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SHORT COMMUNICATION

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Agrivoltaics mitigate drought effects in winter wheat

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Abstract

Climate change is expected to decrease water availability in many agricultural production areas around the globe. At the same time renewable energy concepts such as agrivoltaics (AV) are necessary to manage the energy transition. Several studies showed that evapotranspiration can be reduced in AV systems, resulting in increased water availability for crops. However, effects on crop performance and productivity remain unclear to date. Carbon-13 isotopic composition ($\delta^{13}C$ and discrimination against carbon-13) can be used as a proxy for the effects of water availability on plant performance, integrating crop responses over the entire growing season. The aim of this study was to assess these effects via carbon isotopic composition in grains, as well as grain yield of winter wheat in an AV system in southwest Germany. Crops were cultivated over four seasons from 2016–2020 in the AV system and on an unshaded adjacent reference (REF) site. Across all seasons, average grain yield did not significantly differ between AV and REF (4.7 *vs* 5.2 t ha^{-1}), with higher interannual yield stability in the AV system. However, $\delta^{13}C$ as well as carbon-13 isotope discrimination differed significantly across the seasons by 1‰ (AV: −29.0‰ *vs* REF: −28.0‰ and AV: 21.6‰ *vs* REF: 20.6‰) between the AV system and the REF site. These drought mitigation effects as indicated by the results of this study will become crucial for the resilience of agricultural production in the near future when drought events will become significantly more frequent and severe.

KEYWORDS
Agrivoltaics, carbon isotope discrimination, grain yield stability, water use efficiency, $\delta^{13}C$

1 | INTRODUCTION

Renewable energy concepts are necessary to sustainably produce energy in future. The use of photovoltaics (PV) to produce energy is increasing, since not only production costs have decreased over the last years, but also potential installation sites are large in number and area. However, the highest share of potential installation area for PV in Germany is represented by agricultural land with around 50% of total area (Destatis, 2022). Combining agricultural and solar energy production on the same area as a dual land-use system is therefore promising and known as agrivoltaics (AV). A recent study by Wirth (2021) indicates a theoretical technical potential of 1.7 TW$_p$ for AV systems with elevated panels in Germany, considering all areas with perennial crops and one third of arable area, with a surface density of 0.6 MW$_p$ ha^{-1}. To ensure agricultural production on that area and within this AV concept, PV modules are arranged in a way that agricultural machinery can pass to cultivate the area. Nevertheless, no matter how the solar panels are integrated in the area, this will lead to a shading of crops cultivated in the system with effects on crop productivity. In a meta-analysis by Laub et al. (2022) field crops like potatoes, lettuce and soybean showed a negative yield response regardless the shade level. The majority of data used in this meta-analysis was retrieved from experiments with artificial shadings (cloths or nets), yet these results only give a first estimate of the crop response to shading, since the studies barely consider alteration of microclimatic conditions. However, several studies showed that the microclimatic conditions in AV systems change. Marrou et al. (2013), Amaducci et al. (2018), Barron-Gafford et al. (2019) and Ali Abaker Omer et al. (2022) demonstrated, for instance, that soil moisture increased or remained longer on a higher level in their AV system compared to the control treatments, based on reduced evapotranspiration through shade. Effects of reduced evapotranspiration on crop performance in AV systems are, however, understudied so far. Combined investigations on stomatal response, carbon assimilation and productivity of crops will yield information about plant productivity and water use and could give a first impression on differences between crops cultivated in AV and on an unshaded reference (REF) site, as well as to characterize soil water availability on both sites. Yet, such data are missing but will be crucial to determine whether AV systems can also act as mitigation strategy in dry areas in the face of climate change (Schweiger and Pataczek, 2023).

Carbon isotope ratio ($\delta^{13}C$) and carbon-13 isotope discrimination (CID) can, thereby, provide important information on carbon assimilation and transpirational water loss with both components being crucial for crop productivity (Seibt et al., 2008). Lower enrichment in carbon-13 (more negative values) and greater values of CID are correlated with increased stomatal conductance, indicating a higher carbon assimilation potential (Gao et al., 2018). This correlation is frequently employed as a proxy for water use efficiency (WUE) (Farquhar and Richards, 1984; Kaler et al., 2018; Ma et al., 2021; Mininni et al., 2022). Using measurements of $\delta^{13}C$ instead of point measurements like e.g. gas exchange techniques, hold benefits for providing an estimate of stomatal closure integrated over time and throughout the entire growing season (de Souza et al., 2005; Farquhar and Richards, 1984).

Hence, the aim of this study was to evaluate these ecophysiological and grain yield responses for winter wheat across multiple growing seasons when subjected to altered microclimatic conditions, i.e. soil water availability, in an AV system and on an unshaded REF site, using carbon isotopic composition of winter wheat grains. For this, data were collected in an AV plant in southwest Germany over four seasons from 2016/17 until 2019/20. We hypothesized that (i) AV systems mitigate drought effects in plants cultivated, i.e. greater CID and more negative $\delta^{13}C$ values in the AV system across all seasons, and (ii) that these drought mitigation effects can compensate for reduced radiation in the AV system, enhancing interannual yield stability in increasingly variable climates.

2 | MATERIALS AND METHODS

2.1 | Experimental set-up and location

The research site (47.85° latitude, 9.14° longitude, approx. 660 m above sea level) is located on an organically managed farm in Herdwangen-Schönach in southwest Germany, with a long-term average air temperature of 8.7°C and long-term average annual rainfall of 905 mm (climate data taken from the nearest weather station at Billafingen, less than 2 km from the research site, 47.83° latitude 9.13° longitude, 537 m above sea level; source: Agricultural Meteorology Baden-Wuerttemberg, published by the Agricultural Technology Centre Augustenberg (LTZ); accessible at www.wetter-bw.de). The AV system with 194 kWp was established on an area of 0.3 ha, with elevated bifacial solar panels and around 5 m clearance height (Schindele et al., 2020; Trommsdorff et al., 2021; Weselek et al., 2019).

The soil texture is classified as sandy loam and soil samples from November 08, 2018 were analyzed for plant-available nitrogen (N_{min}; 0–30, 30–60, 60–90 cm), plant-available P and K, organic carbon, total nitrogen, pH and grain size distribution (0–30 cm) in the AV system and on the REF site (Table S1). The results of the analyses indicated homogeneous soil conditions for the whole trial site.

In the seasons 2016/17, 2017/18 and 2018/19, winter wheat (*Triticum aestivum* var. "Elixer C", fodder wheat, 200 kg ha^{-1}) was sown on a strip of 19 m width and 24 m length in the AV plant and on an unshaded REF site in 20 m distance between mid-October and the end of October (Table S2). In the previous seasons either clover grass or potato was cultivated on the same area.

In the season 2019/20 winter wheat was sown on the total area underneath the AV and on the REF site, meaning that the preceding crop differed between the wheat strips with either previously cultivated clover grass, winter wheat, potato or celeriac (Table S2). Additionally, an undersown cover crop was sown together with winter wheat in this season, consisting mainly of ryegrass and clover ("Green Carbon Fix", Camena Samen, Lauenau, Germany).

Details on the agricultural management of the field site in the seasons 2016/17 and 2017/18 can also be found in Weselek et al. (2021).

The climatic conditions, specifically accumulated precipitation, differed substantially between the four seasons. In 2016/17 and 2017/18, precipitation accumulated to 1351 mm and 916 mm, respectively, with mean temperatures of 8.6 °C and 9.7 °C (Weselek et al., 2021). In 2018/2019 around 1302 mm precipitation accumulated over the vegetation period, whereas the season of 2019/2020 showed a reduction in precipitation of around 49% (671 mm) over the cultivation period compared to the previous season (Figure 1). Comparing the accumulated precipitation of each season with the long-term average annual rainfall of 905 mm on the farm indicates that the seasons 2016/17 and 2018/19 can be considered as seasons with abundant precipitation. Mean temperatures in 2018/19 and 2019/20 were 8.6 °C and 9.0 °C, respectively.

2.2 | Harvest, sample preparation and measurements

Plots with a size of 1 m^2 were harvested at physiological maturity. In the seasons 2016/17, 2017/18, 2018/19 four plots in the AV system and four plots on the REF site were harvested. In the season 2019/20, 16 plots in the AV system and on the REF site were harvested (Figure S1). Within the AV system, the four plots were

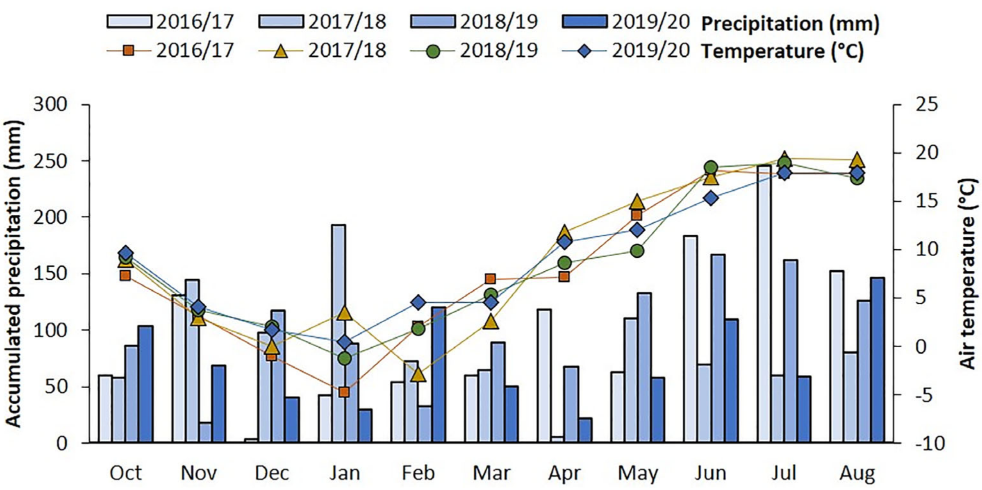

FIGURE 1 Accumulated precipitation (mm) and average air temperature (°C in 2 m) in the seasons 2016/17, 2017/18, 2018/2019 and 2019/2020. Data obtained from the weather station Billafingen, Germany (47.83° latitude 9.13° longitude, 537 m above sea level; source: Agricultural Meteorology Baden-Wuerttemberg, published by the Agricultural Technology Centre Augustenberg (LTZ); accessible at www.wetter-bw.de).

located within the panel rows, with two plots being located between the northern and central panel row, and two plots being located between the southern and central panel row. To minimize border effects, the plots were situated with a distance of 5 m to the edges of the AV facility.

After harvest, the entire wheat stalks were dried in drying cabinets for 48 hours at 30°C. Stalks were weighed, ears were trashed and grains were weighed to determine yield.

Wheat grain was milled with a ball mill and analyzed for $\delta^{13}C$, using an Euro Elemental analyzer coupled to a Finnigan DELTAplus XP continuous-flow isotope ratio mass spectrometer (Thermo Fisher Scientific) at the University of Hohenheim. The CID was then calculated with following equation based on Farquhar et al. (1989):

$$CID\,(‰) = \frac{\delta_a - \delta_p}{1 + \delta_p} \times 1000, \tag{1}$$

where δ_a is the isotopic composition of the atmosphere (−8‰) and δ_p is the isotopic composition of the sample.

2.3 | Statistical analysis

Data was analyzed using the GLIMMIX procedure within the SAS 9.4 software (SAS, Cary, USA). A linear mixed model was developed in order to evaluate yield and carbon isotope composition data. The model equation was as follows:

$$y_{imn} = \mu + r_i + w_m + x_n + e_{imn} \tag{2}$$

where μ is the general effect, r_i is the fixed effect of the i-th treatment (AV or REF site), w_m is the fixed effect of the m-th block (south or north within each strip), x_n is the fixed effect of the n-th preceding crop and e_{imn} is the residual error associated with y_{imn}.

If data was analyzed across the seasons an analogous model to (2) can be fitted by adding year k:

$$y_{ikmn} = \mu + r_i + w_m + x_n + \rho_k + (r\rho)_{ik} + e_{ikmn} \tag{3}$$

where ρ_k and $(r\rho)_{ik}$ are the effects of the k-th year and its interaction effects with treatment. All other effects are defined analogous to model (2).

In all analyses, residuals were graphically checked for normality and homogeneous variances. Where significant differences were found via F-test, multiple comparisons were performed based on the Tukey test. Least Squares Means (LS-means) between the corresponding terms were compared at $p < 0.05$ using the PDIFF (pairwise differences) option.

Due to a significant pre-crop effect in the season 2019/20, data of plots where wheat was sown directly after wheat were excluded from analysis to not underestimate yield of the corresponding area due to increased pest pressure.

3 | RESULTS

Across all seasons from 2016 until 2020 $\delta^{13}C$ (‰) values as well as CID (‰) differed significantly by 1‰ between winter wheat grains of plants grown within the AV system and the unshaded REF site, with more negative $\delta^{13}C$ values and a higher degree of CID in the AV system (Table S3). Similarly, analysing data of the seasons separately demonstrated in every season a significant difference of around 0.6–1‰ between the AV system and the REF site in both, $\delta^{13}C$ and CID (Figure 2, Table S3).

In contrast, winter wheat grain yield (t ha^{-1}) did in general not vary significantly between the AV system and the REF site across the seasons (Table S3). Significant differences in yield between the two sites with lower yield in AV were only measured in one of the seasons (2018/19) (Figure 2, Table S3).

Assessing the relationship between winter wheat grain yield and $\delta^{13}C$ indicated a general tendency of lower yields corresponding with less negative $\delta^{13}C$ values, meaning that crops which discriminated less against carbon-13 (i.e. closed their stomata more often or longer) also produced lower yields. Exceptions were found on the REF site in the

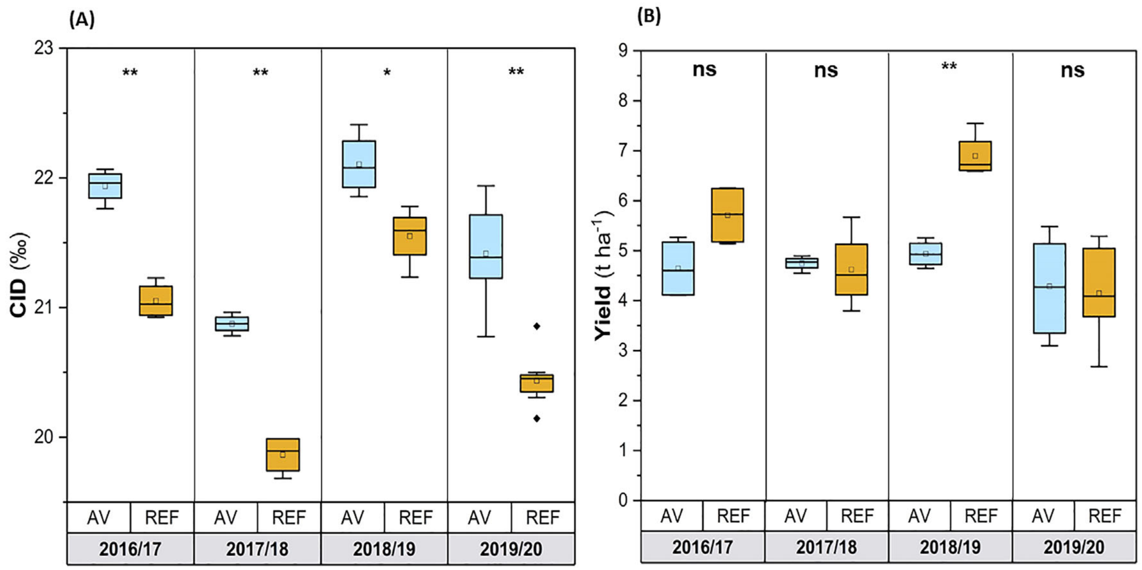

FIGURE 2 Effects of an agrivoltaic system on drought mitigation and yield: **(A)** Carbon-13 isotope discrimination (CID, ‰) in winter wheat grains and **(B)** grain yield (t ha^{-1}) of winter wheat cultivated in an agrivoltaic system (AV) and on an adjacent unshaded reference site (REF) between 2016–2020 at Herdwangen-Schönach (Germany). *, ** Significant differences at 0.05, 0.001 significance levels.

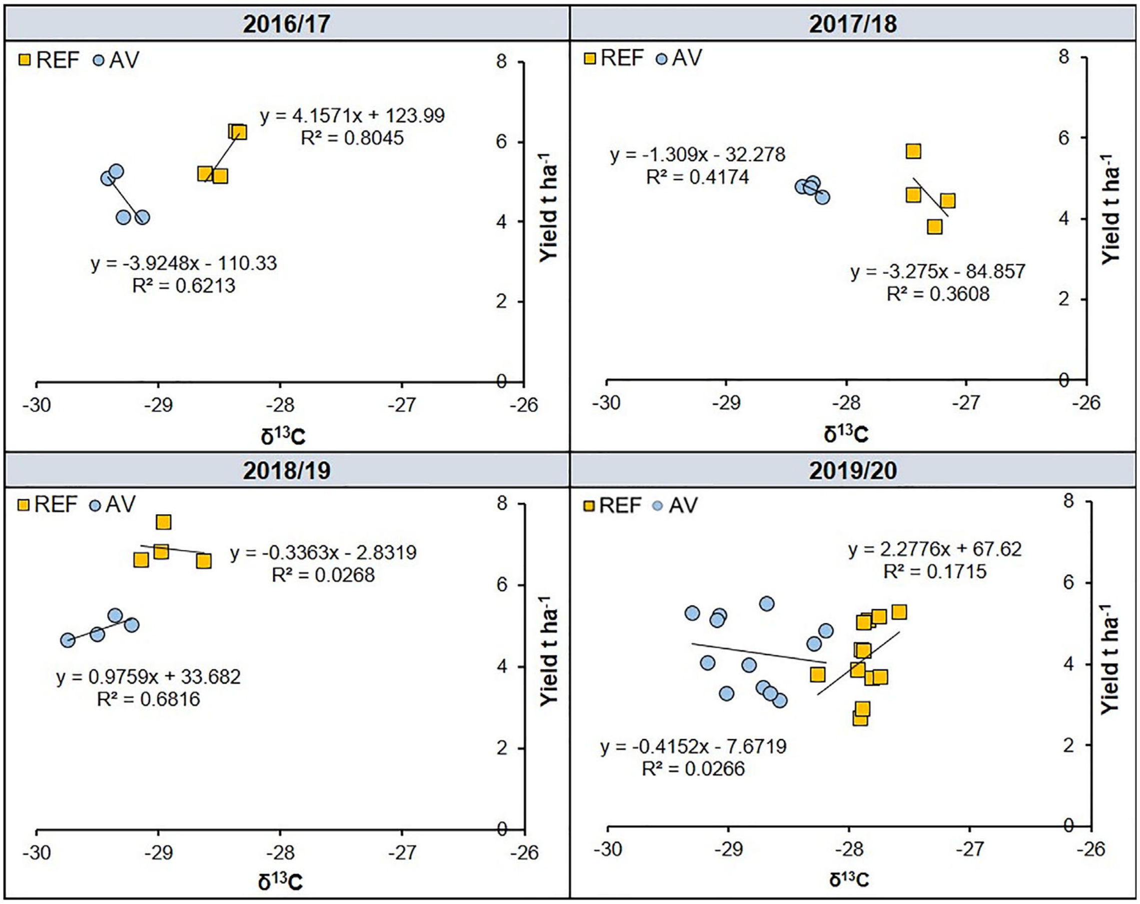

FIGURE 3 Relationship between winter wheat yield (grain, t ha^{-1}) and $\delta^{13}C$ (‰). Crops were harvested in four seasons (2016/17, 2017/18, 2018/19, 2019/20) either in an agrivoltaic system (AV) or on an unshaded reference site (REF) in 20 meters distance.

TABLE 1 Coefficients of variation (CV, %) of winter wheat grain yield in four seasons (2016/17, 2017/18, 2018/19, 2019/20) and across all seasons (2016-2020) in an agrivoltaic system (AV) and an unshaded reference site (REF) in 20 meters distance. n = sample size.

	Coefficient of variation (%)				
	2016/17	2017/18	2018/19	2019/20	2016-2020
AV	13	3	5	21	16
REF	11	17	6	21	26
n	4	4	4	12	24

seasons 2016/17 and 2019/20 and in 2018/19 in the AV system, where crops produced higher yields with less negative $\delta^{13}C$ values (Figure 3).

Interannual yield stability, assessed via the variation coefficient, exhibited lower variation in the AV system across all seasons, indicating a greater yield stability in the AV system (Table 1; AV: 16 *vs* REF: 26). Especially in the hot and dry season 2017/18, the coefficient of variation was 14% lower in the AV system than on the REF site.

4 | DISCUSSION

4.1 | Agrivoltaics mitigate drought effects in winter wheat

It was hypothesized that AV systems mitigate drought effects on crops (greater CID and more negative $\delta^{13}C$ values). The results of this study confirm that the investigated AV system significantly affects $\delta^{13}C$ and CID in winter wheat across all seasons irrespective of weather conditions. Thus, AV seems to significantly mitigate drought effects on winter wheat. Comparable results have been demonstrated in a half-density AV system in Montpellier (France), where the system mitigates drought effects by improving WUE of crops growing in the AV system compared to an unshaded REF site (Marrou et al., 2013).

These drought mitigation effects may be related to reduced evapotranspiration or, more specifically, reduced transpirational water loss in the AV system, as already found in other studies (Adeh et al., 2018; Barron-Gafford et al., 2019). A higher rate of CID indicates thereby the capacity of plants to keep stomata open over a longer period of time and to have a higher stomatal conductance, potentially reducing physiological stress or increasing assimilation (Condon et al., 2004; Farquhar and Richards, 1984). Although values differed significantly between AV and REF site in every season, differences were more pronounced in the hot and dry seasons of 2017/18 and 2019/20, with differences of 1‰, instead of 0.6–0.8‰ in the other two seasons, indicating the suitability of AV in either hot and dry climates or under perspectives of climate change with increasing drought events.

4.2 | Across all seasons, wheat yield did not differ between the agrivoltaic system and the reference site

It was furthermore hypothesized that winter wheat yields in the AV system were similar to the REF site in dry and hot seasons due to a stabilizing effect of the AV system based on the aforementioned drought mitigation effects. Correspondingly, grain yield did not differ between AV and REF. However, yield was more similar or even the same in the hot and dry seasons of 2017/18 and 2019/20, indicating a certain alignment between the two sites. Only one season (2018/19), which also exhibited the smallest difference in CID between crops of AV and REF, resulted in significant yield differences. Since this season was rather wet, light limitations in the AV system may have resulted in lower yields due to light limitation without any benefits from drought mitigating effects. Yet, across all seasons, yield in the AV system was more stable than on the REF site, which provides benefits in the face of climate change, with increasing yield variations and extreme weather events (Powell et al., 2012).

Although drought mitigation effects were detectable in every season, this had no effect on total wheat yield. This is in contrast to other studies, which demonstrated that greater CID led to increased wheat grain yields (Becker and Schmidhalter, 2017; Condon et al., 2004; Farquhar and Richards, 1984; Kunz et al., 2022; Lopes and Reynolds, 2010). CID is frequently used as proxy for WUE (Seibt et al., 2008). However, the relationship between WUE and yield is complex, as various AV studies presented contrasting results, depending upon the geographical location of the AV system, the associated climatic conditions and the crop being cultivated (Barron-Gafford et al., 2019; Marrou et al., 2013). Additionally, the climatic demand, which is one of the factors influencing the systems' actual evapotranspiration below the panels, is another driver of this relationship (Marrou et al., 2013). In studies that measured WUE directly (i.e. daily CO_2 uptake/transpirational water loss), agrivoltaics improved WUE for tomatoes growing in a hot desert climate (Arizona, USA, Barron-Gafford et al. 2019). However, chiltepin (*C. annuum* var. *glabriusculum*) demonstrated significantly greater yield and transpiration in the same AV system, but no effect on WUE, whereas jalapeno (*C. annuum* var. *annuum*) exhibited an increased WUE, but no effect on yield. Also, in the AV system in Montpellier (France) not all of the lettuce varieties expressed an increased WUE under the PV modules and even if they did, this was most of the time not reflected in dry matter accumulation (Marrou et al., 2013). Marrou et al. (2013) concluded that the genotypes differed in their sensibility to shade in terms of dry matter build-up, limiting the potential effects of improved WUE on yield. This may also explain the different yield effects in the season 2017/18 in our pilot plant in Heggelbach, where winter wheat, although facilitated by the system in terms of water loss, displayed no significant effect on yield, but potato yield increased significantly by 11% in the AV system (Weselek et al., 2021). These results indicate that AV systems have an effect on crops in general, but drought mitigation effects on yields will be crop-specific. Crops, where water availability and yield are closer related, e.g. tubers, or crops, where mainly fresh matter is marketed, may thus benefit more from these mitigation effects in an AV system even under mild drought conditions.

5 | CONCLUSIONS

The results demonstrate that agrivoltaics can mitigate drought effects as compared with unshaded conditions in the long-term, indicated by the increase in CID and the more negative values of $\delta^{13}C$ in the wheat grains. However, this effect was not translated into yield differences in the AV and REF site. Yet, this may change with increasing drought intensity and/or frequency in the future, a different location of the AV system in a hotter and drier climate and greater physiological stress or by the choice of a different crop, e.g. vegetables, where yield consists of fresh biomass with a higher water content and a greater dependence on a higher soil moisture and reduced evaporative demand under water limiting conditions. Since this study was the first to analyse stable carbon isotope composition in an AV system, future studies should thus combine such kind of analyses with gas exchange measurements to validate the findings of this study. In general, agrivoltaics should be recognized as a promising strategy of renewable energy production as well as a technology to mitigate drought effects by decoupling crop production from increasingly hostile environmental conditions. With this, agrivoltaics can facilitate resilience of agriculture in a drying world.

AUTHOR CONTRIBUTIONS

A.S., P.H. and S.Z. acquired the funding for the work. L.P. and A.S. developed the idea of this manuscript. A.W. and A.B. provided yield data from the seasons 2016/17 and 2017/18. L.P. conducted the statistical analysis, produced all graphs and wrote the first manuscript draft. A.S. gave intensive feedback on the first draft. All authors contributed to developing the final manuscript.

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DATA AVAILABILITY STATEMENT

The dataset compiled and analysed in this study is available in the Zenodo repository: https://doi.org/10.5281/zenodo.10049848

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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