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Vertical Agrivoltaics System on Arable Crops in Central France: Feedback of the First Year of Operation

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Abstract. Since the development of Agrivoltaics with panels placed above the plants, a new system is tested with vertical mounted bifacial photovoltaic panels, of which we present the results of the first year of two experimental sites. Such installations bring a lower shading level on the plant compared to fixed tilt or single axis tracking systems and could potentially suit fields with crops having low demands of shading. However, unlike more standard PV systems, few studies have detailed the effects of such devices on field crops. In this first experimental year, bifacial vertically mounted PV system showed interesting results with a stable or even a slight increase in annual crop yields. Also, harvest quality indicators are maintained or present favorable evolution indicating a high potential of vertical PV systems for Agrivoltaics.

Keywords: Vertically Mounted Bifacial Photovoltaic System, Annual Crops, Yields and Harvest Quality

1. Introduction

European agriculture is already and will continue to be exposed to various stresses that may damage crop yield [1]. At the same time, European electricity demand is growing. To meet food security and energy demand needs, the worldwide deployment of Agrivoltaics is accelerated by combining both agricultural and electrical production on the same plot of land, thus allowing enhanced land usage [2], [3].

Several benefits of Agrivoltaics on crops are expected such as reduction in water consumption [4], [5]. Annual and drought factors therefore need to be considered when studying crop response to shading (i.e. proportion of unavailable radiation to the crop); for instance, hot and dry weather conditions could be favorable for Agrivoltaics [6]. Also, to compensate for lower available radiation, plants enhance their light interception capacity in Agrivoltaic systems [6], due to the shade avoidance syndrome [7]. On the other hand, light interception can decrease with higher shading level [8] and severe shading level in Agrivoltaic devices is likely to impair photosynthesis [5], [8]. Then, yield decrease has been reported with severe shading [8], [9], [10]. In contrast, moderate shading (for instance between 29 % and 44%) can allow an increase in biomass, thanks in particular to more efficient water use, as recently shown with alfalfa [11]. This highlights the need for maintaining an adequate shading level according to the crop.

Agrivoltaic technologies impose various daily shading patterns on crops in terms of quantity of unavailable radiation to the crop and daily period of application. Unlike horizontal panels, which are often steerable and apply shading at the hottest periods of the day [5], vertical panels provide a lower daily shading level by reducing the available radiation only in the morning and at the end of the day. This distinction in daily shading period matters since the daytime impact of radiation reduction is probably substantial for plant photosynthesis. Thus it is challenging to extrapolate and predict the effects of shading by vertical panels (hereinafter referred to as VAPV) on crops from the results of shading experiments centered on solar noon. Further experiments are thus needed to better understand the shading effects provided by vertical panels on crop yield and quality. Here, the annual crop yields at two experimental sites equipped with vertical panels are presented for 2022.

2. Material and Methods

2.1. Agrivoltaic system, studied crops, and experimental strategy

The two experimental sites are Channay (47°53’27.6’’N, 4°17’38.4’’E, organic) and Valpuiseaux (48°22’58.8’’N, 2°17’31.2’’E, conventional) (Figure 1). They are equipped with vertical panels aligned in the north-south axis delimiting 14 and 7 culture strips (VAPV zone), described in Figure 1d. Control zone is located in the south (Figure 1). This study is focused on wheat *Triticum aestivum* L. (SENSAS, EHO GOLD and ENERGO varieties), barley *Hordeum vulgare* L. (AMISTAR variety), lentils *Lens culinaris* (ANICIA variety) at Channay; and wheat *Triticum aestivum* L. (COMPLICE variety), moha *Setaria italica* at Valpuiseaux.

Channay experiment was designed to be as close as possible to what growers should expect from a full-scale system [12] and thus, the entire row strip width is used to analyze the yield. In the Valpuiseaux case on the other hand, there is a higher sampling resolution inside a culture strip. For moha, there were 6 microplots in the width of the crop strip, spanning from west to east and including its whole length. For wheat, the strip is split either in 12 microplots or 9 microplots. Crops are grown on up to 3 strips in Channay (wheat; 3, barley; 1, lentils; 3). In Valpuiseaux, both moha and wheat were studied on 2 crop strips. At Channay, soil analyses were performed by Alliance BFC before device implementation resulting in a yield potential mapping of the area (Figure 1c).

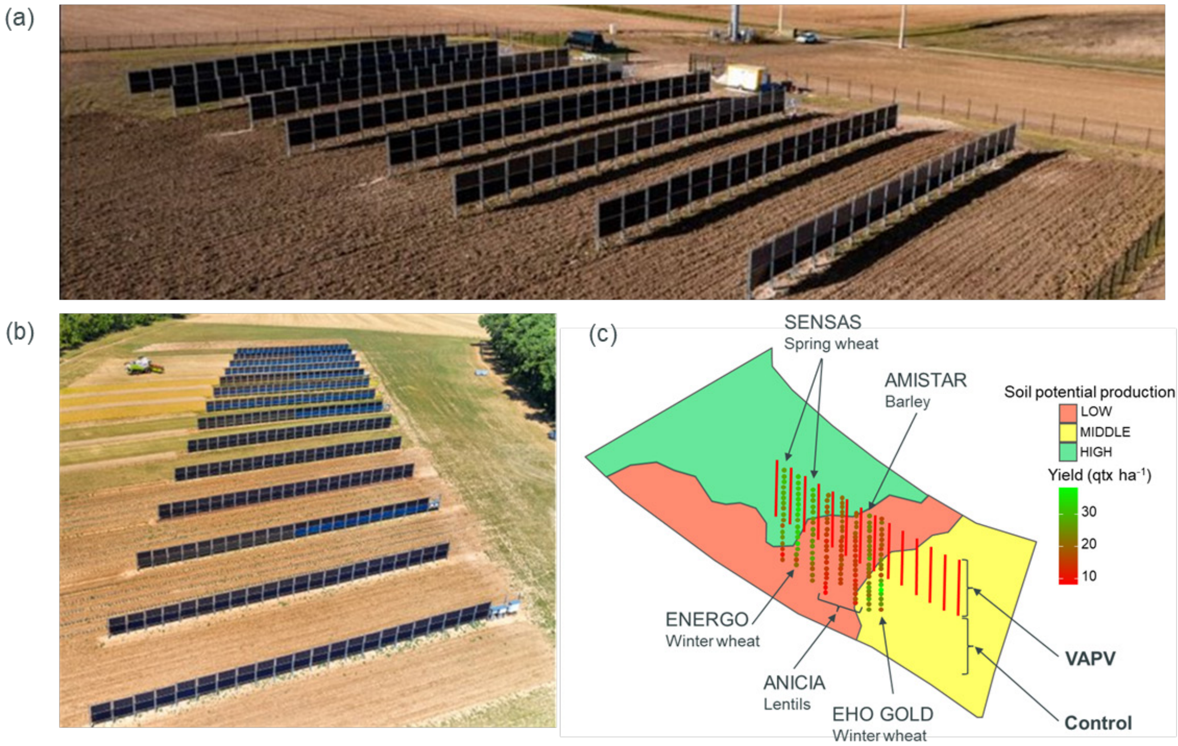
2.2. Microclimate and shade level modelling

In Channay and Valpuiseaux, air temperature, rain cumulation, and humidity were averaged every hour with weather monitoring stations (Weenat®, France), placed 1.3 m above the ground. Those stations were installed in both the control and the VAPV zones in Channay while there was only one station in the control zone in Valpuiseaux. The two sites are normally cultivated without irrigation since water supply systems are hardly compatible with VAPV.

We performed ray tracing on a grid point mesh on the ground at an hourly resolution with our in-house PV performance software SolarOPS [13]. The input meteorological data were retrieved from the European PVGIS online data. A post-processing methodology allows to extract the cumulative intercepted radiation on a monthly basis. Compared to the control zone, the VAPV zone exhibited in average 14 % and 18% shading level on the culture strip in Channay and Valpuiseaux, respectively for the period from March to August 2022.

2.3. Plant monitoring and harvest

Along with standard soil preparation and fertilization, sowing was done on 14/11/2021; 08/03/2022; 29/03/2022; 15/04/2022 for EHO GOLD, ENERGO; SENSAS; AMISTAR and ANICIA, respectively in Channay. Seed amounts were 400-450 kg ha^{-1}, 100 kg ha^{-1} and 30 kg ha^{-1} for the wheat, lentils, and barley.



(d)

Sites	VAPV Characteristics	Climate recording	2022 studied and analysed crops	Agronomic measurment: Plant phenoloy / development	Harvest	Yield components
Channay	~ 240 kW, 12 m pitch design with 8 m crops, 2 x 1,5 m biodiversity strips and 2 x 0.5 void	Daily air min, max, mean temperature (°C), humidity (%), Wind (direction, km h^{-1}), rain (mm)	Wheat, Barley, Lentils	Emerged crops (m^{-2})	Yield (qtx ha^{-1}), specific weight (kg hl^{-1}), grain humidity (%)	Thousand grain yield (g), Cobs density (m^{-2})
Valpuiseaux	~110 kW, 10 pitch design with 9 m crops and 2 x 0.5 void		Wheat, Moha	Plant height (cm)		Cobs density (m^{-2})

Figure 1. Pictures of Valpuiseaux (a), Channay (b), variety implantations with raw yield data and soil potential production mapping in Channay (c) and summary of experimental sites characteristics supplied with vertical agrivoltaics PV panels (VAPV), climate, varieties, and agronomic measurements for both sites (d).

In Valpuiseaux, sowing was performed on 10/11/2021 and 12/05/2022 with seed amounts of 135 kg ha^{-1} and 25 kg ha^{-1} for COMPLICE and moha, respectively. In Channay, emerged plants were counted by hand using a 1-meter stick (sample size are n = 8-10). The VAPV zone was split in two subzones: middle and exterior (i.e., close to the panels) of the strip. Plant heights were recorded in Valpuiseaux with a ruler (n = 4 and 12 per culture strip and per zone for moha and wheat, respectively). The cob density was hand-counted at both sites, approximately 10 days before harvest, using a 25 cm-diameter hoop randomly placed in the strip. There were 4 repetitions per zone for wheat in Valpuiseaux. In Channay, there were 10 repetitions per culture strip of control zone and 20 repetitions for the VAPV zone (middle and exterior subzones).

In Channay, yields (kg ha^{-1}) were recorded with an 8m wide combine harvester (CLAAS, Germany), gathering in one pass the whole crop strip (Figure 1c) on 08/07/2022, 19/07/2022, 04/08/2022 for Barley, Wheat, and Lentil. In Valpuiseaux, yields were measured using a 1.5 m combine harvester (Wintersteiger classic plus, WINTERSTEIGER®, Austria) on 15/07/2022 and on 22/09/2022 for wheat and moha, respectively. At both sites, harvest quality variables were recorded concomitantly with harvest as followed: In Channay for one zone (control or VAPV) and for one strip, 3 samples randomly chosen in the combine harvester were used to analyze together grain humidity (%), specific weight (kg hl^{-1}) and protein levels (%) (Infratec, FOSS®, France). Number of grains from 3 other samples were also counted (Datacount S60, WINTERSTEIGER®, Austria) and precisely weighed to determine the weight of thousand grains (g). In Valpuiseaux, both grain humidity and specific weight (measured at the same 15% humidity level) were recorded during harvest (Classic GrainCageTM, WINTERSTEIGER®, Austria). In Channay, grain humidity is not available for wheat due to technical issues.

2.4. Data analysis

The effect of VAPV shade and the crop (variety factor) were tested by two-way ANOVA. For each culture, mean of control is shown above the control boxplot and both variation and statistical difference (1-way ANOVA) compared to control is shown above the VAPV boxplot (***, $p < 0.001$; **, $p < 0.01$; *, $p < 0.05$).

3. Results

3.1. Effect of vertical panels on microclimate

The cumulative growing degree days (GDD, Tbase = 10°C) were similar between the two sites, from the 13th to the 200th day of the year, (732.1 °Cd and 671.7 °Cd, for Channay and Valpuiseaux, respectively). Again, over this timeframe, the cumulative precipitations were 255.4 mm and 199.9 mm in Channay and Valpuiseaux, respectively. The VAPV effect on the daily minimum, maximum and mean temperatures, along with rain, was studied at the Channay site. On the daily scale, no difference appears between the VAPV and control zones considering temperature or air humidity (not shown). Thus, GDD between VAPV and control zone were roughly similar with +1.8 % difference on the 200th (harvest of Wheat in Channay) day of the year in the VAPV zone compared to the control zone.

3.2. Effect of vertical panels on plant development

The density of emerged plants, studied in Channay, were not affected by the VAPV zone but were highly dependent on studied varieties ($p < 0.001$). For each variety, considering both control and VAPV zone, average numbers of plants were 266 ± 11 m^{-2}, 183 ± 21 m^{-2}, 227 ± 20 m^{-2}, 206 ± 18 m^{-2}, 245 ± 8 m^{-2} for SENSAS, EHO GOLD, ENERGO (wheat), ANICIA (lentils) and AMISTAR (barley), respectively.

In Valpuiseaux, plants were significantly taller ($p < 0.05$) in the VAPV zone, with a height of 90.6 ± 8.2 cm and 66.3 ± 4.4 cm, compared to the control zone: 78.8 ± 9.2 cm and 59.5 ± 2.5 cm for moha and wheat, respectively. The VAPV zone did not affect the cob density at both sites (not shown), unlike variety ($p < 0.001$). In Valpuiseaux, considering both control and VAPV zones, average cob density of COMPLICE was 190 ± 38 m^{-2}. In Channay, cob density was on average 260 ± 41 m^{-2}, 206 ± 35 m^{-2}, 248 ± 40 m^{-2}, and 228 ± 42 m^{-2} for SENSAS, EHO GOLD, ENERGO and AMISTAR, respectively.

3.3. Maintained or higher yield and higher grain weight between vertical panels

In Channay, due to the three zones of potential soil production (Figure 1c), yield is analyzed separately per zone. Indeed, when combining all varieties, soil potential production zones have a significant impact on normalized yield (centered reduced method) for both control and VAPV zones (not shown, 2-way ANOVA, $p < 0.001$).

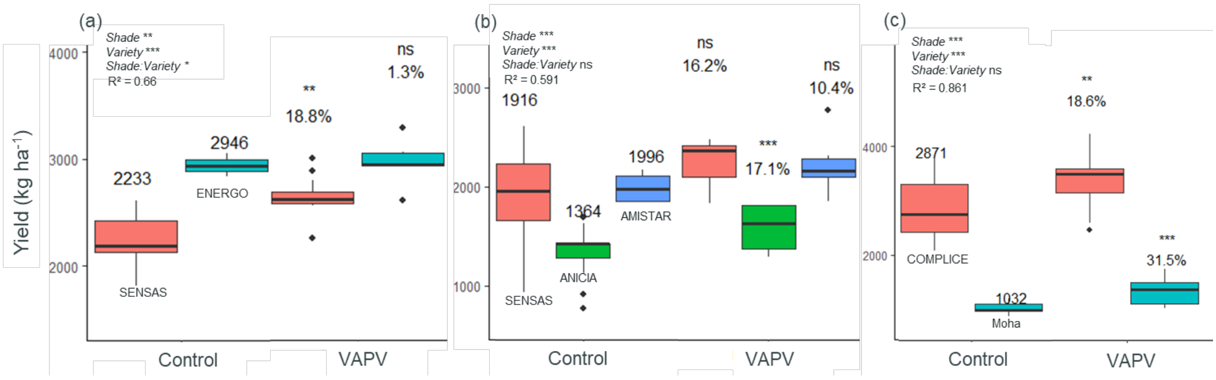


Figure 2. Effect of the vertical agrivoltaic panels (VAPV) on yield in Channay for high soil production zone (a), low soil production zone (b) and in Valpuiseaux (c).

Data were limited for the middle soil yield potential. Therefore, yields are only presented for high and low soil potential zones in Figure 2 (a and b, respectively). There were not enough data to analyze EHO GOLD yield (Figure 1c). The yield is significantly increased considering all crops in the VAPV zone compared to the control for both Channay (Figure 2a, b) and Valpuiseaux (Figure 2c). Considering a single variety, yield increase is particularly significant for SENSAS and ANICIA in Channay and for COMPLICE wheat and moha in Valpuiseaux (Figure 2). For the other varieties, yield variations were mostly higher in the VAPV zone compared to control but not statistically significant. In Valpuiseaux, particularly moha yield was higher in the middle of the strip, considering 4 out of 6 blocks compared to the entire control zone (+ 45 %, $p < 0.001$) (not shown).

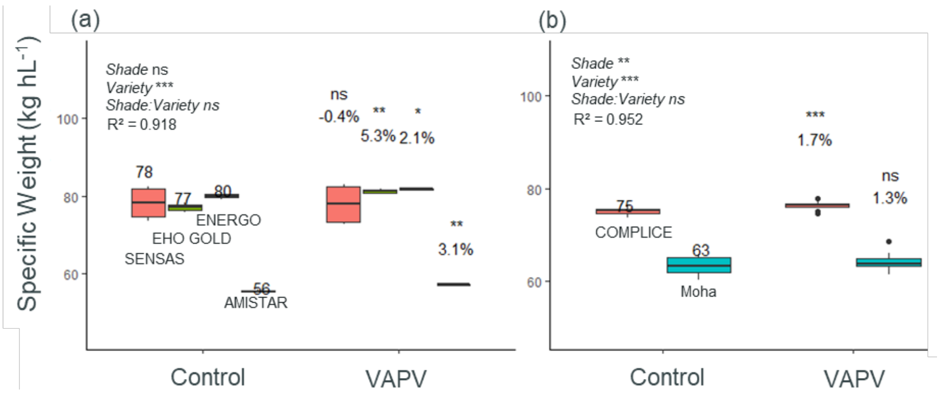


Figure 3. Effect of the vertical agrivoltaic panels (VAPV) on specific weight in Channay (a) and in Valpuiseaux (b).

In line with yield variation, the thousand grains weight, only measured in Channay, was increased in the VAPV zone considering all varieties (not shown, 2-way ANOVA, $p < 0.05$). The increase was significant for EHO GOLD and AMISTAR (+ 0.9 % and + 2.8 %, respectively $p < 0.05$). The specific weight was also slightly but significantly increased (EHO GOLD, ENERGO, AMISTAR, COMPLICE) or maintained (SENSAS, moha) in the VAPV zone compared to the control for both sites (Figure 3).

3.4. Towards drier grains and conserved protein levels

The grain humidity is either maintained (SENSAS, AMISTAR) or significantly decreased (EHO GOLD, ENERGO) in the VAPV zone compared to the control zone in Channay (Figure 4a). Similarly, the grain humidity is 11.2 ± 0.4 % in the control zone and it also decreased in the VAPV zone (-9.7%, $p < 0.001$) for moha in Valpuiseaux. Interestingly, the lower grain humidity was again found in the 4 middle bands of the strip compared to the control zone (-12.4%, $p < 0.001$) (not shown). In Channay, the VAPV zone did not significantly change the protein levels of the wheat varieties whereas it significantly increased for the barley variety (AMISTAR) compared to the control (Figure 4b).

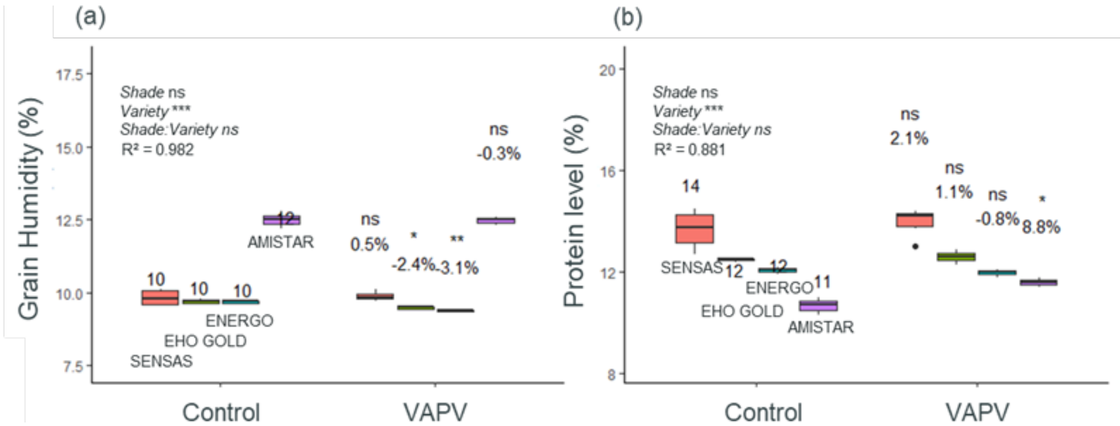


Figure 4. Channay: effect of the vertical agrivoltaic panels (VAPV) on grain humidity (a) and protein level (b).

4. Discussion

As such, the VAPV system does not seem to affect the crop growth cycles as growing degrees days are similar between VAPV and control [14], [15], [16]. This postulate should be confirmed in the next cycles.

Physiological and morphological changes have been reported with crops exposed to slight to moderate shading in previous studies. The taller plants observed in Valpuiseaux are thus consistent with previous agrivoltaic analyses [6]. Taller plants are usually associated with an increase of the plant leaf area with decreased available light [6], [17], [7]. This acclimatation may allow an increase in light capture efficiency under shade, but it is dependent on crop variety, on shade intensity and on the photoperiod applied [8], [10].

Higher plant leaf areas may also result in higher daily plant transpiration between vertical panels where crops are not shaded during the drier and hotter period of the day, conversely to tilted panels [4]. Since wind reduction between panels is expected [18], it would be interesting to investigate whether reduced evapotranspiration might permit higher plant transpiration in the VAPV zone and thus allow higher photosynthesis at the plant scale, outside shading periods.

The year 2022 was the driest and warmest year in France for a long time. This year could be representative of the expected unfavorable weather conditions that could become typical in Europe in the coming years. These unusual conditions account for the low yields observed on non-irrigated farms. In this context, we reported either a moderate increase or maintained yields at both sites. However, it should be noted that for Valpuiseaux, the soil yield potential heterogeneity has not yet been investigated. In addition, it is not possible to fully correlate yield evolution to its components in Channay, as yield component sampling does not consider the differences of the soil potential, conversely to yield sampling. Nevertheless, slight increases or at least maintained thousand grain weight, and its proxy the specific grain weight, are observed in the two VAPV sites. Previous studies showed that under moderate to severe shade, wheat grain weight tends to be decreased [19], [17], [8]. Our results are in line with studies performed under low shading, where slight increases of wheat yield, along with higher leaf area index, leaf or plant net photosynthetic rate, were reported (shading < 15% applied either from jointing [17] or from anthesis [8]).

As reported in the literature for low shading conditions [17], no effect of VAPV on cob density was detected, which is also in line with the maintained or higher yields measured. Similarly as reported in the literature, slight shading does not seem to affect grain density [17]. However, moderate-to-high shading can affect grain density [19], again depending on shading level, and such effect in VAPV should be examined in the next crop cycles.

Two key aspects of grain quality were analyzed, grain protein level and grain humidity. Only measured in Channay, wheat grain protein level was not affected by vertical panels. In previous studies, the increase of the protein level of shaded wheat has been reported together with grain yield decrease [9]. On the other hand, we also reported an increase of barley protein level as observed in a precedent study with 50% shading reporting a decreased barley yield [20]. Measured for the two sites with different crops, grain humidity appears to be decreased in the VAPV area. Considering the absence of the negative impact on yield in 2022, the humidity reduction observed in the VAPV zone is of particular interest since the grains are often dried to the right moisture level for storage. This aspect should be considered in the economic study of such system.

5. Conclusion

Vertical agrivoltaic photovoltaic systems showed interesting results during the first year of these experimental setups, with a stable or even a slight increase in annual yields, for various crops widely used in Europe such as lentils, wheat, barley, or Moha. Between vertical panels, yield increases are partly attributed to the higher thousand grain weights. Also, harvest quality indicators are maintained or present favorable evolution, indicating a promising use of vertical panels. Further work is necessary to accurately explain the origins of yield variations and challenge the 2022 results over multiple crops cycles.

Author contributions

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Data availability statement

The data that support the findings of this study are available from the corresponding author, etienne.drahi@totalenergies.com, upon reasonable request.

Competing interests

The authors declare no competing interests.

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