

Leveraging Species Composition for Yield Improvement in Agrivoltaics Projects on Extensively Managed Grasslands

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Grassland Species Importance

- Grassland species vary in growth patterns, phenology, and seasonal dynamics.
- Macronutrient content and digestibility differ significantly across species.
- Certain species have lower productivity and nutritive value.
- The prevalence of low-yielding species often reflects extensive or minimal management practices (e.g., unmanaged or low-input grasslands).

Research Goals

- Using simulations, compare yield outcomes of different species compositions under open-sky versus vertical agrivoltaics (AgriPV) conditions with adequate soil depth.
- Assess how shallow soils (low water capacity and associated stress) affect species yield and productivity.

Materials and methods

1. Python Agrivoltaics Simulation Environnement (PASE)

PASE [1] was used as a modeling environment to build the AgriPV system. It orchestrates agro-pedo climatic data collection, PV central configuration, direct and diffuse irradiance maps computation and crop modeling.

2. Gras-Sim Grassland Model and PFTs

Gras-Sim [2] simulates of the growth dynamics of multispecies grasslands by grouping several grass species in four Plant Functional Types (PFT).

PFT	Productivity	Digestibility	Phenology Timing	Soil Fertility
A	High	High	Very early	High
B	High	Medium	Early	High
C	Low	Low	Late growth	Medium
D	Low	Very Low	Very late	Low

PFT D is especially symptomatic of extensive management [3], since low intensity grazing leads to low soil fertility. The growth and senescence vegetative and reproductive parts of grass are simulated by integrating PFT composition and associated parameters, weather data, soil texture and depth. The spatialized irradiance output of PASE is used to compute potential growth, that is then diminished by a seasonal, water stress and nitrogen stress factors. Soil is assumed to be a single layer. Water and soil nitrogen dynamics are described in the associated article [2]

3. Configuration

AgriPV system

The simulated AgriPV system consists of vertically mounted PV panels with 25% Ground Coverage Ratio (GCR) (0.5 m from ground, 2.2 m high, 8.8 m inter-rows). The measurement zone is a 2 interrow-long line perpendicular to panel rows. A large PV installation relative to the measurement zone minimizes edge effects.

Weather data

An 11-year weather dataset (2005–2015) for Gembloux, sourced from PVGIS and Agri4cast, was used to ensure representative annual averages while capturing variability from extreme years.

Gras-Sim parameters:

- Soil: loamy, depth 10–100 cm (10 cm increments)
- PFT composition: four configurations (100% PFT A, B, C, or D)
- Fertilization: none
- Management: five cuts per year on fixed dates (18/05, 23 /06, 17/07, 18/09, 14/11)

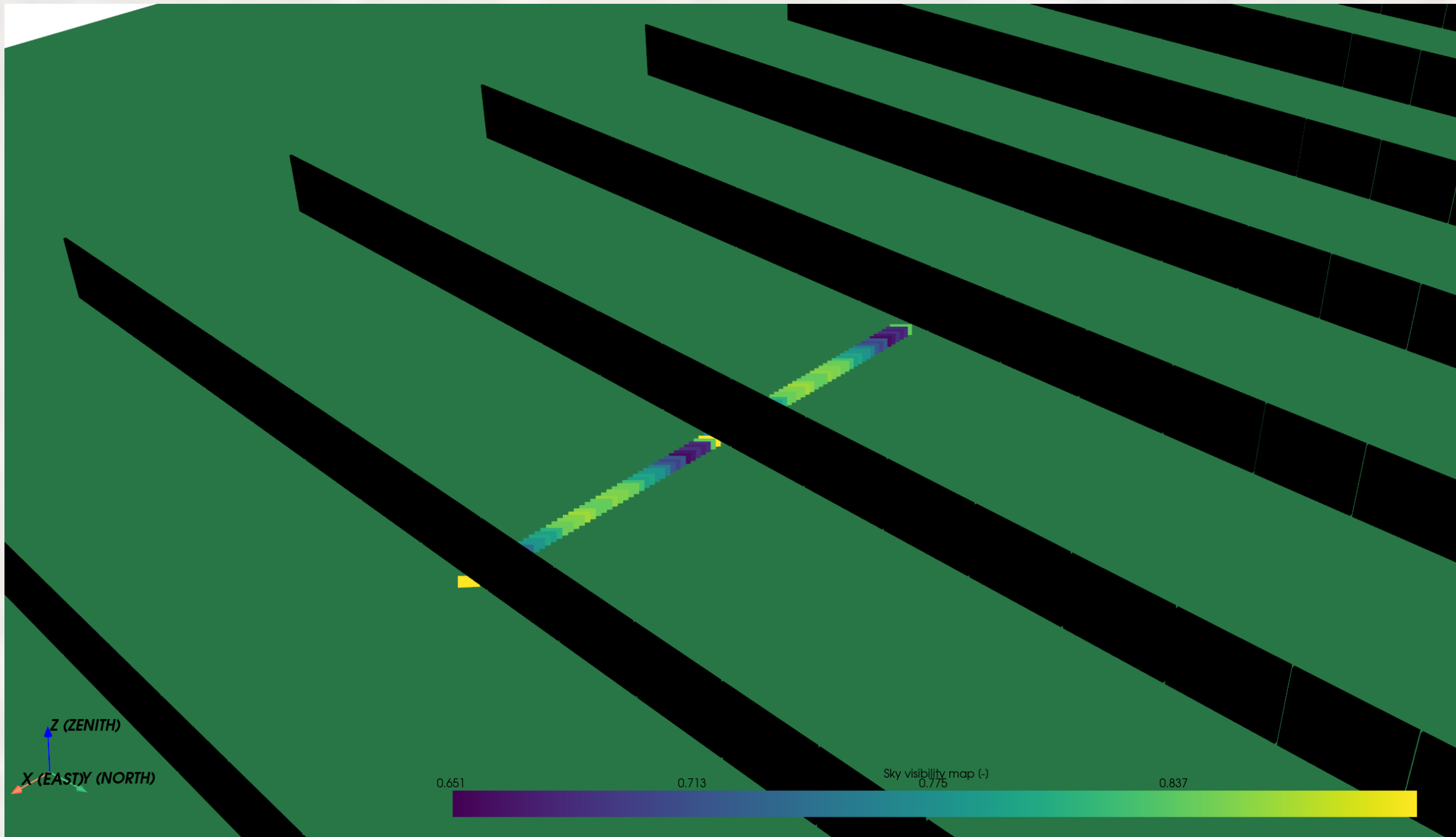


fig.1 AgriPV configuration and measurement zone

References

- [1] Bruhwiler, R. et al. Modelling light-sharing in agrivoltaics: the open-source Python Agrivoltaic Simulation Environment (PASE 1.0). Agroforest Syst 98, 2747–2764 (2024). <https://doi.org/10.1007/s10457-024-01090-8>
- [2] Kokah E. U., et al., Modeling the daily dynamics of grass growth of several species according to their functional type, based on soil water and nitrogen dynamics: Gras-Sim model definition, parametrization and evaluation. Journal of Agriculture and Food Research, Volume 14 (2023), 100875, ISSN 2666-1543, <https://doi.org/10.1016/j.jafr.2023.100875>.
- [3] Pablo Cruz, et al. Typologie fonctionnelle de graminées fourragères pérennes : une classification multitraits. Fourrages, 2010, 201, pp.11-17. (hal-02667215)

Results

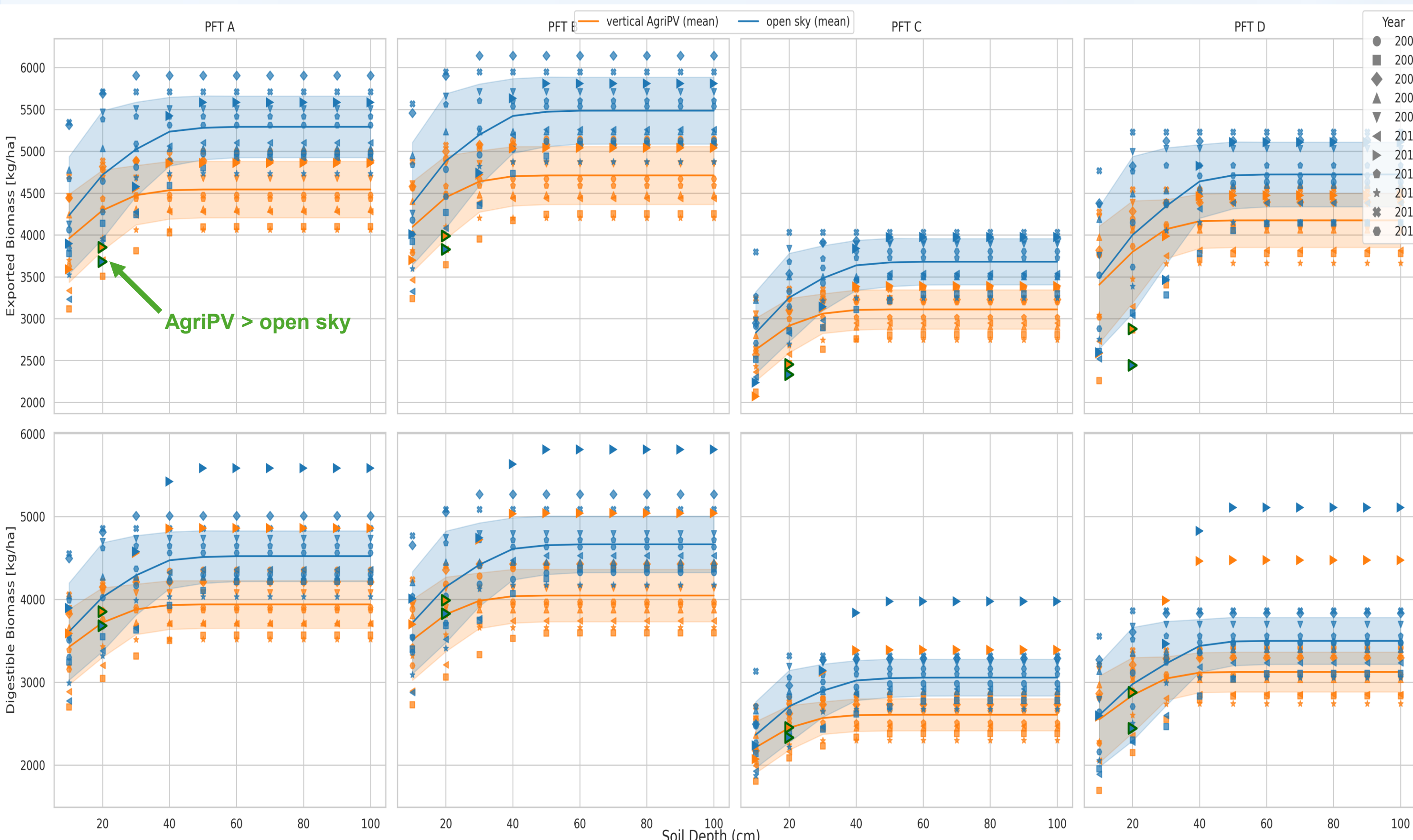


fig.2 Mean annual exported (cut) biomass and digestible biomass in function of soil depth and PFT. Colored zones represent the standard deviation around the mean. Year 2011 is highlighted in green.

The mixed linear model :

Yield ~ PFT * Configuration * Soil Depth + (1|Year)

was used to assess the effects of plant functional type (PFT), configuration (open-sky vs. vertical PV), and soil depth, including their interactions, on annual yield. The model accounts for random variation across years.

Effect	Estimate (kg/ha)	p-value
Intercept	4595	/
PFT B (vs A)	+156	0.084
PFT C (vs A)	-1458	<0.001
PFT D (vs A)	-725	<0.001
Vertical PV (vs open-sky)	-386	<0.001
Vert. * PFT D	+230	0.073
Soil depth (/10cm)	+91	<0.001
Vert. * s.d.	-47	0.001
Other effects	N.S.	

1. Vertical AgriPV (25% GCR) can outperform open-sky configuration in low soil water capacity and drought conditions

In dry years (e.g., 2011), shallow-soil grasslands benefit from the shading provided by vertical AgriPV. Reduced irradiance lowers evapotranspiration, mitigating extreme water stress. This highlights the potential of AgriPV systems in drought-sensitive regions. Maintaining forage yield during drought is crucial for sustaining herd size and farm resilience. While in wet years supplementary hay is abundant and affordable, in dry years consistent yields enable farmers to feed their herds or sell surplus grass when hay is scarce and expensive.

2. Vertical AgriPV (25% GCR) with PFT A and B can outperform open-sky systems with PFT C and D in non-limiting water conditions.

Shifting from PFT C and D to PFT A and B can help maintain or even improve yields in vertical AgriPV systems. This advantage can be realized through appropriate species selection and management practices.

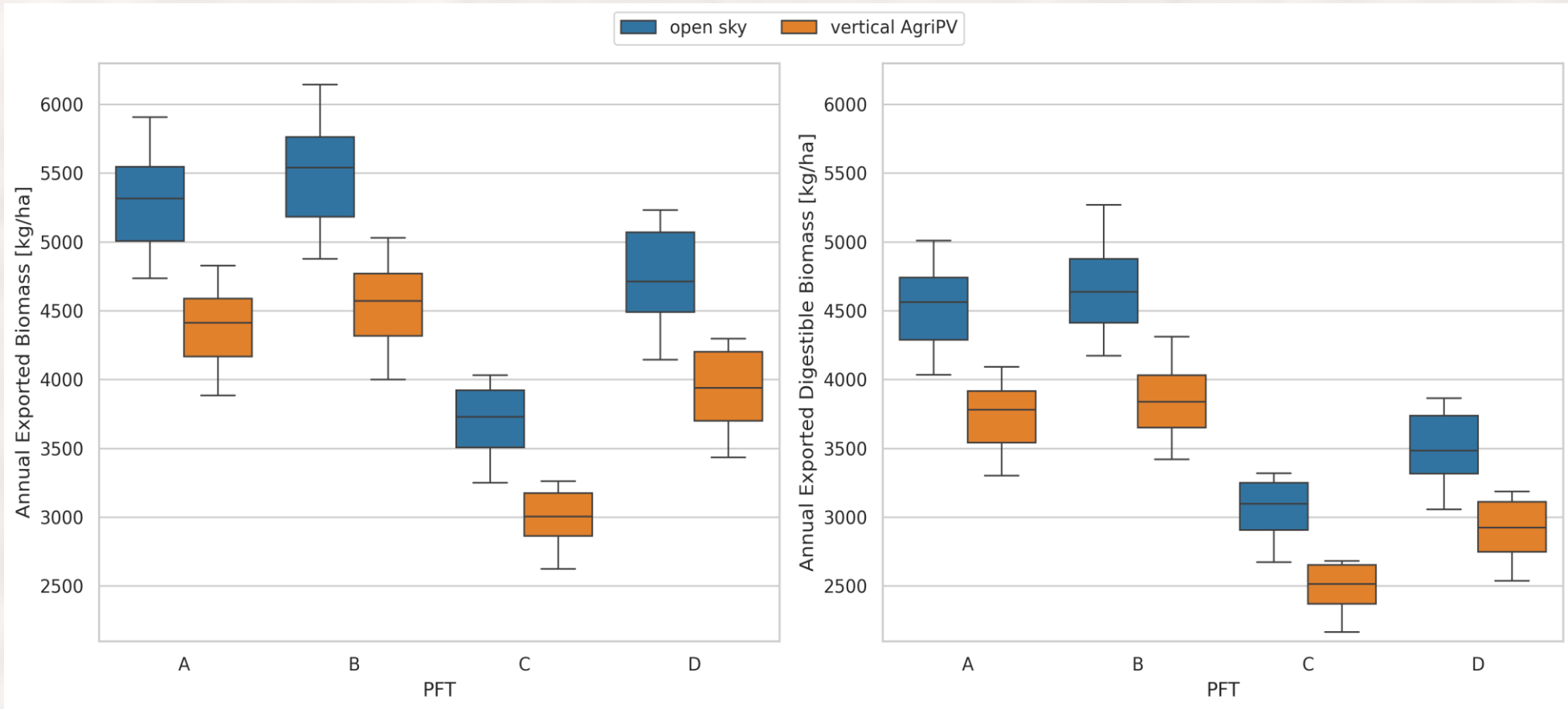


fig.3 Mean annual exported biomass and digestible biomass in function of PFT for soil depth = 100 cm. Box corresponds to quartile.

3. Vertical AgriPV (25% GCR) reduces the negative impact of low soil water capacity on yield.

The statistical analysis (*Vert. * s.d.*) indicates that soil depth has a smaller effect on yield under vertical AgriPV conditions. In other words, shallow soil yields are less impacted by vertical AgriPV than deep soil.

Mean yield reduction with vertical AgriPV:

- 50-100 cm soil depth: -13.7 %
- 10-40 cm soil depth: -8.45 %

Conclusion and future work

These results show how Vertical AgriPV (25% GCR) can help maintain grassland yield in drought conditions, and that PFT composition has a strong effect on yield. Adjusting PFT composition on poorly managed grasslands could improve yield in AgriPV systems. It is important to note that these findings are based on simulations and should be further validated with field data. Also, results have been generated for Gembloux, with relatively favorable soil texture and climate. Future simulations should include more water-limiting scenarios. Gras-Sim, like most crop models, has only been validated under open-sky conditions. Future work should focus on studying grass growth responses to AgriPV microclimates using a bottom-up, process-based approach. Integrating plant functional-structural models (FSPM) would support more detailed analysis of plant-environment interactions.