

Highlights

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- First highlight

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Roxane Bruhwyler^a, Mathieu Delandmeter^a, Xavier Fettweis^a, Benjamin Dumont^a, Frédéric Lebeau^b

^a*Transdisciplinary Agroecosystem Platform for Integrated Research (TAPIR), TERRA, GxABT, ULiège, Gembloux, 5030, Belgium*

^b*DEAL, BioDynE, GxABT, ULiège, Gembloux, 5030, Belgium*

Abstract

Write the abstract here.

Keywords: agrivoltaics, modelling, climate change, stics, rotation, crop model

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

To be completed with TAPIR funding and ask to other authors.

Acronyms

AV Agrivoltaics.

BAU "business-as-usual".

Email address: roxane.bruhwyler@uliege.be or roxane.bruhwyler@hotmail.com (Roxane Bruhwyler)

CAPEX Capital Expenditure.

ESM Earth System Model.

GCR Ground Coverage Ratio.

GHI Global Horizontal Irradiance.

NECP National Energy and Climate Plan.

OPEX Operational Expenditure.

PASE Python Agrivoltaic Simulation Environment.

PBM Process-Based Crop Models.

PV Photovoltaic.

SSP Shared Socioeconomic Pathways.

1. Introduction

Agrivoltaics (AV), the co-location of Photovoltaic (PV) electricity generation and agricultural crop production, has emerged as a promising strategy to simultaneously address land use pressure, development goals for renewable energy production, and the need for climate adaptation in farming systems. Literature demonstrates that partial shading from PV panels can buffer crops against heat and drought stress, potentially maintaining or even improving yields during extreme events or in arid climate, while generating PV electricity (Tan et al., 2025). However, the magnitude and direction of AV effects on crop development are highly crop-specific and local context and system-dependent.

Belgium’s temperate oceanic climate, characterized by limited sunshine duration, rainy and mild winters and moderate summer temperatures, at the moment, offers little scope for AV yield benefits (Reher et al., 2024). However, projected increases in heat wave frequency and summer drought may progressively shift this balance and make AV more attractive by allaying concerns about agricultural land losing its primary purpose. Indeed, AV is

currently facing strong opposition in Belgium despite its ambitious target of increasing installed PV capacity by 30% by 2030, compared with 2025 levels. 

The Final Updated Belgian National Energy and Climate Plan (NECP) present the final updated targets of each region of the country for PV production by 2030. Flanders has set itself a target of 10 GWp of installed capacity, whereas Wallonia and the Brussels-Capital Region have set annual production targets of 5100 GWh and 1250 GWh respectively (European Commission, 2025). Taken together, these regional targets imply an installed capacity of around 17 GWp by 2030 for Belgium, compared with 13 GWp in 2025 (IEA PVPS, 2025). Belgium must therefore maintain its current rate of installing new PV capacity and install 1 GWp per year in order to meet the target set for the early 2030s. Nevertheless, deploying large-scale PV installation in one of Europe’s most densely populated and agriculturally intensive countries is creating tensions regarding land use management. AV has been identified and recognized by the European Commission as one potential pathway to reconcile these competing demands (European Commission, 2022).

 To date, however, the actual deployment of AV in Belgium remains minimal: the only large installation is the 10 MWp system commissioned in 2023 and developed by etherra and located in Wierde (Namur, Wallonia), which combines sheep grazing and beekeeping across 13 hectares. Small greenhouse projects incorporating solar panels have also been launched in Wallonia (Livre Blanc, 2024). Meanwhile, in Flanders, small-scale pilot projects above orchards have been launched by KU Leuven (Reher et al., 2025, 2024). In Wallonia, no legal framework for AV currently exists. The latest legal directive regarding the installation of PV panels on agricultural land, dated March 2024, completely prohibits it unless the project is a pilot initiative that does not compromise the land’s primary agricultural function and is designed to demonstrate compatibility with it (Borsus, 2024). Flemish legislation is also quite strict, prohibiting by default the development of PV projects on agricultural land and recognizing as AV—and accepting—only projects on perennial crops (tree and small fruits), representing 3.3% of the Flemish agricultural land use and 1.7% of Belgian agricultural land use (Statbel, 2025). In such cases, the installation must be set up by the farmer on a plot adjacent to the existing farm site, use semi-transparent PV technology, and supply 50% of the farm’s electricity consumption (Agentschap Landbouw en Zeevisserij and Departement Omgeving, 2025). This regulation is quite restrictive, as  the costs associated with elevated structures suitable for orchards and the semi-transparent technology significantly increase the AV installation’s Cap-

ital Expenditure (CAPEX) (Trommsdorff et al., 2024). These laws reflect the general agricultural sector’s opposition, driven by fears that a new industry will increase pressure on agricultural land and make access to it even more difficult (RTBF, 2024). To address these concerns while enabling the country to meet its goals for increasing installed PV capacity, less restrictive legislative frameworks should be established in both regions to authorize agri-voltaic projects on a broader scale, provided they meet certain strict criteria designed to protect agricultural land. While a maximum Ground Coverage Ratio (GCR) may be imposed to prevent abuse, it is appropriate to evaluate projects on a case-by-case basis based on their ability to maintain a certain level of average agricultural yield over several years, as France does under its highly specific legislative framework for AV on field crops.

The aim of this study is therefore to guide the development of AV in Belgium by identifying the potential impact of two types of low-CAPEX AV systems on the major field crops of the country. To ensure maximum relevance and realism, this in silico analysis examines this impact, based on a plausible long-term rotation, through multi-year simulations and under future climate conditions. These findings are intended to inform both regional governments—so they can make future decisions that adapt legal frameworks in a way that does not hinder solar developers while still protecting the primary function of agricultural land and also inform project developers, so they can comply with future regulations.

2. Material and methods

Simulations were performed from year 2013 to year 2100 in Gembloux (Belgian Hesbaye region) using the Python Agrivoltaic Simulation Environment (PASE) (Bruhwyler et al., 2024; Bruhwyler, 2025), an open-source tool for AV modelling, co-simulating with the Process-Based Crop Models (PBM) STICS (Beaudoin et al., 2022). Two future climate scenarios and two AV system configurations were studied. The simulated rotation is an 8-year rotation including principal field crops grown in Belgium. The following subsections provide details on all the elements introduced here. Two conditions are compared along this work: full-sun reference (REF) and AV conditions, allowing to compute the relative results defined as AV/REF.

2.1. The Python Simulation Environment

The version 1.0 of PASE was used in this work and has previously been presented in details in (Bruhwylers, 2025). This open-source tool available on [gitlab](#) (DEAL, Université de Liège, 2024) allows to evaluate the PV energy production and the crop growth of a diversity of AV system. It enables through a ray-casting algorithm the calculation of the light microclimate received by crops under the 3D AV configuration at high spatial and temporal resolutions. The spatially resolved irradiance at sub-daily resolution is then aggregated into daily irradiation to serve as input for the PBM that spatially assess the crop development.

2.2. Weather and future climate scenarios data

The historical climate data was based on actual weather data covering the period from 2013 through 2024. Hourly Global Horizontal Irradiance (GHI), air temperature and wind speed data from 2013 to 2019 were taken from PVGIS (European Commission, Joint Research Centre (JRC), 2026b) for the same location as the ICOS weather station of Lonzée (ICOS Carbon Portal, 2026) that provided all the weather data from 2020 to 2024 (50.55162, 4.746234). To complete the data from PVGIS for the period 2013-2019, daily rainfall and air vapour pressure data were taken from the AGRI4CAST Resources Portal (European Commission, Joint Research Centre (JRC), 2026a) at the closest location from Lonzée, corresponding to the grid 100094 (50.47228, 4.59257). The ICOS station's raw data was available at a half-hour resolution and was aggregated on an hourly basis for use in PASE.

This work analyses the evolution of the AV impact on crop development with climate change, comparing results under historic climate with results under two future climate scenarios of the Shared Socioeconomic Pathways (SSP): SSP3-7.0 and SSP5-8.5. The weather data for these two scenarios were extracted from the output of the MAR 3.14 regional model (developed by the Laboratory of Climatology and Topoclimatology at the University of Liège) and driven by the EC-EARTH3-VEG Earth System Model (ESM) (Döscher et al., 2022).

The choice of SSP3-7.0 as the primary scenario is grounded in the current scientific consensus on likely emission trajectories. In fact, according to the IPCC Sixth Assessment Report, policies implemented by the end of 2020 are projected to result in a global warming of 3.2°C [2.2–3.5°C] by 2100 without further strengthening of climate commitments (IPCC, 2023). This

makes the SSP3-7.0 scenario as the more realistic upper-bound reference for near-term planning. SSP5-8.5 was also explored in this study in order to account for the worst-case scenario, even though it is unlikely (Hausfather and Peters, 2020). At the regional scale, Fettweis et al. (2023) applied the same rationale in their downscaling study for Wallonia, explicitly selecting SSP3-7.0 as the most plausible scenario for long-term adaptation planning, while SSP5-8.5 is retained as a worst-case boundary necessary to explore the $+4^{\circ}\text{C}$. This dual-scenario approach allows the sensitivity of AV performance to the full plausible range of future climatic conditions to be characterized. EC-EARTH3-VEG was chosen to drive the MAR because, among the six ESM used in Fettweis et al. (2023), it is the ESM that provides the best representation of the current climate (1981–2010) relative to observations (i.e., the MAR driven by ERA5 reanalyses). EC-EARTH3-VEG produces also the most extreme future projections in terms of climate anomalies for the same SSP.

Under the SSP3-7.0 and SSP5-8.5 scenarios, regional climate projections for Wallonia downscaled with MAR v3.14 forced by EC-Earth3-VEG project a significant and progressive warming, most pronounced in summer. This warming is accompanied by a marked increase in heatwave frequency and a significant rise in reference evapotranspiration approaching $+1\text{ mm/day}$ in July–August, reflecting the combined increase in temperature, vapour pressure deficit, and surface solar irradiance (Fettweis et al., 2023). While annual precipitation totals show no statistically significant change, a consistent seasonal redistribution is projected, with wetter winters and significantly drier summers.

The historical and future weather data used are available in the supplementary materials.

2.3. Agrivoltaic system configurations

Two contrasting AV system configurations with the same row spacing of 13m were investigated in this study: a fixed south-facing tilted system (35°) and a vertical bifacial east-west oriented system. This row spacing of 13m allows the passage of standard 12m wide field machinery with a 50 cm non-cultivated safety buffer on each side. This spacing also ensures full compatibility with machinery widths corresponding to the integer divisors of 12 m, making the system adaptable to a wide range of farm equipment configurations without requiring dedicated machinery investment. The fixed system under study consisted of two panels oriented in portrait mode, giving a GCR

of 36.7%, whereas the panels were oriented in landscape mode in the vertical installation, giving a GCR of 20.0%. These configurations were selected for this work also as boundary cases: the fixed south-facing configuration representing the most penalising geometry in terms of light penetration for crop growth as opposed to the vertical configuration. They are also representing the configurations with the lowest CAPEX and operational expenditure Operational Expenditure (OPEX) options within the AV design space (Willockx et al., 2023; Hauff, 2026). Parameter files for these configurations in PASE are available in the supplementary materials.

2.4. Crop rotation simulation

The 8-year rotation simulated in this work is the one presented as "business-as-usual" (BAU) in Delandmeter et al. (2026), as it was designed (i) to reflect the actual land use in Wallonia (Statbel, 2025) while (ii) complying with good agricultural practices such as alternating winter and spring crops and legal requirements such as the mandatory establishment of cover crops preceding spring crops. However, the rotation, presented in Figure 1, is longer than usual. It includes main field crops grown in Belgium.

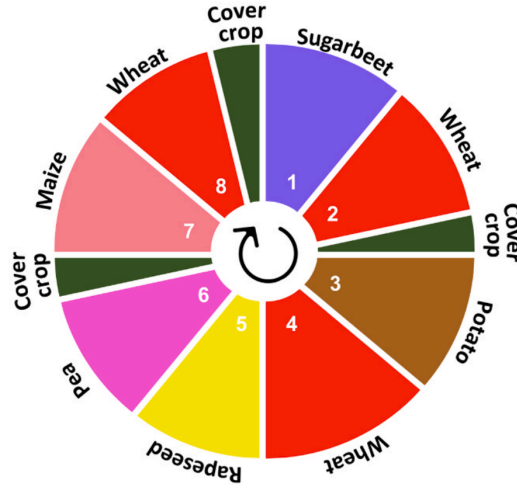


Fig. 1 Field crops 8-years rotation studied and previously presented as the BAU rotation in (Delandmeter et al., 2026)

The rotation was simulated in STICS with the same plant, soil and crop management parametrization files as in Delandmeter et al. (2026). The only exception is that the nitrogen stress parameter has been disabled in order to



isolate the effects of AV shading and climate change from crop management-related variability. This approach assumes optimal nitrogen management by the farmer, a standard assumption in long-term climate impact assessments aimed at quantifying environmentally-driven yield responses under potential growing conditions (REF) (Reidsma et al., 2010). The 8-year rotation was shifted 8 times, starting on year 2013 with a different crop of the rotation for each shift. This allowed to have the each crop of the rotation simulated each year as prescribed in Delandmeter et al. (2026).

3. Results and discussion

Faire une figure montrant les différences de rendement relatif entre les deux configurations PV : deux subplots (gauche = south-tilted AV, droite = vertical AV) avec les crops en x et un boxplot du rendement relatif pour les 5 périodes/scénarios. Fait, voir Figure2.

Faire une figure montrant les différences d'irradiance résiduelle entre les deux configurations PV : deux subplots (gauche = south-tilted, droite = vertical) avec les crops en x et une bar donnant l'irradiation résiduelle sur la période de culture pour les 5 périodes/scénarios. Fait, voir Figure 3.

+

Figure qui explique les différences entre cultures en montrant la variance de l'irradiance résiduelle au cours de l'année et/ou montrant l'effet du kt sur l'irradiance résiduelle et la répartition des classes de kt dans l'année. Fait, voir Figures 4 et 5.

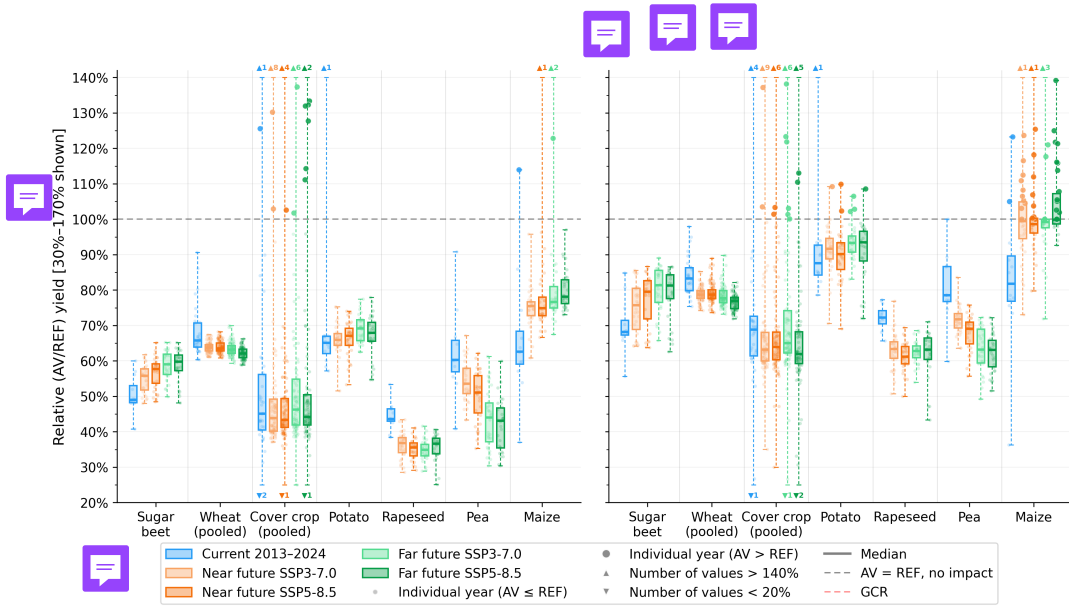


Fig. 2 Fix south-tilted AV and (b) vertical AV relative yield boxplots for each crop of the rotation in the current climate and under near and far futures with two scenarios : SSP3-7.0 and SSP5-8.5

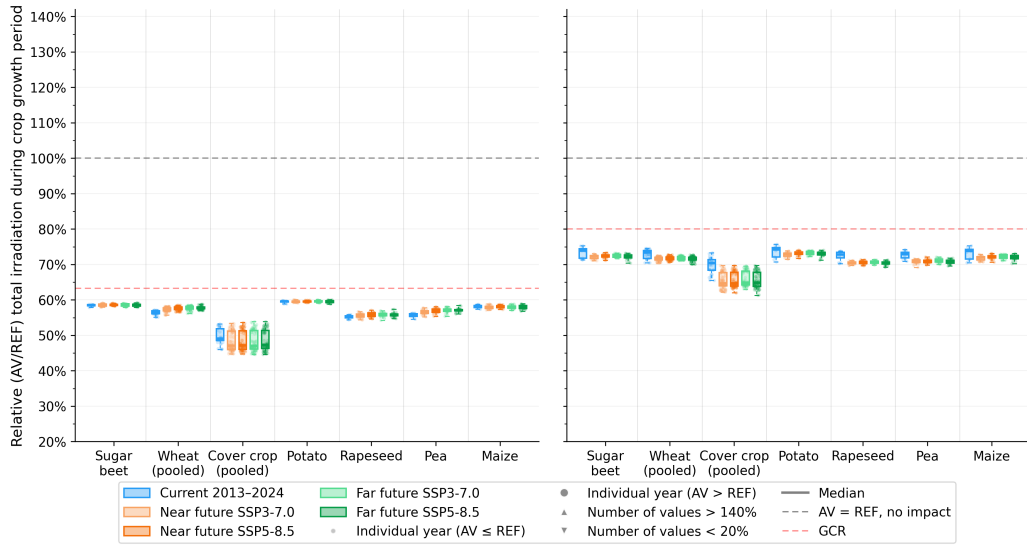


Fig. 3 (a) Fix south-tilted AV and (b) vertical AV relative irradiation boxplots for each crop of the rotation in the current climate and under near and far futures with two scenarios : SSP3-7.0 and SSP5-8.5



Faire comme dans Delandmeter et al. 2026 mais pour le rendement relatif : calculer les SPEI index de 1980 à 2100 en utilisant 1980 à 2011 comme référence. On peut ensuite mettre en relation le rendement relatif en y avec le SPEI en x. Un subplot par culture et 5 lignes sur chaque subplot (Current, NF SSP370, FF SSP585, NF SSP585 and FF SSP585). Mettre aussi la distribution des SPEI. ==> J'ai commencé à calculer le SPEI dans mon code python en utilisant le module indices.spei de la librairie python climate indices. Cependant les distributions disponibles dans cette fonction sont seulement celles de pearson et gamma. J'ai lu que celle utilisée dans la littérature pour le calcul de SPEI (Vicente-Serrano) est la log logistic. J'ai donc ajouté cette distribution aux différents possibles mais je dois encore vérifier le calcul.

Est-ce qu'il ne serait pas aussi intéressant/possible de faire une analyse PCA pour trouver les paramètres qui influencent le plus le rendement relatif ? Par exemple le paramètre culture de sensibilité à l'irradiation, de sensibilité au stress hydrique, à l'irradiation totale sur la période de culture, au stress cumulé sur la période de culture, ... ==> Plutôt faire les corrélations de Spearman, une régression Random Forest et peut-être calculer les valeurs SHAP ?

4. Conclusion

Write conclusion here.

Credit authorship contribution statement

Roxane Bruhwyler: Conceptualization, Methodology, Software, Validation, Writing - Original Draft, Funding acquisition. **Frédéric Lebeau:** Conceptualization, Project administration, Funding acquisition, Writing - Review and Editing.

Appendix A. PASE 1.0 architecture: class diagram

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Total number of word (including references): ?
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Abstract number of words: ?
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