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HoPVen – Impacts of agrivoltaics on hop production and biodiversity

Increasing temperatures, altered precipitation patterns, and a growing frequency of extreme weather events pose significant challenges to hop cultivation in Europe, particularly in the Hallertau region, the world's largest hop-growing area. The research project "HoPVen" investigated the effects of agrivoltaics (AV) on soil moisture, plant health, hop yield and quality, as well as on flora and fauna, in a two-year field trial conducted during the 2024 and 2025 growing seasons. As part of the experiment, the hop varieties Hallertauer Tradition (HTR) and Herkules (HKS) were cultivated under two different shading treatments, corresponding to reductions in solar radiation (RSR) of 28 % and 37 %, respectively, and compared with an unshaded control. The results demonstrated that the agrivoltaic system improved soil moisture retention, particularly during the comparatively dry growing season 2025. While powdery mildew infestations increased under the AV system, hop aphid settlement was noticeably reduced. Hop yield declined with increasing shading intensity; however, shading had only a minor effect on alpha acid concentration and hop oil content. No significant effects of the agrivoltaic system on flora and fauna within the hop field were observed. Instead, biodiversity patterns were primarily influenced by agricultural management practices. These findings indicate that agrivoltaic systems may support climate change adaptation in hop cultivation without adversely affecting the characteristic agroecosystem. Further optimisation of system design and management is required to improve yield performance and maintain plant health.

Descriptors: Hops, climate change, renewable energy, agrivoltaics, Hallertau, hops cultivation

1 Introduction

Hop cultivation in Europe, particularly in the Hallertau region, is increasingly challenged by changing climatic conditions [1]. As a native floodplain plant, hop requires moderate summer temperatures and adequate precipitation to achieve high yields and alpha acid contents [2]. In 1969, Kohlmann et al. [2] described the Hallertau as an optimal hop-growing region, reporting a long-term (1927–1961) mean annual temperature of 7.4 °C and annual precipitation of 814 mm. In comparison, the current climate normal (1991–2020) indicates a mean annual temperature of 9.1 °C and annual precipitation of 884 mm [3]. Without adaptation measures, yield losses of up to 18 % are projected for European hop-growing regions under future climate conditions [1]. Traditional land hop varieties, including Hallertauer Mittelfrüher, Spalt Spalter, and Tettnanger, response particularly sensitive to climatic changes. Similar responses have been reported for the aroma hop variety Perle [4]. Agrivoltaic (AV) systems have recently emerged as a promising strategy to enhance climate resilience in agriculture. They can reduce land-use competition between food production and renewable energy generation while providing additional benefits for crop production [5]. Reported effects include improved soil moisture retention, reduced exposure to extreme weather events, and enhanced water availability [6]. Positive yield responses under AV systems compared with conventional open-field cultivation have been observed particularly in berry crops and fruiting vegetables [7]. In 2023, the first agrivoltaic system in combination with hop cultivation was established in the Hallertau region (Fig. 1).

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The primary motivation for implementing the system was to increase resilience to climate change and extreme weather events while reducing economic vulnerability to fluctuations in the hop market. Due to limited knowledge on the interaction between hop cultivation and agrivoltaic systems, the "HoPVen" project was initiated in 2023 with funding from the German Federal Ministry of Agriculture, Food and Regional Identity. The project investigates the potential of agrivoltaic systems to improve climate resilience in hop production and assesses their effects on crop performance, biodiversity, and ecosystem functioning. The research consortium comprises the University of Applied Sciences Weihenstephan-

Triesdorf (HSWT), the Bavarian State Research Center for Agriculture (LfL), the Fraunhofer Institute for Solar Energy Systems (ISE), AgrarEnergie GmbH & Co. KG, and hop grower Josef Wimmer.

2 Materials and methods

2.1 Experimental design

The first commercial agrivoltaic (AV) system combined with hop cultivation is located near Au in der Hallertau in the Hallertau hop-growing region. The AV system is structurally comparable to conventional steel trellis systems used in the region. Photovoltaic modules are installed at a height of seven metres, corresponding to standard hop trellis height, and are mounted at a 20° inclination (Fig. 2). Hop plant growth is limited from normally seven metres to a maximum height of six metres to maintain a one-metre clearance between the plants and the photovoltaic (PV) modules. The clearance is designed to protect the PV modules from being overgrown by hop plants.

The pilot site is used for research purposes and covers an area of two hectares. Two hop varieties are cultivated: the aroma hop variety Hallertauer Tradition (HTR) and the bitter hop variety Herkules (HKS). Each variety is grown under three different treatments: an unshaded control and two shading treatments. The shading levels are achieved using PV modules of different sizes. Based on simulations conducted by the Fraunhofer Institute for Solar Energy Systems, the larger modules result in a reduction in solar radiation (RSR) of 37 %, while the smaller modules reduce incoming radiation by 28 %. Replicates were established within each shading zone, resulting in a strip-plot design. Due to the technical constraints of the pilot installation, full randomisation was not possible; therefore, a pseudo-replicated block design with four replicates per treatment was implemented. The experimental layout is shown in figure 3.

Fig. 1 Pilot and research agri-photovoltaic site in the Hallertau (Photograph by the author)

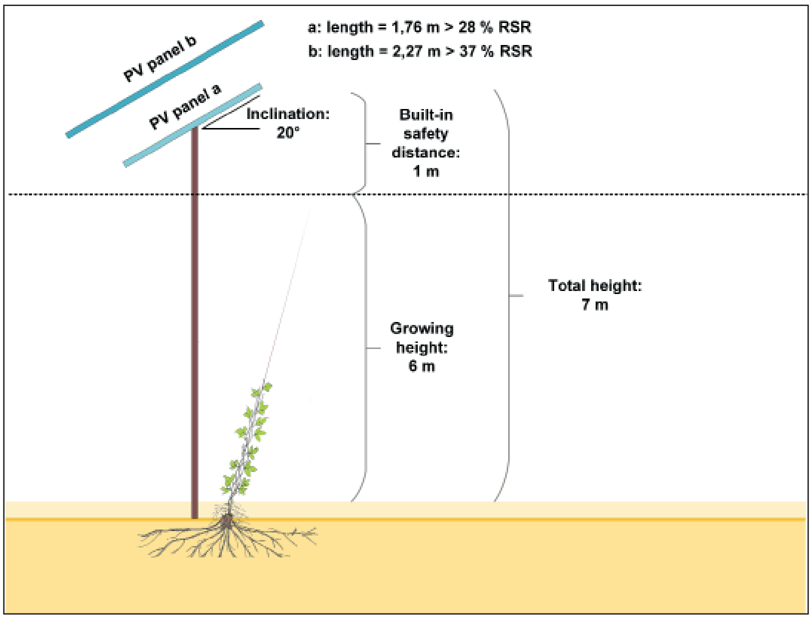

Fig. 2 Technical design of the pilot hops agrivoltaic system (Source: Own illustration)

Unshaded control plots were established along the outer boundaries of the experimental site. The dark blue zones represent the 37 % shading treatment, while the light blue zones correspond to 28 % shading. The yellow strips indicate two consecutive experimental plots, each consisting of 12 hop plants.

To minimise potential soil-related confounding effects, the Normalised Difference Vegetation Index (NDVI), derived from historical satellite data, was calculated prior to plot establishment and used to support site homogeneity assessment.

2.2 Weather condition and soil moisture

Air temperature, precipitation, soil water content, and soil water tension were monitored at the test site using a LoRa (Long Range Radio) based sensor network (Weenat). Soil water tension (kPa) was measured using Watermark granular matrix sensors (Irrometer, ; Fig. 4). Soil volumetric water content (Vol. %) was estimated using capacitive sensors (HydraScout).

Soil water tension was recorded at depths of 30 and 60 cm. Volumetric water content was measured at depths from 10 to 60 cm in 10 cm intervals. The reference level for all depth measurements was defined as the soil surface after hop cutting in spring (cutting line).

All soil moisture sensors were installed in trial plots of the hop variety Herkules. In 2024, sensors were installed in the control and the 28 % shading treatment. In 2025, sensor installation covered the control and both shading treatments.

2.3 Diseases and pests

To evaluate the impact of the AV system on plant health, hop plants were assessed in accordance with guidelines of the European and

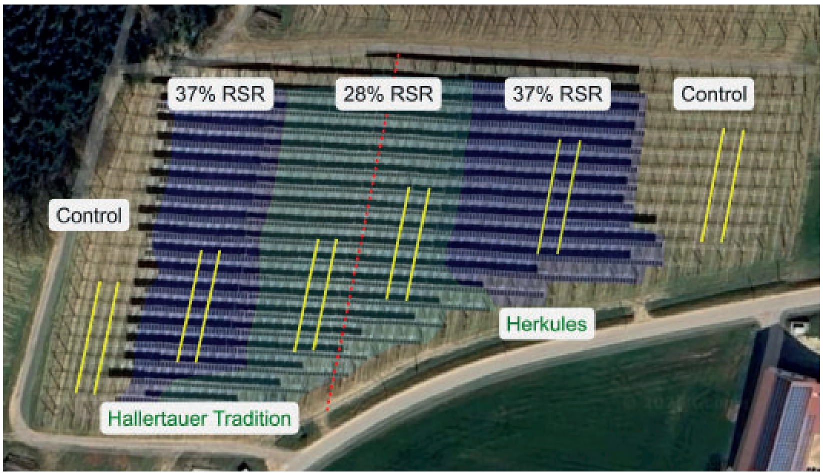

Fig. 3 **Experimental layout of the HoPVen project. Dark blue areas correspond to 37 % shading, light blue areas to 28 % shading. The yellow strips each represent two consecutive experimental plots. The red line marks the boundary between hop varieties (Map base: Google Maps; processing: QGis)**

Fig. 4 **Watermark and capacitive soil moisture sensors (Photograph by the author)**

Mediterranean Plant Protection Organization (EPPO). Powdery mildew (*Sphaerotheca macularis*) infestation was evaluated following EPPO PP 1/215 [8], based on the proportion of infected samples among 100 randomly selected leaves and cones from the middle and upper leaf layers.

Hop aphid (*Phorodon humuli*) infestation was assessed according to EPPO PP 1/22(3) [9]. For each plot, 50 leaves were examined: 25 from the upper, 13 from the middle, and 12 from the lower sections of the bines.

2.4 Yield and quality

For each shading variant and hop variety, four replicates of 20 hop bines were harvested from the stock using a cutting device (Fig. 5). Subsequently, cones were separated from the bines using a hop-picking machine, and wet hop yield was measured.

Fresh hop cones were dried in a hop kiln to stabilise the harvest. Dry matter content of the hop cones was determined by differential weighing. Based on these measurements, yield was calculated in kilograms per hectare (kg ha^{-1}) at a standardised water content of 10 %.

Alpha acid content (% by mass) was analysed using conductometric measurements according to EBC Method 7.4, "Lead Conductance Value of Hops" [10]. Bitter compounds were quantified by extracting alpha acids from hop cones with toluene, followed by conductometric titration using a lead acetate solution ($Pb(CH_3COO)_2$).

The hop oil content was determined by steam distillation following EBC Method 7.10, "Hop Oil Content of Hops and Hop Products" [11].

2.5 Statistics

Due to the technical layout of the experimental system, a fully randomised design was not feasible (Fig. 3). Therefore, inferential statistical analyses were limited to selected variables. An analysis of variance (ANOVA) was performed for hop yield because the results were replicable over the trial years. After assessing the effect of year and confirming no significant interaction, an additive ANOVA model without interaction terms was applied (yield ~ variant + year). This approach accounted for annual effects and enabled comparison of treatments across years.

2.6 Flora and fauna

Vegetation surveys were conducted in 6 × 6 m experimental plots using the Braun-Blanquet method [12]. Four plots were established: two within the agrivoltaic system, representing the two shading treatments, and two in a nearby hop garden without photovoltaic modules, serving as reference areas. The reference plots were used to compare vegetation under shaded conditions with vegetation in hop

Fig. 5 **Harvest under the agrivoltaic system (Photo: Felix Kaspar Rosic, Frankfurter Allgemeine Zeitung/F.A.Z.)**

cultivation unaffected by the agrivoltaic installation (Fig. 6).

Fig. 6 **Location of the vegetation survey plots and pitfall traps within the study area Map base: Open Street Map (Source: Own illustration)**

To characterise site conditions, the recorded plant species were assigned ecological indicator values, including light, nutrient, and moisture preferences, according to Ellenberg [13]. These indicator values were used to infer environmental conditions from the species composition of each plot. Vegetation was classified according to the vegetation units described by Hilbig and Nezadal [14].

Ground beetles (*Carabidae*) were selected as an indicator group for assessing the effects of the agrivoltaic system on fauna. As a species-rich group commonly found in agricultural landscapes and sensitive to environmental changes, ground beetles are well suited for evaluating habitat conditions and biodiversity in agroecosystems. The abundance and activity of ground beetles were recorded in both shaded and unshaded areas of the agrivoltaic system to assess potential effects of the photovoltaic modules on microclimatic conditions and species composition.

Ground beetle activity and species composition were assessed using pitfall traps following established standard methods [15–20]. Sampling periods were defined according to published survey guidelines [19,21,22], and traps were sampled at two-week intervals over a period of four months.

Captured individuals were identified to species level following Trautner [23]. However, specimens belonging to the genera *Amara* and *Bembidion* could not be assigned reliably to species due to high morphological variability.

Statistical analyses of arthropod data were based on the methodological framework described by Licht [24], which was originally developed and applied in studies investigating soil, flora, and fauna communities of sheep pastures.

3 Results

The results include the trial years 2024 and 2025. It is notable that further scientific literature [25] concerning hop yield and ingredients is available and used for the yield and quality description.

3.1 Weather conditions during the growing seasons

During the 2024 growing season (1 May to 15 September), total precipitation amounted to 589 mm, which was 216 mm higher than in 2025 (373 mm). In addition to the higher precipitation, the mean air temperature during the 2024 growing season was 2.3 °C higher than in 2025.

3.2 Soil moisture and precipitation

At a soil depth of 30 cm, soil water tension was generally higher in the control variant than in the shaded areas during both growing seasons (Fig. 7) In 2024, soil water tension in the 28 % RSR treatment increased more slowly from July onwards and responded more strongly to precipitation events than the control. A similar pattern was observed in 2025, with the 28 % RSR treatment showing a more moderate increase in soil water tension compared with the control. In addition, the 37 % RSR treatment exhibited lower soil water tension than the other treatments from July onwards. Following precipitation events, soil water tension decreased more strongly in the 37 % RSR treatment and remained at lower levels for most of the season. Only during a prolonged dry period in August did soil water tension increase substantially.

At 30 cm depth, the mean soil water tension in 2024 was 86 kPa in the control and 71 kPa in the 28 % RSR treatment. In 2025, mean soil water tension increased to 114 kPa in the control, while values of 100 kPa and 92 kPa were recorded for the 28 % and 37 % RSR treatments, respectively.

At a soil depth of 60 cm, soil water tension showed a different pattern (Fig. 8) In 2024, soil water tension remained at a comparable level in the control and 28 % RSR variants until the end of June. From July onwards, both treatments followed a similar seasonal trend; however, soil water tension was generally higher in the 28 % RSR treatment. In contrast, lower soil water tension was consistently observed in the shaded treatments during the 2025 growing season, except during periods of higher precipitation.

At 60 cm depth, mean soil water tension in 2024 was 60 kPa in the control and 70 kPa in the 28 % RSR treatment. In 2025, mean soil water tension was 108 kPa in the control, 78 kPa in the 28 % RSR treatment, and 88 kPa in the 37 % RSR treatment.

Volumetric soil water content rose with increasing shading intensity in both growing seasons (Fig. 9). Differences between treatments were particularly pronounced in 2025, when the shaded treatments consistently exhibited higher soil water contents than the control.

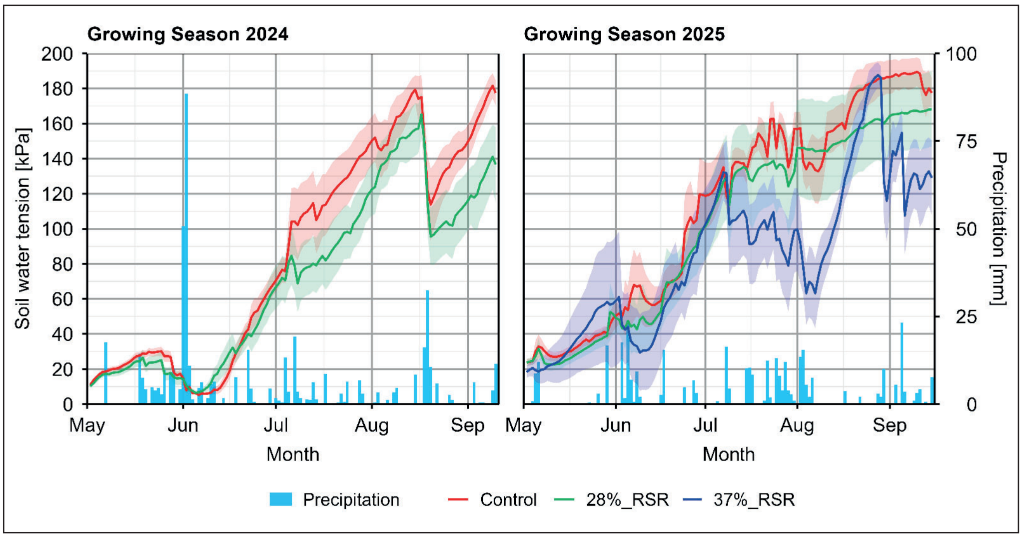

Fig. 7 **Precipitation, mean soil water tension, and standard error of soil water tension at a depth of 30 cm during the 2024 and 2025 growing seasons for the control, 28 % RSR, and 37 % RSR treatments. Shaded areas indicate the standard error of the mean**

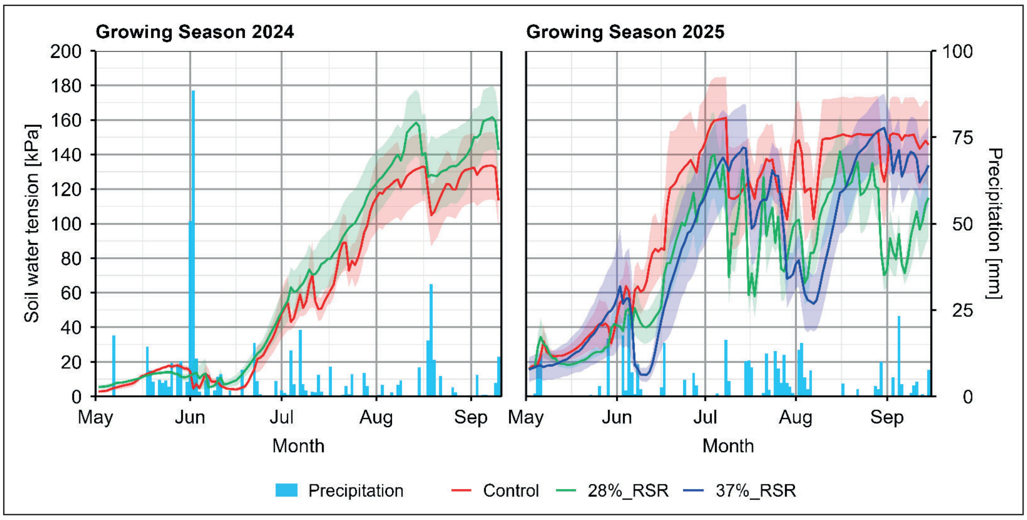

Fig. 8 **Precipitation, mean soil water tension, and standard error of soil water tension at a depth of 60 cm during the 2024 and 2025 growing seasons for the control, 28 % RSR, and 37 % RSR treatments. Shaded areas indicate the standard error of the mean**

3.3 Diseases and pests

In hop aphids (*Phorodon humuli*), shaded treatments showed lower initial infestation levels, particularly in 2025 (Fig.s 10 and 11). However, after establishment in the stock, slightly higher infestation levels were observed in the agrivoltaic treatments compared with the control.

Powdery mildew (*Sphaerotheca macularis*) showed a clear seasonal and interannual pattern. In 2024, a high level of infestation was observed, whereas in 2025, powdery mildew incidence was negligible. In 2024, shaded treatments exhibited higher infestation levels than the control, both on leaves (Fig. 12) and cones (Fig. 13).

Differences between hop varieties were also observed, with HTR showing lower susceptibility to powdery mildew than HKS. Within HKS, the 28 % RSR treatment showed higher infestation levels than the 37 % RSR treatment at several assessment dates.

3.4 Hops yield and quality

A clear trend of decreasing hop yield with increasing shading intensity was observed (Fig. 14). A statistically significant reduction compared with the control was not consistently observed at 28 % shading across all years. At 37 % RSR, yield was consistently and significantly lower.

On average over the trial period, HTR showed a yield reduction of 13 % (9–17 %) at 28 % shading and 31 % (27–38 %) at 37 % RSR. In HKS, yield reductions were 16 % (11–19 %) at 28 % shading and 35 % (33–38 %) at 37 % RSR. Overall, HKS responded more sensitively to shading than HTR.

According to the additive ANOVA model (yield ~ variant + year), adjusted for annual effects, significant differences were detected between all three treatments in both varieties.

As shown in Table 1, alpha acid and hop oil content were also affected by shading. With the exception of HKS in one year, alpha acid content at 28 % RSR differed only slightly from the control. At 37 % RSR, alpha acid content showed a moderate decrease in both varieties.

In HKS, hop oil content showed a slight decrease under shading, whereas no consistent differences were observed in HTR. With the exception of the HKS in 2023, alpha acid levels at 28 % RSR differed little from the control. However, a further increase in shading to 37 % resulted in a moderate decrease in alpha acid content.

The HKS exhibited a slight decrease in hop oil content in shaded variants, though no notable differences were observed in the HTR variety.

3.5 Flora

The study plots were classified as belonging to the class *Stellarietea mediae* (chickweed–shepherd's-purse communities). This vegetation class is characterised by plant communities strongly influenced by agricultural management. Typical species included *Elymus repens* (couch grass), *Capsella bursa-pastoris* (shepherd's-purse), *Stellaria media* (common chickweed), and *Lamium purpureum* (purple deadnettle) (Fig. 15 and Fig. 16) [14]. These communities are typical of intensively managed agricultural systems and partially shaded arable habitats, and are therefore also representative of the accompanying flora in hop-growing areas.

A total of 19 plant species were recorded in 2024 and 22 species in 2025. The mean number of species per plot was 10.4 in 2024 and 9.4 in 2025, which is below the average species richness reported for hop gardens (12.1 species) [26].

The most frequently occurring species across all plots included *Poa spp.* (bluegrass), *Lamium purpureum*, *Capsella bursa-pastoris*, and *Senecio vulgaris* (common groundsel), with *Poa spp.* being the most consistently abundant species throughout the study period.

The recorded species were characterised by high light requirements (Ellenberg indicator value L) and high nitrogen demand (indicator value N) (Fig. 17 and Fig. 18). No clear differences in species composition or cover were observed between plots within the agrivoltaic system and those without photovoltaic coverage.

Analyses of species abundance and Ellenberg indicator values showed species-specific variability; however, no differences were detected in the abundance of the five most common species. Overall, no significant differences in vegetation composition or cover were observed between shaded and unshaded plots.

3.6 Fauna

As observed for the vegetation, no clear effect of the agrivoltaic system on ground beetle communities was detected. Instead, ground beetle assemblages were primarily influenced by land management practices, including soil tillage and plant protection application.

Ground beetle catches (Table 3) were dominated by species typical of agricultural landscapes, including *Anchomenus dorsalis*, *Brachinus explodens*, *Harpalus rufipes*, *Harpalus affinis*, *Poecilus cupreus* and *Pterostichus niger*.

Species diversity across plots was generally low, with Shannon diversity indices ranging between 1 and 2. Evenness values ranged from 0.5 to 0.7, indicating a relatively balanced distribution of individuals among species. Species richness was similar across plots, although Plot B2 showed the highest number of species (19 species).

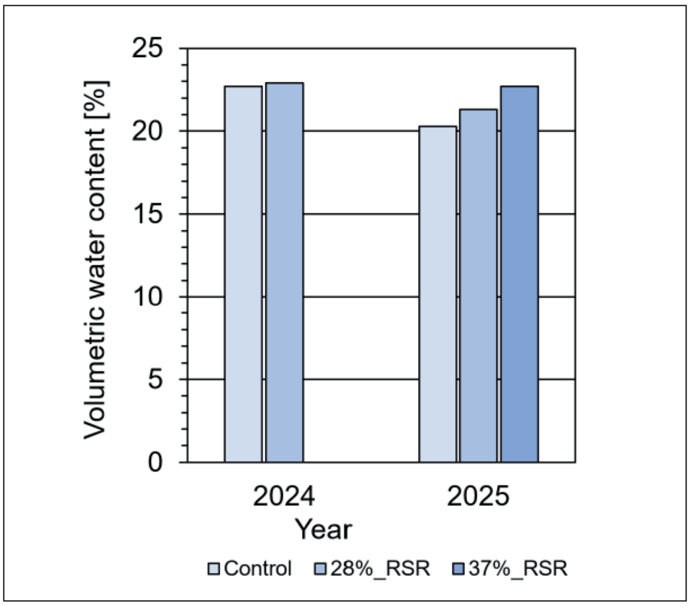

Fig. 9 **Volumetric soil water content across the soil profile (0–60 cm) in 2024 and 2025 for the control and shading levels of 28 % and 37 %**

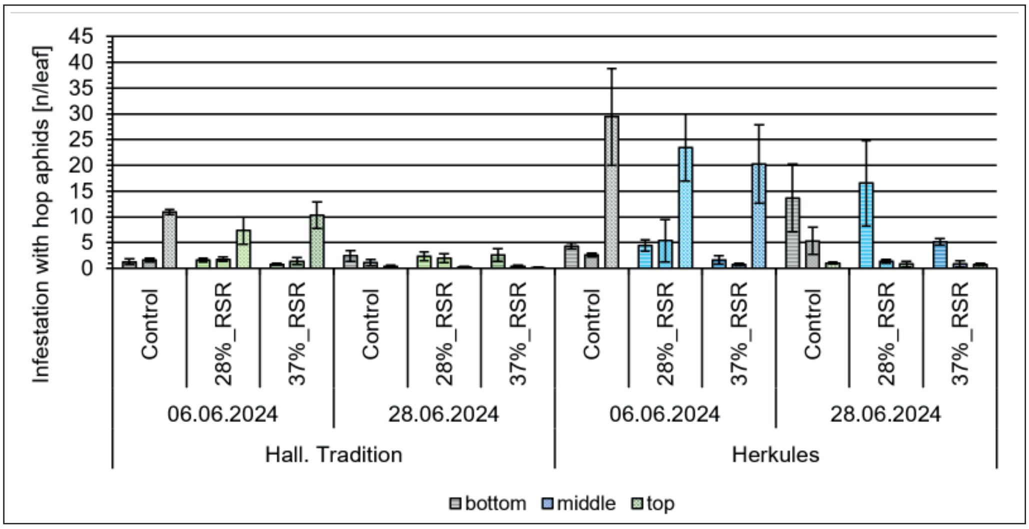

Fig. 10 **Assessment of hop aphid infestation on three leaf layers: bottom, middle, top at two different dates of the two hop varieties of the year 2024**

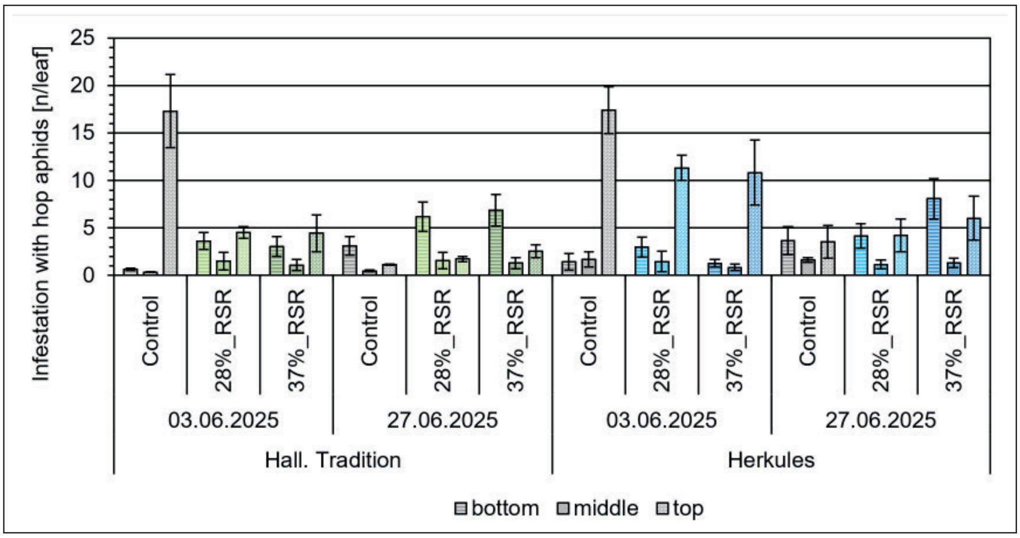

Fig. 11 **Assessment of hop aphid infestation on three leaf layers: bottom, middle, top at two different dates of the two hop varieties of the year 2025**

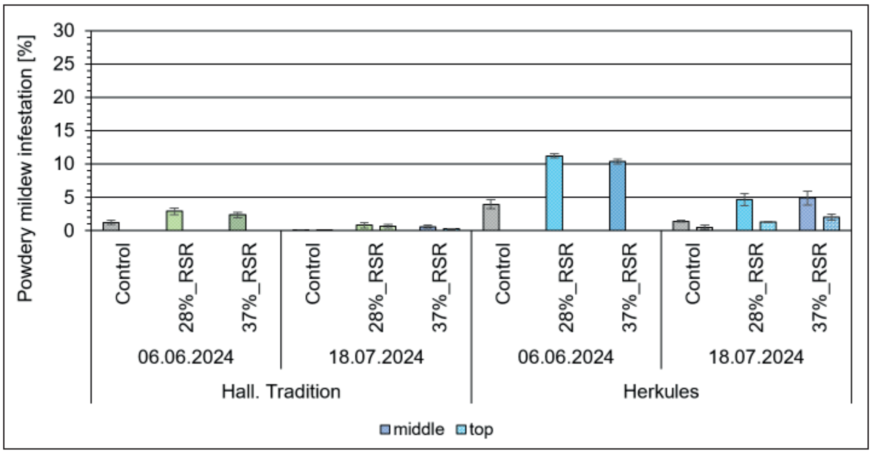

Fig. 12 **Powdery mildew infestation of hop leaves in the middle and top leaf layer at the first and second assessment dates of the year 2024**

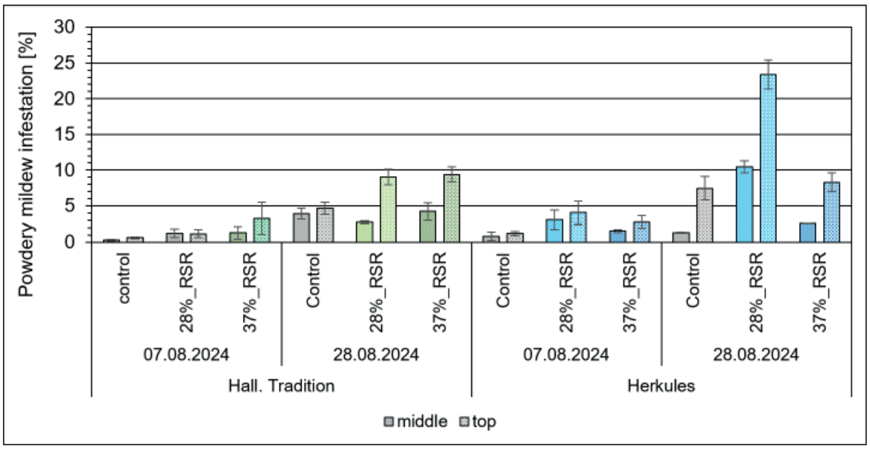

Fig. 13 **Powdery mildew infestation of hop cones in the middle and top leaf layer at the third and fourth assessment dates for the year 2024**

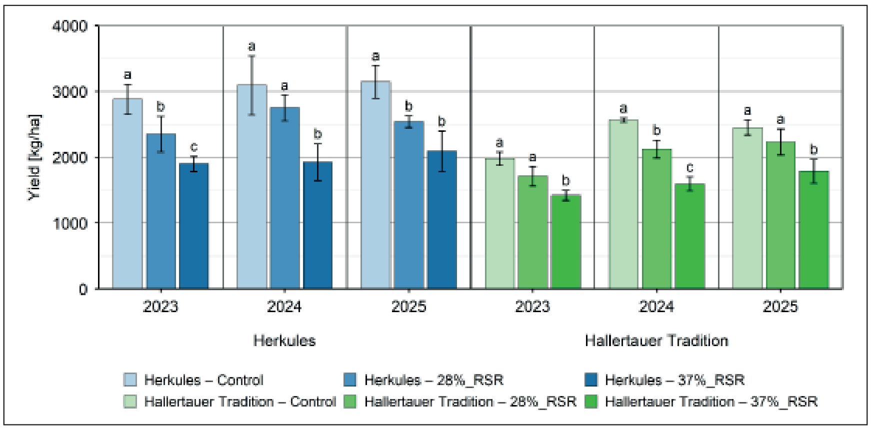

Fig. 14 **Hop yield for the varieties Hallertauer Tradition and Herkules at different shading levels through the agrivoltaics site in 2023, 2024 and 2025**

Activity density varied between 1146,95 and 2887,66 individuals per sampling period. The highest activity densities were recorded in Plot A0 (2436,89) and Plot B2 (2887,66). These plots were located adjacent to forest edges, which likely acted as source habitats influencing local species abundance.

The species composition observed is similar to that expected on intensively farmed arable land. Statistical analysis revealed no significant impact of the agrivoltaic system on the flora or ground beetles. The species composition and activity patterns of the two groups studied are comparable to those of typical hop gardens without PV modules and those with 28 % and 38 % coverage.

4 Discussion

The results indicate that the agrivoltaic system may influence key microclimatic and agronomic parameters in hop cultivation. Lower soil water tension and higher volumetric soil water content suggest that agrivoltaic systems can contribute to soil moisture conservation, with the effect depending on shading intensity. Reduced radiation input is associated with lower evapotranspiration losses, which is reflected in the higher and more persistent soil moisture observed in shaded treatments. At the same time, reduced aboveground biomass under shading is linked to lower plant water demand, which may further contribute to the observed soil moisture patterns [27]. The visibly higher soil moisture in shaded areas supports the assumption of reduced evaporative losses under decreased solar radiation [28].

The increased incidence of powdery mildew under shaded conditions can be attributed to altered microclimatic conditions, particularly reduced light availability, which favours fungal development [29]. Higher infestation levels in moderately shaded treatments compared with strongly shaded treatments may be explained by differences in canopy density and host plant vigour. In addition, the higher susceptibility of HKS compared with HTR is consistent with previously reported varietal differences in disease resistance [30,31].

The lower initial infestation of hop aphids in shaded treatments may be related to altered visual or physical conditions affecting aphid migration from winter hosts to hop plants, although this mechanism remains speculative.

Yield reductions with increasing shading reflect the central role of solar radiation in photosynthetic activity and biomass production [32]. The stronger decline under high shading levels suggests a non-linear response of yield to reduced radiation availability. The lower sensitivity of HTR compared with HKS may be associated with its lower yield potential and its genetic background, which includes older, less intensively bred hop varieties [33].

Changes in hop quality parameters follow a similar pattern, as the formation of secondary metabolites is closely linked to photosynthetic activity and assimilate availability [34]. But these compounds respond more moderate to the reduced sunlight.

The vegetation within and around hop fields reflects typical conditions of intensively managed agricultural landscapes. Species composition is dominated by light- and nutrient-demanding taxa and is strongly shaped by management intensity [14]. Frequent use of plant protection products contributes to reduced species diversity and favours a small number of stress-tolerant generalist species [26,35].

Similarly, arthropod communities are strongly influenced by agricultural practices, resulting in pronounced temporal and spatial variability [36]. Ground beetle assemblages are dominated by generalist species that contribute to biological pest control in agricultural systems [37–38]. In addition, proximity to semi-natural habitats, such as field margins or forest edges, plays an important role in shaping species composition [39].

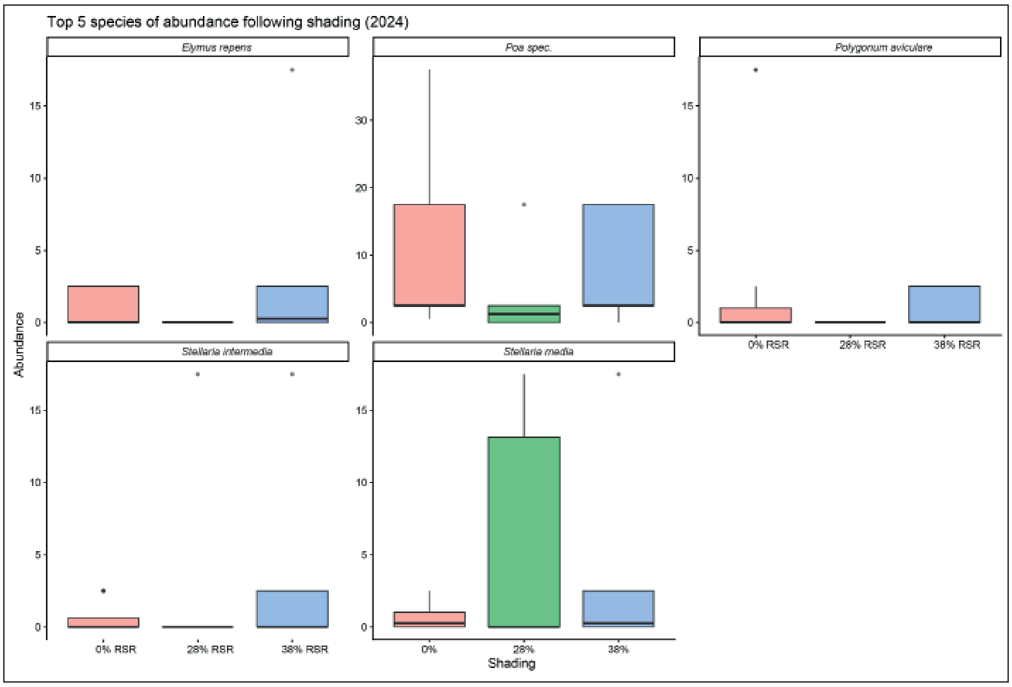

Fig. 15 A comparison of the five most common plant species in relation to the shading treatments in the 2024 trial year

Overall, the results suggest that agrivoltaic systems do not exert a dominant effect on floral and faunal community composition compared with agricultural management and landscape context. Instead, their primary influence appears to be mediated through microclimatic modification, particularly changes in radiation and soil moisture conditions.

5 Conclusions

Agrivoltaic systems in hop cultivation show potential to enhance climate resilience, particularly through improved soil moisture retention. In both trial years, increased soil water content and reduced soil water tension were observed under the photovoltaic modules, with the strongest effects occurring in the drier year 2025.

However, shading resulted in yield reductions, while hop quality parameters remained comparatively stable. In addition, shaded conditions were associated with increased incidence of powdery mildew, whereas hop aphid pressure was reduced.

Biodiversity patterns were primarily driven by agricultural management practices such as soil tillage and plant protection measures, while the influence of the agrivoltaic system was comparatively minor.

Overall, the system offers opportunities to support climate change adaptation in hop production, but requires further optimisation

Table 1 Alpha acid and hop oil content of Hallertauer Tradition and Herkules under different shading levels of the agrivoltaic system in 2023, 2024, and 2025

Hop Variety		Hallertauer Tradition				Herkules			
Year	**Variant**	**α-acids [%]**	**SD**	**Hop Oil [ml/100g]**	**SD**	**α-acids [%]**	**SD**	**Hop Oil [ml/100g]**	**SD**
2023	Control	5,1	± 0,2	0,74	± 0,03	16,3	± 1,3	2,92	± 0,30
	28 %_RSR	5,4	± 0,2	0,88	± 0,08	14,6	± 0,9	2,40	± 0,09
	37 %_RSR	4,9	± 0,3	0,72	± 0,14	14,9	± 0,8	2,25	± 0,24
2024	Control	5,7	± 0,3	1,37	± 0,21	17,1	± 0,9	2,50	± 0,34
	28 %_RSR	5,4	± 0,4	1,27	± 0,14	16,9	± 0,7	2,56	± 0,13
	37 %_RSR	4,8	± 0,2	1,19	± 0,12	16,3	± 0,7	2,31	± 0,10
2025	Control	5,1	± 0,1	0,84	± 0,15	16,4	± 0,9	3,01	± 0,24
	28 %_RSR	5,0	± 0,1	0,94	± 0,12	16,4	± 0,4	2,61	± 0,18
	37 %_RSR	4,6	± 0,3	0,87	± 0,11	15,9	± 1,0	2,46	± 0,12

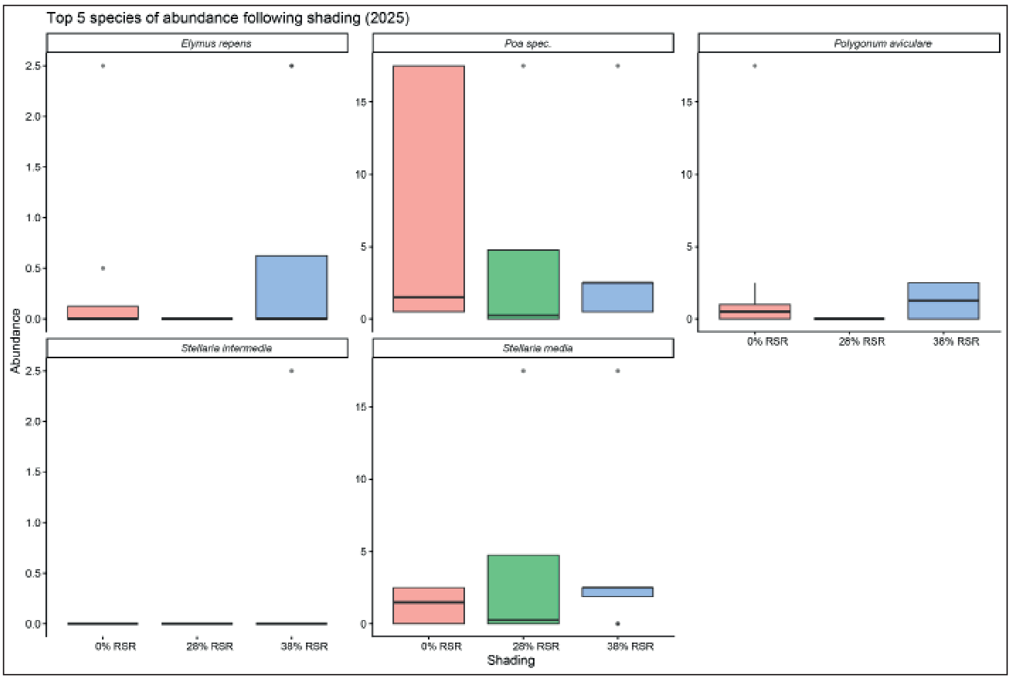

Fig. 16 **A comparison of the five most common plant species in relation to the shading treatments in the 2025 trial year**

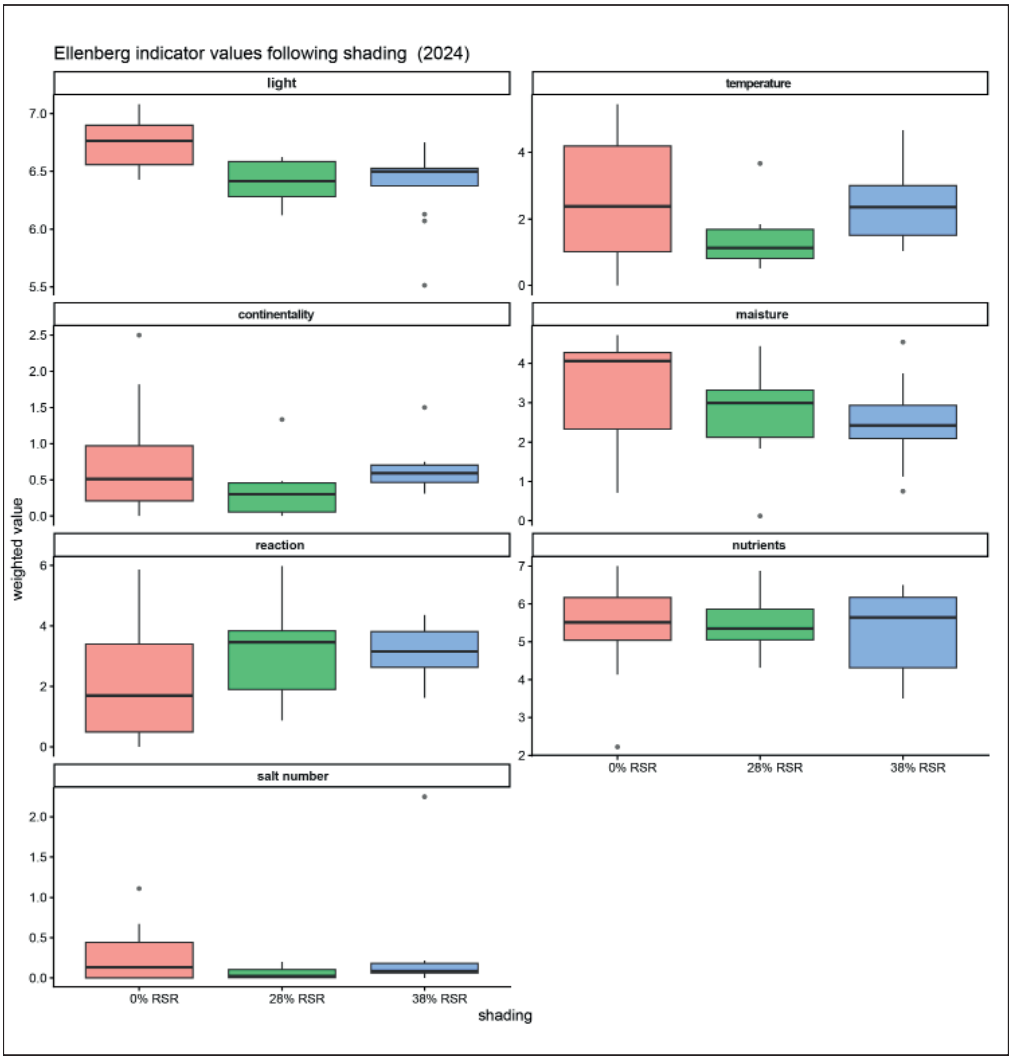

Fig. 17 **Classification of the flora under the AV plant according to the Ellenberg index values to determine site conditions respective to the shading degrees for the trial year 2024**

of shading intensity and variety selection.

Based on initial project results, the agrivoltaic system design was modified, and the module inclination was adjusted from 20 ° to 45 ° to increase radiation availability during the main growing period.

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Conflict of interest

The authors declare there are no conflicts of interest.

CRediT authorship contribution statement

Manuel Riedl: Conceptualization; Formal analysis, Investigation, Visualization, Writing – Original Draft. Sebastian Wagenbrenner: Formal analysis, Investigation, Visualization, Writing – Original Draft. Tobias Troidl: Writing – review & editing. Julia Pauly: Writing – review & editing. Prof. Dr. Michael Beck: Writing – review & editing, Supervision. Prof. Dr. Markus Reinke: Writing – review & editing, Supervision. Johann Portner: Writing – review & editing. Stefan Fuß: Writing – review & editing.

AI statement

The authors used ChatGPT (OpenAI, San Francisco, CA, USA) and DeepL (DeepL SE, Köln, Germany) during manuscript preparation to improve grammar, clarity, and readability. The tools were not used to generate data, perform analyses, or independently interpret results. All scientific content, conclusions, and final wording were reviewed and approved by the authors, who take full responsibility for the manuscript.

6 References

1. Mozny, M., Trnka, M., Vlach, V., Zaldud Z., Cejka, T., Hajkova, L., Potopova, V., Semenov, M. A., Semeradova, D., Büntgen, U.: Climate-induced decline in the quality and quantity of European hops calls for immediate adaptation measures, Nat. Commun., **14** (2023), no. 1, p. 6028, DOI: https://doi.org/10.1038/s41467-023-41474-5.
2. Kohlmann, H., Kastner, A. and Kamm, L.: Der Hopfen: Bedeutung, Anbau und Betriebswirtschaft, Hopfen-Verlag, Wolnzach, 1969.
3. DWD: Lufttemperatur: vieljährige Mittelwerte 1991–2020, Accessed: Feb. 4, 2026, Available at: https://www.dwd.de/DE/leistungen/klimadten-deutschland/mittelwerte/temp_9120_SV_html.html?view=nasPublication&nn=16102
4. Forster, A.; Gahr, A.; Schüll, F. and Bertazzoni, J.: The impact of climatic conditions on the biogenesis of various compounds in hops, BrewingScience, **74** (2021), pp. 160–171, DOI: https://doi.org/10.23763/BrSc21–17gahr.
5. Scharf, J.; Grieb, M. and Fritz, M.: Agri-Photovoltaik, Stand und offene Fragen, Technologie und Förderzentrum im Kompetenzzentrum für nachwachsende Rohstoffe, Straubing, 2021.

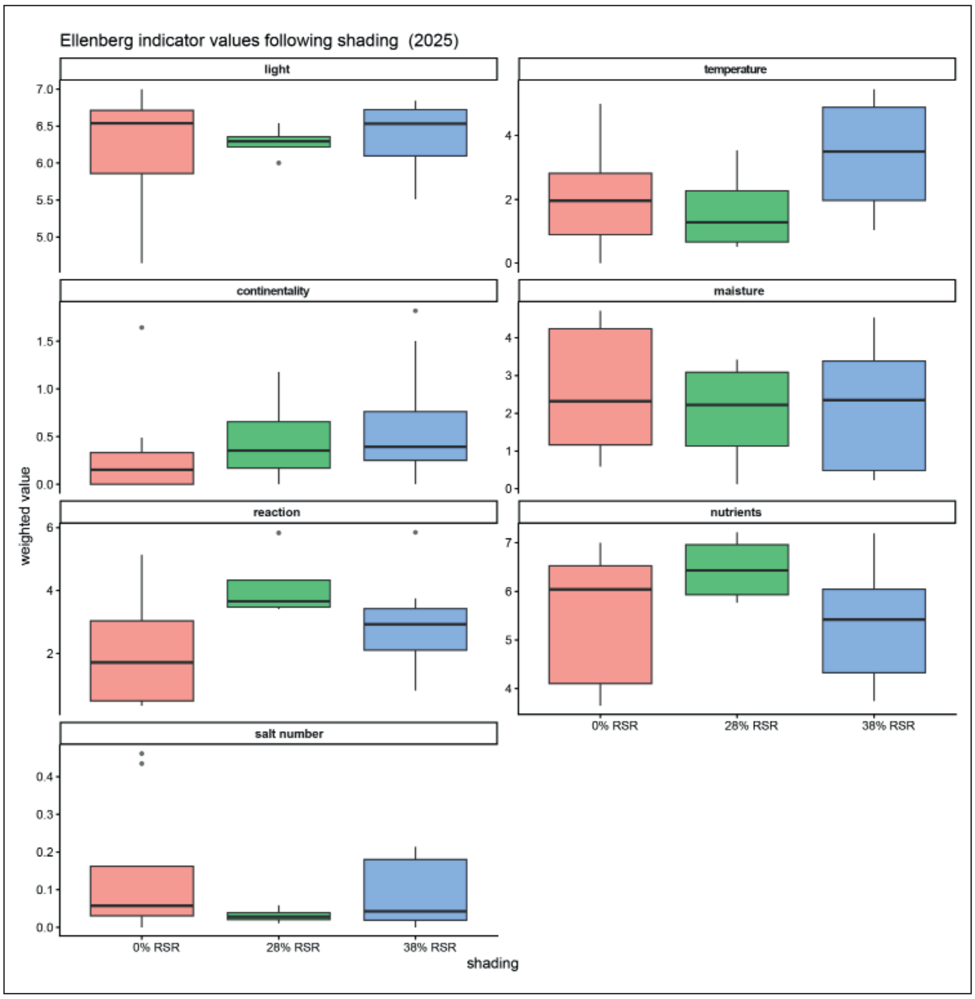

Fig. 18 **Classification of the flora under the AV plant according to the Ellenberg index values to determine site conditions respective to the shading degrees for the trial year 2025**

Table 2 **List of species caught in Carabidae traps, including information on activity density**

Species	A_0	A_28	A_38	B2	B1
Abax carinatus		9,71	16,27		10,05
Abax parallelepipedus	9,71		2,25		
Amara spec.	19,42	6,47	22,11	19,42	13,78
Anchomenus dorsalis	58,25	236,25	93,81	289,88	19,35
Anisodactylus binotatus	9,71	3,24	4,49	2,77	1,96
Anisodactylus signatus				9,71	1,39
Bembidon spec.	9,71			1,39	
Brachinus explodens	58,25	16,18	53,89	220,53	46,29
Calathus fuscipes	38,83	22,65	41,92	51,32	181,00
Carabus coriaceus				6,93	1,96
Carabus granulatus	9,71	3,24	2,25	15,26	
Carabus purpurascens		3,24		1,39	
Dolichus halensis				1,39	
Harpalus affinis	165,05	45,31	71,86	148,40	57,32
Harpalus distinguendus	9,71		11,24	8,32	

Tab. 3 **The key parameters and indices of the ground beetle communities across all study sites throughout the entire study period.**

Indicator	B 2	B 1	A 0	A 28	A 38
Activity density	2887,66	1146,95	2436,89	1381,88	1152,60
Number of species	19,00	15,00	15,00	16,00	16,00
Diversity	1,83	1,70	1,66	1,88	2,05
Evenness	0,62	0,63	0,61	0,68	0,74
individuals	2082,00	763,00	251,00	427,00	576,00
Sample size (n)	19	15	15	16	16

6. Jeyasingh, R. A. I.; Devakumari, M. S. and Manuel, R. I.: Impact of Agrivoltaics irrigation and soil moisture dynamics A review, J. Emerg. Technol. Innov. Res., **12** (2025), no. 10, DOI: https://doi.org/10.56975/jetir.v12i10.570091.
7. Laub, M.; Pataczek, L.; Feuerbacher, A.; Zikeli, S. and Högy, P.: Contrasting yield responses at varying levels of shade suggest different suitability of crops for dual land-use systems: a meta-analysis, Agron. Sustain. Dev., **42** (2022), no. 3, p. 51, DOI: https://doi.org/10.1007/s13593–022–00783–7.
8. EPPO: PP1/215(1) - Sphaerotheca humuli on hop, n.d., Accessed: Feb. 4, 2026, Available at: https://pp1.eppo.int/standards/PP1–215–1
9. EPPO: PP1/022(3) - Phorodon humuli, n.d., Accessed: Feb. 4, 2026, Available at: https://pp1.eppo.int/standards/PP1–022–3
10. European Brewery Convention: 7.4 - Lead Conductance Value of Hops, Powders and Pellets, Accessed: Mar. 25, 2026, Available at: https://brewup.eu/ebc-analytica/hops-and-hop-products/lead-conductance-value-of-hops-powders-and-pellets/7.4
11. European Brewery Convention: 7.10 - Hop Oil Content of Hops and Hop Products, Accessed: Mar. 25, 2026, Available at: https://brewup.eu/ebc-analytica/hops-and-hop-products/hop-oil-content-of-hops-and-hop-products/7.10
12. Braun-Blanquet, J.: Pflanzensoziologie: Grundzüge der Vegetationskunde, 3rd revised and enlarged ed., Springer, Wien, 2012.
13. Ellenberg, H.: Scripta Geobotanica IX: Zeigerwerte der Gefäßpflanzen Mitteleuropas. Verlag Erich Goltze, Göttingen, 1974.
14. Hilbig, W. and Nezadal, W.: Stellarietea mediae (D3) vogelmieren-Ackerunkrautgesellschaften, Selbstverlag der Floristisch-soziologischen Arbeitsgemeinschaft e.V., Göttingen, 2023.
15. Blick, T.: Handbuch landschaftsökologischer Leistungen - Empfehlungen zur aufwandsbezogenen Bewertung, 3rd ed., Selbstverlag der VUBD, n.d.
16. Kiechle, J.: Die Bearbeitung landschaftsökologischer Fragestellungen anhand von Spinnen, in: Trautner, J. (ed.): Methodische Standards zur Erfassung von Tierartengruppen, Margraf Verlag, 1992.
17. Mühlenberg, M. Freilandökologie. 3. Auflage. Quelle & Meyer, Heidelberg, 1993.
18. Schuch, S.; Ludwig, H. and Wesche, K.: Erfassungsmethoden für ein Insektenmonitoring: eine Materialsammlung, BfN-Skripten, no. 565, Bundesamt für Naturschutz, Bonn-Bad Godesberg, 2020, DOI: https://doi.org/10.19217/skr565.
19. Trautner, J.: Laufkäfer - Methoden der Bestandsaufnahme und Hinweise für die Auswertung bei Naturschutz- und Eingriffsplanungen, Margraf Verlag, 1992.
20. Trautner, J. and Fritz, M.-A.: Handbuch landschaftsökologischer Leistungen - Empfehlungen zur aufwandsbezogenen Honorarermittlung, Vereinigung umweltwissenschaftlicher Berufsverbände Deutschlands, 1999.
21. Duelli, P.; Studer, M.; Katz, E.: Minimalprogramm für die Erhebung und Aufbereitung zooökologischer Daten als Fachbeiträge zu Planungen am Beispiel ausgewählter Arthropodengruppen. In: Riecken, U. (Hrsg.): Möglichkeiten und Grenzen der Bioindikation durch Tierarten und Tiergruppen im Rahmen raumrelevanter Planungen. Schriftenreihe für Landschaftspflege und Naturschutz H. 32. Landwirtschaftsverlag, Münster, 1990, pp. 211–22222.
22. Luthardt, V. et al.: Methodenkatalog zum Monitoring-Programm der Ökosystemaren Umweltbeobachtung (ÖUB) in den Biosphärenreservaten Brandenburgs, FH-Eberswalde, 2006.
23. Trautner, J.: Die Laufkäfer Baden-Württembergs. Band 2: Spezieller Teil 2, synoptischer Teil, Ulmer, Stuttgart, 2017.
24. Licht, T.: Böden, Flora und Fauna von Schafkoppeln, Würzburger Geographische Arbeiten, no. 91, 1996, Available at: https://opus.bibliothek.uni-wuerzburg.de/frontdoor/index/index/docId/24385
25. Riedl, M.: Auswirkungen einer Agri-Photovoltaikanlage auf Mikroklima, Pflanzenentwicklung, Pflanzengesundheit, Ertrag und Inhaltsstoffe von zwei Hopfensorten in der Hallertau, Weihenstephan, Bachelor Thesis, 2024.
26. Brandes, D.: Über die Unkrautvegetation der Hopfengärten in der nördlichen Hallertau, Bayerische Botanische Gesellschaft, 1988.
27. Beltz, H.; Brückner, U.; Krüger, E.; Pfleger, I.; Röber, R. and Sourell, H.: Bewässerung im Gartenbau, Ulmer, Stuttgart, 2010.
28. Weselek, A.; Bauerle, A.; Hartung, J.; Zikeli, S.; Lewandowski, I. and Högy, P.: Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate, Agron. Sustain. Dev., **41** (2021), no. 5, p. 59, DOI: https://doi.org/10.1007/s13593-021-00714-y.
29. Schlagenhaufer, S.: Erstellung einer witterungsgestützten Befallsprognose zur Bekämpfung des Echten Mehltaus (*Podosphaera macularis*) an Hopfen (*Humulus lupulus*), Christian-Albrechts-Universität Kiel, PhD thesis, 2010.
30. Gesellschaft für Hopfenforschung (GfH): Herkules, Available at: https://www.hopfenforschung.de/sorte/herkules/
31. Gesellschaft für Hopfenforschung (GfH): Hallertauer Tradition, Available at: https://www.hopfenforschung.de/sorte/hallertauer-tradition/
32. Diepenbrock, W.; Ellmer, F. and Leon, J.: Ackerbau, Pflanzenbau und Pflanzenzüchtung, 4th ed., Eugen Ulmer Verlag, Stuttgart, 2016.
33. Nottebohm, T.: Hopfenliebe: Aroma, Bittere, Sorten, Anbau und optimale Verwendung im Bier. Mit kreativen Rezepten aus aller Welt, Verlag Eugen Ulmer, Stuttgart, 2020.
34. Biendl, M., Engelhard B. Forster A., Gahr A., Lutz A., Mitter W., Schmidt R., Schönberger C.: Hopfen: Vom Anbau bis zum Bier, 1st ed., Fachverlag Hans Carl, Nürnberg, 2016.
35. Bundesamt für Naturschutz: Umfassendes bundesweites Biodiversitätsmonitoring: Ergebnisse einer Vilmer Fachtagung, BfN-Skripten, no. 585, Bundesamt für Naturschutz, Bonn, 2021, DOI: https://doi.org/10.19217/SKR585.
36. Unterseher, M.; Morawetz, W.; Klotz, S. and Arndt, E. (eds.): The canopy of a temperate floodplain forest: results from five years of research at the Leipzig Canopy Crane, Universität Leipzig, Leipzig, 2007.
37. Lövei, G. L. and Sunderland, K. D.: Ecology and Behavior of Ground Beetles (Coleoptera: Carabidae), Annu. Rev. Entomol., **41** (1996), no. 1, pp. 231–256, DOI: https://doi.org/10.1146/annurev.en.41.010196.001311.
38. Bayerische Landesanstalt für Landwirtschaft (LfL): Laufkäfer in der Agrarlandschaft. vielfältig – zahlreich – nützlich, Freising, 2019.
39. Schröter, L. and Irmler, U.: Lauf- und Kurzflügelkäfer der Ackerflächen, no. 35.

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