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A GIS-Based Method for Assessing the Potential Agronomic Impact of Agrivoltaics in Grassland

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Abstract. *The growing demand for clean renewable energy deployment, driven by the European Green Deal, presents challenges, particularly due to land pressure in the rural regions. Agri-PV systems offer a potential dual land use to meet renewable objectives while reducing impact on agriculture. This study proposes a GIS-based methodology to evaluate the agronomic impact of Agri-PV on grassland, applying a high-resolution spatial analysis across 139 pedo-climatic regions in Wallonia, Belgium. The simulations use the Gras-Sim crop model embedded in the open-source tool PASE to estimate biomass production under four agrivoltaic configurations (canopy, vertical, and two south-oriented systems at different heights) and the control. For each design, multiple ground cover ratios (0.2 to 0.5) are tested over a 10-year period. Results indicate that vertical and canopy systems, especially in low-root-depth soils, can maintain grass yield compared to the yield in a control region without panels thanks to reduced evapotranspiration, sustaining the crop during drought periods. Conversely, low height configurations with high GCR showed a reduced biomass. The approach, combining different designs and territorial soil and climate conditions, provides first insights into grassland performance and the critical parameters affecting the crop dynamics.*

Keywords: *Agri-PV, Grassland, Renewable Energy, Agronomic Impact, GIS, PASE*

1. Introduction

The European Commission launched two ambitious plans to mitigate the climate change: the European Geen Deal and the Restoration Law. The European Green Deal comprises a set of measures to reduce greenhouse emissions by 55% by 2030 [1]. The Restoration Law, approved in 2024, sets binding targets to restore degraded ecosystems aiming to reduce the impact of natural disasters [2]. On one hand the Green New Deal requires a massive deployment of renewable energy resources, including Photovoltaic (PV), which currently finds its main application in rooftop PV and ground-mounted PV, with the second one being the most promising for accelerating the installation of PV. On the other hand, the Restoration Law proposes to restore specific habitats and species and, considering the additional constraints of the zero net artificialization [3], a factor which could limit the deployment of ground-mounted PV systems.

One promising solution, evaluated in this study, is the installation of agrivoltaics systems (Agri-PV). Agri-PV)combines the production of solar photovoltaic energy with agriculture, allowing for the simultaneous use of land for energy and food production [4].

The field of agrivoltaics modeling is still emerging and under active development. A recent study reviewed the state of the art in Agri-PV modelling, simulation, and optimisation, as well as the challenges that remain [5].Former studies have evaluated the theoretical potential of agrivoltaics systems in terms of elevated agrivoltaics on arable land in Europe to highlight the implications on design, land use and economic level [6]. Additionally, open-source software tools have been released for a 3D modelling of the PV and crop production [7] in order to propose a transparent evaluation of the PV projects. PASE integrates a detailed modelling of pastures using the Gras-Sim [8] simulation environment which incorporates an advanced pasture modelling to simulate the amount of biomass production for the specific land and, based on the designated management practices, the harvested biomass.

The theoretical potential of pastures seems high; pastures accounts for 34% of the European territory [9], and the Agri-PV integration within pasture has a particular relevance for its economic benefits, notably for the breeding sector and the management of the Agri-PV arrays [10]. Nevertheless, the impact on agronomic production of grassland, based on a 3D shading analysis on in-use technical configurations, is not yet fully assessed in the current studies related to GIS analyses.

This study presents a methodology for conducing complex agronomic simulations on a large spatial scale and with reasonable computational time to analyze the influence of specific locations on grassland yield at a gridded level across various Agri-PV configurations.

2. Materials and Methods

The study is conducted using the open-source software tool PASE 1.2, developed by a consortium led by the Digital Energy & Agriculture Lab (DEAL) of Gembloux Agro-Bio Tech (University of Liège). The tool has been enhanced to simulate multiple development scenarios at the regional spatial scale to analyze the impact on agricultural and energy productivity in pasture-based systems.

We study the influence of two factors on the agronomic yield of the grassland: the peculiar characteristics of the pedo-climatic regions and the type of Agri-PV installation. The study is conducted for 139 pedoclimatic regions located in Wallonia, Belgium, using weather data from the Agri4Cast database [11] and the PVGIS data [12] for the solar resource. Single hourly simulations are run on the centroid for each pedo-climatic region averaging on the soil parameters (sand, clay, coarse fragment and organic content in %) from EU databases [13], [14], [15] with uniform soil depth in the region from the ESDB database associating respectively the values 1300 mm, 700 mm, 500 mm and 300 mm to the ROO values 1, 2, 3 and 4 of the ESDB database [16].

The soil parameters allow us to compute, for each simulation point, the Available Water Capacity (AWC) and the wilting point, which characterize the hydric stresses of the crop and may lead to under performance in case of periods of drought. The AWC is defined (eq. 1) as:

$$\text{AWC} = \left(\begin{matrix}0.2576-0.002\times \text{Sand} + 0.0036\times \text{Clay} + \\ 0.0299\times \text{OM}\end{matrix}\right) \times Root_{depth} \times \left(1-\frac{\text{Coarse}}{100}\right) \qquad (1)$$

where the root depth is in mm and the sand, clay, organic matter and coarse fragment fractions are provided in %.

Meanwhile, the wilting point is defined (eq.2) as :

$$\text{Wilting}_{\text{point}} = \left(\begin{matrix}0.026+0.005\times \text{Clay} + \\ 0.158\times \text{OM}\end{matrix}\right) \times Root_{dep} \quad \times \left(1-\frac{\text{Coarse}}{100}\right) \qquad (2)$$

One of the objectives is also to evaluate how design parameters (Ground Cover Ratio (GCR), panel height/orientation), in Table 1, affect crop yield.

Table 1: *Four design configurations used in the study.*

Configuration	Tilt (°)	Azimuth (South = 180°)	Height (m)
Canopy	*12*	*232.5*	*5*
Vertical	*90*	*90*	*3*
South-oriented (2 m height)	*25*	*180*	*2*
South-oriented (1 m height)	*25*	*180*	*1*

For this purpose, each configuration is simulated for GCR values between 0.2 and 0.5, with the transect length, corresponding to the interest region, equals to twice the row spacing. A control region is defined in a position without PV panels. The simulations are applied in PASE using ray-tracing algorithms, rather than relying on proxies, to account for the available light on the ground for the specific technical configuration for ten-years of simulations (2006 to 2015). A panel of size 1m (x-axis) x 1.6m (y-axis) is used for the simulation.

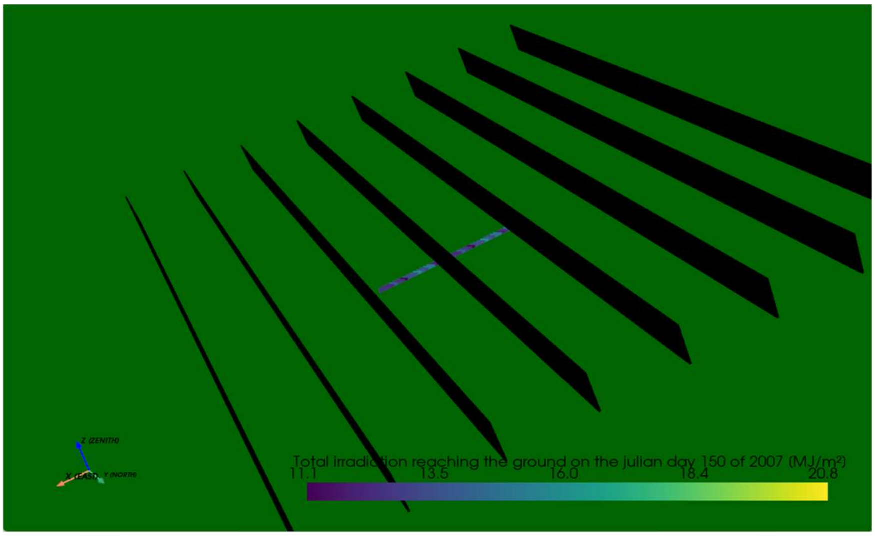

Figure 1: *Setup of the vertical PV configuration and choice of the interest region to estimate the Rel_{yield}.*

As provided in Figure 1, a setup is provided for each configuration for a GCR=0.2. A pre-defined interest region is identified in the region below the panels with 40 regularly spaced samples. The average biomass harvested between the panels (interest region) $Productivity_{crop,AV}$ is compared to the $Productivity_{crop}$ without PV panels in a control region through the ratio, to define the Rel_{yield} (eq.3).

$$Rel_{yield}\ [\%] = 100\ x\ \frac{Productivity_{crop,AV}}{Productivity_{crop}} \qquad (3)$$

The management practices and the grassland species play a significant role in grass growth for the same scenario. The management practices include the use of PFT A Type of grassland with grassland management practices, with grazing at a mean sward height of 0.05 meters, no fertilization and five cuts per year taking place at fixed dates (18/05, 23/06, 17/07, 18/09, 14/11).

3. Results and discussion

The simulations have been launched on a common laptop with 16 Gb RAM and the methodology allows, due to the hypothesis and the aggregations, to provide the results in a few hours of simulation for the 1390 simulations per PV configuration (4) and per GCR (4).

The results provide insights on the following questions:

1. *What is the role of the pedo-climatic conditions for Gra-Sim and which impact on the territorial distribution of the variables and the interannual variability ?*
2. *What is the impact of the agrivoltaics design (configuration and GCR) on the Rel_{yield}?*

3.1 The role of pedo-climatic conditions

A first analysis has been conducted to test what is the impact of the pedo-climatic conditions on the productivity results. A regional-based benchmark has been deployed, for three different root depths and for different soil parameters and climate conditions. A northern region (35285 as ESDB ID) with deep roots (1300 mm) is compared to a southern region (36006) with different climatic conditions and soil parameters except for the equivalent root depth and with a region of lower root depth (300 mm), which may be more sensitive to drought events due to the lower AWC (eq.1).

When comparing two fields of high root depth (Figure 2 for the year 2015), the biomass productivity and the harvested biomass are comparable. Although their soil water content evolves differently based on the field properties and the climatic conditions, there is no water stress observed in both regions, unaffecting productivity. The results provided, on average for 10 years, show no specific differences except for:

- *An interannual variability due to the climate conditions.*
- *A Rel_{yield} which is reduced as we increase the GCR due to the higher grass shading, though comparable among the regions.*

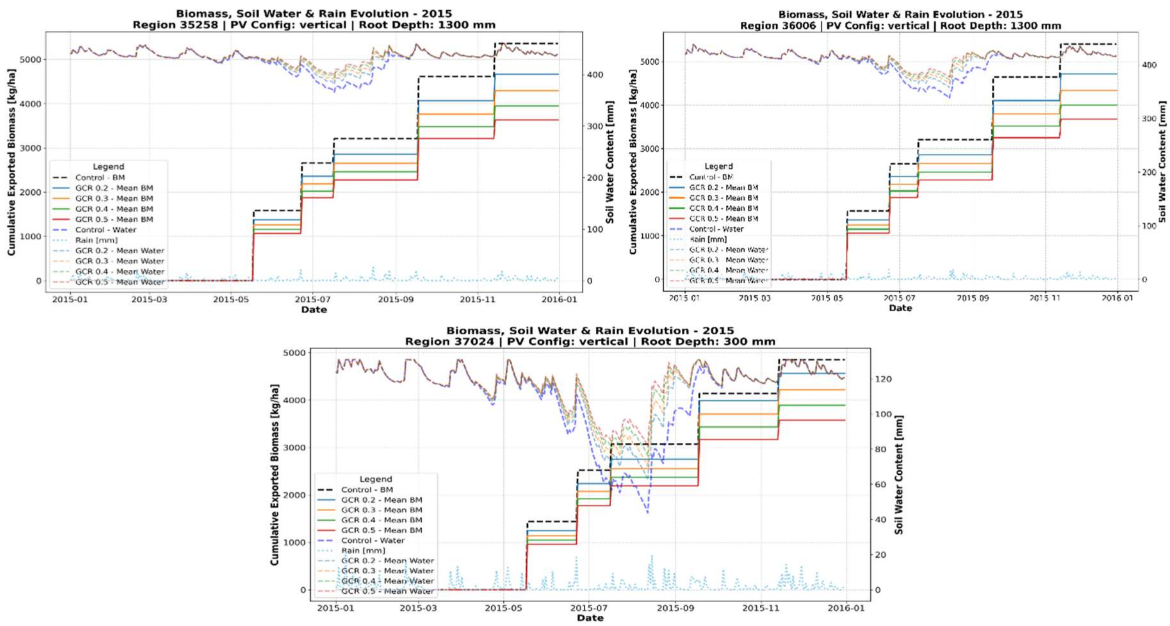

Figure 2: *Harvested biomass and water availability (year 2015) for two similar regions and one contrasted region for the vertical configuration (similar results are observed for the other configurations).*

When comparing their results with the third region (Figure 2), it is observed that the Agri-PV can mitigate the drought phenomena and safeguard the soil water content, allowing for higher Rel_{yield} with the coloured lines (based on the GCR) tending to approach the black dotted line (control region) after the period in which the highest water stresses affected the plant growth.

These results are even more visible when comparing the vertical design configuration maximal Rel_{yield} (Figure 3) in which the regions with lower root depths show differences up to 18% on the Rel_{yield} in Wallonia.

Figure 3: *Maximal Rel_{yield} (lower root depths underlined) for the vertical configuration with GCR=30%.*

3.2 The role of the configuration design

Important parameters, when characterizing the Agri-PV plant are the tilt, the orientation, the height and the GCR, which has an impact on the shading level of the plants and the PV productivity.

For this study, four configurations are tested for four different GCRs as provided in Table 1. While Figure 3 has already shown that the variability for deeper roots is limited (up to 2.8% differences), a comparison among the four configurations is provided in Figure 4 and Table 2.

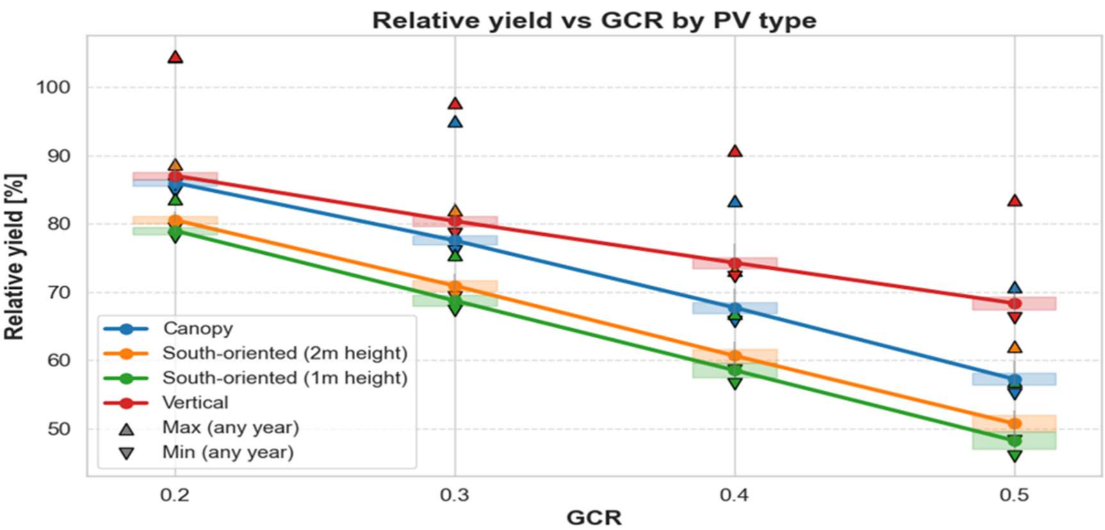

Figure 4: *Mean, maximal, minimal, global maxima and global minima Rel_{yield} evolution per ground cover ratio and PV type.*

Table 2: *Summary of results for the four configurations and for each GCR.*

Configuration	GCR	Max Rel yield [%]	Min Rel yield [%]	Average Rel yield [%]	Global Min [%]	Global Max [%]
Canopy	*0.2*	*88.74*	*85.47*	*86.04*	*84.76*	*104.41*
Canopy	*0.3*	*80.39*	*76.81*	*77.54*	*75.95*	*94.99*
Canopy	*0.4*	*70.53*	*66.88*	*67.71*	*65.7*	*83.33*
Canopy	*0.5*	*59.83*	*56.39*	*57.25*	*55.02*	*70.71*
South-oriented (2 m height)	*0.2*	*81.81*	*80.1*	*80.53*	*79.39*	*88.75*
South-oriented (2 m height)	*0.3*	*72.62*	*70.3*	*70.91*	*69.24*	*81.98*
South-oriented (2 m height)	*0.4*	*62.75*	*59.92*	*60.67*	*58.6*	*73.14*
South-oriented (2 m height)	*0.5*	*52.71*	*49.81*	*50.74*	*48.24*	*62.03*
South-oriented (1 m height)	*0.2*	*79.79*	*78.58*	*78.97*	*78*	*83.62*
South-oriented (1 m height)	*0.3*	*69.9*	*68.18*	*68.73*	*67.24*	*75.45*
South-oriented (1 m height)	*0.4*	*60.06*	*57.76*	*58.54*	*56.53*	*66.89*
South-oriented (1 m height)	*0.5*	*49.77*	*47.43*	*48.24*	*45.89*	*56.99*
Vertical	*0.2*	*89.58*	*86.38*	*87.03*	*85.74*	*104.54*
Vertical	*0.3*	*83.13*	*79.51*	*80.36*	*78.6*	*97.79*
Vertical	*0.4*	*77.09*	*73.36*	*74.27*	*72.29*	*90.71*
Vertical	*0.5*	*71.07*	*67.35*	*68.34*	*66.15*	*83.5*

The results confirm the variability of the average Rel_{yield} and the presence of an interannual variability as, for some years, the global maxima strongly differ from the average yield, for fields with low root depth (as in Figure 3). For the same root depth, there is a territorial variability, but it is limited and mostly due to the meteorological conditions and the soil content, which affects the AWC.

While the overall effect of Agri-PV remains limited (e.g. vertical configuration), it can mitigate drought phenomena (at lower root depths), leading to Rel_{yield} values exceeding 100% (Figure 4). The vertical and canopy setups also benefit from a more homogeneous light distribution, which is positive for the crop yield. The configurations with lower height and higher GCR, on the contrary, tend to affect the Rel_{yield} more strongly due to higher crop shading. The results for the two south-oriented configurations strongly approach, although the highest design benefit from a maximal Rel_{yield} up to 5% higher, suggesting exploring intermediate configurations, such as at 3 meters.

4. Conclusion

In conclusion, this study demonstrates the ability to run complex agronomic simulations, completed on a laptop within a few days for a large area like the Walloon region (16,844 km²), and the possibility to gather interesting insights. This has been possible thanks to the internal optimisation of PASE on the light modelling, enabling large-scale assessment of Agri-PV. Despite being relatively small compared to the entire EU, the region shows notable variability in Rel_{yield} due to its diverse pedo-climatic zones and potential designs, highlighting its potential for broader-scale studies, such as across the EU and with more detailed root depths maps.

Taller designs and vertical configurations maximize Rel_{yield} for fields at low root depth which host most of the grassland in Belgium and have currently lower attractivity for the farmers. This feature could have a positive impact on the land pressure and the competition for accessing the land in Belgium, as Agri-PV could grant financial benefit for the farmers while preserving the crop production at acceptable level. This study could also bring some insights to the regional administrations, which are still defining the acceptable level of yield or sunlight losses for the Agri-PV project.

Further insights

It would be also interesting to explore the following features:

- *Improve spatial resolution and refine assumptions on soil depth variability for accurately assessing the impacts at regional scale.*
- *Test additional management practices available in Gras-Sim, which may have an impact into the harvested biomass.*
- *Compare additional PV configurations, such as the tracking systems.*
- *Consider the PV structure shading, field slope, local microclimate, lateral water transfer and runoff phenomena.*
- *Study the land equivalent ratio of each design considering the energy production component, which is not analyzed in this study to focus on grassland production.*

Data availability statement

The public data supporting the findings of this article are subject to third-party restrictions and cannot be publicly shared due to licensing conditions that explicitly prohibit redistribution, commercial use, or applications beyond the original purpose. As such, the data cannot be deposited in a public repository. No private data is used for the analysis.

Author contributions

Simone Vitale*: Project Administration, Conceptualization, Methodology, Software, Formal analysis, Data Curation, Visualization, Writing – Original Draft, Methodology, Funding acquisition.*

Frédéric Lebeau*: Funding Acquisition, Supervision, Validation, Writing – Review & Editing, Conceptualization.*

Jonathan Leloux*: Funding Acquisition, Supervision, Validation, Writing – Review & Editing.*

Competing interests

The authors declare that they have no competing interests.

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