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One Year of Grassland Vegetation Dynamics in two Sheep-Grazed Agrivoltaic Systems

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Abstract. In agrivoltaic systems with solar fixed panels, the provision of ecosystem services by agricultural productions could be compromised due to very large changes in plant microclimate. But we still do not know properly the changes in grasslands ecosystem services. On two sheep-grazed sites located in lowland (Braize, Br) and upland (Marmanhac, Ma) grasslands of central France, we studied for one year the direct effects of various shading conditions induced by solar fixed panels on abiotic variables (light, water and soil temperature) and on vegetation (daily growth height, forage quantity and quality, number of species). Under exclosure of grazing, three treatments per site were set up, control (without solar-panel influence), inter-rows (variable influence) and panel (full influence). The results showed that light was reduced by 93% on average over the year in the shade of the panels with a cooler soil temperature of 2.6°C on Ma and 3.4°C on Br compared to the control. However, the soil moisture response varied between sites, depending on the different seasonal rainfall events and on soil texture. This resulted in 2.6 (Ma) to 3.2 (Br) times faster daily height growth and better forage quality. However, annual biomass production and species number showed no difference between the control and the panel. Only the inter-row treatment, which receives variable shading conditions throughout the day and seasons, shows variable biomass responses across sites. Experimental work will continue for several years in order to parameterise models to simulate the ecosystem services of agrivoltaic parks over the long term.

Keywords: Biomass, Growth, Microclimate, Quality, Photovoltaic Panel, Species Number

1. Introduction

The 2018 multiannual energy plan of the French government set a target for renewable energy production by photovoltaics (PV) of 35-45 GW by 2028. To meet this target and avoid land-use conflict, agrivoltaic systems could combine agricultural activity and photovoltaic systems. The agricultural activity under the solar panels can be very diverse, ranging from market gardening, orchards and vineyards to livestock farming activity. Cropland and grasslands are considered to be one of the best ecosystems for the implementation of solar panels [1]. Some studies calculating the Land Equivalent Ratio in market gardening or grazed grassland show that there is no conflict of land use but rather a higher benefit and yield [2], [3]. However, in view of the few studies available, especially in France and in grassland areas, the ability of agrivoltaic systems to deliver ecosystem services is questioned.

A few recent studies have shown the influence of the presence of solar panels on grassland biomass production, but with contrasting effects. Two studies showed a significant reduction in biomass measured under solar panels compared to the control treatment [3], [4], while two other studies showed a positive effect in the summer period [3], [5]. The biomass produced in the shade of the panels could therefore be lower on average per year than in the control, while having a marked seasonal dynamic with a higher response in the summer period [3], [5], [6]. One of the determinants of biomass production is the growth rate of the plants. This was recently studied by Weselek et al. [7] who observed the height of four types of crops, including a ryegrass-white clover mixture, over two years. Growth could be higher under panels with a 30% reduction in radiation, however, a reduction in year-round yield would be likely while still having a positive effect of PV during hot and dry periods. Nevertheless, the response of herbaceous species to shading varied greatly [8], [9], [10]. Regarding forage quality and botanical composition, knowledge is still very sketchy in agrivoltaic situations. Andrew et al. [3] showed an increase in forage quality in the shade of the panels and very little change in botanical composition, while Armstrong et al. [4] observed a decline in species number. It is therefore expected that botanical composition evolution will depend on species adaptation to shade to optimise light capture.

The main objective is to study the dynamics of vegetation height growth, annual biomass and forage quality, as well as species richness, of grasslands on a lowland and an upland sites, in response to variable microclimate induced by the presence of solar fixed panels.

2. Materials and methods

2.1 Site Description

Two sheep-grazed agrivoltaic systems in France were monitored from summer 2020 to spring 2021 (Fig 5). The lowland site of Braize (Br) (46.68°N, 2.64°E, 235 m altitude) has been operated since October 2018 on sandy soil. The previous land use was a nursery and then sown before PV setup with Lolium perenne, Trifolium repens and Festuca sp. In this site, the dominant species are Vulpia bromoides in the control and inter-row and Dactylis glomerata in the panels treatment. The upland site of Marmanhac (Ma) (45.02°N, 2.45°E, 840 m altitude) has been exploited since January 2014 on a silty-sandy andosol. The previous land use of this site was a grassland. The dominant species for the three treatments is Arrhenatherum elatius, Agrostis capillaris is also dominant in the control and Poa pratensis dominates in the panel treatment.

On both sites, the photovoltaic panels are south-oriented ground mounted at an angle of 25°. The solar panel tables are 3.5 m wide, with 4 m spacing between rows, at the Br site, and 2.9 m wide, with 1.85 m spacing, at the Ma site. The lowest edge of the panels is 0.8 m above the ground for both sites (see Fig 5).

2.2 Experimental Design

Three treatments were set up: 'Panels' (P, under the solar panels), 'Inter-row' (I, between two rows of panels), and 'Control' (C, without influence of the panels). In a grazing exclusion zone, and for each treatment, three transects were set up (with three probes each) to measure soil moisture and soil temperature at a depth of 20 cm (SMT100, STEP System GmbH, Germany). This depth was chosen so that soil temperature and moisture measurements would be influenced by root activity. Radiation was measured using photosynthetic active radiation (PAR) sensors in treatments P and C, positioned 30 cm above the ground (JYP1000, SDEC, France). For the P treatment, the sensors were placed at half the width of the table to be in homogeneous shading conditions. Vegetation monitoring was carried out with quadrats placed on either side of each soil probe (i.e. in 54 quadrats: 0.50 x 0.50 m). No sowing, irrigation or fertilising are made during the monitoring.

2.3 Measurements

Each probe and sensor take a measurement every 30 seconds and is averaged over a 30 minutes period. The data are processed as monthly averages in relation to the vegetation surveys. On each quadrat, vegetation height was measured weekly. The daily growth (cm d^{-1}) was calculated and then the monthly average was calculated. Each month, and on each quadrat, the biomass of the vegetation (g m^{-2}) was cut at 5 cm height, then dried in an oven (48 h at 60°C). The average of the two quadrats on either side of a probe was calculated (n = 9 per treatment). The quality of the forage was estimated by NIRS (Near Infrared Spectroscopy, FOSS 6500, FOSS NIRSystems, MD, USA) prediction and analysis of total walls (NDF, Van Soest method using a fiber analyser (Fibersac 24, Ankom, NJ, USA) and total nitrogen (N) (Dumas method). Botanical surveys are carried out exhaustively on the quadrats in summer, autumn and spring. For each site and treatment, sum of all species number observed during the three seasons is calculated and averaged.

2.4 Statistical Analysis

When assumptions of normality and homogeneity of variances were not met, Kruskall-Wallis tests were performed (growth, quality, microclimate), followed by Dunn's post-hoc test. When the nonparametric tests were similar to the corresponding single-factor ANOVA, linear mixed models were used (biomass, richness), followed by Tukey's post-hoc test. All statistical analyses were performed in R software (v 4.1.2).

3. Results and discussion

3.1 Microclimate

On both sites, the daily radiation (24h) measured under the panels is on average reduced by 93% compared to the full sun situation in the control (Br: C = 241.31 and P = 17.09 µmol m^{-2} s^{-1}; Ma: C = 277.16 and P = 18.66 µmol m^{-2} s^{-1}; Fig 1). The radiation measured under the panels is composed of 73 % and 67% diffuse radiation, on Braize and Marmanhac, respectively.

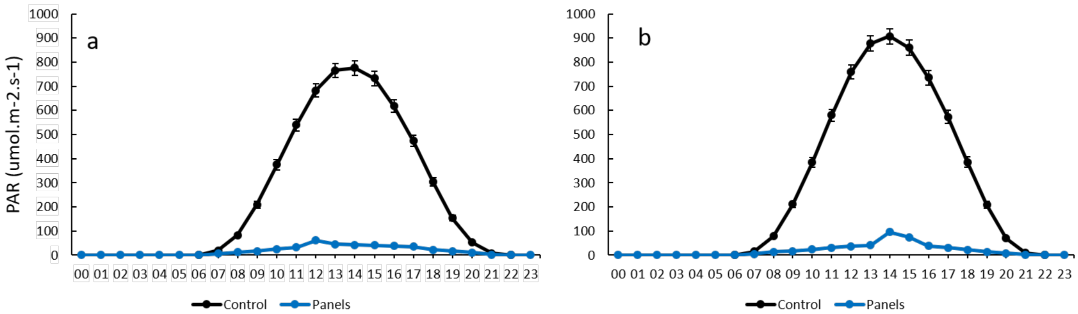

Figure 1. Daily dynamics of PAR (µmol m^{-2} s^{-1}) at the two sites (Br: a and Ma: b) for the control and panels treatments. Each point (hour) corresponds to the annual mean ± standard error.

This results in a reduction in soil temperature of 2.6°C on Ma and 3.4°C on Br (Table 1). The greatest difference in soil temperature is observed during the summer period, from July to August, ranging from 3.8°C on Ma to 6.6°C on Br (not shown). This effect persists in the inter-row but in a more moderate way, 1.8°C on Br and 1.94°C on Ma. Comparing the two sites, we can say that the cooling effect under the panels seems to be more beneficial for the lowland site, which has a higher ambient temperature than the upland site.

In addition, on average over the year, soil moisture is higher under control than under panels on Br (32%) but no significant effect is observed on Ma (Table 1).The inter-row soil moisture is similar to that measured under the panels. The difference in response between the two sites can be explained by different factors. The soil texture is very different between the two sites. The sandy-loam soil on Br has a lower water retention capacity than the andosol on Ma, rich in organic matter. In addition, the reduction in radiation has a very strong effect on potential evapotranspiration, which stabilises soil moisture, particularly in summer. In addition, during rainfall events, the soil under the panels receives less water than in the control and inter-row areas. Thus, the water supply under the panels comes only from runoff through the gaps in the structures (splash effect) and from the horizontal dispersion of water at the top and bottom of the panel tables.

Our results confirm those observed on other agrivoltaic sites [5], [7], [11], but the response of the soil temperature is closely related to the vegetation density, the size of the solar panels, but also to the soil depth measurements. Furthermore, the effects on soil moisture are more complex than those observed for soil temperature because they are multifactorial as explained above. To conclude, the water balance of the soil depends on water inputs (precipitation), which are modified by the presence of the solar panels, and water outputs (evapotranspiration and runoff), which depend on the energy balance received by the plants and the water retention capacity of the soil (linked to the texture).

Table 1. Soil temperature and soil moisture averaged over the year measured in two sites (Br and Ma) for three treatments. For a given variable and site, different letters indicate significant differences ($P \leq 0.05$) according to Kruskal-Wallis test and Dunn's post-hoc test. Mean ± standard error. n=9.

	Site	Control	Inter-row	Panels
Soil temperature (°C)	Br	16.94 ± 0.80 a	15.13 ± 0.79 ab	13.55 ± 0.60 b
	Ma	13.42 ± 0.67 a	11.48 ± 0.65 b	10.87 ± 0.54 b
Soil moisture (%)	Br	13.21 ± 0.68 a	10.77 ± 0.53 b	10.03 ± 0.34 b
	Ma	29.36 ± 0.90 a	31.80 ± 0.82 a	31.81 ± 0.74 a

3.2 Height Growth

Except in winter, height growth was on average 216% and 162% significantly higher under the panels than in the control on Br (C: 0.08 cm d^{-1}; P: 0.24 cm d^{-1}) and on Ma (C: 0.08 cm d^{-1} ; P: 0.20 cm d^{-1}), respectively (Fig 2). The largest difference is observed in spring, ranging from 0.19 cm d^{-1} on Ma to 0.25 cm d^{-1} on Br. In addition, height growth under panels starts earlier in the spring and is more stable throughout the seasons in contrast to the other two treatments which are much more variable throughout the year. This can be explained by a more favourable microclimate for vegetation growth, both in late winter with less frost under the panels and in summer with slower dehydration of the leaves. On Br, the inter-row did not differ from the control throughout the year, while on Ma, the response was similar with the panel treatment except in spring. The variation in inter-row response between the two sites could be explained by the size and density of the panel tables. Indeed, on the Br site, the inter-row is twice as wide as on Ma. More generally, higher height growth under solar panels reflects the ability of plants to improve light capture under shaded conditions, which is generally observed through physiological and morphological changes in leaves and stems and in the developmental timing of plants [8], [12], [13]. Our results are also in agreement with that in general, changes of light quality (low Red: Far Red) stimulates morphological change, such as increased plant height and reduced tillering.

3.3 Biomass Production

Annual biomass production was similar between the control and panel treatments at both sites (Fig 3). This means that the increase in height growth does not translate into an increase in biomass. As we observed more bare soil under the panels, we conclude that plant density is a major determinant of plant biomass response to panel shade. In addition, biomass production varies seasonally [6] but offsets itself on an annual average. Indeed, the panels act as an umbrella and parasol for ewes and lambs as recently observed by Andrew et al. [3]. These authors observed an increase in rumination and idling activities mainly under the solar panels. This behaviour may contribute to animal welfare, but at the same time, it decreases the vegetation cover under the panels due to the trampling effect, which further penalizes biomass production. In grazed agrivoltaic systems with fixed solar panels, a compromise has to be found to satisfy both animal welfare and production, as well as the maintenance of forage production. Therefore, the size of the inter-rows must be sufficient to provide enough light to the plants and thus enough forage for the herbivores.

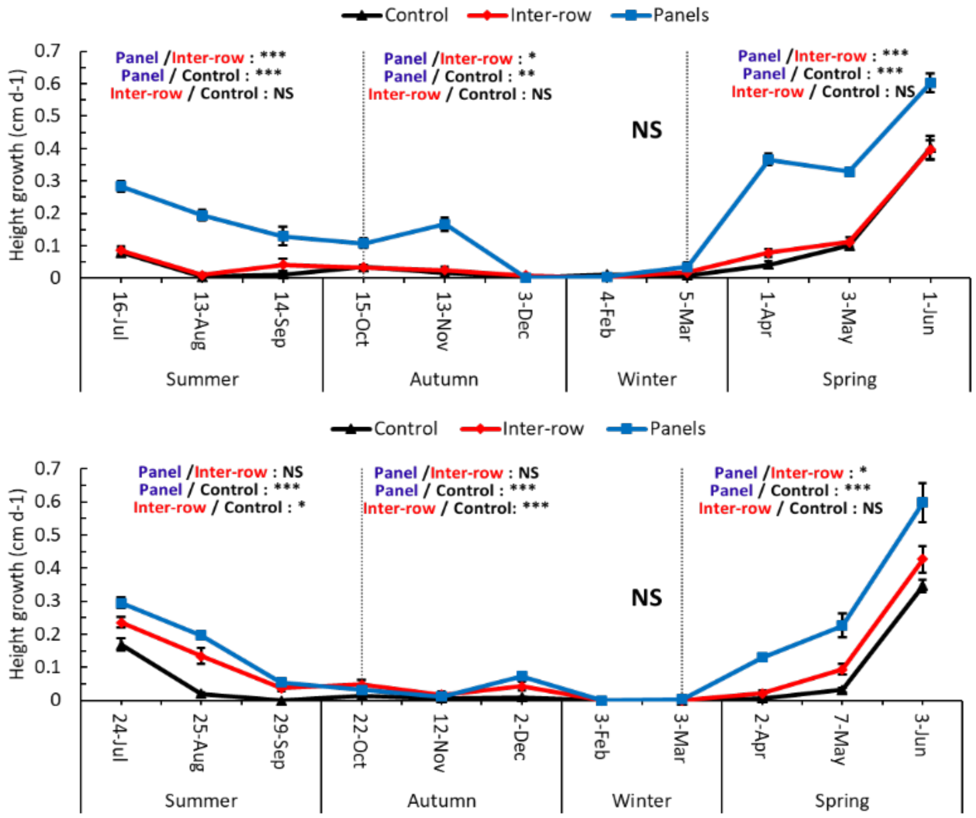

Figure 2. Dynamics of daily height growth (cm d^{-1}) measured in two sites (Br: top and Ma: bottom) for three treatments (control, inter-row, panels). For each season, significant differences are indicated by stars (***: $P < 0.001$; **: $P < 0.01$; *: $P \leq 0.05$) according to the Kruskal-Wallis test and Dunn's post-hoc test; NS: $P > 0.05$. Mean ± standard error (n=9). Dotted lines delimit the period with absence of vegetation cut from 15 th October to 5th March (Br) and from 22nd October to 3rd March (Ma).

In addition, biomass produced in inter-row treatment showed opposite effect between sites (Fig 3). On Br, biomass under panels is 54% higher than in the inter-row treatment and the opposite for Ma (+31% in inter-row compared with panels). These effects could be related to the size of the solar panels, which differ between sites. A large inter-row (4 m on Br) presents microclimatic conditions closer to the full-light control, which are warmer and drier on the lowland site. A narrower inter-row spacing (1.85 m on Ma) allows for diurnal alternating light and shade which would be more beneficial in summer and follow behaviour of the panels treatment.

Moreover, on Braize, the biomass produced under the panels is mostly higher than that in the inter-row except in late spring, which explains this annual effect. On Marmanhac, the biomass production in the inter-row is partly similar to the panels over the year except in late spring and early summer when it is higher.

Our results contradict those obtained in the studies of Armstrong et al. [4] and Andrew et al. [3], which showed lower biomass under the panels. However, the comparison of studies between them is not always easy since many differences exist from one site to another, such as pedoclimatic conditions, vegetation (species, annual/perennial), management (fertilisation, herbivore stocking rate), panel size and height, age of the agri-voltaic installation, etc. Furthermore, the assessment of forage productivity on grassland is not easy to determine in the presence of herbivores [14]. It is important to distinguish between biomass measured from standing biomass or from regrowth following cut. In our case, we measured the biomass produced after regrowth from cuts to simulate the effect of grazing, always at the same location. This allowed us to assess the direct effect of microclimate on biomass production and thus to overcome the spatial heterogeneity of the vegetation and vegetation age effect under grazed conditions. However, our results need to be extended to grazed areas using cages in order to give general conclusions for each site.

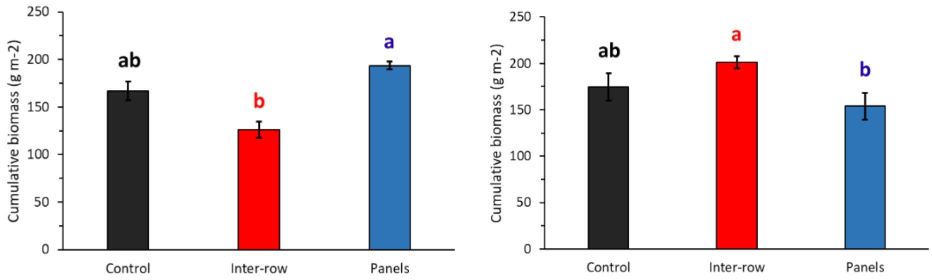

Figure 3. Annual accumulation of biomass (g m^{-2}) measured in two sites (Br: left and Ma: right) for three treatments. Different letters indicate significant differences ($P \leq 0.05$) according to an ANOVA and Tukey's post-hoc test. Mean ± standard error. n=9.

3.4 Forage Quality

The quality of the vegetation is strongly impacted by the treatments (Fig 4).

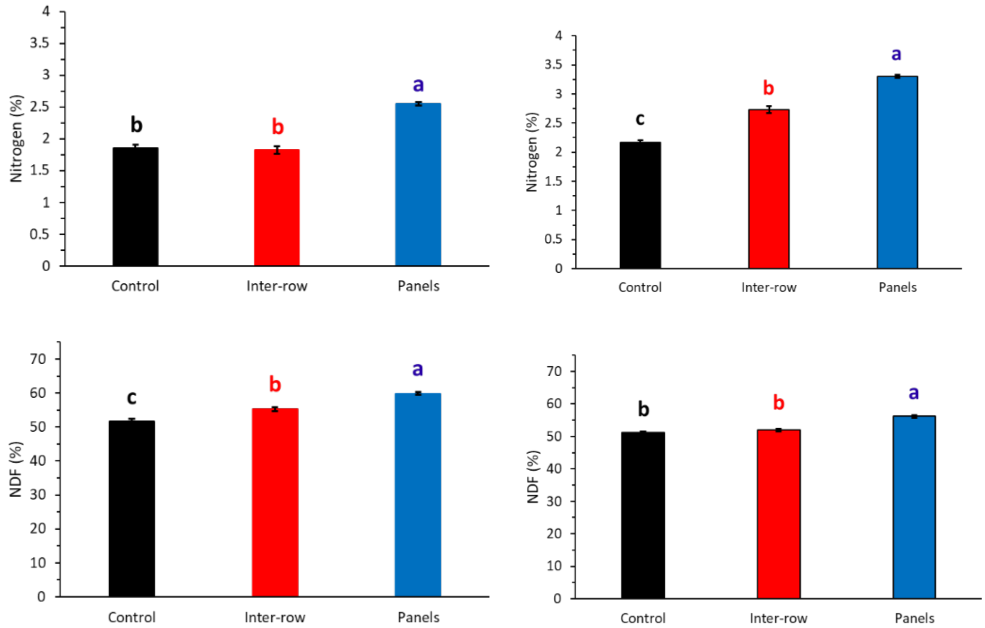

Figure 4. Annual averages of nitrogen (N, %, top) and total fiber (NDF, %, bottom) contents in vegetation measured in two sites (Br: left and Ma: right) for three treatments. Different letters indicate significant differences ($P \leq 0.05$) according to the Kruskal-Wallis test and Dunn's post-hoc test. Mean ± standard error. n=9.

The vegetation under the panels contains more nitrogen, +37% and +52% than in the control, on Br and Ma, respectively. A positive but less marked effect is also observed for the total cell wall content (NDF), +16 and +10% on Br and Ma, respectively. The quality of the inter-row vegetation was either intermediate or similar to that of the control. As soil nitrogen content does not vary between treatments at our sites, the higher total nitrogen content is most likely due to physiological and morphological adaptations of the vegetation to shade, as has been demonstrated for many agricultural productions in agrivoltaic systems [3], [7]. Early studies showed that nitrogen accumulation in plants growing in shade would occur in smaller cells than in full light [15], [16].

The increase in NDF in the shade is not in agreement with most the of the literature results.

Kephart and Buxton (1993) [17] found a negative correlation between NDF and shade, while some other studies found no or slight increase of NDF response with shade for the majority of Poaceae and Fabaceae species [18], [19]. The probable decrease in photosynthesis under shade has direct effects on the allocation of photosynthetically fixed C, which would be preferentially allocated to the formation of support tissues (NDF) to the detriment of the production of soluble sugars.

Furthermore, the intensity of the response varies seasonally [3]. The discrepancy observed with other studies could be explained by other factors such as the different phenological states of the plants, the leaf/stem ratio and the species present between shade and full light conditions.

Overall, we show that on our two agrivoltaic sites, the forage available to ewes and lambs is of a much more varied quality compared to forage available on conventional unshaded grasslands. In addition, results obtained by Andrew et al. [3] showed that the higher nutrient value of the forage on solar pastures compensated for the lower grass mass, leading to similar lamb liveweight gains in both systems.

3.5 Species number

The total number of species, cumulated over three seasons, is similar between treatments at both sites (Table 2). Only in the summer of 2021 and at site Ma, there are on average twice as many species under control as under the panels. The number of species in the Fabaceae family would be lower under panels due to their low shade tolerance, compared to Poaceae [3], [9]. In the long term, it is expected that heliophilic grassland species will disappear in favour of shade-tolerant species [3], [4], [5]. However, this can only happen if there is a sufficient pool of species in the vicinity or if shade-tolerant species are sown. The decline of biodiversity in agrivoltaic systems is problematic as it supports many ecosystem services. A number of forage species have already been tested under varied shade conditions by simulating artificial shade [9], [10], [18], [19], [20], [21]. These data need to be analysed in detail to establish a list of species tolerant to marked shading conditions for selection when establishing agrivoltaic parks. Indeed, species sown before the installation of the photovoltaic park on the Braize site such as Lolium perenne and Trifolium repens are still present in the treatments but in very low abundance.

Table 2. Total species number measured in two sites (Br and Ma) for three treatments. For a given variable and site, similar letters indicate non-significant differences ($P > 0.05$) according to Kruskal-Wallis test and Dunn's post-hoc test. Mean ± standard error. n=3.

Site	Control	Inter-row	Panel
Br	21 ± 1 a	21.33 ± 0.33 a	23.33 ± 1.76 a
Ma	23.67 ± 1.86 a	19.33 ± 1.76 a	17 ± 2.89 a

4. Conclusion

This study shows that, despite a very marked reduction in the amount of light due to the presence of the solar panels, the growth, the quantity and the quality of vegetation are of interest for the livestock systems. This indicates that the grassland vegetation has adapted remarkably well to the shaded conditions. These effects are observed on two sites with very different soil and climatic conditions and very different previous land use situations. However, these beneficial effects observed in the short term must be confirmed by longer-term monitoring under grazing conditions. The maintenance of plant species in grazed agrivoltaic sites is essential to ensure the provision of ecosystem services provided by grasslands. In addition, the performance and behavior of herbivores should complement this initial work.

Data availability statement

The data presented in this study are openly available in Data INRAE (https://entrepot.recherche.data.gouv.fr/dataverse/urep, accessed on 20th July) repository at https://entrepot.recherche.data.gouv.fr/dataset.xhtml?persistentId=doi:10.57745/W0KIUG (accessed on 20th July 2022).

Author contributions

Conceptualization, CBE, CC, CPC and LMa; data curation, CPC and LMa; formal analysis, LMa; funding acquisition, CBE, CC and CPC; investigation, CPC, DC, LMa, LMi, and MR; methodology, CPC, DC, LMa, LMi and MR; project administration, CBE, CC and CPC; resources, CPC, DC, LMa, LMi and MR; supervision, CBE, CC and CPC; validation, CPC and LMa; visualization, CPC and LMa; writing original draft, CPC and LMa; writing, review and editing, CBE, CC, CPC and LMa.

Competing interests

The authors declare no competing interests.

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Supplementary material

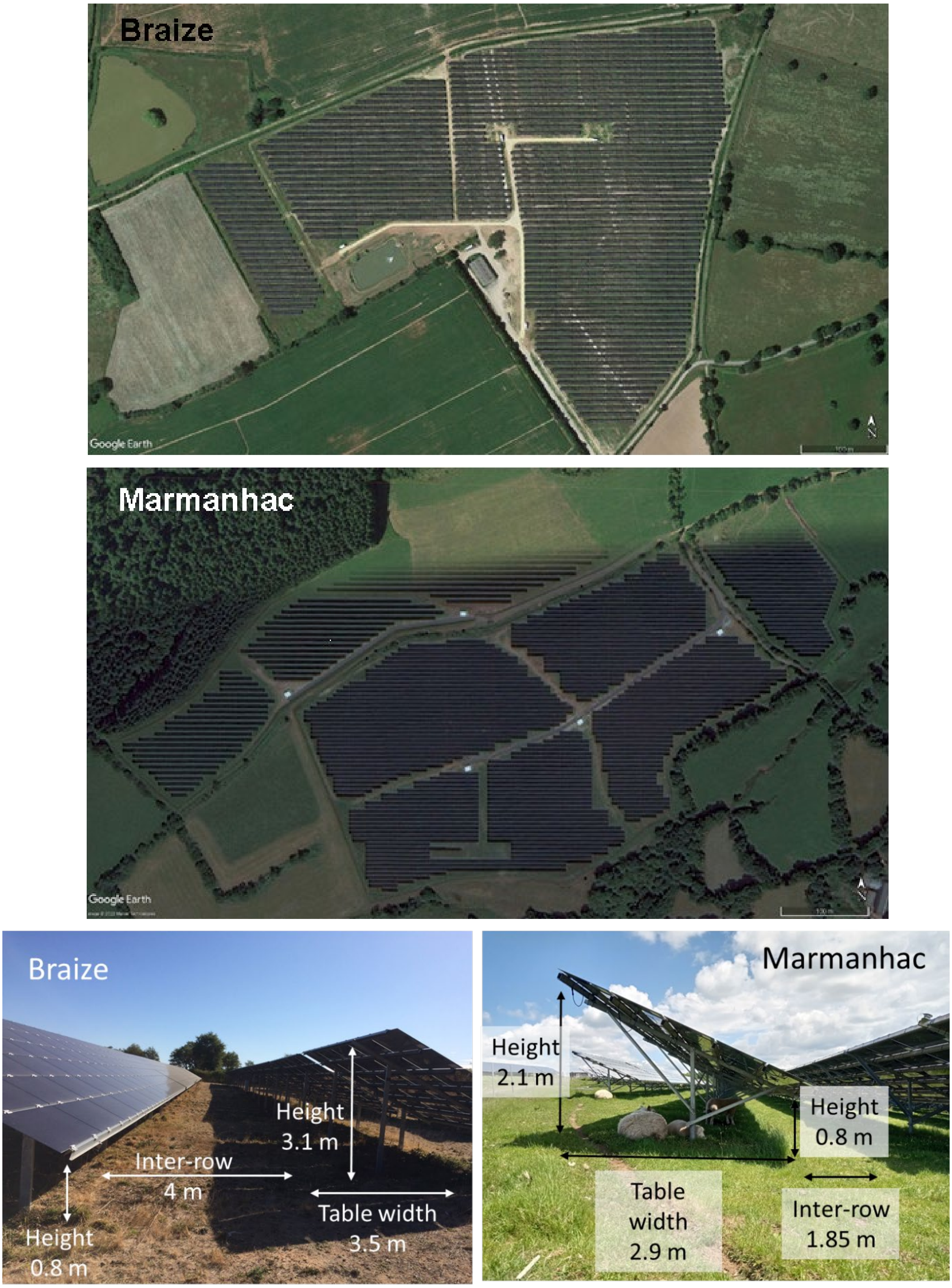

Fig 5: Satellite images (© Google Earth) of the Braize site (top), Marmanhac (middle) and sizes of panels for both sites (bottom).