop model, by reusing parameter values, functions, and entire submodels, and (2) how FLORSYS is used to evaluate the regional climate change impact on weed dynamics and agroecological weed management.

Material and methods

The FLORSYS model (Colbach et al., 2021). Inputs comprise all cultural operations in detail over several years, daily climate data (past or future), soil properties and a weed species pool. The model represents each crop and weed plant individually in simple volumes (cylinders and spilled cones), which grow or shrink based on photosynthesis, respiration and damage (frost, chemical, mechanical). Plants compete for light, water and nitrogen, depending on species properties, plant morphology and neighbour plants. Seed death, dormancy, germination and preemergent growth depend on species, seed depth and soil state variables. Functions are the same for all species, only parameter values vary with species. In addition to daily state variables, FLORSYS predicts annual indicators of crop production, weed harmfulness for crop production and weed contribution to biodiversity.

Benefitting from STICS. (1) The Fortran code of the STICS soil submodel predicting soil temperature, water and nitrogen was included into the C/C++ FLORSYS code with three daily connections: FLORSYS provides technical and climate inputs to STICS, 1D STICS soil layers provide soil data to the 3D FLORSYS soil voxels, and the latter return plant water and nitrogen uptake to STICS. (2) All STICS functions applicable at the plant scale and compatible with the generic FLORSYS plant representation were included in FLORSYS. (3) The corresponding STICS parameter values were used for crop species in FLORSYS and also for similar weed species if no values were measured in our own experiments or found in literature.

***In silico* experiments with the improved FLORSYS model.** First, emergence of 36 weed species was simulated over one year in 15 locations from Northern France, with three soil types and 36 tillage dates. Each combination was simulated 20 times, using 10 climate records from either 1980–1990 or 2010–2020. No weed seed production was allowed to focus solely on emergence patterns.

Then, 10 cropping systems (ranging from conventional to herbicide-free) were simulated over 30 years to include long-term effects and repeated 20 times, using reanalysed interpolated climate series (8-km gridded SAFRAN-ISBA-MODCOU) from either 1950–1980 or from 1990-2020.

Results and discussions

Linking FLORSYS and STICS. The linking operation was described by Colbach et al. (2020) for nitrogen and by Cournault et al. (2023) for water. Recently, equations were taken from STICS to simulate the impact of elevated CO_2 concentration on radiation use efficiency and plant water demand (via increased transpiration). Parameter values taken from STICS for crops include base temperature, temperature thresholds for photosynthesis and frost damage, light extinction coefficient and light use efficiency. For weeds, values of similar crop species were used, e.g., photosynthesis thresholds of winter barley were used for autumn-emerging grass weeds.

Impact of climate change on seasonal weed emergence. The simulations with FLORSYS showed for instance that with recent warmer climate, emergence of the autumn-emerging grass weed *Alopecurus myosuroides* Huds is more frequent in autumn and, to a lesser degree, in spring, but lower in summer (Fig. 1). Consequently, false-seed-bed techniques and delayed winter-crop sowings are less efficient and the risk of this weed emerging in winter crops is higher.

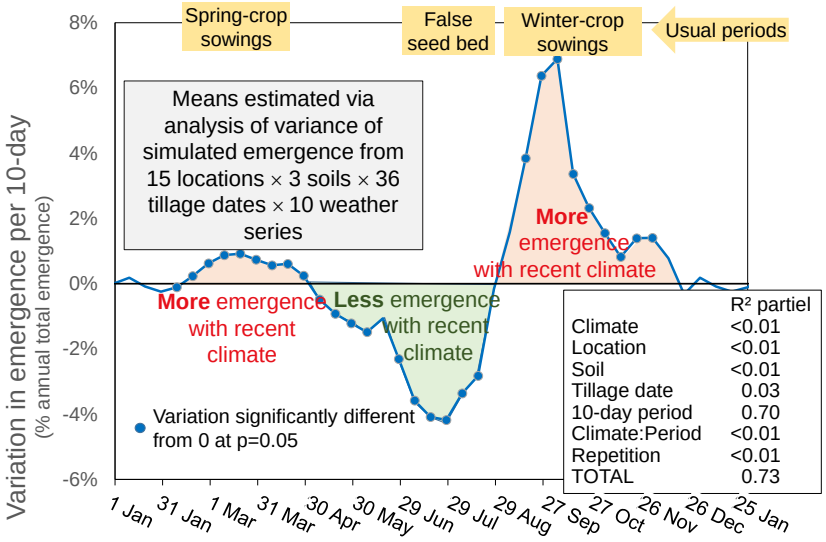


Figure 1: Effect of climate change on seasonal weed emergence (example of *Alopecurus myosuroides* Huds., an autumn-emerging grass weed frequent in winter cereals) in Northern France. Difference per 10-day period of emergence simulated with FLORSYS with climate from 2010–2020 vs 1980–1990

Impact of climate change on crop production, weed harmfulness and biodiversity. The preliminary results show as yet no systematic effect of climate change on these three types of indicators. The latter varied much more with the grown crop species and management operations than with the recent vs past climate series (results not shown). Moreover, there was no systematic increase of weed harmfulness nor systematic decrease in crop production with the recent vs past climate for the 10 tested cropping systems.

Conclusion and Perspectives

FLORSYS makes use of the huge modelling and synthesis effort done by the STICS project in the past by recycling parameter values and equations. But the most important contribution of STICS to FLORSYS is the prediction of soil temperature and resources, allowing FLORSYS to simulate (1) the variability in cropping-system effects due to weather, (2) plant-plant competition for soil resources in heterogeneous multispecies canopies. These processes are essential to evaluate varieties, cropping systems and climate change, and thus to contribute to agroecological weed management.

The next steps will consist to perform simulations in order to identify which cropping systems are efficient for agroecological weed management and resilient to climate change.

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Development of ORCHIDEE-CROP v1.0: a nitrogen-explicit agro-land surface model and its evaluation across European wheat sites

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Keywords: Crop modeling, data assimilation, STICS model, ORCHIDEE land surface model, nitrogen cycle.

Introduction

Nitrogen availability strongly controls crop productivity and carbon exchange, yet its representation remains a major source of uncertainty in land surface models (Kou-Giesbrecht et al., 2023). Many existing formulations rely on simplified nitrogen constraints that insufficiently represent stress effects on key physiological processes such as leaf expansion and senescence (Davies-Barnard et al., 2020; Zaehle et al., 2015). The ORCHIDEE-CROP framework (Wu et al., 2016) was originally developed to integrate crop processes into the ORCHIDEE land surface model through coupling with the agronomic model STICS (Brisson et al., 1998; Brisson et al., 2002), allowing ORCHIDEE to benefit from the agronomic realism of STICS while preserving consistency in carbon, water, and energy fluxes at larger scales. In this coupling, STICS computes crop development and leaf area index (LAI) dynamics, which are used by ORCHIDEE to adjust its carbon allocation scheme under managed conditions.

While the original ORCHIDEE-CROP v0.0 provided a generic representation of crop phenology and carbon allocation, it did not include an explicit nitrogen cycle or nitrogen-driven physiological stress responses. The newly developed ORCHIDEE-CROP v1.0 (Houballah et al., in prep.) introduces a fully coupled carbon-nitrogen framework (based on the most recent version of ORCHIDEE, including the N cycle) and integrates nitrogen derived from STICS to explicitly represent nutrient limitations on leaf development, senescence, and growth. Model evaluation and parameter optimization are performed using the ORCHIDAS data assimilation framework (Bastrikov et al., 2018), assimilating site-level observations of LAI and aboveground biomass. The objective of this study is to present the development of ORCHIDEE-CROP v1.0 and its first evaluation across five temperate European wheat sites, with a particular focus on the added value of STICS-based stress formulations within a land surface modeling framework.

Material and methods

ORCHIDEE-CROP v1.0 builds on ORCHIDEE v3 (Vuichard et al., 2019), which includes an explicit nitrogen cycle and ORCHIDEE-CROP v0.0 (Wu et al., 2016) with crop-specific parameterization. The model couples nitrogen uptake, allocation, and feedbacks on photosynthesis with carbon fluxes, and integrates the nitrogen and water stress schemes from STICS to modulate leaf expansion and senescence. Simulations were performed for five European winter wheat sites (BE-Lon, FR-Aur, FR-Lam, FR-Gri, DE-Kli) representing diverse climatic and fertilization conditions. Nitrogen limitation is represented through a STICS-based formulation acting specifically on LAI development, and model

parameters are optimized using the ORCHIDAS data assimilation framework by assimilating LAI and aboveground biomass observations. Model performance is assessed using RMSE on seasonal LAI dynamics.

Furthermore, nitrogen limitation follows the STICS Nitrogen Nutrition Index (INN) framework, based on a critical nitrogen dilution curve linking plant nitrogen concentration to biomass. The resulting INN is mapped onto bounded stress indices acting on leaf area development. During parameter optimization, dilution-curve parameters are constrained using leaf carbon-to-nitrogen ratios from ORCHIDEE to ensure physiologically realistic nitrogen concentrations across the biomass range. Water stress is represented following the STICS formalism through bounded indices derived from relative soil water availability.

Results and discussions

As initially shown with ORCHIDEE-CROP v0, coupling STICS crop formalisms with ORCHIDEE improves crop phenology simulations; the nitrogen-explicit ORCHIDEE-CROP v1.0 further extends this improvement by explicitly representing nitrogen limitation effects on LAI development, notably through more realistic seasonal trajectories of leaf area index, senescence, and aboveground biomass. Parameter optimization using the ORCHIDAS data assimilation framework enhances consistency between simulated and observed crop development across contrasting European sites, while simulations under well-fertilized conditions remain largely unchanged, indicating that nitrogen stress does not degrade crop dynamics when nitrogen is non-limiting. After optimization of parameters controlling LAI development and senescence, the RMSE of simulated LAI dynamics is substantially reduced compared to the non-optimized configuration. This implementation illustrates a hybrid modeling strategy in which key agronomic formalisms from STICS are selectively integrated into ORCHIDEE, improving the representation of nitrogen and carbon interactions and their effects on photosynthesis and growth while preserving the robustness and scalability of the land surface model. Water stress follows the STICS stress framework, using bounded indices acting on stomatal conductance, leaf growth, and senescence derived from relative soil water availability obtained from the 11-layers soil hydrology model of ORCHIDEE, and is implemented consistently within the ORCHIDEE-CROP coupling. Extending the evaluation across additional sites, crops, and climatic contexts will be essential to strengthen parameter robustness and predictive capacity and to foster collaboration with the STICS community on model spatialization and global agronomy.

Conclusion

This study presents ORCHIDEE-CROP v1.0, a nitrogen-explicit land surface model integrating STICS LAI representation and the corresponding nitrogen and water stress formulations within a fully coupled carbon-nitrogen framework. The selective incorporation of key STICS agronomic formalisms improves the representation of canopy development, senescence, and biomass dynamics under nitrogen-limited conditions while preserving model behavior under well-fertilized regimes. Parameter optimization significantly improves simulated LAI dynamics, and a multi-site optimization is able to identify a common parameter set yielding consistent improvements compared to site-specific calibrations. and consistent with STICS wheat parameterizations. These results support a hybrid integration strategy that combines the agronomic realism of STICS with the robustness and scalability

of ORCHIDEE, providing a solid basis for future multi-site, multi-crop, and spatialized applications in collaboration with the STICS community.

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ArchiCrop, adding the 3D dimension to STICS

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Keywords: crop model, FSPM, plant architecture, light interception, multiscale, OpenAlea

Introduction

Crop models are widely used to simulate numerous ecophysiological and biophysical processes at the crop scale throughout the entire crop development cycle (Boote et al., 2013). However, these models rely on simplified processes models taking benefits from spatial homogeneity assumptions. Mobilizing these approaches in heterogeneous systems such as intercrops could therefore introduce significant uncertainty (Gaudio et al., 2019). This is particularly true for strongly non-linear processes, such as light interception, that are highly sensitive to spatial heterogeneity (Barillot et al., 2014). In contrast, Functional–Structural Plant Models (FSPMs) simulate most processes at the organ scale, and thus explicitly account for spatial interactions, but they thus suffer from a higher complexity, and are computationally intensive. FSPMs also need more detailed parameterization, which limits their applicability beyond experimental settings.

In this study, we propose a multiscale method to reconstruct 3D+t plant architectures from STICS soil-crop model (Brisson et al., 1998) simulation outputs, and more precisely from the simulated LAI and crop height dynamics. The method leverages the function simulated by STICS to compute plant structure in an efficient way, and compares the same process, *i.e.* light interception, at crop and organ scales (Figure 1). Although demonstrated here on sorghum as a case study, the approach can be generalized to other cereal or single stem species, given that their allometries and coordination laws are well-known (Evers et al., 2005).

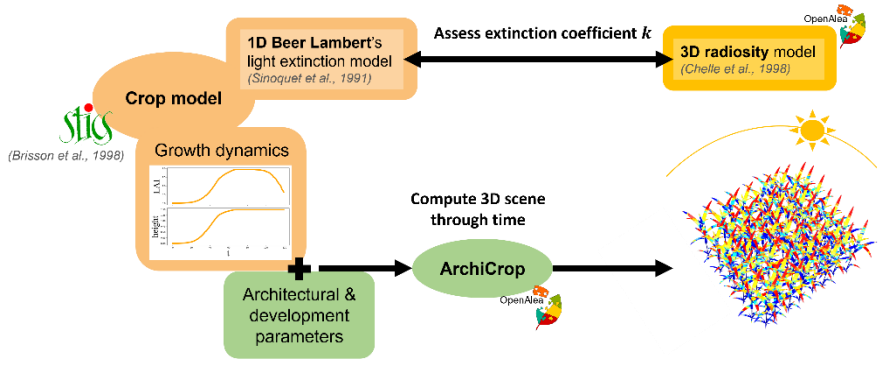


Figure 1: Workflow of multiscale approach to evaluate the validity of light interception formalism in a crop model. From growth dynamics computed by STICS and architectural and development parameters, ArchiCrop computes 3D+t canopies. Computing leaf-resolved light interception on these 3D+t canopies enables us to estimate an emergent dynamic extinction coefficient and to compare it with the constant one used by Beer-Lambert law in STICS.

Material and methods

We developed ArchiCrop, a model that reconstructs the set of 3D plant architectures that follow the exact same dynamics simulated by STICS: 1) LAI and crop height are downscaled at plant scale knowing spatial arrangement. 2) Viable interval values of ArchiCrop parameters are computed analytically based on STICS dynamics, ensuring a set of possible solutions. 3) Daily growth is distributed

among growing phytomers according to the development scheme (e.g. phyllochron). ArchiCrop model is implemented within OpenAlea platform (https://github.com/openalea/ArchiCrop). Leaf-resolved 3D light interception is computed using OpenAlea.Caribu (Chelle and Andrieu, 1998). Light extinction coefficient k for 3D+t simulations is computed by inverting Beer-Lambert law. In this study, various sorghum architectures are simulated by varying the leaf insertion angle θ from 10 to 90 degrees (Kenchanmane Raju et al., 2020; Truong et al., 2015) and the number of leaves N from 12 to 28 (Clerget et al., 2008).

Results and discussions

Leaf insertion angle influences the absorbed Photosynthetically Active Radiation (aPAR) by the sorghum canopy, with greater leaf insertion angles leading to increased light interception, for same LAI dynamics (Figure 2A). At end crop growth stage, the variability in aPAR computed from the 3D plant architecture was significatively higher (around 12%) compared to that of STICS. The variation of k with leaf insertion angle was approximated by a polynomial, such that $k(\theta) = -0.000060\,\theta^2 + 0.0089\,\theta + 0.58$ ($R^2 = 0.83$, Figure 2B). Our approach helps analyzing the uncertainty brought by plant architecture in crop-scale processes, and deriving new formalisms to better account for its effects in crop models, $e.g.$ a leaf-angle-dependent k.

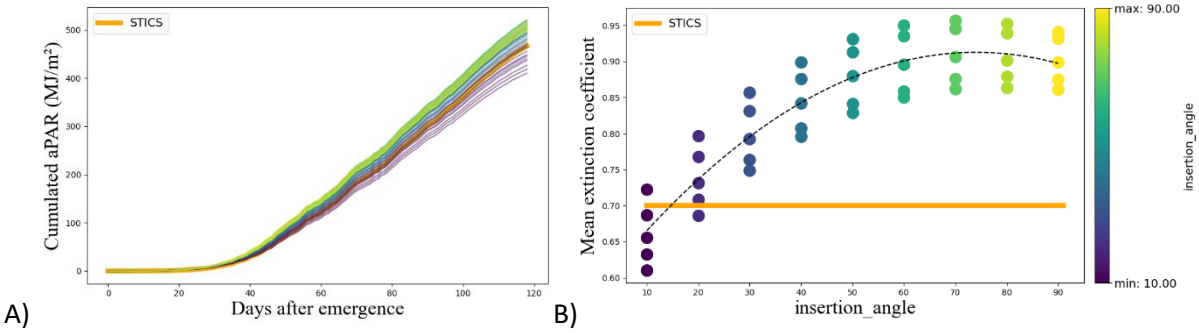


Figure 2: A) Cumulated aPAR by the sorghum canopy throughout crop growth, as computed using Beer-Lambert law in STICS (orange) and using Caribu on 3D scenes generated with ArchiCrop (color bar). B) Polynomial approximation (dashed line) of the mean extinction coefficient as a function of leaf insertion angle (°) computed from aPAR from 3D scenes (points, colored by angle), and parametrized as a constant in STICS (orange). The color bar shows leaf insertion angle, with values ranging from 10° (purple) to 90° (yellow).

Conclusion

ArchiCrop offers a novel approach to efficiently provide architecture to crop models by dynamically generating the set of 3D plant architectures defined from the crop-scale constraints and botanical knowledge. ArchiCrop can be used to test the validity of simplified assumptions in STICS by explicitly simulating those processes at a finer scale, as we explicit it on the light interception process. It also enables us to quantify the influence of phenotypic variability on the simulation of target processes, while accounting for environment and management effects simulated by STICS. Identifying the sources of uncertainty linked to spatial heterogeneity could help refine formalisms using this two-scale approach and improve STICS formalisms to simulate heterogeneous systems without FSPM complexity, in particular for intercrops.

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Coupling MAELIA and STICS: Toward New Opportunities for Agricultural Modelling Approaches

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Keywords: agent-based model, soil-crop model, farming system, agricultural territory, integrated assessment and modeling

Introduction

MAELIA (Modelling of socio-Agro-Ecological system for Landscape Integrated Assessment, http://maelia-platform.inra.fr) is an agent-based modelling platform that simulates field dynamics within a territory, farmer decision-making processes at field (crop management) and farm level (workload), shared resource management (e.g. water), according to forced environmental (climate) and socio-economic (markets) contexts. It is used to assess a wide range of scenarios related to climate change, agricultural systems (crop rotations and crop management), farm functioning (workload and machinery), shared resources (water, organic waste, etc.), and agri-food chains (e.g., biogas, biomaterials, bioplastics). Beyond hydrology, water management, agro-chain and biorefinery models, MAELIA integrate two pattern-based soil-plant models: the crop model AqYield (Tribouillois et al., 2020) and the grassland model HerbSim (Duru et al., 2009). They together allow the simulation of different temperate monospecific crop types and grassland systems.

STICS is a crop model capable of simulating an even broader range of crops, including intercrops (Coucheney et al., 2015; Beaudoin et al., 2023). However, it relies on fixed crop management practices (fixed date–dose inputs) or simple crop management decision rules (e.g. irrigation optimisation).

We coupled the two models to enable each farmer agent in MAELIA to trigger, in each of their fields, farming practices (e.g., tillage, sowing, fertilization, irrigation, harvesting) based on a large set of decision rules, while the biophysical effects of these decisions are simulated by a dedicated instance of STICS at the field level.

Material and methods

The coupling relies on a client–server architecture designed to be minimally intrusive in STICS. An autonomous server capable of spawning multiple independent instances of STICS is responsible solely for performing soil–crop simulations. MAELIA acts as the client and controls the STICS's daily simulation loop: for each simulated day, MAELIA requests that the server advance all fields by one time step and sends event-based technical operations when needed. The STICS server can simulate crop and soil dynamics for all fields simultaneously at a daily time step. All communications between MAELIA and the STICS server use a simple JSON-based protocol, making the coupling easy to implement and maintain. This architecture ensures functional independence between the two models while enabling tight operational synchronization. It also simplifies maintenance, updates to STICS versions, and future extensions of interactions between STICS and MAELIA.

Results and discussions

First, integrating STICS significantly expands MAELIA's crop portfolio, enabling simulations of new cereals, legumes, forage crops, cover crops, and crop mixtures. By leveraging the extensive crops available in STICS—including tropical or diversification crops—MAELIA can represent a much broader diversity of cropping systems without requiring additional development and calibration efforts in MAELIA's soil-plant models. This greatly enhances the platform's ability to explore innovative or emerging cropping systems and diversification strategies. For example, it will be possible to apply MAELIA to assess scenario regarding the sugar cane agro-chains in Reunion Island thanks to the new STICS calibration for this crop (Kebalo et al., 2025).

Second, because crop management decisions in MAELIA are driven by a large set of decision rules, resource availability, farmer's workload and machinery constraints, and policy incentives, STICS simulations can now account for multi-drivers of interannual crop management variability. For example, irrigation decisions derived from MAELIA's representations of resource availability or water allocation scenarios can be evaluated in STICS in terms of e.g., crop water stress and productivity.

Overall, the coupling substantially improves scenario-analysis capacities. Policy scenarios (e.g., nitrogen-use regulations, water quotas), innovative cropping systems (new crop species, mixed crops), collective resource management (e.g., irrigation water, organic waste), and crop management sensitive to climate variability can now be evaluated consistently from the plot to the territorial scale using the MAELIA–STICS model chain.

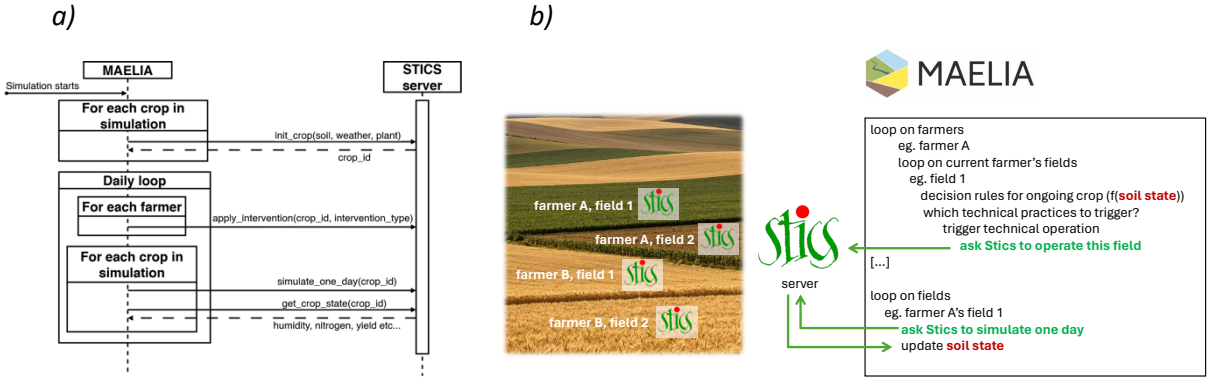


Figure 1: a) sequence diagram and b) general representation of the MAELIA–STICS coupling

Conclusion

The coupling of MAELIA with STICS represents a major advance toward integrated modelling of agricultural systems, combining the strengths of MAELIA's agent-based decision modelling with the robustness and generality provided by STICS. The resulting coupled system offers enhanced capacity to analyze agricultural strategies, resource management options, and policy impacts across diverse scenarios. It opens new perspectives for research on agroecological transitions, climate-change resilience, and sustainable management of agricultural territories. The coupling architecture developed around STICS is fully generic, making it suitable for integration with modelling platforms other than MAELIA.

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PASE as a preprocessor to simulate crops growing in heterogenous microclimate conditions with STICS and pySTICS

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Keywords: PASE, microclimate modelling, agrivoltaics, agroforestry, intercropping

Introduction

The Python Agrivoltaic Simulation Environment (PASE) is a 3D modeling framework designed to simulate heterogeneous microclimates within complex agricultural systems. Originally developed for agrivoltaics (AV) research (Bruhwyler, R. et al., 2024), PASE can represent any spatially detailed scene where microclimate varies across short distances and time. Currently, as presented in Figure 1, microclimate modeling in PASE is limited to detailed light simulations and an empirical wind model for vertical structures such as vertical AV or windbreaks. Future developments aim to incorporate additional microclimate components to enhance environmental realism. Microclimate heterogeneity significantly influences crop development and productivity, making its accurate representation essential for reliable agro-environmental modelling. Although STICS represents canopy light interception through a radiative transfer formalism, this description is restricted to crop canopy geometry and relies on spatially averaged state variables. As a result, the model cannot explicitly address 3D heterogeneity or shading from non-plant structures, limiting its applicability to complex environments. To address this, PASE serves as a preprocessor, producing high-resolution, spatially explicit microclimate data. These outputs are coupled with JavaSTICS and pySTICS to simulate crop growth and yield under 3D variable environmental conditions. This integration enhances predictive capacity for a diversity of systems: AV, agroforestry, orchards, intercropping systems, urban agriculture, etc.

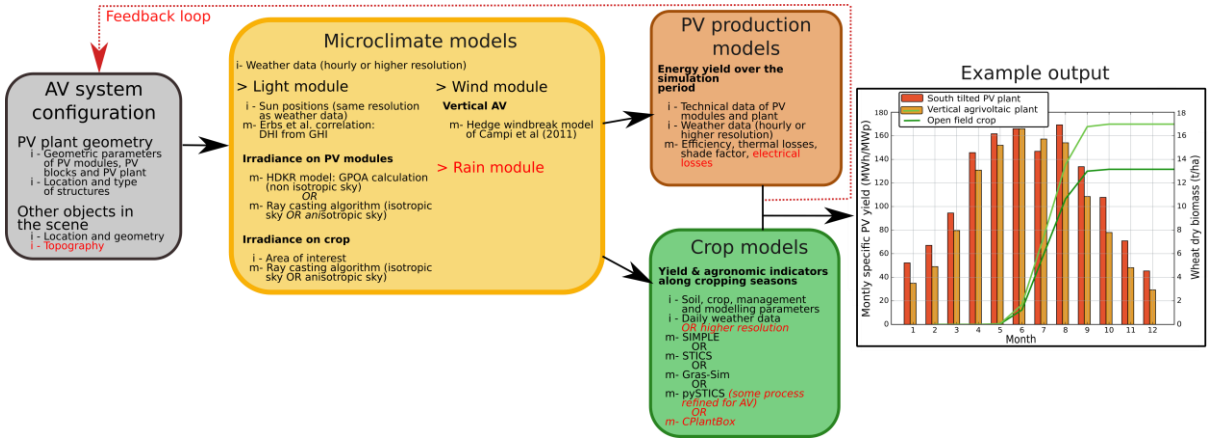


Figure 1: PASE 1.3.0 organigram: main modules and their interactions, the inputs (i -), the models (m-) available (in black) and the future developments (in red).

Preprocessing of light microclimate

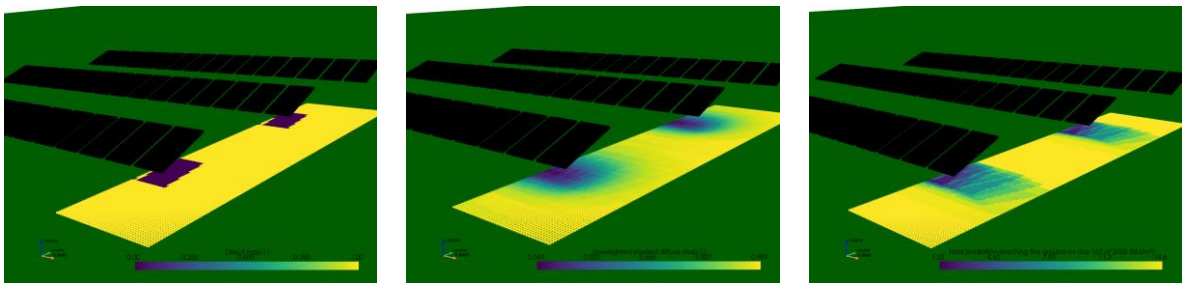
Parametrization of PASE occurs via text files in YAML format in which each entry is documented in terms of the parameter's nature and role, unit in case of physical quantities and accepted values (both type and range). Parametrization gives control to the user over the site configuration as well as numerical aspects of the simulation (time and space resolution, etc.). Input data are weather variables: global horizontal irradiance (GHI, W/m²) and air temperature (°C) with a sampling period between 1 s

and 1 hour, as well as precipitation (mm) and vapor pressure (hPa) at any timestep between 10 min and 1 day. GHI and air temperature can be automatically downloaded from the PVGIS non-interactive API based on the site's location while the precipitation and vapor pressure must be provided in data files.

PASE then initiates ray casting light computations in the scene: sun positions and irradiance components are computed, the 3D scene is prepared (containing obstacles such as structures, PV modules in the case of AV, trees in the case of agroforestry), interest points are placed in the scene and the sky dome is discretized following the Reinhart discretization model (Bourgeois, D., et al., 2008). Ray casting computations run in parallel and thus reduce computing time. They provide metrics for both direct and diffuse components of irradiation. For the direct component, shading is computed on each interest point of the scene at each timestep and provides a Boolean mask: each interest point is either in the shade or under direct irradiation from the Sun. For the diffuse component, it is a sky view factor computed as the fraction of sky area not obstructed by obstacles over total sky area. Then irradiance data is aggregated with the output of the ray casting. For the direct component, direct horizontal irradiance is applied on the mask. For the diffuse, the sky view factor contributions are weighted with the cosine of the zenith angle and the anisotropic sky radiance distribution, which depends on Sun position and sky type (i.e. overcast, intermediate or clear sky, Igawa N., 2014 and Darula S. & Kittler R., 2002). Diffuse horizontal irradiance is multiplied with the shaded diffuse weights matrix. Finally, the direct and diffuse components are summed for each timestep and integrated on the day.

Results and discussions

Figure 2 illustrates the resulting spatialized daily irradiation at the crop level. This and other weather data are then fed into the crop modeling step of the workflow, as parametrized by the user (SIMPLE, Gras-Sim, JavaSTICS or pySTICS). Crop development is therefore also computed for each interest point of the scene, accounting for the local light microclimate. In the current coupling, PASE provides a 3D description of the light environment, while STICS/pySTICS remains responsible for the crop thermal balance based on this radiative input. In the longer term, however, thermal microclimate processes will also be explicitly simulated within PASE.



(a) (b) (c)

Figure 2: Irradiance components on June 15th, 2020 (a) direct irradiance mask at 10:00 AM (b) diffuse irradiance sky view factor map and (c) spatialized daily irradiation.

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Metamodeling as a tool to facilitate virtual ideotyping

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Keywords: Functional-Structural Plant Models (FSPMs), metamodeling, ideotype, crop mixtures, rapeseed, fababean

Introduction

Crop diversification is a key lever for the agroecological transition. For instance, rapeseed-fababean mixtures can improve and stabilize rapeseed yields by regulating pest and improving nitrogen nutrition, while reducing the use of chemical inputs (Lorin et al., 2015, 2016). However, the benefits of crop mixtures are highly variable, reflecting a lack of practical guidelines for combining species traits. Understanding plant-plant interactions that drive competition, complementarity and facilitation is therefore essential. Experimental studies can be supported by mechanistic modelling to explore the large combinations of species, genotypes and growth conditions. Both crop models and functional-structural plant models (FSPMs) enable virtual ideotyping (Blanc et al., 2021; Sambakhé et al., 2024) to define trait combinations to achieve different goals. Because virtual ideotyping is an optimization task requiring a large number of simulations, metamodeling can be used to alleviate computational efforts, as an approximation using statistical or machine learning methods. Metamodels can notably facilitate sensitivity analyses that are essential for virual ideotyping in order to classify plant parameters. Here we illustrate the use of metamodeling for FSPM-based virtual ideotyping for rapeseed, and we discuss the potential applications to crop models and the synergies between the two approaches for advancing virtual ideomixing (Litrico et al., 2015).

Material and methods

We used the FSPM SIMBAL (SIMulated *Brassica* Associated with Legumes) that simulates shoot and root architecture of rapeseed in which C and N fluxes determine organ growth (Perthame et al., 2023). Here we only considered light interception as the main output of the model, and investigated parameters related to aerial architecture for the distribution of leaf surfaces, leaf and petiole dimensions, petiole insertion angle, node length and phyllochrone in order to define ideotypes of rapeseed plants. The ranges of variation of these parameters were assessed from previous experiments and literature (Perthame et al., in prep). A set of 1000 simulations was performed over a maximin Latin hypercube design to ensure a good exploration of parameter space. Light interception in rapeseed monoculture stands was simulated over the vegetative phase for one pedoclimatic context (Gif-sur-Yvette, France in 2023). Different metamodeling methods were trained using 1000 simulations obtained by SIMBAL: linear regression, Gaussian processes, random forests, gradient boosting and neural networks. We used dimension reduction for Gaussian processes, that were fitted on the two main components of a PCA, whereas for the other methods one metamodel was fitted per timestep. Metamodel outputs were then compared by cross validation. Sensitivity analyses were then performed directly on the metamodels to compute Sobol indices.

Results and discussions

The lowest errors between FSPM simulations and metamodel predictions were obtained for the Gaussian processes method, closely followed by methods based on decision trees (random forest, gradient boosting). Neural networks performed poorly as they require a higher number of simulations for training (Figure 1A). Sensitivity analysis applied to the different metamodels showed that parameter ranking differed between metamodeling methods. The three best methods showed that phyllotaxy had the highest impact on light interception (Figure 1B for Gaussian processes). Interestingly, Gaussian processes displayed higher interactions between parameters, likely due to their inherent structure.

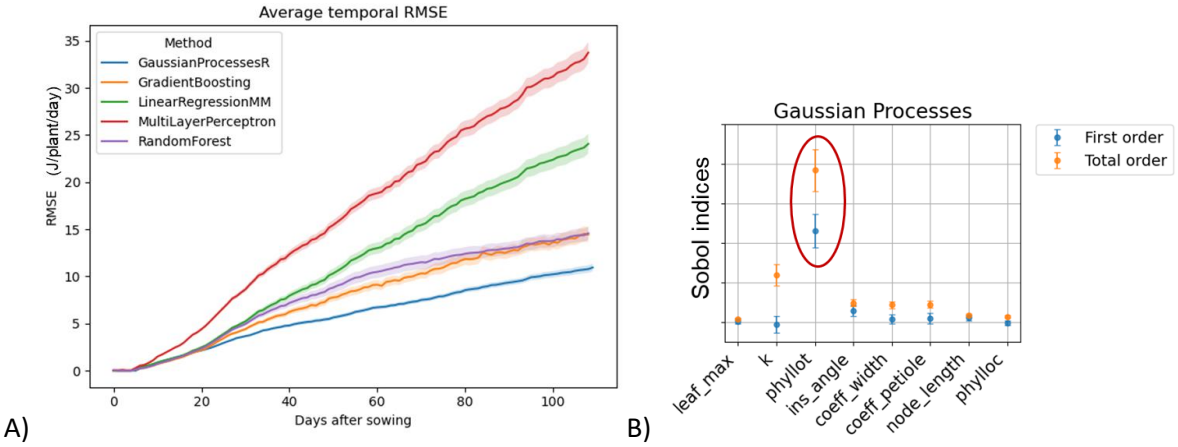


Figure 1: A) Comparison of Root Mean Square Error (J/plant/day) on cumulated intercepted light between SIMBAL simulations and metamodel predictions. Errors were averaged over the 10 replicates of the cross validation for each day. Ribbons represent the standard error around the mean. B) First and total order Sobol indices computed from the Gaussian Processes metamodels for the position of the largest leaf (leaf_max), the skewness of leaf distribution (k), phyllotaxy (phyllot), petiole insertion angle (ins_angle), width to length leaf ratio (coeff_width), petiole to leaf length ratio (coeff_petiole), node length (node_length) and phyllochrone (phylloc).

Conclusion

Our results show that different metamodeling methods can provide contrasted results, Gaussian processes and decision trees methods being the most suitable ones. Metamodeling also enabled to efficiently compute Sobol indices and classify plant parameters with phyllotaxy as a major parameter in our case study. Ultimately virtual ideotyping using FSPMs can help design breeding targets. Although our approach was only tested on a FSPM here, metamodeling applied to crop models is also useful for virtual ideotyping over large geographical areas (Sambakhé et al., 2024). We argue that combining virtual ideotyping at plant and crop scales with both FSPM and crop models could help to design productive and resilient crop mixtures.

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Points of attention when transferring STICS formalisms to another model: the case of Growing Degree-Days in a grassland model

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Keywords: STICS, GRASSIM, grassland modeling, growing degree-days, temperature thresholds.

Introduction

The relationship between environment and plant development has been established for a long time and mechanistic phenology modeling has therefore become a central component of crop growth modeling. The complexity of existing models varies according to the number of developmental phases represented and the environmental variables considered (Chuine et al., 2024). Among these models growing degree-days (GDD) is one of the most used method and may be considered as a single-phase, temperature-only formulation (Chuine et al., 2024; Paredes et al., 2025). However, McMaster & Wilhelm (1997) highlighted that even when using the same canonical equation for GDD (Eq. 1), different assumptions can be made. In the GGD equation, the $[(T_{min} + T_{max})/2]$ term is sometimes replaced by the average daily temperature (T_{avg}), which, if computed from hourly temperature measurements, represents better the integral of the diurnal temperature curve (McMaster & Wilhelm, 1997). In addition to the base temperature (T_{base} or TDMIN in STICS), which is the lower temperature required for plants to grow, some methods use a ceiling temperature (T_{upper} or TDMAX in STICS), for a maximal contribution to GDD (Eq. 2), to represent a termination of the growth above it. Models such as STICS use another formalism instead: T_{upper} is considered rather as an optimum than a ceiling (Eq. 3). Above this temperature, the contribution to GDD (UDEVCULT in STICS) decreases linearly until a temperature of interruption (T_{stop} or TCXSTOP) (Brisson et al., 2009). In addition to the calculation methods detailed above, temperature thresholds values (T_{base} and T_{upper}) also critically affect GDD calculation. While species-dependent, they also depend on other factors such as the phenological stage or the cultivar (Wang & Engel, 1998). For simplicity, they are often considered constant throughout the full cycle for the same species which might not always be true (Paredes et al., 2025).

$$GDD = \left(\frac{T_{max} - T_{min}}{2}\right) - Tbase \quad (1)$$

$$GDD = \begin{cases} 0 & if\ T_{avg} \le T_{base} \\ T_{avg} - T_{base} & if\ T_{base} < T_{avg} \le T_{upper} \\ T_{upper} - T_{base} & if\ T_{avg} > T_{upper} \end{cases} \quad (2)$$

$$GDD = \begin{cases} 0 & if\ T_{avg} \le T_{base} \\ T_{avg} - T_{base} & if\ T_{base} < T_{avg} \le T_{upper} \\ \frac{T_{upper} - T_{base}}{T_{upper} - T_{stop}} * (T_{avg} - T_{stop}) & if\ T_{avg} > T_{upper} \\ 0 & if\ T_{avg} > T_{stop} \end{cases} \quad (3)$$

In this context, borrowing equations across process-based plant models requires caution, as variations in GDD computation and base temperature can modify phenological thresholds and lead to parameters sets that differ in value while giving similar statistical performance (Chuine et al., 2024; McMaster & Wilhelm, 1997). While this study does not aim to provide an exhaustive comparison of existing phenological models, it, nevertheless, uses a case study to illustrate the bias that can arise when GDD equations from the STICS model (Brisson et al., 2009) are applied within the GRASSIM model, whose phenological stages parameterization relies on different assumptions (Kokah et al., 2023).

Material and methods

Meteorological data from the year 2017 were collected in Belgium by meteorological stations from the PAMESEB network in Michamps (50.038°N, 5.808°E) and Louvain-la-Neuve (50.401°N,

4.383°E) to compare two regions with different climates. Hourly air temperature (°C) at 1.5 m was used to compute daily T_{avg} (°C). Different GDD computation methods were tested to assess their influence on simulated phenology: (i) the GRASSIM approach, using a T_{base} fixed at 0 °C and no T_{upper}; (ii) a more mechanistic variant with species-specific thresholds (e.g. T_{base} at 4 °C vs. 8 °C); and (iii) a formalism including a T_{stop} parameter that reduces GDD accumulation at high temperatures, as in STICS. Threshold values were based on Brisson et al. (2009), Ollerenshaw & Baker (1981), and Paredes et al. (2025).

Results and discussions

In 2017, climate was milder in Louvain-la-Neuve ($T_{avg\text{-}annual}$ = 10.9°C) than in Michamps ($T_{avg\text{-}annual}$ = 8.8°C) globally explaining a bigger GDD accumulation at the end of the year. When changing T_{base} from 0°C to 4°C and from 4°C to 8°C, fewer GDD were accumulated (up to 2.5 times lower). This change had more effect in Louvain-la-Neuve due to milder T_{avg} in spring. Concerning the increase in T_{upper}, it had a reduced effect (less than one GDD) because only one day had T_{avg} above 25°C. This also explains why using STICS formalism (Eq. 3) with a T_{stop} set to 35°C and 40°C did not affect the GDD computation under this temperate climate (not shown in Figure 1, as no differences were observed with Eq. 2). The respective effect of changing T_{base}, T_{upper}, and T_{stop} should thus be considered relative to the climate conditions of the case-study. For instance, introducing a T_{stop} parameter would have stronger consequences in warmer climates, where it would better account for heat-related reductions in development. In this context, transferring formalisms and temperature thresholds to another model such as the GRASSIM grass-growth model (Kokah et al., 2023), in which phenological stages are parametrized in thermal time with a base of 0°C, may introduce bias. For example, in Michamps, the "ear at 10 cm" stage, which occurs at 500 GDD when calculated with a 0 °C base temperature, moves from April 30th to June 1st when T_{base} is increased to 4 °C. This shows that a phenological stage calibrated at 0 °C becomes inconsistent when another base temperature is used to compute GDD, with major implications for simulated grass growth.

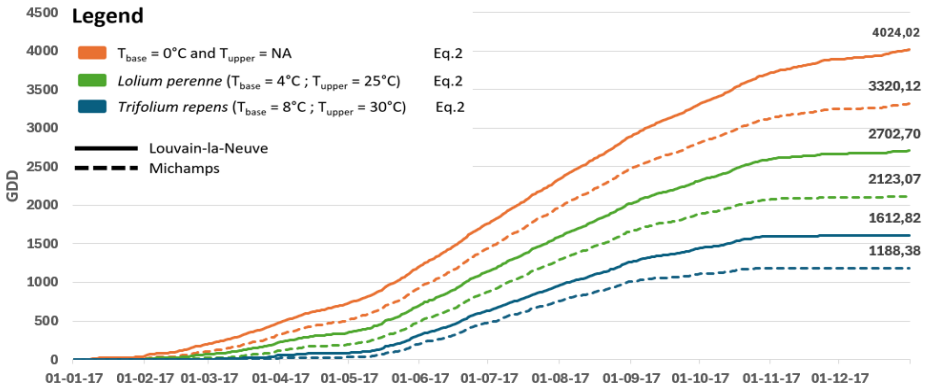


Figure 1: Comparison of GDD according to the method and temperature thresholds used for 2017.

Solutions include using the parametrization associated with the chosen formalism, but since GRASSIM covers four grasses functional types (Kokah et al., 2023), supplementary specific parametrization of phenological stages could be needed. This should rely on datasets with at least 20 observations from 3 to 5 sites to capture diverse environmental conditions, as parameter values are highly dataset-dependent (Chuine et al., 2024). As the aim is to improve legumes modeling in GRASSIM, future work should also explore the inclusion of photoperiod effects on phenology, as in STICS (cf. UPVT) (Brisson et al., 2009) or in Wang & Engel (1998).

Conclusion

This work therefore highlights the importance of consistency in thermal time calculation methods and temperature thresholds when transferring parameterizations between models. Ensuring methodological coherence is essential to avoid biases in phenological predictions and to improve the reliability of modeling across contrasting climates.

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Session IV

New formalisms, parameterization of new species and development of tools around the STICS model

Evaluating calibration strategies for a new winter wheat cultivar in STICS

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Keywords: calibration, estimation, crop model, winter wheat, varietal parameters

Introduction

Crop models are essential tools for simulating crop growth, development, and yield in response to the environment and agricultural practices. To remain relevant, they must be regularly updated to incorporate new cultivars, whose agronomic characteristics are rapidly evolving as a result of genetic progress. However, calibrating varietal parameters remains a complex and uncertain step. This study proposes a rigorous methodology for selecting the variables and parameters to be estimated when calibrating a new cultivar in the STICS model. Using the Rubisko soft winter wheat variety, we apply for the first time to experimental data the sequential calibration procedure developed by Wallach et al. (2024). The objective is to evaluate different calibration strategies according to the availability of biomass and/or leaf area index (LAI) data, and to identify the most robust criteria to guide modelers in the parameterization of new cultivars. This work is a follow-up of AgMIP ongoing efforts to harmonize calibration practices and reduce variability between modelers, while improving the predictive capacity of crop models.

Material and methods

The data comes from multi-site, multi-year trials conducted by ARVALIS in France on the Rubisko variety. The dataset includes observations of phenology, LAI, above-ground biomass, number of grains, and yield. The STICS model (Beaudoin et al., 2023) was calibrated using the sequential method proposed by Wallach et al. (2024), using the R package CroptimizR (Buis et al., 2023) in combination with its wrapper function for STICS available in the R package SticsOnR (Lecharpentier et al., 2023). Ten to twelve varietal parameters chosen for estimation based on their sensitivity (Ruget et al., 2002) and expert knowledge, covering phenology, leaf growth, biomass production, and grain filling. We considered the variety Arminda parameter values as default ones. Four calibration strategies were tested according to the availability of dynamic variables for leaf growth and biomass production: no LAI nor biomass, only LAI, only biomass (with and without RUE parameters), both LAI and biomass. The evaluation of the strategies was based on three criteria: the physiological plausibility of the estimated parameters, the decomposition of the mean square error (MSE), and the analysis of residuals, compared on independent calibration and evaluation sets.

Results and discussions

All the strategies tested improved the model's performance compared to the default parameterization (Arminda cultivar). Phenological parameters are estimated in a stable and consistent manner, while those related to leaf growth and biomass show differences depending on the strategy. Strategies incorporating LAI data result in better simulated dynamics of vegetation cover and biomass, with flatter residuals and reduced bias. On the other hand, joint calibration of parameters related to radiation use efficiency (RUE) and leaf growth leads to physiologically implausible estimates and overestimations of biomass. The strategy based solely on LAI observations

proves to be the most robust: it reconciles the consistency of the estimated parameters, good accuracy on dynamic variables, and limited biases on yield. These results confirm that the choice of calibration variables strongly influences the quality of the simulation (Figure 1 for plant biomass), in interaction with the structure of the experimental dataset.

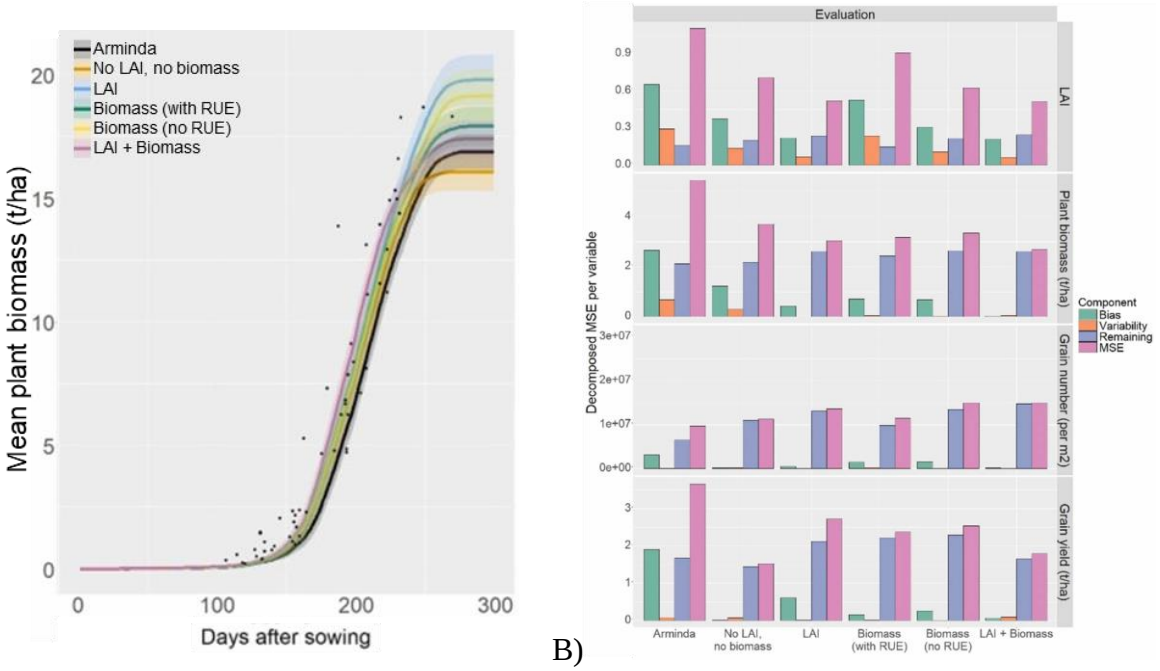


Figure 1: Evaluation of calibration strategies for the evaluation data sets with A) Observed and simulated plant biomass (t/ha) by STICS. Black points represent observations, colored lines represent the average of the variables over the different simulations for each calibration strategy and the colored ribbons represent the standard error around the mean, and B) Decomposed MSE (Mean Square error, pink) into bias (bias2, turquoise), difference in variability (SDSD, orange) and residuals (LCS, mauve) faceted for the strategies

Conclusion

This study proposes an operational methodology for calibrating new cultivars in the STICS model, combining a sequential approach with objective evaluation criteria. Application to the Rubisko variety shows that calibration based on LAI is the best strategy for achieving a compromise between physiological realism and predictive performance. The results also highlight the need to acquire regular measurements of LAI and biomass, particularly around maximum LAI and maturity, in order to improve the robustness of estimates. These findings provide concrete benchmarks for the parameterization of other wheat varieties and, more broadly, for updating crop models in light of genetic progress. Ultimately, this approach will help to improve the reliability of agronomic simulations and their use in assessing the impacts of climate change or supporting varietal selection.

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AgMIP Calibration Protocol: results, implementation and new directions

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Keywords: Crop model, parameter estimation, parameter selection, CroptimizR

Introduction

Crop model parameters are generally not directly measurable and must therefore be estimated through calibration procedures, typically by minimizing the discrepancies between simulated and observed variables across different environments. In practice, a wide range of calibration strategies is used, differing in optimization methods, parameter selection, definition of objective functions, and types of data employed (Seidel et al., 2018). A major issue is that the chosen calibration approach can strongly influence model outcomes (Wallach et al., 2021; Wallach et al., 2025a).
Since 2018, the AgMIP Calibration Group has pursued three main objectives: documenting and comparing current calibration practices, proposing a widely applicable standard calibration protocol, and developing tools for its implementation. In an initial phase, a protocol dedicated to phenology data was proposed. This has since been extended to a more general calibration protocol applicable to essentially any dataset and crop model (Wallach et al, 2024).

Material and methods

The protocol addresses two main challenges in crop model calibration: selecting parameters to estimate and handling multiple observed variables. It recommends using all observed variables with simulated equivalents, because fitting as many processes as possible should maximize the overall realism of the simulations. Parameters are first selected and estimated by sequentially minimizing Ordinary Least Square (OLS) problems by variable groups (e.g., all phenological variables together, all time-series of a given variable together, and remaining variables individually). Within each group, one parameter per variable (or two for time-series) identified by the user as likely to reduce systematic bias is automatically selected for estimation. Additional candidate parameters, expected to explain part of the variability across environments, are either selected for estimation or kept to their default values based on the corrected Akaike Information Criterion (AICc). By penalizing the number of parameters to be estimated relative to the amount of available data, the AICc-based selection step effectively manages the trade-off between dataset size and parameterization, helping to prevent overfitting. Treating one variable group at a time greatly simplifies the numerical problem, but may lead to a poor final fit to some variables, if the simulated values of those variables are affected by fitting subsequent variable groups. Therefore, the protocol includes a final, weighted least squares (WLS) step, where all selected parameters are estimated together, with weights derived from the sequential OLS steps results. Post-hoc diagnostics assesses the extent to which the estimated parameters reduce bias and visualize feedbacks between variable groups.

The protocol was tested with the STICS model on artificial data (Wallach et al., 2024), with DSSAT-NWHEAT on real data (Wallach et al., 2025b), and in a recent multi-model experiment. Both OLS and WLS optimizations used a multi-start Nelder–Mead simplex algorithm, with 20 repetitions for WLS,

including one starting from the sequential OLS steps results and others from randomly sampled values within user-defined parameters bounds.

The protocol is being integrated into CroptimizR (Buis et al., 2024), a generic R package for crop model parameter estimation. A dedicated function automates the full AgMIP workflow and generates all diagnostics. The package allows testing alternative algorithms and options within the protocol and can be applied to any crop model for which a wrapper exists or can be developed.

Results and discussions

The multi-model study demonstrates that the protocol is applicable to a wide range of model structures. It was designed to handle essentially any dataset, the current studies did not require any dataset-specific adjustments. Overfitting, a major concern in calibration due to the large number of model parameters, was not observed, prediction errors were similar to fitting errors.

In the multi-model study, all teams achieved very good results for phenology and biomass, while performance for other variables was lower. Average final relative root mean squared errors for the calibration data ranged from 0.2 for time to stem elongation to 0.35 for biomass N, with yield performing second worst at 0.29. Although there was variability between modeling teams, trends were consistent across all teams, suggesting these results may represent the best achievable with the given dataset.

However, in some cases, WLS minimizations starting from randomly sampled values resulted in lower criterion values than those from the results of the sequential OLS steps. Variability in parameter values and minimized criterion across the 20 WLS repetitions also highlighted the systematic presence of local minima and the inherent complexity of this problem, which typically includes 10 to 20 parameters to estimate. This raises questions about whether the multi-start Nelder–Mead simplex algorithm is the most appropriate choice for this step.

Conclusion

The AgMIP calibration protocol is broadly applicable to essentially all crop models and datasets. It is grounded in statistical parameter estimation theory and model expertise and includes diagnostic tools to better interpret calibration results. The protocol, together with its implementation in CroptimizR, represents a promising candidate for a standardized and reproducible calibration procedure for crop models.

Ongoing evaluations focus on alternative algorithms, such as global optimization methods, to determine whether the multi-start Nelder–Mead simplex approach is sufficient for the WLS step and to further improve calibration robustness.

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Evaluating the STICS model for simulating grapevine development and new formalisms across contrasting soil types at a local scale in Saint-Émilion

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Keywords: STICS, Grapevine, Model evaluation, Saint-Émilion, Yield, Soil types

Introduction

Viticulture and grape production are increasingly threatened by climate change (van Leeuwen et al., 2024). To ensure vineyard resilience, it is essential to find adaptation strategies. Within this context, the French Vitilience project aims to promote and assess combinations of viticultural practices that enhance vineyard resilience across different winegrowing regions. Crop models are key tools for simulating crop functioning and predicting vineyard responses at the plot scale under different agropedoclimatic conditions and managements. Among the different available crop models developed for grapevine (e.g., NVINE, WaLIS, VineLogic, CropSyst, Vitisim), the STICS model (Beaudoin et al., 2023) stands out for its versatility and the range of processes it can simulate (García de Cortazar-Atauri, 2006 ; Zhu et al., 2021). This study has two main objectives. First, we evaluate the accuracy of the STICS model to simulate key agronomic variables for grapevines, including phenology, yield, and vine water status, at a local scale in three different soil types. Secondly, we test recent STICS model developments for grapevine in a new git branch to evaluate whether they improve simulations and notably potential yield in Saint-Émilion compared with the standard version. This work will provide a foundation for subsequent simulations of the experimental vineyard sites of the Vitilience project.

Material and methods

STICS version 10.4.1 was used to simulate a vineyard site in the Saint-Émilion appellation (South-West of France), with two cultivars, *Vitis vinifera* L.cv. Merlot (M) and *Vitis vinifera* L.cv. Cabernet franc (CF), cultivated across three soil types: clay (A), gravel (G), and sand (S). The model was parameterized with a database including records from 2004 to 2016. Climate inputs were extracted from SAFRAN (8×8 km grid) and soil parameters were derived from field measurements on each plot. To parametrize the different soil types on STICS, profiles were dug for each plot to measure gravel content, fine earth, organic matter, clay content after decarbonation, total nitrogen, and organic carbon, allowing the estimation of gravimetric water content at field capacity and at the witling point. Vines were managed under a simple Guyot system (6000 vines per ha^{-1}) without irrigation, with a vertical shoot-positioned (VSP) training system and rows oriented north-south. Finally, key vine measurements included phenological dates and yield components. Observed variables and STICS outputs are summarized in table 1.

Model performance was evaluated using quantitative statistical indicators EF (Nash Sutcliffe efficiency), RMSE (Root mean square error), RRMSE (Relative root mean square error), and BIAS for various observed data from the site.

Table 1: Observational data

Observed data (for each soil and cultivar 2004-2016)	Measures	STICS Outputs
Phenology	50% budbreak (DOY), 50% flowering (DOY), 50% veraison (DOY)	Ilev, iflo, ilaxs
Water status	predawn leaf water potential (Mpa)	Psibase (Mpa)
Yield components	Fresh weight (kg/cep) Number of grapes	pdsfruitfrais (t.ha) nbinflo

To address the second objective, we used a STICS development version integrating new parametrization and formalisms from Strullu et al. (2024), initially developed for the Champagne context. These modifications account for carbon and nitrogen fluxes associated with pruning and shoot management, adjusting sink strength and nitrogen demand of berries as a function of the number of inflorescences. We then compared the simulations with those from the standard STICS version to assess whether these developments improve the performance of the evaluated variables under the local conditions of Saint-Émilion.

Results and discussions

Preliminary analyses are ongoing and results will be presented at the seminar.

Conclusion

This study evaluated the performance of the native STICS model to simulate key grapevine variables across contrasting soil types and two cultivars at a local scale. In addition, a development version of STICS integrating new parametrization and formalisms was tested and compared with the standard version. These findings are expected to improve the model's predictive capacity for local scale assessments of vineyard adaptation to climate change.

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Evaluation of STICS performance for predicting C and N mineralization kinetics and N_2O emissions from contrasted litter types on urban lawn soils

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Keywords: urban green spaces, lawn soils, N_2O, CO_2, soil mineral N, litter decomposition

Introduction

Urban green spaces (UGSs) are ecosystems that can play a key role in urban sustainability by providing services such as carbon (C) storage, biodiversity conservation and urban cooling. Lawns, which represent a significant proportion of UGSs worldwide, can receive a diversity of litter types (*e.g.* tree leaves, grass clippings) that can be exported instead of recycled into the soils (Ferlauto et al., 2024). Recycling this litter could improve soil organic status and fertility, but it may also present some potential risks of nitrous oxide (N_2O) emissions. N_2O emissions and Nitrogen (N) and C mineralization kinetics are notably known to vary between plant residues having different biochemical characteristics. The N and soluble contents and C:N ratio of crop residues have been identified as relatively good predictors of N_2O emissions (Abalos et al., 2022 ; Lashermes et al., 2022) and N and C mineralization (Justes et al., 2009), respectively. Most of this current knowledge concerns cropland systems but less is known about other ecosystems such as UGSs, which harbour a great diversity of plants and soils under contrasted management practices.

In this context, our objective is to challenge and evaluate the ability of STICS to simulate C and N mineralization kinetics and N_2O emissions of biochemically diverse litter types on lawn soils. Hence, we will assess the genericity of the model and its formalisms initially developed for simulating crop residue decomposition and the functioning of arable soils. More specifically, we will evaluate STICS performances for simulating i) CO_2 release and soil mineral N content for diverse litter types decomposing in the soil and on the soil surface, and ii) N_2O emissions associated with litter decomposing on the soil surface of two contrasted lawn soils.

Material and methods

The evaluation of STICS in this new context will be based on data from two soil incubation experiments (Künnemann et al., 2024). In Experiment 1, the CO_2 release and soil mineral N were monitored during 94 days for i) 9 litter types mixed with a low-intensity management soil (organic C = 1.8 %, pH = 5.8, bulk density = 1.4 $g.cm^{-3}$) and ii) 3 litter types mixed with an organically rich soil derived from high-intensity management practices (organic C = 6.0 %, pH = 6.7, bulk density = 0.8 $g.cm^{-3}$). In Experiment 2, we monitored during 14 days the early CO_2 and N_2O releases and soil mineral N for a selection of 5 litter types decomposing on the soil surface of both contrasted soils. The 9 investigated litter types were leaves from trees (3 deciduous and 1 evergreen) and shrubs (3), 1 green grass and 1 mixture of senescent grasses. In both experiments, litter was applied at a rate equivalent to 3 Mg dry matter per ha.

The current standard version of STICS (10.4.1) and a version integrating recently proposed improvements for simulating mulch decomposition and for estimating the denitrification potential (Chaves et al., 2024) will be confronted to the experimentally obtained data. Comparison of simulated and observed dynamics for CO_2 release, soil mineral N and N_2O emissions as well as

statistical goodness of fit criteria will be used to evaluate model performance. The study of two soils with different soil properties such as water retention capacities or pH combined with two different settings of WFPS (water-filled pore space) for one soil in Experiment 2 should also enable to assess whether the relative influence of these factors is properly taken into account in the model formalisms for predicting N_2O emissions.

Results

For the 9 investigated litter types, C:N ratios ranged from 8 to 103, Van Soest soluble fraction ranged from 20 to 66 % and lignin content from 2 to 38 %. Among them, we notably selected 4 litters with high soluble fractions and high C/N ratio (low N contents), allowing to better decipher the respective influence of each variable on C and N mineralization and on N_2O emissions. Cumulative CO_2 fluxes and soil mineral N dynamics from litter decomposing in experiment 1 are shown in Figure 1: green litter with a low C/N (LoA) decomposed faster and exhibited a net release of mineral N compared to senescent litter which decomposed more slowly and induced N immobilization.

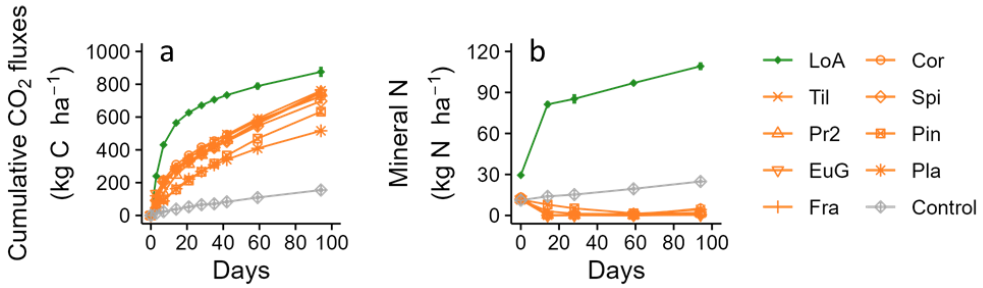


Figure 1: (a) cumulative CO_2 fluxes and (b) soil mineral N for 9 litters incubated over 94 days in the low-intensity management lawn soil of Experiment 1. LoA: *Lolium arundinaceum*, Til: *Tilia × europaea*, Pr2: Meadow mix, EuG: *Euonymus grandifloras*, Fra: *Fraxinus angustifolia*, Cor: *Cornus alba*, Spi: *Spiraea vanhouttei*, Pin: *Pinus radiata*, Pla: *Platanus × acerifolia*. Control: control soil without litter.

Conclusion and perspectives

Expected results should allow to evaluate the genericity and robustness of STICS formalisms to predict C and N mineralization kinetics and N_2O emissions from litter decomposing in soils from UGSs, on litter and on soil types that had not been previously studied with the model. This will allow to propose potential improvements or if the model proves to be satisfactory, some indicators (*e.g.* N_2O emission factors, humification coefficients) could be calculated for the different litter types and be made available for decision support in UGS management practices. We could later envisage the possibility to extend the model validity domain to other ecosystems, or at least to validate some STICS modules (*e.g.* residue decomposition, N_2O emissions) for cropping systems with diversified plant associations (*e.g.* agroforestry systems with trees and herbaceous plants).

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Tropicalization of the STICS model: insights from sugarcane calibration and nitrogen dynamics in tropical volcanic soils

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Keywords: Perennial crop, Tropics, N fertilization, N losses

Introduction

The STICS model (Brisson et al., 2003) has been mainly developed and tested in temperate regions, making its adaptation, or tropicalization, a crucial step for robust use in tropical agroecosystems. Sugarcane, a perennial crop of major economic importance, provides a challenging test case due to its long cycle, strong dependence on nitrogen (N) inputs, and the diversity of soil types found in tropical islands such as La Réunion. This contribution synthesizes results from three complementary studies aiming to tropicalize STICS for sugarcane-based systems: (i) calibration and robustness assessment of sugarcane crop growth across contrasted environments (Kebalo et al., 2025); (ii) parameterization of nitrogen mineralization and fertilization response in volcanic and tropical soils; (iii) calibration and evaluation of nitrogen losses (NH_3 volatilization, N_2O emissions, and NO_3^- leaching) under tropical conditions. Together, these studies provide a consolidated framework to improve tropical applications of STICS and to support sustainable management of sugarcane production systems.

Material and methods

The first study focused on calibrating and validating STICS simulations of sugarcane growth under optimal nutrient conditions. Parameterization used crop cycles from four countries, including measurements of below- and aboveground variables (Chevalier et al., 2025; Jones et al., 2019). Validation relied on 62 additional R570 cycles and 158 cycles from 30 international varieties (Christina et al., 2020). Structural parameters governing phenology, biomass allocation, and canopy development were adjusted, and performance was evaluated on aboveground biomass, LAI, and harvest traits. The climatic domain of validity was assessed by analysing model errors along gradients in temperature and water availability.

The second study aimed to improve the representation of nitrogen availability in andic and non-andic tropical soils in La Reunion. Ten sites (four andic, six non-andic) with fertilized and unfertilized treatments were used (Chevalier et al., 2025). For andic soils, clay content was adjusted on unfertilized plots to match observed mineralization and linked to allophane content. For non-andic soils, fine silt was incorporated into the clay fraction to establish a separate calibration curve. The orgeng parameter (N immobilization) was optimized using 10 observations from fertilized plots. Validation was conducted with 22 datasets from four sites (TERO project, eRcane).

The third study calibrated nitrogen losses using a multi-year dataset of 12 sugarcane cycles with mineral and organic fertilization (poultry manure, pig slurry, sewage sludge), including measurements of NH_3 volatilization, N leaching, and N_2O emissions (SOERE-PRO, Poultney, 2021). Validation used the multi-site TERO database (4 sites, 6–11 cycles) with observations of yield, N uptake, and soil C and N stocks. Calibration was sequential: (i) plant N uptake, (ii) NH_3 volatilization through adjustment of maximum volatilization rate and pH threshold, and (iii) N_2O emissions and

nitrate leaching via optimization of the daily nitrification rate adapted to tropical soils.

Results and discussions

Sugarcane growth: robust simulation across tropical environments. STICS satisfactorily simulated biomass accumulation, intercepted radiation, and biomass partitioning across parameterization and validation datasets. Despite calibration on Réunion varieties only, the model demonstrated strong robustness across international varieties, maintaining reasonable accuracy for biomass at harvest. Error analysis across climatic gradients revealed a decrease in accuracy in extreme conditions. This provides a roadmap for future improvements, such as refining temperature responses, water-stress functions, and variety-specific traits.

Improved representation of N mineralization and fertilization response in volcanic soils. The adjusted relationships linking clay content (or fine silt correction) to soil allophane successfully reproduced observed N mineralization dynamics in both andic and non-andic soils. This constitutes an important step toward representing the unique physicochemical properties of volcanic soils, particularly their high capacity to stabilize organic matter. Calibration of N immobilization improved the simulation of N availability following fertilization. Validation across 22 observations showed satisfactory agreement for N uptake and biomass response, demonstrating the parameterization's transferability across different sites and soil types.

Calibration of N losses under tropical conditions. Sequential calibration improved the representation of gaseous and leaching losses. Adjusting volatilization parameters allowed the model to reproduce the magnitude of NH_3 volatilization across mineral and organic fertilization scenarios. Optimizing the maximum daily fraction of ammonium that can be nitrified, which is typically higher in warm, moist tropical soils, significantly improved the model's ability to simulate measured N_2O emissions and NO_3^- leaching fluxes. Validation with multi-site TERO data demonstrated that the calibrated model can reproduce yields, N uptake, and soil N and C trends across a wide range of organic fertilization systems.

Conclusion

This work presents a comprehensive effort to tropicalize the STICS model for sugarcane-based systems. The three studies collectively show that: i) STICS can robustly simulate sugarcane biomass production across varieties and climatic conditions, although leaf dynamics remains a priority for improvement; ii) Volcanic soil characteristics, especially allophane content and associated mineralization behavior, can be effectively integrated to improve predictions of N availability and fertilization response; iii) Calibration of N volatilization, nitrification, N_2O emissions, and nitrate leaching allows the model to capture the major nitrogen loss pathways typical of tropical systems. Together, these advances significantly enhance STICS's capacity to evaluate agronomic and environmental performance in tropical sugarcane systems.

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Integrating agricultural practices into the STICS model: a new tool for simulating crop nitrogen fertilization

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Keywords: STICS, nitrogen fertilization, nitrogen balance sheet, water catchment area.

Introduction

Water catchment areas (WCA) are exposed to pollution from agricultural, industrial, or domestic sources, which can lead to their permanent closure. Between 1994 and 2013, 7716 WCAs intended for drinking water supply were abandoned in France, and 39% of these closures were linked to pollution from nitrates and pesticides. Vulnerable zones with regard to nitrate pollution are subject to specific requirements to implement “good agricultural practices” such as the adoption of balanced fertilization practices for crops. To reproduce agricultural practices in these zones in terms of nitrogen fertilization, we designed a new tool involving new formalisms in the STICS model and a new option in the R wrapper of the STICS model (SticsOnR package). The objective was to develop a generic tool to allow the simulation of crop N fertilization in function of agricultural practices and pedoclimatic conditions at the crop rotation scale.

Material and methods

Simulations were performed at the scale of the Merobert WCA of 3670 ha situated near Chartres in France which surface is covered at 93 % by cropland dominated by arable farming. To determine the N fertilization of crops we used the balance sheet method developed by COMIFER (COMIFER, 2013). The final simplified balance used allows the mineral nitrogen fertilization (Nfert) to be computed as follows:

$$Nfert = Pf - (Pi + Ri + Mh + Mhp + Mr + MrCI + Xa + Nirr) + L + Rf \quad \text{(equation 1)}$$

Here, Pf represents the crop nitrogen requirement, defined according to the crop type and expected yield (COMIFER and regional references). The terms Pi, Ri, Mh, Mhp, Mr and MrCI account for initial plant N uptake, soil mineral nitrogen, humus mineralization, grassland turnover, crop residue decomposition, and cover crop residues, respectively. Xa groups together potential organic inputs. Nirr represents nitrogen supplied through irrigation, L nitrate leaching losses, and Rf the closing soil nitrogen balance. Several of these components are determined using reference tables (“abaques”) provided by COMIFER, the Chamber of Agriculture, or the regional reference framework (DREAL and DRAFF Centre-Val de Loire, 2023). Humus mineralization (Mh) is estimated for each crop and soil combination thanks to the use of the STICS model, and Pi, Ri and L are simulated by the model. Equation 1 was therefore used to estimate the mineral nitrogen fertilizer requirements of the simulated crops (Figure 1).

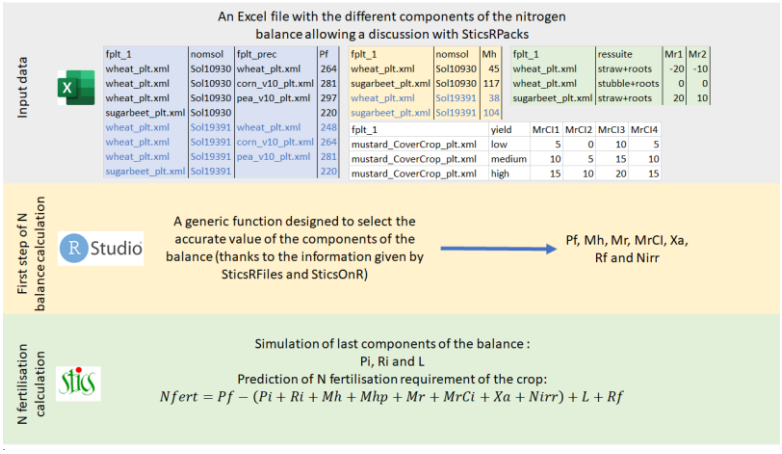


Figure 1: Schematic representation of tool functioning for N fertilization calculation. *NB: Mhp is not available for the moment.*

Results and discussions

Nitrogen fertilization of crops varies according to year and soil type. The average simulated nitrogen fertilization at the WCA scale for the different crops is consistent with farmers' practices (Table 1). The effects of year and soil are statistically significant on crop fertilization ($p < 0.01$), whereas the effect of crop rotation is weaker and significant only for wheat and rapeseed.

Table 1: Average nitrogen fertilization simulated and observed for different crops at the scale of the WCA (data from the Eure-et-Loir Chamber of Agriculture).

Crop N fertilization (kg N ha^{-1})	Winter wheat	Rapeseed	Winter barley	Corn	Spring pea	Potato	Sugar beet
Simulation	194 ± 17	183 ± 20	141 ± 20	157 ± 10	0	158 ± 10	108 ± 8
Observation	190	170	145	140	0	140	90

In this study, a potential yield was assigned to each soil type, and fertilization was calculated accordingly, assuming homogeneous soil conditions within each plot. These assumptions introduce distortions compared to real field conditions, although the simulated fertilization remains consistent with farmer practices at the WCA scale. The exact proportions of soil types within individual plots are unknown, and the yield targets chosen by farmers cannot be determined. To better assess the impact of these uncertainties, a sensitivity analysis of model outputs to yield objectives and soil type distribution would be valuable.

Conclusion

The integration of the COMIFER nitrogen balance sheet method into the STICS model and SticsRPacks provides a robust tool for simulating crop N fertilization. Simulated values are consistent with farmer practices, while accounting for pedoclimatic and agricultural practices variability. This tool opens new perspectives for assessing nitrogen management strategies in vulnerable WCA. The full integration of this tool into a released version of the SticsRpacks packages and STICS model remains to be completed. This work was funded by the ANR project MisEauVert (2024-2028).

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Towards improved simulation of tropical soil organic matter mineralization in soil-crop models

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Keywords: soil organic nitrogen, model intercomparison, soil-crop simulation, tropical environments

Introduction

Soil Organic Matter (SOM) mineralization plays a central role in carbon (C) and nitrogen (N) cycling, soil fertility, and crop N supply. In soil-crop models such as STICS (Beaudoin et al., 2023; Brisson et al., 2008), predictive equations, developed and calibrated in temperate soils (Clivot et al., 2017), link SOM mineralization to soil properties (i.e., clay, pH, carbonates, C/N, soil temperature, soil water content). However, tropical soils differ profoundly from temperate soils. They are generally more acidic, highly weathered, and dominated by Fe/Al oxides, with distinct SOM stabilization mechanisms involving amorphous minerals such as allophanes. As a result, temperate-based model equations often perform poorly under tropical conditions. Furthermore, tropical soils, characterized by low pH and specific mineralogy, typically fall outside the calibration range of existing models.

Results from the Agricultural Model Intercomparison and Improvement Project (AgMIP) "Low Input farmin system" team have shown that, under unfertilized conditions, simulated crop yields vary greatly among soil–crop models (Couëdel et al., 2024). This variability is largely explained by differences in how models represent and simulate SOM-derived N mineralization, which constitutes the main N source for crops in low-input tropical systems. Such discrepancies generate substantial uncertainty in simulating current smallholder farming low-input systems, the impact of climate change and the interest of sustainable intensification management options in tropical regions (Falconnier et al., 2020).

There is therefore a strong need to "tropicalize" SOM mineralization equations, by adapting model formalisms and parameterizations to better represent the functioning of tropical soils. Such improvements are essential to enhance the reliability of soil–crop models in low-input systems, where SOM mineralization drives crop N nutrition and long-term soil fertility.

Material and methods

This work is conducted within the ALAMOD project, which aims to consolidate large, quality-controlled soil datasets to strengthen model representations of SOM dynamics. In this context, our methodological approach is organized into two complementary components, each planned to span approximately 1.5 years, and relying on distinct data sources to address short- and long-term SOM mineralization processes.

1. Short-term soil N mineralization

We will conduct an intercomparison of major soil-crop models (STICS, DSSAT, APSIM...) within the framework of the AgMIP, in order to assess their ability to simulate soil organic matter -derived nitrogen mineralization under tropical conditions.

Because field experiments on bare soils with regular measurements of soil mineral N are extremely scarce, we will use an indirect proxy approach to estimate the SOM-derived N supply, assuming no N losses and no external N inputs:

$$\text{Soil N supply from SOM} = \text{Crop N uptake} - \Delta\text{Soil Mineral N}$$

With ΔSoil Mineral N the difference between final and initial soil mineral nitrogen. Situations with water stress can be considered as long as the ΔSoil Mineral N is measured.

We will compile a dataset from the literature and existing CIRAD sites including field experiments that provide, at a minimum, soil mineral N measurements at the beginning and end of the cropping season and plant N uptake. These experiments will be selected to represent a wide diversity of tropical soils. We will focus our analysis on cereal-based systems, particularly maize, but also sorghum and millet. These crops are commonly represented in modeling frameworks and are widely cultivated across tropical regions, which makes them suitable reference systems for evaluating model performance in simulating SOM-derived N mineralization.

2. Long-term SOC and SON dynamics

We will evaluate the performance of the STICS model in simulating long-term soil organic carbon (SOC) and soil organic nitrogen (SON) dynamics under tropical conditions. To this end, long-term experimental data on SOC and SON will be compiled, quality-controlled and harmonized from a database hosted by ANAEE-France (research unit InfoSols). This comprehensive database includes multi-year observations from tropical experiments, providing a robust basis for assessing the model's ability to reproduce observed SOC and SON trends over decadal timescales.

Expected results and perspectives

This study is expected to identify the main soil properties controlling SOM-derived N mineralization in soil-crop models. The comparison of model performances across diverse tropical soils will help refine equations and parameterizations to better represent SOM mineralization under tropical conditions. This work will also contribute to the development of improved model formalisms and to the provision of an open, harmonized database, supporting the wider modeling community in tropical environments.

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Simulation of N_2O emissions in Eastern Canada: evaluation of a model ensemble

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Keywords : Nitrous oxide, STICS, DNDC, DSSAT, DAYCENT

Introduction

Crop models simulating the soil–plant system are continuously being improved to better account for the effects of climate, crop management, and soil properties on plant growth and greenhouse gas emissions. However, these models still have some limitations, such as their ability to represent certain management practices and their often oversimplified descriptions of plant physiology and soil microbial processes. Nitrous oxide (N_2O) emissions are one of the main sources of agricultural greenhouse gases and are difficult to simulate accurately because they are influenced by many soil variables, including temperature, water, nitrate, and ammonium contents. This challenge is particularly evident in winter and spring in northern regions, where snow cover and soil freezing modify soil processes (Del Grosso et al., 2022; Wagner et al., 2017). This study draws on a long-term field experiment conducted in Ottawa and evaluates four soil–plant models (DayCent, DNDC, DSSAT, and STICS) under conditions characterized by snow cover and freeze–thaw cycles, providing insights into their ability to simulate N_2O emissions in northern regions.

Material and methods

Two flux towers located at an experimental field site in Ottawa (ON, Canada) were used to measure N_2O fluxes quasi-continuously from two management practices using the flux gradient method (Pattey et al., 2006). These long-term measurements (2002–2023) of N_2O fluxes, along with agronomic data, were used to evaluate the performance of the DayCent, DNDC, DSSAT, and STICS models in simulating crop growth and N_2O emissions at daily, weekly, and annual time steps under conventional management and beneficial management practices (BMPs) (Table 1). The four models were considered collectively as a multi-model ensemble, allowing us to assess both their individual performance and the ensemble response.

Table 1: Crop type, conventional and BMP management at the flux tower site

Year	Crop	Conventional	BMP	Year	Crop	Conventional	BMP
2002	Corn	Urea	Coated urea	2013	Corn	Early planting	Late planting
2003	Wheat	-	-	2014	Wheat	Early planting	Late planting
2004	Canola	100% N fert	60% N fert	2015	Canola	Early planting	Late planting
2005	Wheat	Urea	Ammonium nitrate	2016	Soybean	Early planting	Late planting
2006	Corn	Manure-spring	Digestate-fall	2017	Corn	No inhibitors	Dual inhibitors
2007	Wheat	Manure-spring	Digestate-spring	2018	Corn	No inhibitors	Dual inhibitors
2008	Soybean	-	-	2019	Wheat	No inhibitors	Dual inhibitors
2009	Canola	Spring N fert	Split N fert	2020	Soybean	-	-
2010	Corn	Split N fert	Split-reduce N fert	2021	Corn	No inhibitors	Dual inhibitors
2011	Wheat	100% N fert	40% N fert	2022	Wheat	No inhibitors	Dual inhibitors
2012	Canola	100% N fert	40% N fert	2023	Corn	No inhibitors	Dual inhibitors

Results and discussions

Overall, the model ensemble accurately simulated crop yields, with normalized root mean square errors below 30% (data not shown). The weekly average N_2O emissions simulated by the four models agreed reasonably well with the measurements during the growing season, with model efficiencies (optimal value = 1) of 0.7 under conventional management and 0.75 under BMPs. Regarding the individual performance of each model, the initial simulations showed that STICS and DSSAT struggled to reproduce the spring thaw emission peaks (Figure 2a). The addition of new functions in STICS and DSSAT to better represent this period improved the ability of these models to simulate seasonal emissions (Figure 2b). These empirical functions use soil temperature thresholds or cumulative cold degree-days to define a period during which emissions increase due to freeze–thaw processes (Wagner-Riddle et al., 2007; 2017). Freezing disrupts soil aggregates and releases organic substrates and mineral N into thin films of unfrozen water, where restricted oxygen diffusion promotes denitrification. Because gas diffusivity is very low in frozen or partially frozen soils, N_2O can accumulate over winter and is then released rapidly during spring thaw when microbial activity resumes and soil pores reopen. In the fall, all four models tended to slightly overestimate emissions.

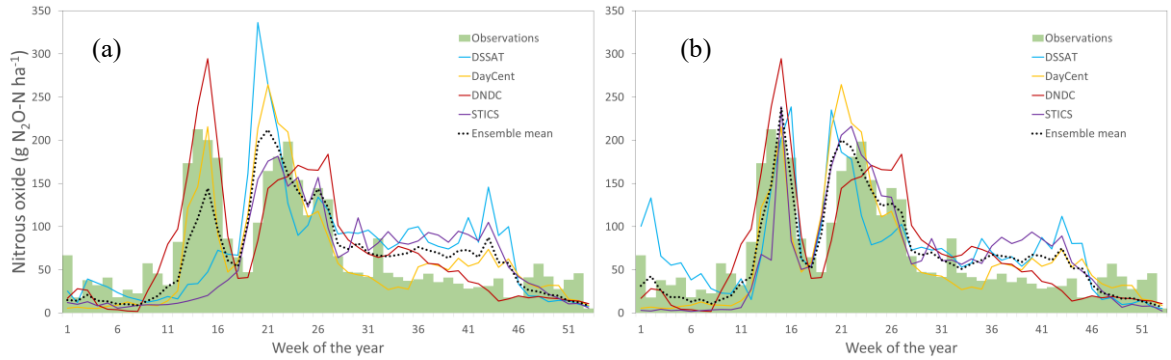


Figure 1: Measured and simulated N_2O emissions from conventional management averaged by week across 22 years with the default (a) and improved STICS and DSSAT models for spring thaw emissions (b).

In this study, as in several previous ones, the model ensemble mean generally showed better performance statistics than the individual models. Comparing the strengths and weaknesses of the models provided valuable insights for possible model improvements.

Conclusion

After the improvement of spring thaw emissions in STICS and DSSAT, the four models were able to reproduce fairly well the annual and seasonal N_2O emissions for both the conventional and BMP treatments. However, at the daily time scale, the specific timing of denitrification events and diffusion of N_2O to the soil surface may not be well simulated due to limitations in the ability of models to simulate accurately diffusion, N_2O consumption and microbial processes. This work paves the way for future studies aiming at understanding the performance of diversified crop rotations and BMPs to develop resilient agricultural production systems achieving low GHG emissions in the face of climate change and stresses the importance of included spring thaw emissions in BMP assessment.

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Model-Based Nitrogen Strategies for Sustainable Potato Production

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Keywords: Strategic N recommendation, soil and climate, Identifying NEMO, STICS, Rainfed Potato

Introduction

Sustainable potato production requires optimized nitrogen (N) management that balances yield and environmental protection. Commonly, recommendations based on economic optimum N approaches focus on profit but neglects environmental costs of reactive N release and the variability of yield responses under changing weather and soil conditions. These challenges are pronounced in Prince Edward Island (PEI), Canada's leading rainfed potato-producing province, where sandy soils and high rainfall increase the risk of N losses to groundwater and estuaries. We applied the Identifying Nitrogen Ecophysiologically Modeled Optimum (Identifying NEMO) framework (*Mesbah et al., 2017*) and the STICS crop model calibrated for potato under Canadian conditions (*Morissette et al., 2016*) to develop soil- and climate-specific N recommendations. Unlike static empirical yield-to-N curves, Identifying NEMO links crop ecophysiology and multi-decadal climate variability to identify optimum N rates that balance yield stability and environmental outcomes.

Materials and methods

STICS v9.2 was calibrated and validated for Russet Burbank using multi-year datasets from Québec and New Brunswick with the crop coefficient method (Morissette et al., 2016). The calibration was refined using the resistance-based evapotranspiration approach. Model accuracy was assessed with RMSE, NRMSE, EF, and R^2. The model was then used to simulate yield responses to incremental N rates (0–350 kg ha^{-1}) over 30 years of climate data for three representative soils across four regions (Summerside, New Glasgow, Charlottetown, and Souris) (Fig. 1). Table 1 summarizes dominant soil and climate characteristics, illustrating PEI's east–west gradients in rainfall and growing degree days (GDD).

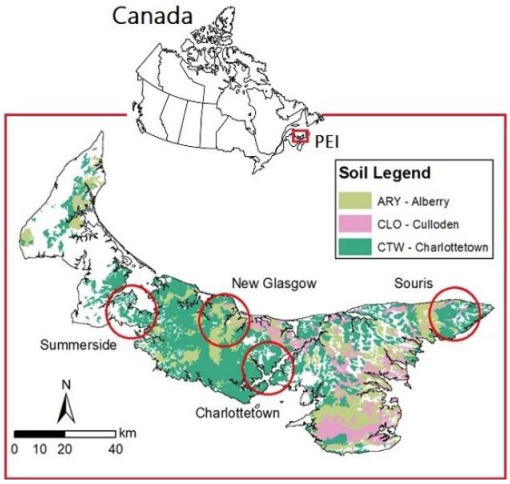


Figure 1: Four study regions and their dominant soils.

Table 1: Dominant soil and May-Oct climate characteristics across four potato-growing regions in PEI.

(a) Soil properties (common across regions)						(b) Median climate (May–October, 1984-2022)			
	Texture	Sand (%)	Clay (%)	Org. C (%)	AWC (% v)	Region	Rain (mm)	GDD (°C, base 5)	Wind ($m\ s^{-1}$)
CLO	Loamy sand	82	4	0.96	6.4	Souris (East)	502	1610	5.4
ARY	Sandy loam	71	6	0.72	8.1	Charlottetown (Central)	515	1650	4.0
CTW	Sandy loam	56	12	1.4	11.8	New Glasgow (North-central)	580	1680	5.5
						Summerside (West)	489	1730	4.8

The Mitscherlich–Baule-Plateau (MB-P) function was fitted annually to derive the yearly optimum N (N_{opt}). The optimum nitrogen-use efficiency (NUE_{opt}) was identified from trade-offs between dry yield loss (< 0.5 t ha^{-1}) and environmental stability (R^2 criterion) following *Mesbah et al. (2017)*.

Results and discussion

STICS reproduced LAI, biomass, and N uptake with good accuracy (NRMSE ≈ 25–30%, EF = 0.83–0.88). The resistance approach reduced bias for LAI and total biomass under rainfed conditions. Our results indicated that recommended N rates varied widely (Table 2). For example, for a target dry yield of 8 t ha^{-1}, soils with higher available water capacity (CTW = 11.8 % v) required 48–82 kg ha^{-1} less N than sandier soils (CLO = 6.4 % v). Across all soils, western PEI (Summerside) required less N (121–175 kg ha^{-1}) than eastern PEI (Souris, 149–231 kg ha^{-1}). $\overline{\Delta Y}$ represents the average yield loss relative to the maximum achievable yield, which ranges from 0.1 to 2 t ha^{-1}. $\overline{\Delta N}$ values indicate whether N is in excess (+) or deficit (–) relative to the target yield and vary by soil and climate. For example, for years when yield is greater than target yield (Y>Yexp), $\overline{\Delta N}$ ranges from -24 kg ha^{-1} (Summerside CTW) to +106 kg ha^{-1} (Souris CLO), while for Y<Yexp $\overline{\Delta N}$ ranges from -14 kg ha^{-1} to +126 kg ha^{-1}. Ideally, a $\overline{\Delta N}$ near zero represents a situation where the recommended N at the start of the season achieves the target yield, regardless of seasonal climate variability. Additional N can be applied during the season, depending on weather, to aim for a higher target yield.

Table 2. Soil- and climate-specific recommended N rates for an 8 t ha^{-1} dry yield target across PEI.

	Summerside			New Glasgow			Charlottetown			Souris		
Soil	CLO	ARY	CTW	CLO	ARY	CTW	CLO	ARY	CTW	CLO	ARY	CTW
$P_{(Y>Y_{exp})}$ (%)	19	56	78	29	61	91	42	72	85	20	31	27
N_{rec} (kg ha^{-1})	175	152	121	177	137	116	166	138	118	231	150	149
$\overline{\Delta Y}$ (t ha^{-1})	0.4	0.9	1.2	0.4	1	1.7	0.1	0.5	1	1.6	1.6	2
$\overline{\Delta N}$ (kg ha^{-1}) Y<Yexp	61	9	-6	66	12	-14	40	8	-14	126	40	33
$\overline{\Delta N}$ (kg ha^{-1}) Y>Yexp	40	-18	-24	24	-12	-23	13	-22	-33	106	-2	17

Relative to the provincial guideline (208 kg ha^{-1}), Identifying NEMO recommended an average reduction of 35 kg ha^{-1} to achieve a relatively high yield of 9 t ha^{-1}, with only 0.5 t ha^{-1} yield loss. This reduction corresponds to modest private costs (CAD $490 ha^{-1}) but substantial environmental benefits (CAD $385–2 870 ha^{-1} yr^{-1}) due to lower reactive N release based on related cost benefit study (*Van Grinsven et al., 2013*).

Conclusion

Integrating Identifying NEMO with STICS, particularly with the resistance evapotranspiration approach, demonstrates the value of process-based modeling for adaptive N management in rainfed potato systems. The findings suggest that moderate yield targets can lower N inputs with minimal yield penalties, especially in regions with higher soil water-holding capacity. This shift from static to risk-aware recommendations supports more efficient and environmentally responsible fertilizer use. The approach also enables a two-stage strategy—applying conservative base rates early and adjusting in-season based on weather or soil data. Future research should validate these model-derived insights under field conditions and explore integration with decision-support tools, offering a pathway toward sustainable and climate-resilient potato production systems.

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Session V

Climate change: Using the model as a tool to explore adaptation and/or mitigation strategies

Assessing crop model adequacy for future climates

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Keywords: crop models, climate change, wheat yield, free-air CO2 enrichment, drought and heat stress

Introduction

Climate change poses significant challenges to agricultural systems by progressively altering atmospheric CO_2 concentrations, air temperatures, precipitation patterns, solar radiation levels, and the frequency and intensity of extreme weather events. These evolving conditions require to continuously adapt agricultural management practices and breed for crop varieties that can maintain productivity under increasing environmental constraints. Meanwhile, breeding programs aim to develop cultivars that are more resilient and efficient in their use of resources. Process-based crop models are essential tools for understanding and predicting the impact of climate change on agricultural production and for designing and assessing adaptation strategies, such as varietal selection, adjusting sowing dates and optimizing management practices. However, these models' robustness and predictive capacity critically depend on their ability to accurately represent the complex interactions between plants and their environment across diverse pedo-climatic conditions, including those beyond the current range of observed environments (Gawinowski et al., 2025).

Material and methods

This study evaluates the capacity of two widely used process-based crop models, APSIM and STICS, to simulate wheat crop responses under projected future climatic conditions. Specifically, we assessed their ability to reproduce the combined effects of elevated atmospheric CO_2 concentrations, prolonged water stress and high-temperature episodes using wheat experimental data from Free-Air CO_2 Enrichment (FACE) trials conducted in Australia (Asseng et al., 2019; Fitzgerald et al., 2016), Germany (Manderscheid et al., 2020) and the United States (Kimball et al., 1995). The experimental design included combinations of CO_2 concentrations ranging from 370 to 600 ppm, as well as rainfed and irrigated regimes and temperature increases of between 0 and 3 °C during the grain-filling period.

Results and discussions

While both models accurately reproduced the effects of elevated CO_2 under either drought or high-temperature stress when considered separately, their predictive accuracy declined when these stressors occurred simultaneously, revealing limitations in their representation of the interactive effects of climate on crop performance. The results obtained from this model evaluation, which was conducted under field-realistic, future-like conditions, confirm the ability of APSIM and STICS to evaluate the impact of future climate scenarios (Figure 1). Ongoing work focuses on testing and refining these models further to improve their ability to accurately capture the complex responses of plants to multiple interacting climatic stresses. In some situations, STICS notably underestimate the effects of water stress on biomass production, but this finding is generalized among crop models (Noia Junior et al., 2025; Webber et al., 2025). These improvements are expected to make the models more robust and reliable for projecting the impacts of climate change on crop performance

and provide valuable guidance for developing adaptation strategies and supporting crop breeding programs.

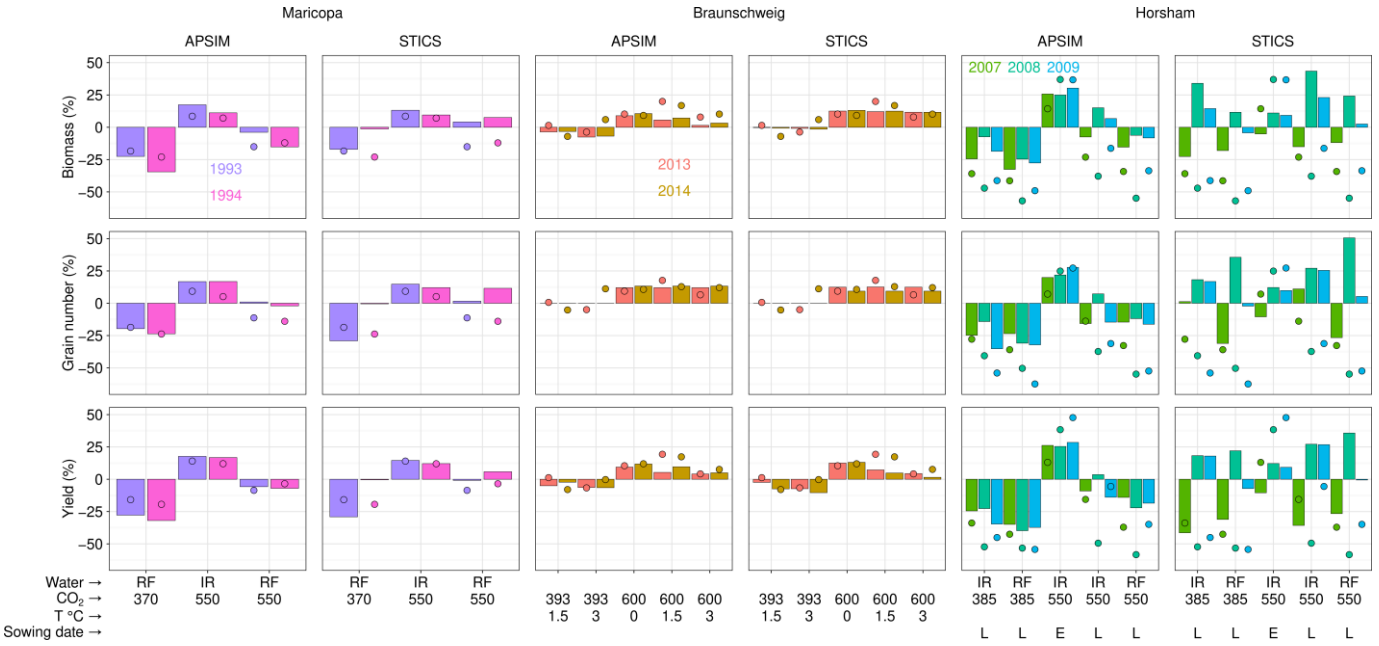


Figure 1: Observed and simulated relative variations (%) between control conditions (ambient CO, and temperature, irrigated) and fluctuating conditions (elevated CO_2, high temperatures and water stress) for plant biomass, grain number and grain yield at harvest for three sites (Maricopa, Braunschweig, Horsham) and two models (APSIM, STICS). Points represent experimental variations and barplots represent simulated variations. Different colors indicate the different years of each experiment. Maricopa combines CO_2 370 vs 550 ppm and water deficit irrigated (IR) vs rainfed (RF), Braunschweig combines CO_2 393 vs 600 ppm and temperatures of +0, +1.5 and +3°C, and Horsham combines CO2 385 vs 550 ppm with water deficit irrigated (IR) vs rainfed (RF) and temperatures through early (E) and late (L) sowing dates.

Conclusion

Overall, this study highlights the strengths and limitations of APSIM and STICS in modelling crop responses to future climatic conditions involving multiple interacting stressors. Enhancing the models' ability to simulate these combined effects is crucial to improving the robustness of climate impact assessments. Continued development and evaluation of the models under diverse experimental conditions will ultimately strengthen their relevance in supporting agricultural adaptation strategies and guiding crop breeding efforts in the context of climate change.

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CLIMODIF: Simulating Crop Rotations with STICS under Climate Change in the Barrois area in France

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Keywords: methodology, modeling, cropping system, multicriteria analysis

Introduction

Rising temperatures and altered rainfall patterns driven by climate change are undermining crop yields worldwide. Preliminary work (Gigot et al., 2021; Deytieux et al., 2023) conducted by ARVALIS and INRAE highlighted the importance of adopting a multi-criteria approach to better support farmers in adapting their practices to expected future climatic conditions. The aim of the CLIMODIF project is to develop a robust and generic methodology, based on interactions with farmers, designed to bridge field-level information with crop, disease, economic and multicriteria-analysis models. Crop modelling is a key element of the process, because it integrates knowledge and data provided upstream, and its outputs condition downstream models that depend on it. The STICS crop model (Beaudoin et al., 2023; Brisson et al., 1998, 2002) was chosen because it met all our needs: (1) it was already demonstrated as robust in the French context, (2) it enables the simulation of crop rotations, (3) it implements all the species of the CLIMODIF project, and (4) it required a shorter appropriation time due to internal expertise. The objectives regarding STICS were therefore to configure it, integrate it in the workflow, and analyze its outputs under the field context of the project.

Material and methods

The study focuses on the “Grand Est” region in France, and more specifically the “Barrois” area (around 8000 km²). This pilot area was selected due to its challenging conditions faced by farmers, including shallow soils, irregular rainfall, limited crop diversity and high weed pressure.

The first step was to characterize standard practices in this area. To capture a wide range of possible situations, variants of the reference rotation (rapeseed - wheat - winter barley) were created to increase crop diversity and extend the rotation to a maximum of five years. Reference management practices (sowing dates, soil tillage, variety, fertilization practices) were defined by consulting local studies and farmers before being integrated into STICS .tec files. Information about soils came from ARVALIS soil database and expertise (Table 1). Water balance was initialized on Julian day 222 for all crops, considering that initial water content is 50% of the maximum possible for the first 50cm, and 80% for lower soil layers. Initial soil nitrogen content was empirically parameterized based on the fate of residues from the preceding crop. The STICS 10.3.0, JavaSTICS 1.5.3 and R package SticsOnR 1.3.0 were used.

For the simulations, DRIAS climatic data provided by the Drias plateform (Météo-France data, CERFACS, IPSL) were downloaded via the SICLIMA platform developed by AgroClim-INRAE. Three periods were considered: 1991-2020 (Reference Past), 2031-2070 (Near Future) and 2071-2100 (Far Future). To reduce computation time, simulations started every 10 years from 1990 up to 2080, only in the selected three time periods. Twenty-five grid cells covering the entire area of interest and three climate models (CNRM-CM5 / ALADIN63, CNRM-CM5 / RACMO22E and EC-EARTH / RACMO22E)

under RCP 8.5 were used.

Table 1: Soils in the "Barrois" area in the "Grand Est" region (France).

Soil parameters (STICS terminology)	"G2": shallow clay-limestone on hard, cracked limestone (Haute-Marne and Aube)	"G2.5": medium clay-limestone on hard limestone (Meuse)	"G3": Medium clay limestone on hard limestone (Haute-Marne)
Argi (%)	35.1	43.9	35.4
Norg (%)	0.30	0.30	0.30
Calc (%)	6	5	10
Obstarac (cm)	60	90	85
CsurNsol (%)	10	4.8	8.7
Soil water capacity (mm)	81	95	109

Results

As an example of output focusing on growth stages, Figure 1 shows violin plots of the stage AMF ("maximum acceleration of leaf growth, end of juvenile phase") for the three periods and the "G2" soil type. There is a clear tendency in the future for earlier AMF stages for wheat, barley and rapeseed in comparison with reference past. For this criterion, there seems to be little impact of soil type (data not shown).

Differences in days between median values of AMF stage and crop cycle duration were computed for each period and each species (Table 2). It turns out that, compared with Reference Past, sowing-AMF and crop cycle durations tend to be reduced by 10 days in Near Future and up to 20 to 25 days in Far Future. Those tendencies were observed for all species except for rapeseed AMF stage.

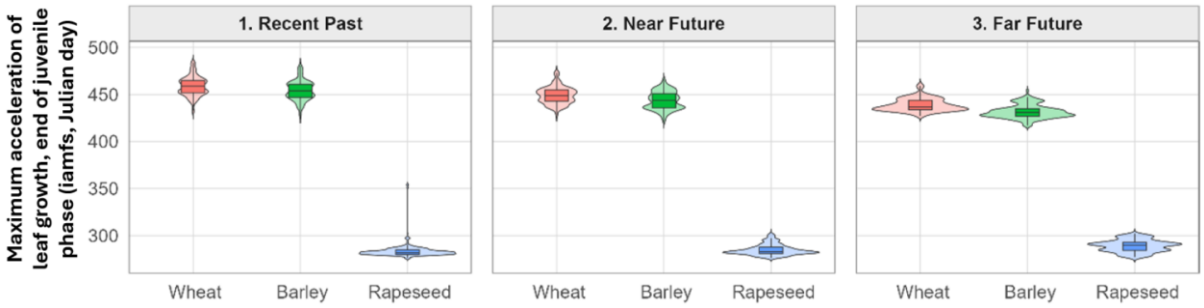


Figure 1: Date of reaching the stage "maximum acceleration of leaf growth, end of juvenile phase" (AMF in STICS terminology) as simulated by STICS crop model for 3 climatic periods (Reference Past: 1991-2020, Near Future: 2031-2070 and Far Future: 2071-2100). Only results for the "G2" soil type are presented. Species are represented by red, green, and blue violin plots for wheat, barley and rapeseed, respectively.

Table 2: Differences in days between median values of the "maximum acceleration of leaf growth, end of juvenile phase" stage (AMF in STICS terminology) and crop cycle duration, for Near Future – Reference Past (NF – RP), and Far Future – Reference Past (FF – RP) periods.

Crop	AMF stage		Crop cycle duration	
	NF – RP (days)	FF – RP (days)	NF – RP (days)	FF – RP (days)
Wheat	-10	-22	-8	-15
Barley	-11	-24	-8	-17
Rapeseed	+1	+5	-11	-20

Conclusions and perspectives

Preliminary results for the reference rotation (rapeseed - wheat - winter barley) in the future under RCP 8.5 suggest earlier AMF stages for cereals (−10 to −24 days), slightly later AMF stages for rapeseed (+1 to +5 days) and shorter crop cycles, with an average reduction of 10 to 20 days compared with the recent past, for the near and distant future, respectively. Mean yields are projected to rise (+22% on average, data not shown) probably due to the offsetting of CO2 fertilization on abiotic stresses as modelled by STICS. These changes are associated with reduced evapotranspiration (−8 to −18%), and fewer frost days (−10 to −16 days) (data not shown).

Other steps in the CLIMODIF project include co-designing adaptation levers with farmers, defining expected multi-performance profiles, simulating performances of combinations of levers, and selecting promising (or problematic) strategies via multi-criteria analysis. Note that other crops, other RCP scenarios and different price patterns are considered in this project.

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Global Sensitivity Analysis of STICS Soil Input on CO_2 Net Ecosystem Exchange in Burgundy Vineyards

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Keywords: Elementary Effects, Sensitivity Analysis, Soil, Climate, NEE, Vineyard

Introduction

Agricultural systems are recognized as potential lever for mitigating climate change through photosynthetic carbon uptake (IPCC, 2023), particularly perennial crops that can sustainably store carbon in woody biomass (Scandellari et al., 2016). Among these systems, vineyard ecosystems remain poorly characterized regarding their capacity for carbon sequestration and the effects of both management practices and climate, especially in mid-latitude regions. The recent installation of a CO_2 flux tower in a Burgundy vineyard (Rully, Saône-et-Loire, France) provides a valuable dataset and a basis for model calibration and validation. However, this experimental setup remains spatially limited and cannot fully capture the strong heterogeneity in soils and management practices across the vineyards of Burgundy. This study aims to identify and rank the soil parameters that exert the strongest control on the annual budget and interannual variability of Net Ecosystem Exchange (NEE; the carbon balance at the ecosystem scale) in a temperate vineyard (Rully), based on sensitivity experiments performed with the STICS model (Beaudoin et al., 2023). This is a necessary step toward selecting the key soil variables to measure in vineyards prior to running the STICS model on different “terroirs”.

Material and methods

The STICS model (version 10.2.0) was used to assess the impact of 23 soil parameters on the annual Net Ecosystem Exchange (NEE) for three contrasted climate conditions in Rully: a near-climatological year (2014), a dry and hot year (2003), and a wet and cool year (2013). According to Delandmeter *et al.* (2023), NEE is calculated as the difference between heterotrophic respiration (HR) and Net Primary Production (NPP). HR is directly estimated by the model and NPP is computed as the daily derivative of Total Carbon Content (TCC). TCC is computed as follows:

$$TCC = masecvg * 0{,}42 + mafruit * 0.44 + msrac * 0.38 + mafeuiltombe * 0.42$$

with masecvg, mafruit, msrac and mafeuiltombe referring to biomass of vegetative organs, harvested organs, roots and fallen leaves, respectively. Each output is converted in organic carbon using the coefficients given in the equation. Delandmeter et al. (2023) pointed out the biased simulation of roots and used shoot:root ratios from literature instead. However, no clear value could be found for grapevines, with root:trunk ratios ranging from 0.38 to 2.42 (Bilandžija et al., 2025; Callesen et al., 2023; Miranda et al., 2017). Allometric measurements are currently conducted in the Rully vineyard to determine reference values. For this study, the default msrac output was used for TCC computation.

All simulations are forced with SAFRAN–SIM2 daily climate data (Soubeyroux et al., 2008) retrieved for the location of the Rully nearest grid point (8 x 8 km). They cover a six-year period, including five spin-up years and one analysis year. The cultivar (*Vitis vinifera L. cv*. Pinot Noir) and management practices were configured to replicate those of the Rully vineyard: a vertical shoot positioning system with a planting density of 9,090 plants.ha^{-1}, three annual soil ploughings (DOY = 75, 136 and 197) to a

depth of 10 cm, harvesting based on grape water content, topping when the canopy height exceeds 1.3 m, and winter pruning at DOY = 345.

The Elementary Effects method (Morris, 1991) is used to assess the influence of soil parameters on NEE. This global sensitivity analysis approach is particularly well-suited to exploring the impact of many parameters. First, a random sampling matrix with n columns and i = n+1 rows is generated, where n = 23 corresponds to the number of soil parameters tested. The first row consists of a set of input values generated through complete random sampling, while each subsequent row replicates the previous one with a single input parameter incremented or decremented by Δ = 0.05. Bounds for the soil parameters were set using a database of physicochemical values from 55 Burgundy vineyards (0–30 cm, and 30–50 cm when available). Model simulations are then run with each row as a set of input, giving n+1 NEE output values. The elementary effect of each input (EE), i.e. its degree of sensitivity, is computed following $EE_i = abs((NEE_{i-1} - NEE_i)/\Delta)$. To ensure robustness, the entire procedure is repeated using r = 70 sampling matrices resulting in a total of 4,830 simulations (23 combinations of soil parameters × 70 replicates × 3 six-year periods).

Results and discussions

Among the 23 inputs, seven showed distinctly high EE values: clay content after decarbonation (argi), fraction of soil inert organic carbon (finert), volumetric content of pebbles for the first soil layer (cailloux_1), field capacity (HCCF) and wilting point (HMINF) for both the first and second soil layers. For conciseness, Figure 1 shows the average EE and associated annual NEE budget for each year, each output and the seven parameters.

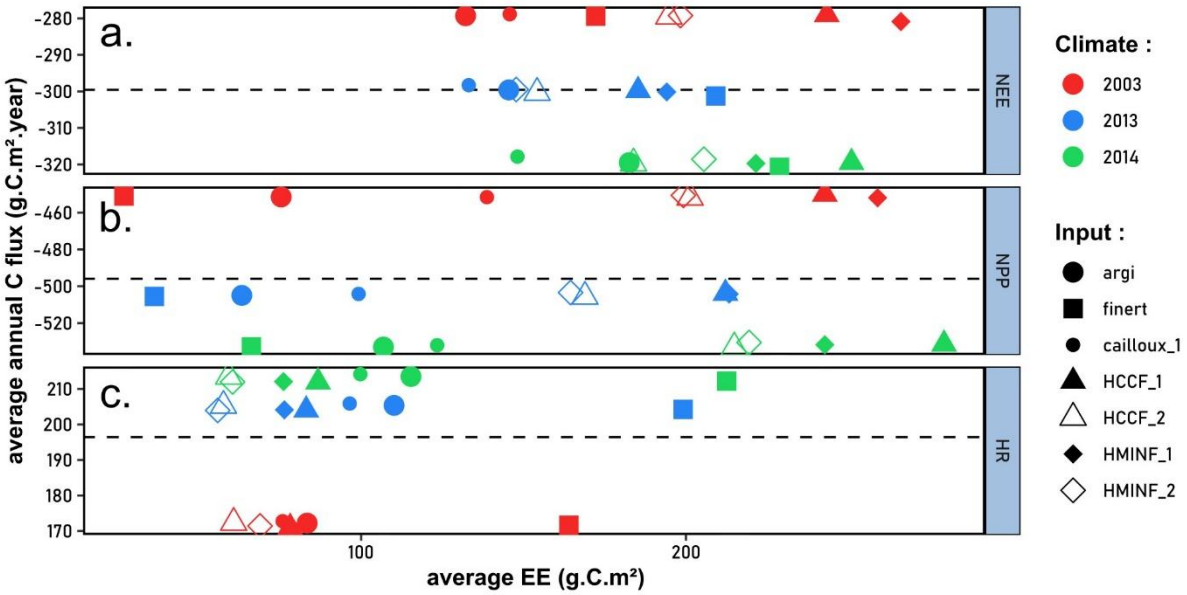


Figure 1: Average EE for the 7 selected inputs and 3 climatic years for NEE (a.), NPP (b.) and HR (c.). Dashed lines display the average value for each output. See text for more details.

The simulations yield a negative average NEE (-295.8 g.C.m^{-2} ; Figure 1a), indicating that the modelled vineyard acted as a carbon sink, consistent with *in-situ* studies (e.g., Marras *et al.,* 2015). The range induced by contrasted climatic context (-243.2 to -330.8 g.C.m^{-2}) accurately reproduces the well-known effect of climate on interannual NEE variability observed in different ecosystems, with stronger sequestration in cold/wet summers than in hot/dry ones. Water-related top-soil inputs, especially HCCF_1, exert a strong impact on NEE for the three years, whereas finert has a more pronounced effect only in 2013 and 2014.

The same analysis is applied to NPP and HR to provide a more comprehensive understanding of the

results. As shown by previous STICS sensitivity analysis (Heuer & Casper, 2011; Ruget et al., 2002), water-related inputs have more control over plant biomass production and thus NPP (Figure 1b). HR is more sensitive to cailloux_1, argi, and even more strongly to finert (Figure 1c). These parameters are known to control the soil organic carbon stock and therefore the microbial activity (Calvet et al., 2021).

Conclusion

The results show that water-related variables (field capacity, wilting point) and parameters related to soil carbon storage (clay content after decarbonation, fraction of inert organic carbon) strongly influence NEE annual budgets. These parameters should be preferentially measured *in-situ* to accurately model the annual budget and interannual variability of carbon fluxes in vineyard ecosystems.

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Impact of climate change on the main cash crop in Belgium

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Keywords: Spatial simulation, yield, stics, crop modelling

Introduction

Cropping systems lie at the interface between soil and climate, and their growth and production levels are directly influenced by both. Climate change has already affected agricultural production for several decades, and the impact of increasingly frequent and intense climatic hazards is expected to strengthen in the coming decades.Crop responses to climate change result from complex interactions between temperature, precipitation, atmospheric CO_2 concentrations, soil properties, and crop species. Given the difficulty of reproducing such future conditions experimentally, It is therefore essential to spatially predict how the production levels of major cash crops may evolve under climate change using modelling tools such as STICS.

Material and methods

The impact of climate change was assessed in Wallonia (southern Belgium), a region that, despite its limited area, exhibits highly heterogeneous pedoclimatic conditions. This diversity makes it well suited for analysing crop-specific pedoclimatic responses and and for generating transferable knowledge to other regions with similar pedoclimatic conditions.

The main cash crops cultivated in the area (winter wheat, rapeseed, maize, potato, and sugar beet) were simulated using the STICS model (Brisson et al., 1998; Beaudoin et al., 2023) combined with soil databases (ISRIC, ESDAC, Géoportail SPW) and climate time series from historical and future warming scenarios (+2 °C, +3 °C, +4 °C), which also account for associated modifications in precipitation. Climate data at a 5 × 5 km resolution were derived from three GCMs (CMCC-CM2-SR5, MIROC6, MPI-ESM1-2-HR) for both the historical period (1980–2010) and the corresponding warming levels (Grailet et al.,2025). Soil data at a 250 × 250 m resolution were restricted to arable land. Similar soils were aggregated within climatic tiles using unsupervised X-means clustering (Pelleg & Moore, 2002), and STICS was run on each clustered soil unit.

Crop parameter files were taken from calibrations developed for Belgium by Delandmeter et al. (2023, 2024) and Lenoir (2024). All data processing, integration, and statistical analysis were conducted in RStudio

Results and discussions

The impact of climate change on major arable crops shows strong variability depending on the crop species, the level of global warming, and the climate model considered (Table 1). Median yields of potato, winter wheat, and maize generally decline across Wallonia under the +2 °C scenario, whereas sugar beet is the only crop showing consistent yield gains at +2 °C.

For several crops, model projections under GCM disagree, contributing to substantial uncertainty. Differences between GCMs and warming levels (+2, +3, +4 °C) are partly driven by atmospheric CO_2 concentrations, which strongly influence plant growth. This helps explain why yield

increases are more frequently observed under +3 °C and +4 °C scenarios than at +2 °C (Table 1, Figure 1). Importantly, higher median yields do not imply greater stability. Yield stability (expressed as the mean divided by the standard deviation) is projected to decrease for nearly all crops (especially rapeseed and sugar beet) with reductions ranging from roughly −5% to −60% under the +3 °C scenario in the CMCC model.

Table 1: Summary of median yield changes relative to the historical period for each crop, across global warming levels and GCMs (CMCC, MIROC, MPI).

	+2°C			+3°C			+4°C		
	CMCC	MIROC	MPI	CMCC	MIROC	MPI	CMCC	MIROC	MPI
Winter wheat	↘	↘	↘	≃	↗	↘	≃	↗	≃
Rapeseed	≃	↗	↘	↘	↗	≃	↘	↗	≃
Sugar beet	↗	↗	↗	↗	↗	↗	↗	↗	↗
Potato	↘	↘	↘	↘	↗	↗	↘	↗	↗
Maize	↘	↘	↗	↘	↘	↗	↘	↘	≃

Furthermore, as shown for winter wheat (Figure 1), regional responses differ significantly. The southernmost part (Jurassian region) and the central part (Condroz–Famenne) of Wallonia are the most vulnerable to climate change, with yield losses reaching up to 60% in some locations under the +2 °C MPI scenario.This vulnerability is largely due to their soil properties, which are characterized by shallower profiles and a higher pebble content."

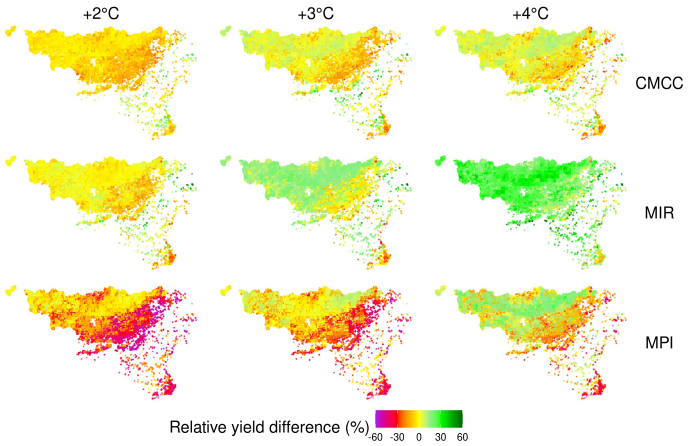


Figure 1: Maps showing relative winter wheat yield changes (in %) under different global warming scenarios and climate models, expressed relative to the historical period.

Conclusion

In conclusion, climate change will affect crops differently, with spatially and temporally variable responses, highlighting the importance of spatial explicit studies to predict local changes and, subsequently, implement adaptation and mitigation strategies tailored to the studied regions. This study also emphasizes the need to consider not only yield trends but also yield stability, which is projected to decline for most crops under global warming due to extreme climate events in certain years.

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Modeling the potential of legume crops to meet protein demand under climate change in Southern Belgium (Wallonia)

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Keywords: digital twin, STICS, faba bean, pea, yield, agricultural regions

Introduction

In a context of transitioning food system through more reliance on food security, reduction of protein meat consumption and increase in protein plant-based diet appear as a promising solution. Legume crop have furthermore the ability to fix atmospheric nitrogen, thus reducing reliance on fossil-based fertilizers, promoting soil health and fertility, mitigating risks associated with intensive monocultures, and preserving biodiversity. Faba beans and peas are the two most cultivated legumes in Europe (Falconnier et al., 2020), and in Belgium. However, these crops are strongly impacted by climatic hazards, highlighting the need to explore their yield potential under the effects of global warming.

Material and methods

A digital twin algorithm was developed to analyze the spatio-temporal variability of protein sourcing in Wallonia, based on the coupling of the STICS model (INRAE) with soil databases (ISRIC, ESDAC, Géoportail SPW) and climatic timeseries for future scenarios, provided by the Climatology Laboratory of the University of Liège (Table 1). The STICS model, well known for its robustness and its ability to simulate a wide range of crops under diverse pedoclimatic conditions (Brisson et al., 2002), explicitly accounts for the CO_2 fertilization effect, stomatal conductance, and several abiotic stresses, including waterlogging. Model outputs (biomass, yield, etc.) were used to validate the calibration against a historical database (2003–2025) for faba bean and pea, in both winter and spring sowing. Additional dynamic measurements from the WAL'PROT FEDER project (ISS PROTEWIN) (since 2023) were also used to support this validation. To validate this calibration, a multi-criteria approach is used, employing several evaluation metrics (RMSE, MAE, R^2) to assess the model's performance. All data processing, integration, and statistical analyses were carried out using RStudio.

Table 1: Level of atmospheric CO_2 concentration (in ppm) for the different global warming scenarios and models at their respective time periods.

Models		*+2°C*	*+3°C*	*+4°C*
CMCC-CM2_SR5	**Years**	2024-2053	2048-2077	2060-2079
	[CO_2]	429	605	741
MIROC6	**Years**	2030-2065	2066-2095	2081-2100
	[CO_2]	545	722	1005
MPI-ESM1-2-HR	**Years**	2045-2074	2071-2100	2081-2100
	[CO_2]	592	757	1005

Results and discussions

Results for winter faba bean indicate a general increase in yield with climate warming compared to the historical scenario (average: 2.8 t DM/ha) (Figure 1). Significant differences appear between models: MIROC shows the highest yields (+25% at +3°C and +103% at +4°C), while CMCC records the lowest (-2.7% at +2°C, +9.5% at +3°C). This increase results from enhanced growth due to more efficient photosynthesis, stimulated by the CO_2 fertilization effect (Vanuytrecht et al., 2012).

Regional effects are marked, reflecting both climatic and pedological differences across Wallonia. The MPI model favors loamy and sandy-loam regions, reaching 4.9 and 4.7 t DM/ha respectively at +4°C, in contrast to the Jurassic region, where yields remain lower (≈ 3 t DM/ha). The CMCC and MIROC models show maximum yields respectively in grassland regions (3.3 t DM/ha) and in the High Ardenne (4.1 t DM/ha) at +3°C. Regarding yield stability, a slight decrease is observed at +2°C, followed by a clear improvement at +3°C and +4°C, reaching up to 79% for MPI compared with 67% under historical conditions. The loamy, sandy-loam, and Campine-Hennuyère regions display higher stability (>75%), whereas the High Ardenne and Jurassic regions show lower stability (<50%).

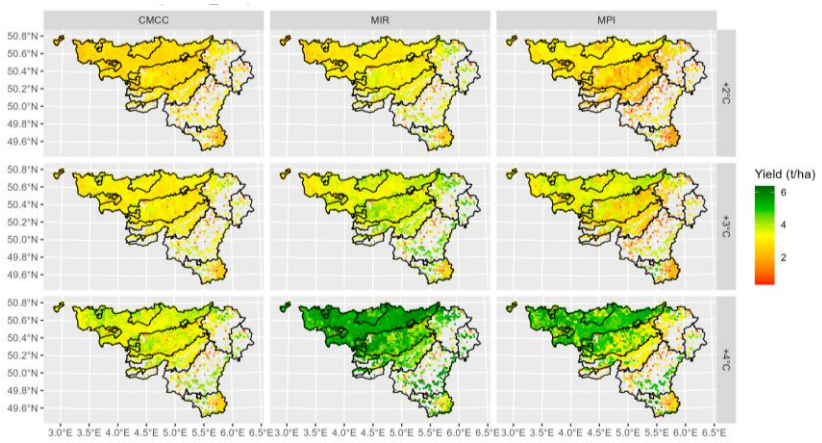


Figure 1: Winter faba bean yields under different climate scenarios across Wallonia.

Increases in waterlogging and thermal stress during vegetative and reproductive stages were reported, while water deficit stress decreases. This trend is attributed to the rising frequency of wet springs and rising atmospheric CO_2, which stimulate growth and improve water use efficiency, further reducing water stress (Ainsworth & Rogers, 2007; Hatfield & Prueger, 2011) and generally leading to greater #grains/m². However, the increased occurrence of wet springs could promote the emergence of diseases, which is not accounted for in the model. In fact, biotic stresses are among the main limitations of the model, although they are also likely to be strongly influenced by climate change. To improve predictive capacity, developing a complementary model to estimate biotic pressure and integrating it with the current simulations would be valuable.

In addition, the robustness of the model depends on the quality and representativeness of field data. Additional sampling across diverse agricultural regions with contrasting soil characteristics is needed to refine calibration validation and ensure more reliable projections at the Wallonia regional scale. Finally, certain STICS parameters require improvement in their calibration quality indicators to enhance overall model performance. Addressing these limitations would strengthen the model's utility for assessing legume performance under future climate scenarios.

Conclusion

This study highlights the potential of digital twin modeling to assess the spatio-temporal variability of legume performance under future climate conditions. For winter faba bean, yield projections suggest an overall positive response to warming, particularly under the MIROC and MPI models, driven by CO_2 fertilization and improved water use efficiency. However, regional contrasts remain strong, with loamy regions showing the highest productivity and stability, while Jurassic and High Ardenne areas appear more vulnerable. The analysis also reveals that climate warming will reshape stress dynamics, with reduced water deficits but increased thermal and waterlogging constraints.

These findings highlight the importance of integrating regional soil-climate interactions into crop adaptation strategies. Agronomic measures, such as species mixtures, could help maintain yield stability and support resilient protein production systems in the face of increasing climate variability.

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