



HAL
open science

Impacts of punctual solar trackers on soil biodiversity in agricultural lands

Valentine Leroy, Guillaume Decocq, Paul-Emile Noirot-Cosson, Ronan Marrec

► To cite this version:

Valentine Leroy, Guillaume Decocq, Paul-Emile Noirot-Cosson, Ronan Marrec. Impacts of punctual solar trackers on soil biodiversity in agricultural lands. *Geoderma*, 2025, 453, pp.117147. 10.1016/j.geoderma.2024.117147 . hal-04850776

HAL Id: hal-04850776

<https://hal.science/hal-04850776v1>

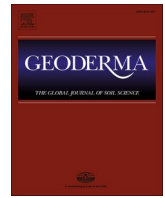
Submitted on 20 Dec 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



Impacts of punctual solar trackers on soil biodiversity in agricultural lands

Leroy Valentine ^{a,b,*}, Decocq Guillaume ^b, Noirot-Cosson Paul-Emile ^{a,1}, Marrec Ronan ^{b,*}

^a Groupe OKWind SAS, Zone du Haut Montigné, 35370 Torcé, France

^b UMR CNRS 7058 "Ecologie et Dynamique des Systèmes Anthropisés" (EDYSAN), Université de Picardie Jules Verne, 1 rue des Louvels, 80000 Amiens, France

ARTICLE INFO

Handling Editor: Y. Capowicz

Keywords:

Photovoltaic
Agrivoltaic
Trackers
Biodiversity

ABSTRACT

The development of renewable energy technologies is growing rapidly, with solar energy being the most promising source. Agrivoltaics in particular offers the advantage to combine crop and energy production on the same land. While many studies have looked at the impact of ground-mounted solar power panels on uncultivated grassland, very few have focused on agrivoltaic structures, and none on dual axis trackers with bi-dimensional turning mount-holding panels and limited ground anchorage. Our study focused on the relative impact of such trackers (via anchorage constraint to farming practices, and mobile shading) on the physical, chemical and biological soil features in both wheat croplands and meadows relative to farming practices known for impacting these features. Using a PLS-PM analysis, we show that despite altered chemical conditions near the tracker and the higher specific plant richness brought by the PV structure, thereby changing environmental conditions, there are no significant effects on organisms compared to agricultural practices. Comparing hay meadows and wheat fields suggests varied impacts, prompting the need for further comparative studies across different agricultural contexts.

1. Introduction

The development of renewable energy technologies is predicted to increase in the coming decades as a way of coping with both energy demand and greenhouse gas reduction (Dincer, 2000; Panwar et al., 2011). Of these, the use of solar energy is the most promising option (IPCC, 2011), but it requires vast surface areas. Priority is given to install photovoltaic (PV) panels on rooftops, in urban areas, on brownfield sites, and on artificial infrastructure, but these still represent a restricted surface. In this context, agrivoltaics (or agrivoltaics) has emerged as a promising option, as it combines agricultural and photovoltaic production on the same land (Dupraz et al., 2011). It may further offer various services to agriculture such as physical protection of crops from climate change and meteorological hazards, new income and greater energy autonomy of the farm. Although agrivoltaics is supposed to act in synergy with agriculture, it also raises other environmental and societal issues that need to be carefully addressed to ensure sustainable development (Hernandez et al., 2019).

Within this framework, most available studies dealt with ground-mounted solar power panels. It has been shown for example that, as a

result of reduced solar irradiation under solar panels, diurnal soil temperature decreases (Armstrong et al., 2016; Marrou et al., 2013; Weselek et al., 2021), suggesting a buffering effect on a daily scale (Barron-Gafford et al., 2019). Soil moisture has been found higher under panels, most likely due to reduced evapotranspiration related to lower temperatures (Marrou et al., 2013), and possibly to lower wind speed (Armstrong et al., 2016). These microclimatic effects can also affect crop yields in a negative or positive way, depending upon the context (Weselek et al., 2021).

Similar results have been reported for grasslands, where plant biomass increased in some studies because of shade effect that helps maintaining higher soil moisture levels (Hassanpour Adeh et al., 2018) but decreased in some others because of the microclimate change (Armstrong et al., 2016; Lambert et al., 2023). Compared with the agronomic impact of PV installations, impact on biodiversity has received little attention so far (Menta et al., 2023; Schweiger and Pataczek, 2023; Uldrijan et al., 2022), in spite of its major role in various agroecosystemic processes (e.g., soil storage of organic matter and carbon, nutrient recycling, and crop pest regulation (Bardgett and Van Der Putten, 2014; Jouquet et al., 2014)). Most available studies concern

* Corresponding authors at: UMR CNRS 7058 "Ecologie et Dynamique des Systèmes Anthropisés" (EDYSAN), Université de Picardie Jules Verne, 1 rue des Louvels, 80000 Amiens, France.

E-mail addresses: leroyvalentine9@gmail.com (L. Valentine), ronan.marrec@u-picardie.fr (M. Ronan).

¹ These authors contributed equally.

grasslands. Some show that the presence of solar panels reduced plant species richness below panels (Bai et al., 2022; Lambert et al., 2023), soil microbial activity (Lambert et al., 2021; Moscatelli et al., 2022) or biomass (Lambert et al., 2023) and the abundance of soil arthropods (Lambert et al., 2023; Menta et al., 2023). As a result of the sensibility of soil organisms to changes in microclimatic conditions (Barnett and Facey, 2016), these studies conclude that alter precipitation patterns and air circulation occurring under PV panels determine a cascade of processes responsible for an uneven spatial heterogeneity of soil fertility, including organic matter level (Moscatelli et al., 2022). The level of influence of PV installations on microclimate, and therefore on the abovementioned impacts, may depend on the PV technology such as its mobility/tracking capacity (Suuronen et al., 2017) and on the panels height, which modifies the shadow size and its spatial dynamics, as well as air circulation. As a result, the impact of the trackers studied here is expected to be lower on microclimate than that of fixed solar panels. In contrast, the effects of PV installations on biodiversity in the context of annual croplands remain largely unknown, even though around 50 % of PV infrastructures are expected to be ground-mounted systems on agricultural land (Chatzipanagi et al., 2023; Dinesh and Pearce, 2016).

In farmlands, agricultural practices strongly affect soil biodiversity, either directly by reducing organisms' vitality or even by killing them (e.g., the use of pesticides or tillage), or indirectly by modifying soil physical and chemical properties (Campbell et al., 2017; Hussain et al., 2009; Lichtenberg et al., 2017; Tsiafouli et al., 2015). Chemical properties (e.g., soil organic carbon and nitrogen content, pH) and physical properties (e.g., soil compaction and moisture, size of mineral particles) directly influence soil fertility and plant growth (Bronick and al, 2005), which may in turn affect abundance and functional relationships among other taxa (Menta and Remelli, 2020) such as earthworms (Edwards and Arancon, 2022), arthropods, or microorganisms (Coleman et al., 2017).

Our study aims to assess direct and indirect (via physical and chemical characteristics of the soil and its vegetation cover) effects of punctual solar trackers on soil biodiversity in farmlands, while accounting for agricultural practices, with a special focus on the impact of shading and ground anchoring. More specifically, we hypothesize that physical and chemical conditions will be altered at the vicinity of the tracker due to a modification of the microclimate caused by shading, the development of spontaneous vegetation and soil disturbance during tracker installation, thus altering the activity of soil communities. Focusing on hay meadows and winter wheat fields in western France, we explored how solar trackers impact environmental conditions and subsequently quantified the relative importance of direct and indirect effects of trackers and agricultural practices on soil biodiversity using Partial Least Squares Path Modelling (PLS-PM).

2. Materials and methods

The 11 study sites were located in Brittany and Pays-de-la-Loire regions, in western France, where solar trackers have been installed between two and seven years: five in hay meadows and six in winter wheat fields. The survey took place between March 14th and August 21st, 2023, when mean air temperature daily rainfall and solar radiation were 16.02 °C, 3.02 mm and 219Wm⁻², respectively (weather data: Meteoromatics Weather API). Average cloud coverage during this period of time at the centre of experimentation (Rennes) was of 4.5 oktas (<http://www.historique-meteo.net/>). Soils were mainly Brunisols in Brittany (including sandstones, shale, and aeolian silts) and Calcisols in Pays-de-la-Loire (<https://geosas.fr>).

We studied PV trackers of Groupe OKwind® (Fig. 1A), which consist of 117-m²-PV panels supported at the top of a 7-m-high mast, so that cropping remains possible beneath. The PV surface moves during the day to track and always face the sun, thanks to a double rotating axis. Panels are composed of bifacial monocrystalline solar cells. These trackers have a small footprint (6.25 m²), but cultivation is not possible in the immediate vicinity of the concrete base, allowing weeds to develop, particularly in cropland (Fig. 1B).

2.1. Field survey and biodiversity data collection

Each protocol was applied to the 11 sites, except two hay meadows where microorganism activity could not be assessed due to disruptions caused by agricultural work (see [Supplementary Material S1 and S2](#)). We selected one solar tracker at each site. When several trackers were implemented, we gave preference to the one with the least external biases (e.g., shading by a hedge or building, edge effect from an adjacent field, ground deformation). We took samples at three different distances and orientations from the mast basis (Fig. 2): (i) 1 m to the north and to the south (always shaded, and in wheat fields, soil not cultivated but with weeds); (ii) 8 m to the north (shaded only part of the day); (iii) 8 m to the south (never shaded); and (iv) 35 m away at the same distance from the edge as the tracker (control points outside the zone of tracker influence, in terms of both shading (Fig. 3) or installation work); hence four sampling locations. Edges were at least at 20 m from the tracker and the control point.

2.1.1. Earthworm abundance

Earthworms were sampled by hand-sorting one soil block (L × W × H: 20 × 20 × 25 cm) at each sampling location at two different periods at least two weeks apart, between March 14th to April 6th. Earthworms were distributed among four ecological groups following (Bouché, 1972): epigeic, red anecic, black anecic, and endogeic. Sampling periods were kept separated in statistical analyses.

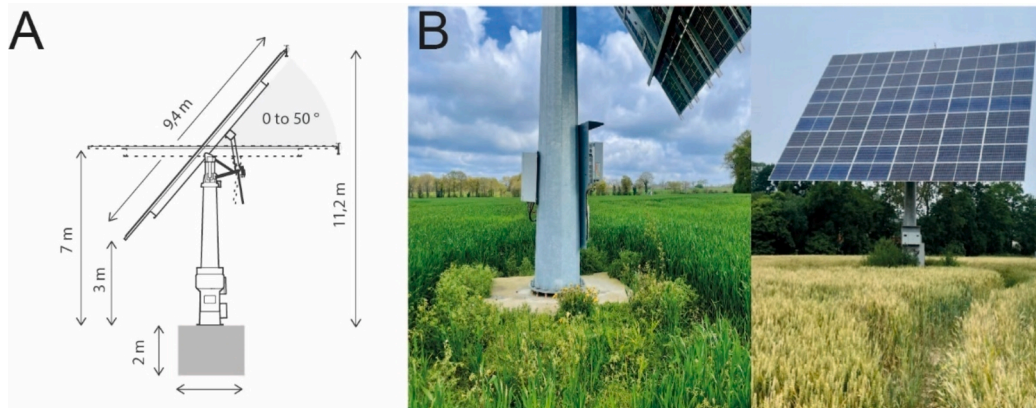


Fig. 1. (A) Technical tracker specifications and (B) impact on vegetation of the difficulty of cultivating in the vicinity of the concrete base.

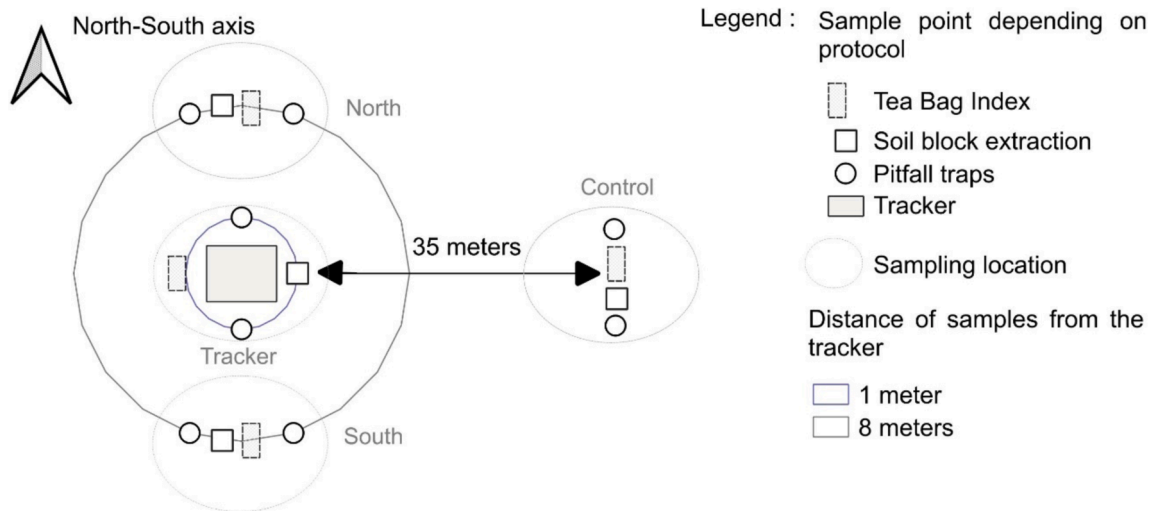


Fig. 2. Sampling design including green tea bags and rooibos tea bags per sampling location to estimate microorganism activity; one soil block extraction per sampling location to measure earthworm abundance: two pitfall traps per sampling location to measure arthropod activity-density.

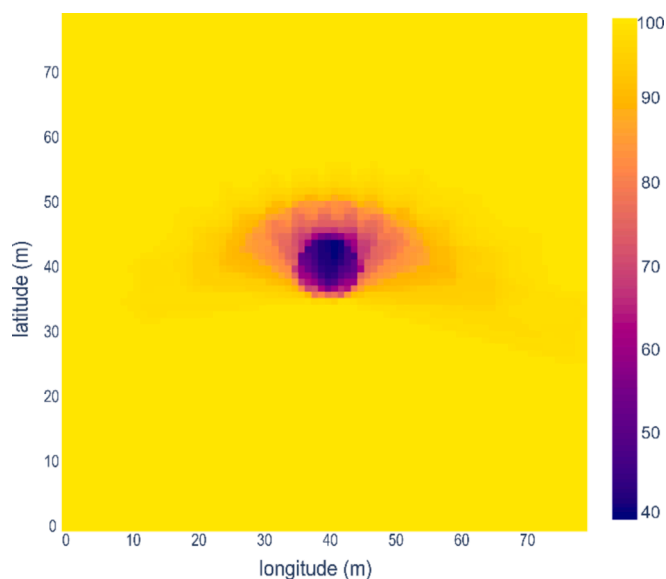


Fig. 3. Spatial simulation of total received radiation ratio (%RR colour scale) over the ground near the tracker during the sampling period. The simulated case study is based on 219Wm^{-2} solar radiation in the area of Rennes (the largest city and weather station in the centre of our study area). The mast corresponds to the central pixel. The figure shows that from 35 m onward, shading is non-existent.

2.1.2. Arthropod activity-density

Surface dwelling springtails, woodlice, millipedes (Julida), and pill millipedes (Glomerida) were trapped using 9-cm diameter pitfall traps at two sampling points 4.5 m apart from each other per sampling location. Traps were filled with 200 mL of water saturated with salt and a few drops of detergent to reduce surface tension and protected from litter and rainfall by an aluminium roof. Traps were set for seven consecutive days before collection and at three periods: (i) from April 17th to April 28th (all but one hay meadow), (ii) from May 2nd to May 24th, and (iii) from June 12th to June 27th. Individuals were identified to the order level (Geoffroy, 1993; Hopkin, 2007; Sutton, 2013), and the activity-density of each taxon was quantified. Values of the two pitfall traps (sampling points) and the sampling periods were kept separated in statistical analyses.

2.1.3. Soil microbial activity

To measure decay rates of organic matter, we used the tea bag index (TBI) method, a standard protocol used as an indicator of soil microbial activity (Keuskamp et al., 2013). Three bags of both Lipton green tea (EAN 87 10,908 90,359 5) and Lipton rooibos tea (EAN 87 22,700 18,843 8) were weighted dry and clean, and buried into the soil at 8 cm deep at each sampling location ($n = 12$ in total per field) and let for 45 ± 3 days (overall, from June 5th to August 22nd). Tea bags were then retrieved, cleaned, and dried at 75°C for 48 h or until bag's weight remains constant. In total, 60 green tea bags and 60 rooibos tea bags were buried over all sampling locations in wheat fields, compared to 36 green tea bags and 36 rooibos tea bags over all sampling locations in meadows. We calculated two TBI parameters: stabilisation (S), the degree to which litter breaks down, which reflects the proportion of non-decomposed, hydrolysable labile fraction that is remaining after incubation; and the decomposition rate (k), the degree and rate by which the labile fraction of the plant material is decomposed (Keuskamp et al., 2013). The stabilisation results in a deviation of the actual decomposed fraction a from the hydrolysable fraction H , and can be interpreted as the inhibiting effect of environmental conditions on the decomposition of the labile fraction:

$$S = 1 - \frac{a_g}{H_g} \quad (1)$$

where a_g is the decomposable fraction and H_g is the hydrolysable fraction of green tea. The decomposable fraction of rooibos tea (a_r) is calculated from the hydrolysable fraction of rooibos tea (H_r) and the stabilisation factor S :

$$a_r = H_r(1 - S) \quad (2)$$

The decomposition rate k is thus calculated using the following exponential decay function:

$$W_r(t) = a_r e^{-kt} + (1 - a_r) \quad (3)$$

where $W_r(t)$ is the weight of the rooibos tea after incubation time t , a_r is the labile and $1 - a_r$ is the recalcitrant fraction of rooibos tea. Values of S and k for the individual tea bags per sampling location were kept separate for statistical analysis.

2.2. Environmental variables

2.2.1. Farming management

Farming practices of the 2022–2023 cropping period were recorded by means of standardised farmer surveys for all fields. For winter wheat fields, the following data were collected: amount of nitrogen ($\text{kg}\cdot\text{ha}^{-1}$), number of pesticide doses applied, tillage intensity. For hay meadows, the following data were collected: number of mowings, average time between mowings episodes, fertiliser type (ranked in order of intensity level: no fertiliser = 0; lagoon water = 1; manure = 2; mineral nitrogen = 3).

2.2.2. Soil sampling and physico-chemical analyses

To characterise the physical and chemical fertility of the soil, 500 g of fresh soil were collected using a 20 cm deep auger at each sampling location between mid and the end of March 2023. The samples were dried and then analysed by the INRAE soil analysis laboratory in Arras (France). Coarse fractions (gravel, pebbles) and fine fractions (proportion of silt, sand, and clay) were quantified ($\text{g}\cdot\text{kg}^{-1}$). Total limestone (CaCO_3), organic carbon (OC) and total nitrogen (N_{tot}) were measured from the fine fraction ($\text{g}\cdot\text{kg}^{-1}$). In the field, we also measured soil compaction using a compaction metre at 8, 16, 24, and 32 cm (kPa; Spectrum Technologies, Inc.), soil pH using a pH metre at the soil surface (Extech Instruments), and soil moisture using TMS-4 dataloggers (TOMST) at each visit of sampling locations. For soil moisture, a 45-minute average was calculated based on three records. A raw moisture signal (50–200 MHz) was inverted and scaled to the numerical range of 1–4095 (raw TDT data). To transform this relative value into volumetric soil moisture (%), specific calibration was used based on (Wild et al., 2019).

2.2.3. Vegetation

In both winter wheat fields and hay meadows, at each sampling point, plant height was measured over an area of 1 m^2 , 0.5 m each side of the sampling point in March, April, May, and June. Plant species richness was calculated based on the identification of all plants over an area of 8 m^2 centred on the two 1 m^2 quadrats once between May and June 2023. In winter wheat only, vegetation cover was quantified over an area of 1 m^2 , 0.5 m each side of the sampling point in March, April, May, and June.

2.2.4. Shade conditions

We estimated the shading intensity per sampling location over each sampling period, as the inverse of the ratio between cumulative radiation reaching on the ground during the given period and the theoretical cumulative radiation received without the tracker's shade over the same period (%RR), as in (Noirot-Cosson et al., 2022), using hourly radiation data (Meteomatics Weather API) (Fig.3).

2.2.5. Microclimate conditions

We implemented a parallel experiment to relate soil and air temperature and relative air humidity data to our measured variables, using relationships of shading intensity with: relative humidity on the one hand, and temperatures on the other hand. In this experiment, local air (15 cm above ground) and soil (5 cm below ground) hourly temperatures were recorded by TMS-4 dataloggers (TOMST) in four winter wheat fields in Brittany, from March 18th to July 7th 2023. Data loggers were distributed evenly around the four trackers, in the eight main cardinal directions, at distances of 5, 10, 15, 20 and 35 m from the mast to cover all shading conditions. We recorded these microclimatic data at the same time as field sampling campaigns i.e., fifteen days per month, from 18 March to April 1st for earthworms; from April 15th to April 30th, from May 05th to May 20th, from June 1st to June 15th for arthropods; and from June 15th to June 30th for microorganisms. We extrapolated microclimate data at our four sampling plots by averaging measured data at the two nearest plots and used records at 35 m south to

the tracker for the control plot).

2.3. Statistical analyses

All statistical analyses were performed in R version 4.3.3 (R. Core Team, 2024). Data from winter wheat fields and hay meadows were analysed separately.

2.3.1. Influence of sampling location

2.3.1.1. Environmental and biological analyses. The effect of sampling location ($n = 4$) on environmental variables and soil biodiversity was quantified using linear mixed-effects models (LMMs) or generalised linear mixed-effects models (GLMMs) and the *glmmTMB* package (Magnusson et al., 2017). Gaussian error distribution models were used for all environmental variables, except for soil moisture, for which a beta distribution model was used, and vegetation cover, stones, and gravel, for which Tweedie distribution models were used. Poisson distribution models were used for all soil biodiversity variables except for stabilisation (S), for which a Gaussian error distribution model was used, and decomposition rate (k), for which a beta distribution model was used. Distribution families were chosen using the function 'fitdist' of the *fitdistrplus* package (Delignette-Muller and Dutang, 2015) and the *DHARMA* package (Hartig, 2017). We included the field ID as a random intercept term in all models to account for potential spatial autocorrelation between sampling locations occurring in the same field. Where results were significant (p -value < 0.05), a Tukey multiple comparison test was applied using the *emmeans* package (Lenth, 2020) to detect which sampling locations differed from each other.

2.3.1.2. Microclimate analyses. Two effects were quantified using linear mixed-effects models (LMMs) using the same procedure as in the previous section. First, the effect of shading intensity on microclimatic conditions and second, the effect of sampling location on microclimatic conditions. Gaussian error distribution models were used for the two models. We included the field ID as a random intercept term in all models to account for potential spatial autocorrelation between sampling locations occurring in the same field. Where results were significant (p -value < 0.001), a Tukey multiple comparison test was applied to detect which sampling locations differed from each other.

2.3.2. Respective importance of solar trackers and farming management on soil biodiversity

2.3.2.1. Relationships between environmental variables. Correlations among environmental variables were quantified using Pearson's tests and the *corrplot* package (Wei et al., 2017), and illustrated using principal component analyses (PCA), separately for wheat fields and hay meadows, using the *factoextra* package (Kassambara, 2017). To avoid over-representation of highly correlated variables in the PCA, we removed variables correlated above a 0.80 threshold. These results were also used as a first approach to define latent variables in PLS-PM analyses (see below).

2.3.2.2. PLS-PM analysis. Relationships between (i) farming practices, tracker's influence on (ii) shading intensity and (iii) environmental conditions near its basis, (iv) vegetation, (v) soil physical properties, (vi) soil chemical properties, and (vii) soil biodiversity were modelled with partial least squares path modelling (PLS-PM) analysis (Sanchez, 2013). PLS-PM are part of path analyses, which are multivariate methods that examine and measure the multiple connections and influences among variable groups (Tenenhaus and Tenenhaus, 2011). This approach is particularly well suited for small samples (Chaput, 2007).

A PLS-PM is made up of two sub-models, namely the inner model and the outer model. The outer model describes the relationships between a

set of manifest variables (MVs) (i.e., observed variables) and a synthetic latent variable (LV) constructed from these manifest variables (usually representing a concept that cannot be measured directly). The LV and its associated MVs form a group called a “block”. Next, the inner model describes the relationships between LVs. In our study, PLS-PMs were made of seven blocks:

- The “farming management” LV, built from the following MVs for winter wheat: amount of nitrogen, number of pesticide doses applied, tillage intensity; and from the following MVs for hay meadows: number of mowings, average time between mowings, fertiliser type.
- As trackers have different types of impact on the environment, we have split the variables concerned into two LVs. Thus, the “shading conditions” LV was built from the following MV: shading intensity and the “tracker basal area” LV was built based on a binary MV defined as to represent the proximity to the tracker structure (0 = more than 1 m; 1 = 1 m from the tracker). As PLS-PM models are based on ordinary regressions, they can handle binary variables (Jakobowicz, 2008).
- The “vegetation” LV, built from the following MVs for wheat fields: vegetation cover, plant species richness, and plant height; and from the following MVs for hay meadows: average height and species richness.
- The “soil physical properties”, built from the following MVs: soil compaction at 8, 16, 24, and 32 cm, stone, gravel, clay, silt, and sand content, and soil moisture.
- The “soil chemical properties” LV, built from the following MVs: total carbon, nitrogen, organic matter, and limestone contents, C/N ratio, and pH.
- The “soil biodiversity” LV. Three separate models were constructed for both wheat fields and hay meadows, by changing the “soil biodiversity” block content. For earthworm abundance, the block was represented by the individual abundances of epigea, endogea, black anecic and red anecic earthworms. For microbial activity, the block was represented by the decomposition rate (k) and stabilisation (S) indicators. For arthropod activity-density, the block was represented by individual activity-densities of springtails, woodlice and millipedes.

We modelled the relationships between all LVs except farming management, shading conditions and tracker basal area. As we expected strong relationships between certain connected LVs, we linked:

- farming management to vegetation, soil physical properties and soil chemical properties, since soil use for farming inevitably leads to changes in soil properties such as nutrient status, pH, organic matter content, weed diversity, and physical properties (Powelson et al., 2011);
- shading conditions to the same blocks since it influences microclimatic conditions, including temperature, air humidity, soil moisture, and light availability (Armstrong et al., 2016; Tanner et al., 2020), and hence may affect soil processes and plant communities beneath the photovoltaic panels (Lambert et al., 2021);
- tracker basal area to the same blocks. The area at the foot of the concrete base is heavily impacted by the installation of the solar trackers and cannot be cultivated, as this would damage the structure as well as farm equipment. Particular ecological and environmental conditions can develop here, leading to specific soil conditions and weed development.
- soil biodiversity LV was linked to the six other LVs.

Given the aim of the study and to avoid an overload of links between LVs, we did not include links between vegetation, soil physical properties and soil chemical properties. A correlation value was used to measure the association between two LVs, and the relationship between each

MV and its associated LV was considered as a linear regression. The soil biodiversity block was constructed in a formative way, meaning that the LV was constructed by its MVs. All other blocks were constructed in a reflective way, meaning that the MVs were caused by, or reflected, their LV.

The final PLS-PMs were built following three steps (Sanchez, 2013): (1) An initial model was fitted with a fixed inner model reflecting the functioning of fields and all possible MVs (Fig. 4A); (2) In a second model, we ensured the unidimensionality of the LVs (i.e., all MVs associated with a LV must be positively correlated to the LV). Then, all MVs negatively correlated to their LV were multiplied by -1 to respect unidimensionality before running the final model (Fig. 4B); (3) In a final model, MVs weakly correlated (i.e., <0.4 ; Sanchez, 2013) with their LV were removed (Fig. 4C). Model quality was assessed by two indicators: goodness-of-fit (GoF) as a compromise between inner and outer models (average communality \times average R^2 of each block), considered good if > 0.70 , and the R^2 for dependent LVs, considered moderately good ≥ 0.5 . To confirm the validity of our models on the collinearity of variables, we calculated the variance inflation factor (VIF) and verified it was < 10 for each model (Bennaceur and Chafik, 2019; Lacroux, 2009).

3. Results

A total of 549 earthworms, 15,994 springtails, 213 woodlice, and 51 millipedes were collected. After excluding damaged tea bags, 91 green tea bags and 86 rooibos tea bags were retrieved (Table 1).

3.1. Influence of sampling location on biodiversity and environmental conditions

3.1.1. Environmental and biological variables

Most biodiversity and environmental variables were influenced by the sampling location irrespective of land cover type. In both winter wheat fields and hay meadows, plant species richness and shading intensity were higher at 1 m from the tracker. On the contrary, pH, soil nitrogen, carbon, and organic matter contents were higher at 35 m from the tracker (and also at 8 m south in winter wheat fields, except for pH). In winter wheat fields, weed cover and plant height were respectively higher and lower at 1 m; soil limestone content was highest at 35 m. Finally, in hay meadows, soil C/N ratio was lower at 1 m and 8 m north to the tracker, while soil limestone content was higher at 1 m from the tracker. For more details, see Supplementary Material, Table S3 for statistical results and Fig. S3.1 to 3.6 for graphs of results.

In terms of biodiversity, neither earthworm abundance nor millipede activity-density significantly differed among sampling locations irrespective of land cover type, while woodlouse activity-density (Fig. 5) was higher at 1 m from the tracker in both wheat fields and hay meadows. In winter wheat fields, springtail activity-density was lower at 1 m, contrary to decomposition rate (k) (Fig. 6) and stabilisation (S) which were lower at 35 m. In hay meadows, springtail activity-density and decomposition rate (k) were higher at 35 m and 8 m north. For more details, see Supplementary Material, Table S3 for statistical results and Fig. S3.7 for graphs of results.

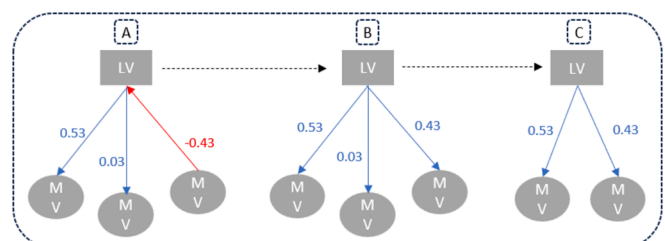


Fig. 4. Three-step procedure of the PLS-PM analysis.

Table 1
Total number of sampled individuals per taxonomic group or number of green/rooibos tea bags.

Type of crop	Number of								
	red anecic earthworms	black anecic earthworms	epigeic earthworms	endogeic earthworms	springtails	woodlouse	millipeds	green tea bags	rooibos tea bags
Wheat	59	25	19	114	14,998	68	20	60	59
Meadow	50	42	12	191	996	145	31	31	27

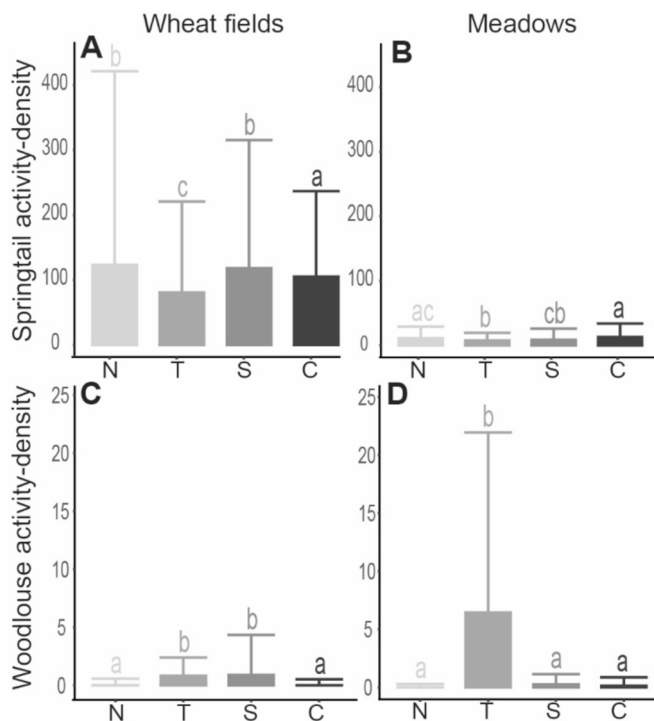


Fig. 5. Mean (\pm SD) springtail (A-B) and woodlouse (C-D) activity-density in winter wheat fields and in hay meadows. Letters indicate significant differences between locations obtained by Tukey tests ($p < 0.05$). N: 8 m North; T: 1 m from the tracker base; S: 8 m South; C: 35 m control.

3.1.2. Microclimate

In model 1 and model 2, results were significant for all variables (Table 2). In model 1, delta relative humidity was higher at 1 m and 8 m north to the tracker (Fig. 7). Soil and air temperature were lower at 1 m and 8 m north to the tracker. Compared to the control, temperature and humidity were stronger at the tracker basis than at the north location.

3.2. Relative importance of solar trackers and farming management on soil functioning

3.2.1. Relationships between environmental variables

Prior to PCA analysis we removed five of the 23 variables for winter wheat fields (Table. S4.1). and six of the 22 variables for hay meadows (Table. S4.2) due to strong correlations ($r > 0.80$). In winter wheat fields and hay meadows, soil compaction at 16 cm was excluded as this variable was correlated with soil compaction at 8 and 24 cm, and nitrogen and carbon contents were excluded, as they were correlated with organic matter content. In winter wheat only, stone and sand contents were excluded as they were correlated with gravel content. In hay meadows only, soil compaction at 32 cm was excluded as this variable was correlated with soil compaction at 24 cm and limestone content and average time between mowings were excluded as they were correlated with pH and number of mowings, respectively.

For winter wheat fields, we retained the first two PCA axes, accounting for 42.6 % of the total variance (Fig. 8A; Table S5.1). The first

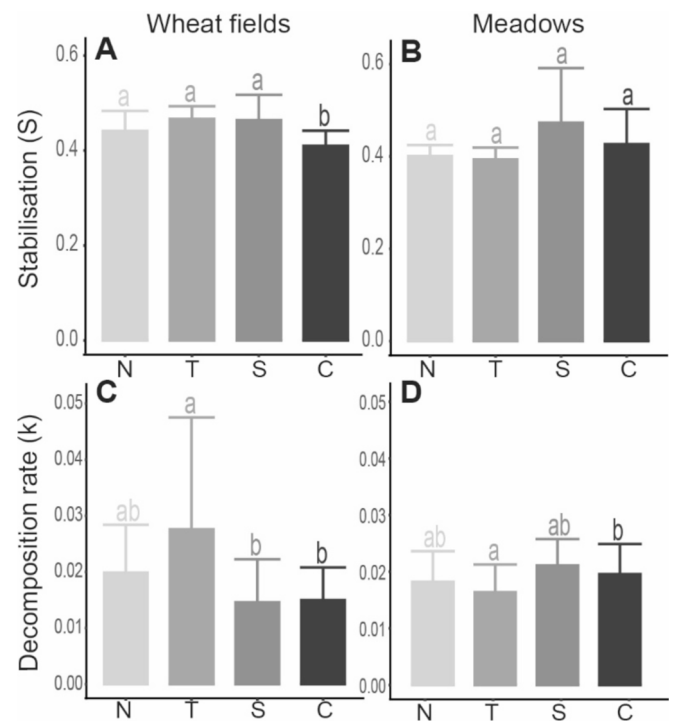


Fig. 6. Mean (\pm SD) stabilisation (S; A-B) and decomposition rate (k; C-D) in winter wheat fields and in hay meadows. Letters indicate significant differences between locations obtained by Tukey tests ($p < 0.01$). N: 8 m North; T: 1 m from the tracker base; S: 8 m South; C: 35 m control.

Table 2
Results of linear mixed models.

Parameters	Model 1 – Shading intensity		Model 2 – Location	
	Chisq	P-value	Chisq	Sampling point
Shading intensity	–	–	25,949	<0.001
Delta relative humidity	5820.8	<0.001	5820.8	<0.001
Delta soil temperature	286.28	<0.001	29,066	<0.001
Delta air temperature	586.27	<0.001	1664.3	<0.001

axis (24.5 %) separates sampling points with high tillage intensity, plant species richness and C/N ratio, from those with high soil compaction and high silt and nitrogen contents. The second axis (18.1 %) mainly opposed sampling sites with high soil nitrogen and organic matter contents, soil compaction and plant height, to those with high silt content. The barycentre for tracker basis stands out from the other locations.

In hay meadows, we also retained the first two PCA axes, accounting for 49.0 % of the total variance (Fig. 8B; Table S5.2). Axis 1 (26.5 %) mainly separates the most mown sampling sites, the wettest soils and highest clay and organic matter contents, from sites with more deeply compacted soils and higher sand and gravel contents. Axis 2 (22.5 %)

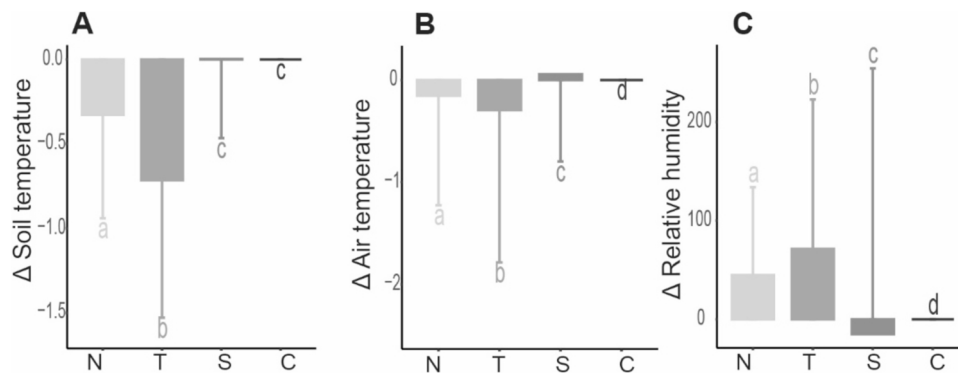


Fig. 7. Mean values of temperature (°C; A-B) and relative humidity (raw TDT data; C). Letters indicate significant differences between locations obtained by Tukey tests post_hoc ($p < 0.01$). N = North, T = Tracker basis, S = South, C = Control.

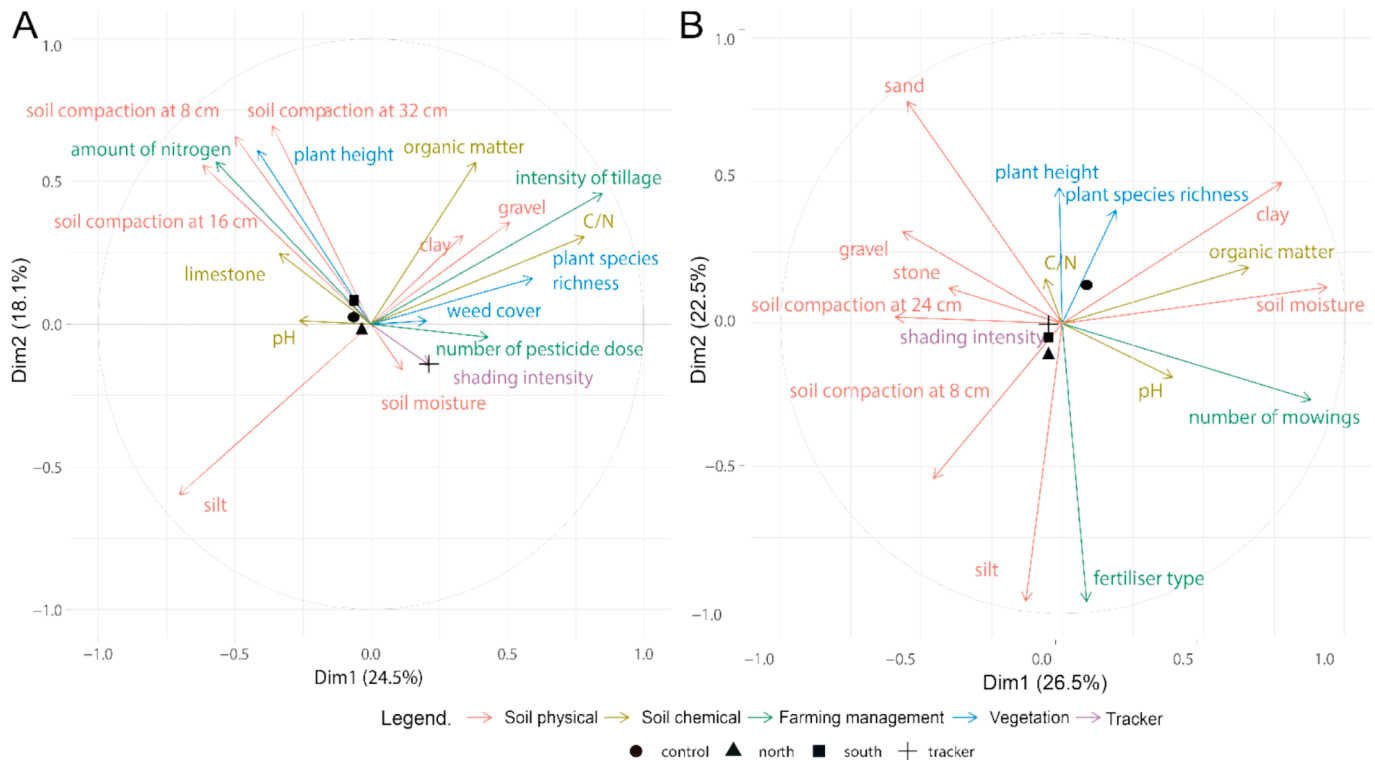


Fig. 8. Results of principal component analyses (PCA) illustrating the relationships between the environmental variables considered in this study, for winter wheat fields (A) and hay meadows (B). Colour groups correspond to the latent variables considered in subsequent PLS-PM analyses. Symbols correspond to the barycentre of each sampling site.

mainly opposed sampling sites with more compacted soil surface, higher silt content and organic fertilisation, to sites with higher sand content. The barycentre control plots is well separated from the other locations.

3.2.2. PLS-PM

The GoF coefficients for all six PLS-PM (abundance of earthworms, activity-density of arthropods, and microbial activity in either winter wheat fields or hay meadows) were at least 0.52 (Table S6), corresponding to good model predictions (Sanchez, 2013). Results of cross-loadings indicated that all reflective blocks were meaningful and strongly constructed in each model (Table S7).

3.2.2.1. Earthworm abundance. The PLS-PM (Fig. 9A) for winter wheat fields revealed that the majority of the variation in earthworm abundance was due to red anecic and endogeic earthworms. The inner model showed that earthworm abundance was well described by its latent

variables (LVs; $R^2 = 0.33$), but that no LV was significantly correlated with earthworm abundance. All reflective LVs were very well described by their manifest variables (MVs; $\rho > 0.83$). Vegetation was very well explained by its related exogenous LVs ($R^2 = 0.81$), mainly positively influenced by being in the tracker basal area, and negatively by farming management. Soil physical properties were very well explained by their related exogenous LVs ($R^2 = 0.83$), mainly positively influenced by farming management. Soil chemical properties were well explained by their related exogenous LVs ($R^2 = 0.33$), mainly negatively influenced by farming management. When both direct and indirect effects of farming management and tracker-related LVs were taken into account (Fig. 10, farming management was the main driver of earthworm abundance in winter wheat fields, followed by tracker basal area.

The PLS-PM (Fig. 9B) for hay meadows revealed that the majority of the variation in earthworm abundance was due to endogeic earthworms. The inner model showed that earthworm abundance was well described

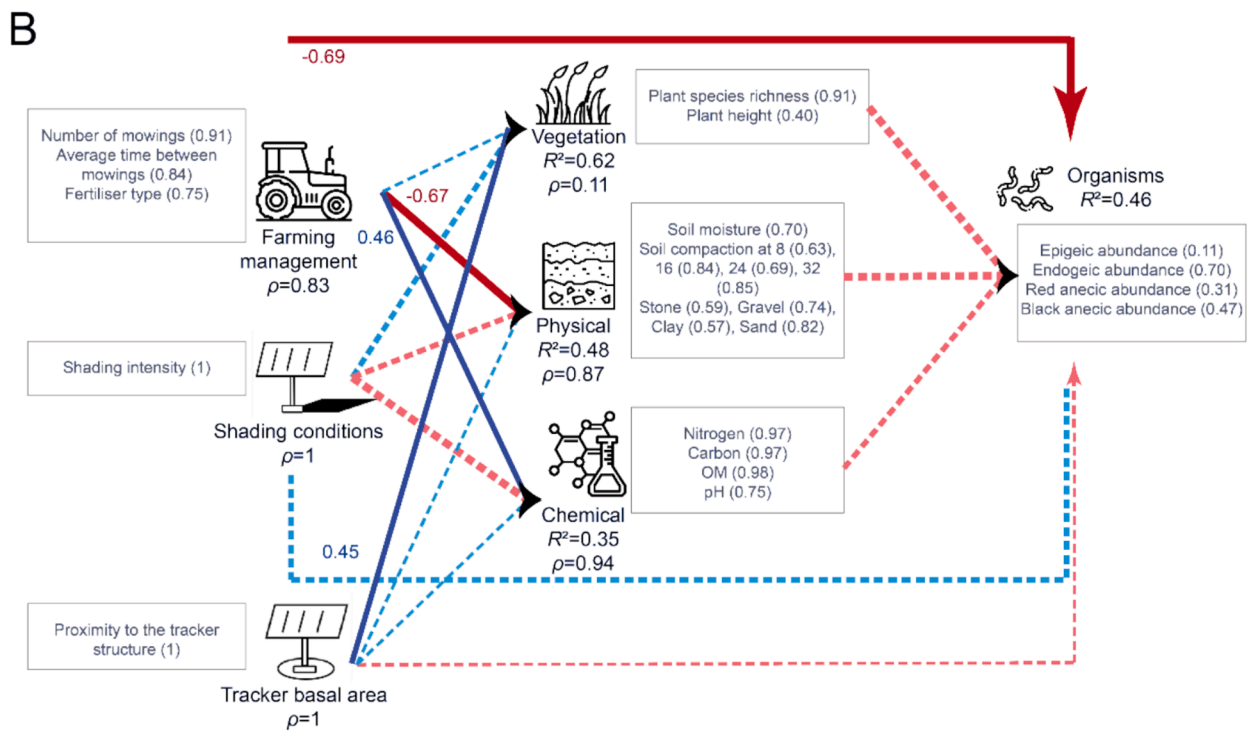
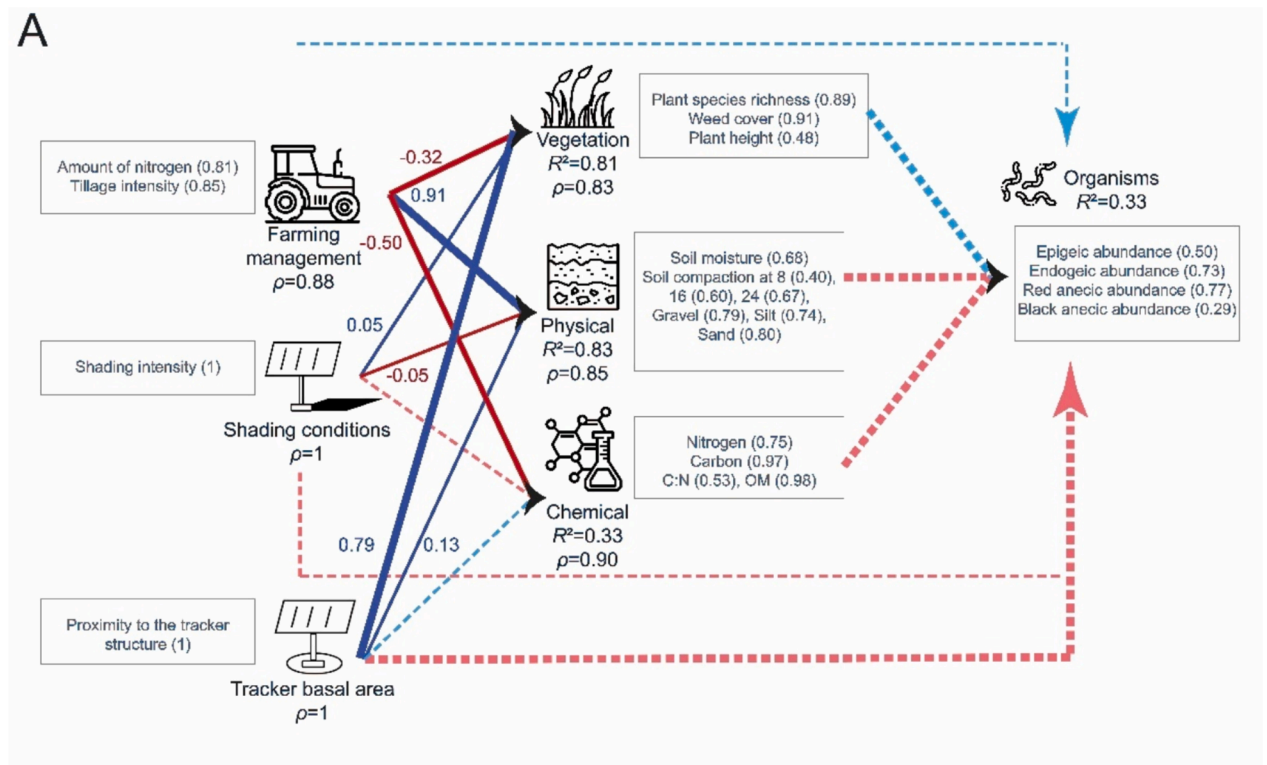


Fig. 9. PLS model describing the relationships between earthworm abundance (“Organisms” LV) in winter wheat fields (A) and hay meadows (B): R^2 is the coefficient of determination for an endogenous latent variable, representing the proportion of variance explained by associated exogenous latent variables. The value in brackets represents the cross-loadings. The width of the arrows represents the level of significance of the link. Blue and red arrows show positive and negative correlations, respectively. Dashed arrows represent non-significant links. The value over each arrow is the correlation coefficient (path effect) between exogenous LVs and the LV organisms. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

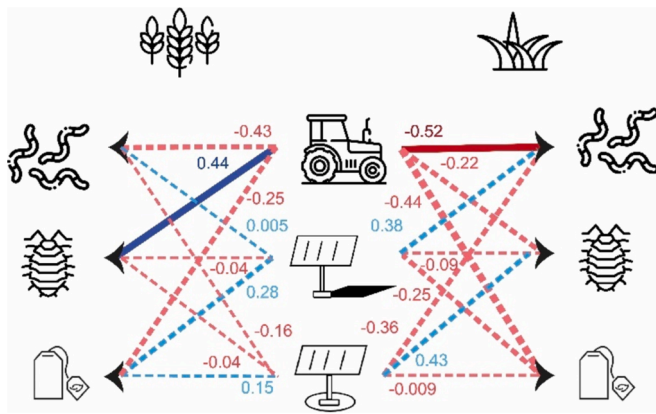


Fig. 10. PLS-Pm results of total effects (indirect and direct) of LVs trackers and total effects of LV farm management on both hay meadows and winter wheat fields on LVs of each organism (earthworms, arthropods, microorganisms). The value in brackets represents the level of correlation between the manifest variable and its latent variable. The dotted arrows represent a non-significant value of the correlation (path effect) between the exogenous LVs and the LV organisms. The size of the arrows represents the level of significance. Blue arrows represent a positive correlation while orange and red arrows represent a negative correlation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

by its latent variables ($R^2 = 0.46$). Only the farming management was significantly negatively correlated with earthworm abundance. All reflective LVs were very well described by their MVs ($\rho > 0.83$) except vegetation ($\rho = 0.11$). Vegetation was well described by its related exogenous LVs ($R^2 = 0.81$), mainly positively influenced by being in the tracker basal area. Soil physical properties were very well described by their related exogenous LVs ($R^2 = 0.83$), mainly negatively influenced by the farming management. Soil chemical properties ($R^2 = 0.33$) were well described by their related exogenous LVs, mainly positively by the farming management. When both direct and indirect effects of farming management and tracker-related LVs were taken into account (Fig. 12), farming management was the main driver of earthworm abundance in hay meadows, followed by shading intensity and tracker basal area.

3.2.2.2. Arthropod activity-density. In winter wheat fields, the majority of the variation in arthropod activity-density was due to springtails, followed by millipedes (Fig. 11A). The inner model showed that arthropod activity-density was weakly described by its LVs ($R^2 = 0.24$). All LVs were not significantly correlated with arthropod activity-density, except for farming management and soil physical properties influencing arthropod activity-density positively and negatively, respectively. All reflective LVs were very well described by their MVs ($\rho > 0.60$). Vegetation was very well explained by its related exogenous LVs ($R^2 = 0.83$), mainly positively influenced by tracker basal area, and secondarily by farming management and shading conditions. Soil physical properties were well described by their related exogenous LVs ($R^2 = 0.39$), mainly negatively influenced by farming management, and then by tracker basal area. Soil chemical properties were well described by their related exogenous LVs ($R^2 = 0.46$), mainly positively influenced by the farming management, and then by tracker basal area, but negatively influenced by shading conditions. When both direct and indirect effects of farming management and tracker-related LVs were taken into account (Fig. 10), farming management was the main driver of arthropod activity-density in winter wheat fields.

In hay meadows, the majority of the variation in arthropod activity-density was due to woodlouse (Fig. 11B). The inner model showed that arthropod activity-density was poorly described by its LVs ($R^2 = 0.18$), none of the LV being significantly correlated with arthropod activity-density. All reflective LVs were well described by their MVs ($\rho > 0.60$). Vegetation was well explained by its related exogenous LVs ($R^2 =$

0.71), positively influenced by tracker basal area and shading intensity, and negatively by farming management. Soil physical properties were very well described by their exogenous LVs ($R^2 = 0.77$), mainly negatively influenced by farming management. Soil chemical properties were weakly explained by their related exogenous LVs, mainly influenced negatively by shading intensity but positively by farming management and tracker basal area. When both direct and indirect effects of farming management and tracker-related LVs were taken into account (Fig. 10), tracker basal area was the main driver of arthropod activity-density in hay meadows, followed by farming management.

3.2.2.3. Microbial activity. In winter wheat fields the variation in microbial activity was equally explained by the two indicators (Fig. 12A). The inner model showed that microbial activity was well described by its LVs ($R^2 = 0.32$) but no LV significantly correlated with microbial activity. All reflective LVs were very well described by their MVs ($\rho > 0.76$). Vegetation was very well explained by its related exogenous LVs ($R^2 = 0.67$), mainly positively by tracker basal area and farming management. Soil physical properties were well explained by their related exogenous LVs ($R^2 = 0.47$), mainly negatively by farming management and shading conditions. Soil chemical properties were well explained by their related exogenous LVs ($R^2 = 0.37$), positively by tracker basal area, and negatively by shading conditions and farming management. When both direct and indirect effects of farming management and tracker-related LVs were taken into account (Fig. 10), shading intensity was the main driver of microbial activity in winter wheat, followed by farming management and tracker basal area.

In hay meadows, the majority of the variation in microbial activity was due to the stabilisation indicator (Fig. 12B). The inner model showed that microbial activity was quite well described by its LVs ($R^2 = 0.41$), but that no LV significantly correlated with microbial activity. All reflective LVs were very well described by their MVs ($\rho > 0.90$). Vegetation was very well explained by its related exogenous LVs ($R^2 = 0.80$), positively influenced by all of these MVs. Soil physical properties were very well explained by their related exogenous LVs ($R^2 = 0.98$), mainly negatively influenced by farming management. Soil chemical properties were well explained by their related exogenous LVs ($R^2 = 0.58$), positively by farming management and tracker basal area, and negatively by shading conditions. When both direct and indirect effects of farming management and tracker-related LVs were taken into account (Fig. 10), farming management was the main driver of microbial activity, followed by shading conditions.

4. Discussion

To our knowledge, this study is one of the first to address the impact of agrivoltaic PV structures on soil organisms, especially including earthworms (Lambert et al., 2023; Menta et al., 2023). It extends previous work on grasslands (Bai et al., 2022; Choi et al., 2023; Hassanpour Adeg et al., 2018; Vervloesem et al., 2022) to annual croplands, winter wheat fields in our case. We focused on the taxonomic groups responsible for recycling soil organic matter in soils to assess whether the presence of solar trackers adds supplementary constraints on soil biodiversity relative to agricultural practices, or on the contrary creates more favourable conditions. Our results clearly show that solar trackers do influence environmental conditions (i.e., physical and chemical properties of the soil and characteristics of the vegetation) at an intensity depending upon the distance from the tracker, which in turn affects soil biodiversity. However, farming practices remain the main determinant of biodiversity patterns and outweigh the influence of solar trackers whatever the taxa and land cover type considered.

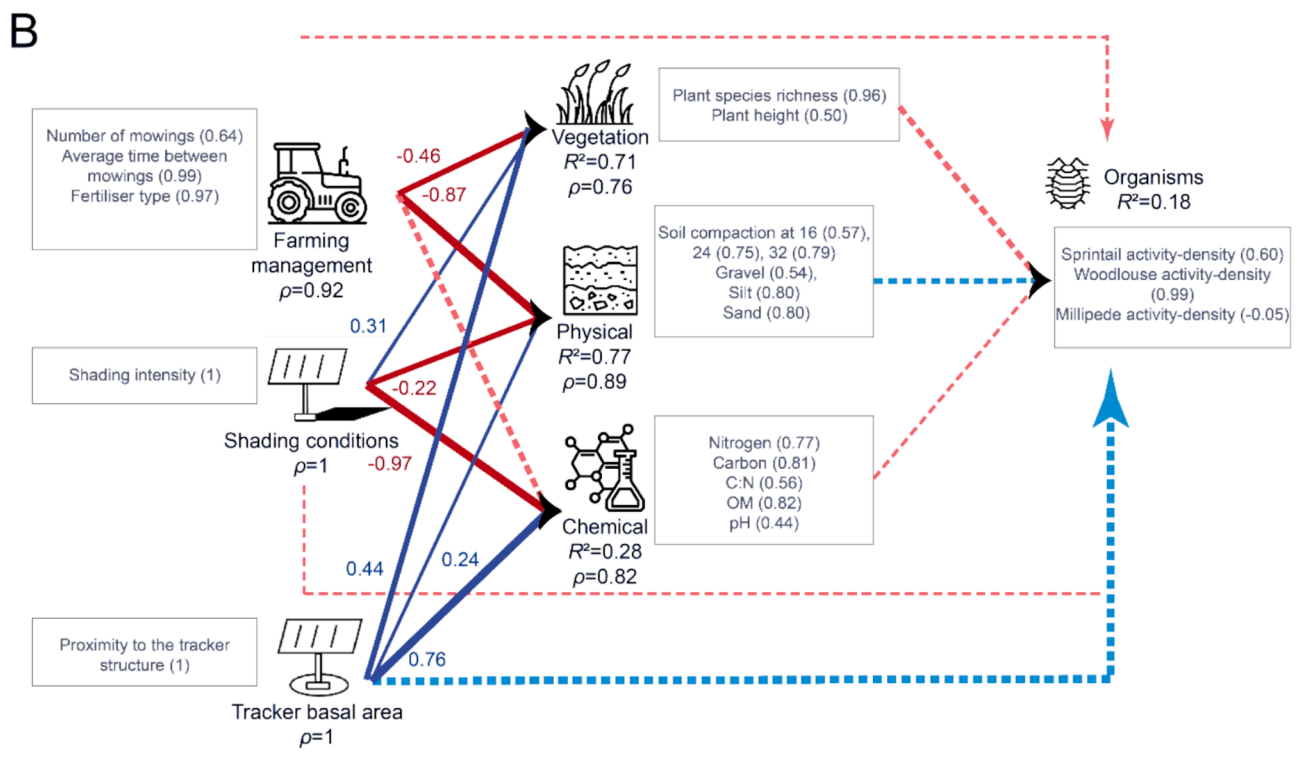
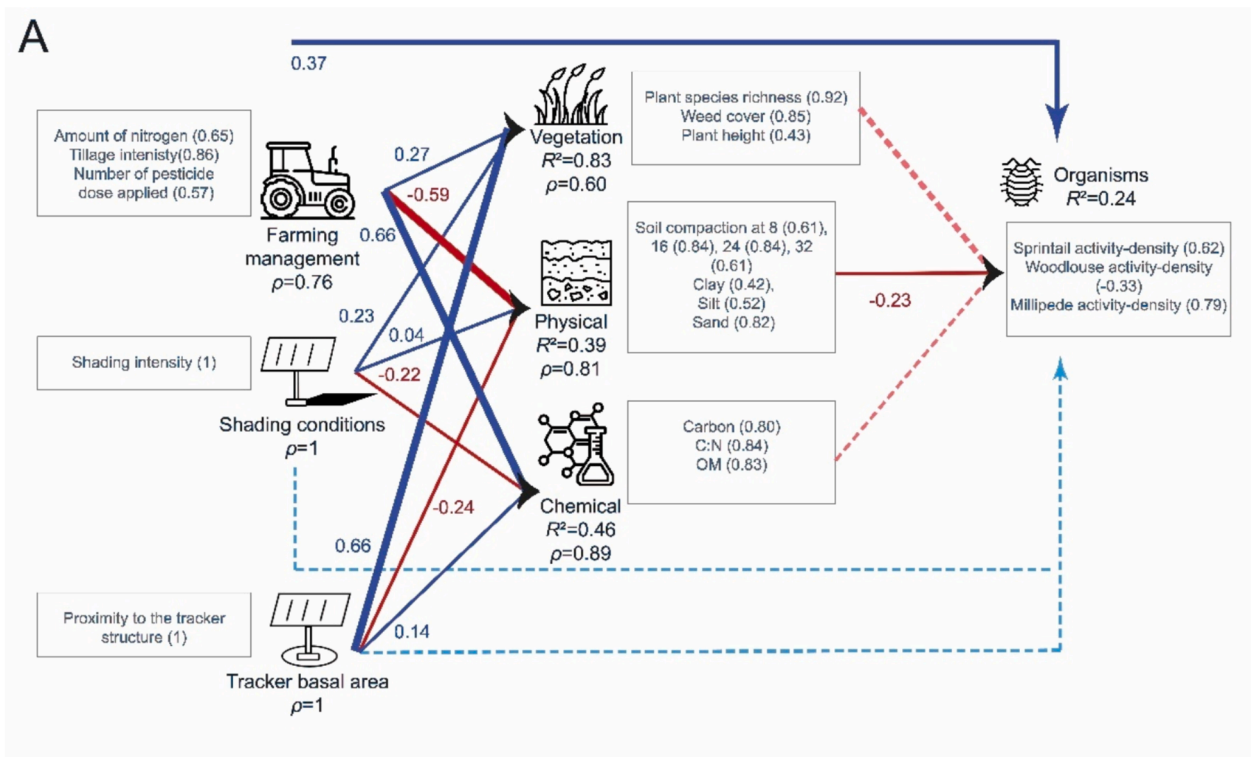


Fig. 11. PLS model describing the relationships between arthropod activity-density (“Organisms” LV) in winter wheat fields (A) and hay meadows (B): R^2 is the coefficient of determination for an endogenous latent variable, representing the proportion of variance explained by associated exogenous latent variables. The value in brackets represents the cross-loadings. The width of the arrows represents the level of significance of the link. Blue and red arrows show positive and negative correlations, respectively. Dashed arrows represent non-significant links. The value over each arrow is the correlation coefficient (path effect) between exogenous LVs and the LV organisms. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

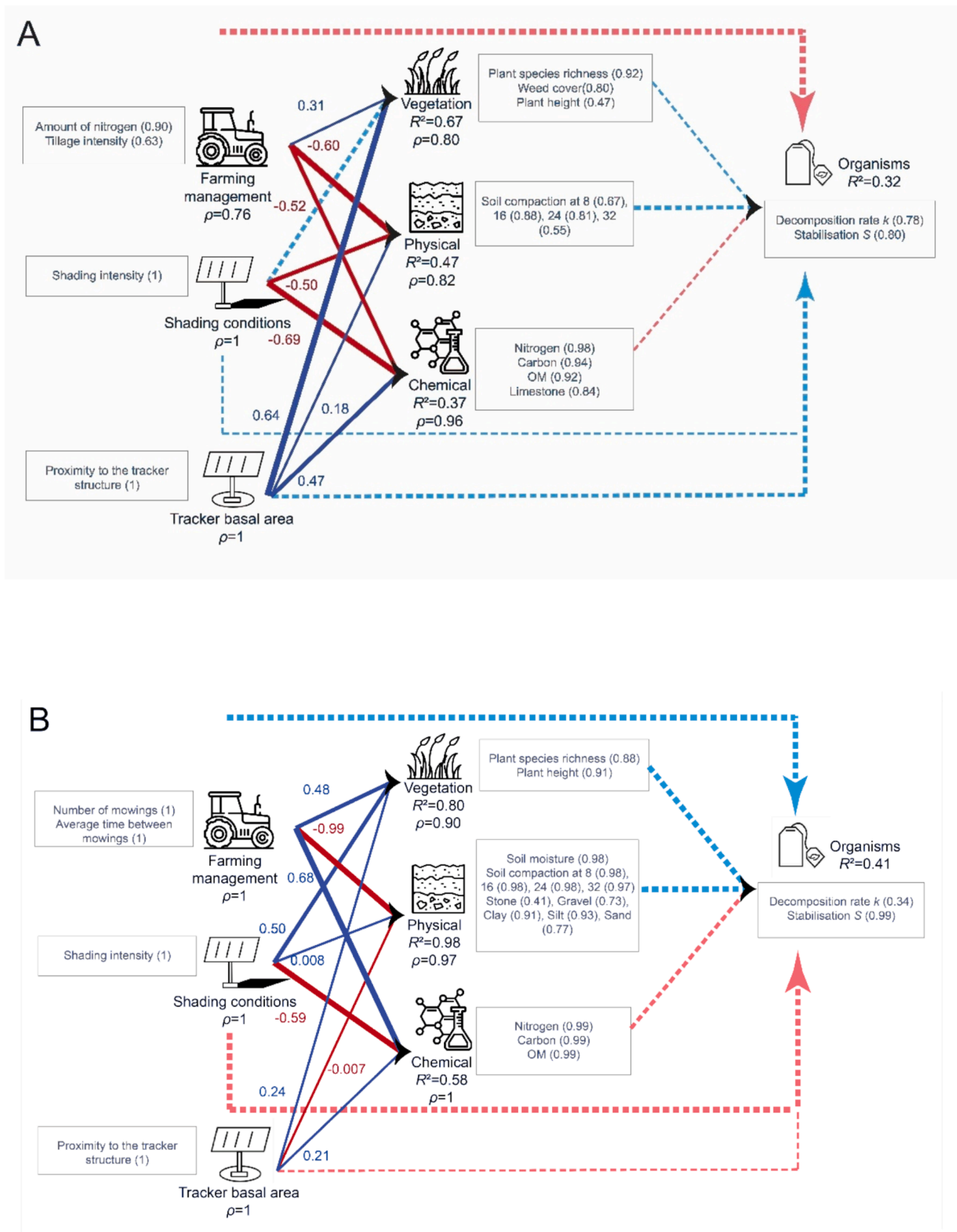


Fig. 12. PLS model describing the relationships between microbial activity (“Organisms” LV) in winter wheat fields (A) and hay meadows (B): R^2 is the coefficient of determination for an endogenous latent variable, representing the proportion of variance explained by associated exogenous latent variables. The value in brackets represents the cross-loadings. The width of the arrows represents the level of significance of the link. Blue and red arrows show positive and negative correlations, respectively. Dashed arrows represent non-significant links. The value over each arrow is the correlation coefficient (path effect) between exogenous LVs and the LV organisms. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.1. Impacts of solar tracker on environmental conditions are distance-dependent

As expected, the closer the solar tracker the stronger the alteration of ground environmental conditions experienced by soil organisms. Firstly, shade intensity is much higher at the foot and north to the tracker than anywhere else. Reduced solar radiation has been associated with modified microclimatic conditions, particularly reduced temperatures (e.g., Suuronen et al., 2017; Weselek et al., 2021; Yue et al., 2021). Our own measurements in four winter wheat fields using 40 TMS-4 temperature loggers distributed in all cardinal directions, from 5 to 35 m around the solar trackers, confirm significantly lower soil and air temperature and higher soil moisture close to the tracker (especially at 1 m and 8 m north) than 35 m apart. The observed differences are however small compared to other studies, which mostly deal with arrays of PV panels just above the ground, whilst we studied punctual PV trackers atop 7 m high masts. It is not surprising therefore that the impact of these agrivoltaic installations on local wind speed and temperature is weak (Armstrong et al., 2016; Moscatelli et al., 2022). Secondly, plant species richness was greater at the basis of the tracker mast than elsewhere both in wheat fields and hay meadows. This result contrasts with those commonly found in the literature (Bai et al., 2022), but again may be explained by the specific structure of the system studied since the trackers are punctual artificial infrastructures, with no more soil pre-emption than isolated trees or electricity poles. Tractors avoid driving close to the mast basis, so that agricultural management within one to three metres around is very limited. This is particularly true in annual crops, as in meadows mowing can be carried out closer to the tracker basis.

Finally, most soil properties change with distance from solar trackers. In both winter wheat fields and hay meadows, we observed a reduction in soil organic matter, carbon and nitrogen content at 1 m and 8 m (only northward in winter wheat fields) from the tracker. This is consistent with studies showing lower soil quality under panels in agrivoltaic systems (Choi et al., 2023; Lambert et al., 2023; Lambert et al., 2021). At 1 m from the tracker, this area is largely bypassed by farmers when working, particularly when spreading organic (e.g., manure and slurry) or mineral nitrogen fertilisers and is even not cultivated in the case of annual crops, which could explain the lower soil organic matter content. At both distances, but especially at 8 m northward, shading could cause a reduced plant biomass, hence result in fewer residues returning to the soil. The decomposition rate could also be higher as observed for wheat here, thanks to higher soil moisture and thus more intense microbial activity. This is consistent with the lower pH at 1 m and 8 m from the tracker. A similar reduction in soil carbon, nitrogen and organic matter content has been reported under arrays of ground-mounted solar panels, mostly in connection with reduced plant productivity (Choi et al., 2023; Lambert et al., 2023; Liu et al., 2023; Moscatelli et al., 2022). Contrary to our expectations, we found no significant distance-related difference in soil compaction in grasslands (Lambert et al., 2021), and even a less compacted soil close to the tracker in winter wheat fields. This suggests that either the compaction caused by the installation work of the tracker faded out over time or the action of soil organisms such as earthworms has loosened the soil surface. Alternatively, the direct vicinity of the tracker may be not compacted by the repeated passages of vehicles, contrarily to the rest of the field.

4.2. Farming practices have an overarching effect over solar trackers on biodiversity

PLS-PM analyses enabled us to model complex relationships between environmental variables and soil biodiversity. Overall, farming management practices are the most important factor in explaining soil biodiversity, while solar trackers have limited influence, even not significant when the multiple influences that the two blocks of variables have on the other blocks are taken into account (Figs. 9–12).

The importance of agricultural practices on soil biodiversity is well known. Once direct and indirect effects of agricultural practices are taken into account, only arthropods were significantly positively affected in winter wheat fields. In annual crops, soil tillage intensity (i. e., depth, with or without inversion) has been repeatedly shown to have both direct (i.e. by killing them directly) and indirect (e.g. by drastically modifying soil conditions such as oxygenation or moisture) detrimental impact on earthworms (Capowiez et al., 2009; Kladvik, 2001), ground-dwelling arthropods (Coleman et al., 2017; Stinner and House, 1990), and microbial activity (Mathew et al., 2012). The type and amount of fertilisers also influence the nature and availability of the resources that form the basis of the diet of studied organisms (Bünemann et al., 2006; Geisseler and Scow, 2014; Li et al., 2013). The activity of earthworms in agricultural soils depends strongly on management practices, such as tillage, residue inputs, manure additions, fertiliser and pesticide use (Mackay and Kladvik, 1985; Marinissen and De Ruiter, 1993). In the case of arthropods, tillage can incorporate crop residues, thus increasing the availability of organic matter in the soil, thereby stimulating the population of arthropods. Indeed, the cessation of soil tillage can lead to a decrease in the springtail's population (Filser et al., 2002). Nitrogen inputs by slurry or mineral fertilisation can also benefit to saprophagous macrofauna (Ponge et al., 2013). In hay meadows, only earthworms were significantly negatively affected by the intensity of farming management (i.e. mowing intensity). Mowing has been shown to decrease some species of earthworms (Frazão et al., 2017), biomass exportation altering soil conditions and the availability of organic matter to be decomposed (Morris, 1978).

Vegetation below the tracker exhibits greater plant species richness in both winter wheat fields and hay meadows, higher ground cover in winter wheat fields, and greater height in hay meadows. Springtails are influenced by the amount of plant biomass, in particular the quantity of fine roots and root exudates produced, which modify abiotic soil conditions and the amount of water and nutrients available (Perez et al., 2013). In addition, woodlice are also sensitive to the composition of plant communities, which modifies the nature of the organic matter present as well as the physical structure of the vegetation (David et al., 1999). Since farmers do not cultivate the area below the tracker, weeds can develop and offer a refuge to soil organisms, in the same way as green or agro-ecological infrastructures voluntarily planted by farmers and land developers (e.g., hedges, fallows, grassed strips, flowerbeds). This is the rationale behind the recommendation to leave uncultivated or flowered spaces around photovoltaic structures (e.g. Grodsky et al. (2023) for ants) or to use this area as fallow land to comply with CAP (Common Agricultural Policy) requirements. Despite this effect on vegetation, the abundance of soil organisms is not affected in our study. This may be because the type of vegetation is not appropriate to provide some additional resources. This would justify sowing flowering plants below the tracker to benefit at several arthropods. However, soil biological quality strongly depends on system management, which directly affects plant (Armstrong et al. 2016) and soil invertebrate (e.g. via grazing; Menta et al. 2023) diversity. Agricultural management may also improve the physical and microbiological quality of PV installations through revegetation (Hernandez et al., 2019) or carbon sequestration via innovative site management practices, such as the co-location of PV and perennial native vegetation (Choi et al., 2023).

4.3. Concluding remarks

In this study, we highlighted that AV solar trackers have very little impact on soil environment and biodiversity compared to the one agricultural practices have. It should be acknowledged however that the PV structure we considered is atypical, since it consists of a punctual high, vertical infrastructure instead of the low, horizontal arrays of fixed panels which have received most of the attention so far in the literature. We clearly showed that environmental conditions were weakly impacted by solar trackers, mostly via shading and soil properties in the

immediate vicinity of the tracker. Since the studied solar trackers have been installed two to seven years before our survey, it is likely that impacts of their installation on soil properties faded out over time. We also showed that these impacts slightly differ between meadows and wheat fields. More studies are needed, encompassing various crops (e.g., cereals, oil seed plants, sugar beet, potato) and grassland types (e.g., hay meadows, pastures) on a broader range of soil types and bioclimatic regions to better document the extent of these impacts. As the infrastructures we considered here were quite elevated (panels located 7 m above the ground) as a result, the shaded area moves rather quickly (Graham et al., 2021; Noirot-Cosson et al., 2022; Suuronen et al., 2017) and field area underneath are only temporarily shaded. Consequently, it would be necessary to evaluate impacts with others type of photovoltaic structures which may impact more soil functioning. However, these first results indicate that punctual solar trackers usefully combine crop/hay and energy production on the same land, while minimizing impact on the local environment and soil biodiversity, hence meet the goal of sustainability.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Valentine Leroy reports financial support was provided by Groupe OKWind. Valentine Leroy reports financial support was provided by Association Nationale de la Recherche et de la Technologie. Paul-Emile Noirot-Cosson reports financial support was provided by Groupe OKWind. Valentine Leroy reports a relationship with Groupe OKWind that includes: employment. Paul-Emile Noirot-Cosson reports a relationship with Groupe OKWind that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank all farmers who gave access to their private properties; Pauline Chagnard and Benoit Fiot for their help during field and lab work; Hélène Horen for her advice on field protocols, Tanguy Riou for modelling and collect of Meteomatics data. This study is part of VL's PhD thesis, which received financial support from the French ANRT (National Association of Research and Technology) and Groupe OKwind®, within the framework of a CIFRE (Industrial Training through Research Convention) doctoral contract (2022/0420).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.geoderma.2024.117147>.

Data availability

Data will be made available on request.

References

- Armstrong, A., Ostle, N.J., Whitaker, J., 2016. Solar park microclimate and vegetation management effects on grassland carbon cycling. *Environ. Res. Lett.* 11, 074016.
- Bai, Z., Jia, A., Bai, Z., Qu, S., Zhang, M., Kong, L., Sun, R., Wang, M., 2022. Photovoltaic panels have altered grassland plant biodiversity and soil microbial diversity. *Front. Microbiol.* 13, 1065899.
- Bardgett, R.D., Van Der Putten, W.H., 2014. Belowground biodiversity and ecosystem functioning. *Nature* 515, 505–511.
- Barnett, K.L., Facey, S.L., 2016. Grasslands, invertebrates, and precipitation: a review of the effects of climate change. *Front. Plant Sci.* 7, 1196.
- Barron-Gafford, G.A., Pavao-Zuckerman, M.A., Minor, R.L., Sutter, L.F., Barnett-Moreno, I., Blackett, D.T., Thompson, M., Dimond, K., Gerlak, A.K., Nabhan, G.P., 2019. Agrivoltaics provide mutual benefits across the food–energy–water nexus in drylands. *Nat. Sustain.* 2, 848–855.
- Bennaceur, A., Chafik, K., 2019. Les fondements de l'usage des équations structurelles dans les recherches en sciences de gestion: Cas de l'approche PLS. *Rev. Contrô Comptab. L'audit*, 3.
- Bouché, M.B., 1972. *Lombriiciens de France*. Ecologie et systématique, INRA Editions.
- Bronick, C.J.R., et al., 2005. Soil structure and management: a review. *Geoderma* 124, 3–22.
- Bünemann, E.K., Schwenke, G.D., Van Zwieten, L., 2006. Impact of agricultural inputs on soil organisms—a review. *Soil Res.* 44, 379–406.
- Campbell, B.M., Beare, D.J., Bennett, E.M., Hall-Spencer, J.M., Ingram, J.S., Jaramillo, F., Ortiz, R., Ramankutty, N., Sayer, J.A., Shindell, D., 2017. Agriculture production as a major driver of the Earth system exceeding planetary boundaries. *Ecol. Soc.* 22.
- Capowiez, Y., Cadoux, S., Bouchant, P., Ruy, S., Roger-Estrade, J., Richard, G., Boizard, H., 2009. The effect of tillage type and cropping system on earthworm communities, macroporosity and water infiltration. *Soil Tillage Res.* 105, 209–216.
- Chaput, L., 2007. Modèles contemporains en gestion: un nouveau paradigme, la performance. PUQ.
- Chatzipanagi, A., Taylor, N., Jaeger-Waldau, A., 2023. Overview of the potential and challenges for Agri-Photovoltaics in the European Union. Publications Office of the European Union Luxembourg.
- Choi, C.S., Macknick, J., Li, Y., Bloom, D., McCall, J., Ravi, S., 2023. Environmental Co-Benefits of Maintaining Native Vegetation With Solar Photovoltaic Infrastructure. *Earths Future* 11, e2023EF003542. <https://doi.org/10.1029/2023EF003542>.
- Coleman, D.C., Callahan, M.A., Crossley Jr, D.A., 2017. *Fundamentals of soil ecology*. Academic press.
- David, J.-F., Deverny, S., Loucougaray, G., Floch, E.L., 1999. Belowground biodiversity in a Mediterranean landscape: relationships between saprophagous macroarthropod communities and vegetation structure. *Biodivers. Conserv.* 8, 753–767.
- Delignette-Muller, M.L., Dutang, C., 2015. fitdistrplus: An R package for fitting distributions. *J. Stat. Softw.* 64, 1–34.
- Dincer, I., 2000. Renewable energy and sustainable development: a crucial review. *Renew. Sustain. Energy Rev.* 4, 157–175.
- Dinesh, H., Pearce, J.M., 2016. The potential of agrivoltaic systems. *Renew. Sustain. Energy Rev.* 54, 299–308.
- Dupraz, C., Marrou, H., Talbot, G., Dufour, L., Nogier, A., Ferard, Y., 2011. Combining solar photovoltaic panels and food crops for optimising land use: Towards new agrivoltaic schemes. *Renew. Energy* 36, 2725–2732.
- Edwards, C.A., Arancon, N.Q., 2022. The Influence of Environmental Factors on Earthworms, in: *Biology and Ecology of Earthworms*. Springer US, New York, NY, pp. 191–232. https://doi.org/10.1007/978-0-387-74943-3_7.
- Filser, J., Mebes, K.-H., Winter, K., Lang, A., Kampichler, C., 2002. Long-term dynamics and interrelationships of soil Collembola and microorganisms in an arable landscape following land use change. *Geoderma* 105, 201–221.
- Frazaão, J., de Goede, R.G., Brussaard, L., Faber, J.H., Groot, J.C., Pulleman, M.M., 2017. Earthworm communities in arable fields and restored field margins, as related to management practices and surrounding landscape diversity. *Agric. Ecosyst. Environ.* 248, 1–8.
- Geisseler, D., Scow, K.M., 2014. Long-term effects of mineral fertilizers on soil microorganisms—A review. *Soil Biol. Biochem.* 75, 54–63.
- Geoffroy, J.J., 1993. Clés d'identification des ordres de diplopedes fréquents dans le sol (Myriapoda). *Diplopoda-Millepattia* 2, 4–28.
- Graham, M., Ates, S., Melathopoulos, A.P., Moldenke, A.R., DeBano, S.J., Best, L.R., Higgins, C.W., 2021. Partial shading by solar panels delays bloom, increases floral abundance during the late-season for pollinators in a dryland, agrivoltaic ecosystem. *Sci. Rep.* 11, 1–13. <https://doi.org/10.1038/s41598-021-86756-4>.
- Grodsky, S.M., Roeder, K.A., Campbell, J.W., 2023. Effects of solar energy development on ants in the Mojave Desert. *Ecosphere* 14, e4668. <https://doi.org/10.1002/ecs2.4668>.
- Hartig, 2017. Package 'dharma'. R Package.
- Hassanpour Adeh, E., Selker, J.S., Higgins, C.W., 2018. Remarkable agrivoltaic influence on soil moisture, micrometeorology and water-use efficiency. *PLoS One* 13, e0203256.
- Hernandez, R.R., Armstrong, A., Burney, J., Ryan, G., Moore-O'Leary, K., Diédhiou, I., Grodsky, S.M., Saul-Gershenz, L., Davis, R., Macknick, J., 2019. Techno-ecological synergies of solar energy for global sustainability. *Nat. Sustain.* 2, 560–568.
- Hopkin, S.P., 2007. A key to the Collembola (springtails) of Britain and Ireland. FSC publications.
- Hussain, S., Siddique, T., Saleem, M., Arshad, M., Khalid, A., 2009. Impact of pesticides on soil microbial diversity, enzymes, and biochemical reactions. *Adv. Agron.* 102, 159–200.
- IPCC, 2011. IPCC special report on renewable energy sources and climate change mitigation.
- Jakobowicz, E., 2008. A Comparison of Component-based Structural Equation Modelling Methods on Sensory Data, in: *ESSEC-HEC Research Workshop Series on PLS (Partial Least Squares) Developments*, Paris.
- Jouquet, P., Blanchart, E., Capowiez, Y., 2014. Utilization of earthworms and termites for the restoration of ecosystem functioning. *Appl. Soil Ecol.* 73, 34–40.
- Kassambara, A., 2017. Practical guide to principal component methods in R: PCA, M (CA), FAMD, MFA, HCPC, factoextra. Sthda.
- Keuskamp, J.A., Dingemans, B.J.J., Lehtinen, T., Sarneel, J.M., Hefting, M.M., 2013. Tea Bag Index: a novel approach to collect uniform decomposition data across ecosystems. *Methods Ecol. Evol.* 4, 1070–1075. <https://doi.org/10.1111/2041-210X.12097>.
- Kladivko, E.J., 2001. Tillage systems and soil ecology. *Soil Tillage Res.* 61, 61–76.

- Lacroux, A., 2009. L'analyse des modèles de relations structurelles par la méthode PLS: une approche émergente dans la recherche quantitative en GRH. XXème Congrès L'AGRH Toulouse 9.
- Lambert, Q., Bischoff, A., Cuff, S., Cluchier, A., Gros, R., 2021. Effects of solar park construction and solar panels on soil quality, microclimate, CO₂ effluxes, and vegetation under a Mediterranean climate. *Land Degrad. Dev.* 32, 5190–5202. <https://doi.org/10.1002/ldr.4101>.
- Lambert, Q., Bischoff, A., Enea, M., Gros, R., 2023. Photovoltaic power stations: an opportunity to promote European semi-natural grasslands? *Front. Environ. Sci.* 11, 1137845.
- Lenth, R., 2020. emmeans: Estimated marginal means, aka least squares means (Version 1.5. 2-1)[R package]. CRAN Left Angle Bracket <https://CRAN.R-project.org/package=emmeans> Right Angle Bracket.
- Li, F., Liu, M., Li, Z., Jiang, C., Han, F., Che, Y., 2013. Changes in soil microbial biomass and functional diversity with a nitrogen gradient in soil columns. *Appl. Soil Ecol.* 64, 1–6.
- Lichtenberg, E.M., Kennedy, C.M., Kremen, C., Batáry, P., Berendse, F., Bommarco, R., Bosque-Pérez, N.A., Carvalheiro, L.G., Snyder, W.E., Williams, N.M., Winfree, R., Klatt, B.K., Åström, S., Benjamin, F., Brittain, C., Chaplin-Kramer, R., Clough, Y., Danforth, B., Diekötter, T., Eigenbrode, S.D., Ekroos, J., Elle, E., Freitas, B.M., Fukuda, Y., Gaines-Day, H.R., Grab, H., Gratton, C., Holzschuh, A., Isaacs, R., Isaia, M., Jha, S., Jonason, D., Jones, V.P., Klein, A., Krauss, J., Letourneau, D.K., Macfadyen, S., Mallinger, R.E., Martin, E.A., Martinez, E., Memmott, J., Morandin, L., Neame, L., Otieno, M., Park, M.G., Pfiffner, L., Pockock, M.J.O., Ponce, C., Potts, S.G., Poveda, K., Ramos, M., Rosenheim, J.A., Rundlöf, M., Sardiñas, H., Saunders, M.E., Schon, N.L., Sciligo, A.R., Sidhu, C.S., Steffan-Dewenter, I., Tschamtké, T., Veselý, M., Weisser, W.W., Wilson, J.K., Crowder, D.W., 2017. A global synthesis of the effects of diversified farming systems on arthropod diversity within fields and across agricultural landscapes. *Glob. Change Biol.* 23, 4946–4957. <https://doi.org/10.1111/gcb.13714>.
- Liu, Z., Peng, T., Ma, S., Qi, C., Song, Y., Zhang, C., Li, K., Gao, N., Pu, M., Wang, X., 2023. Potential benefits and risks of solar photovoltaic power plants on arid and semi-arid ecosystems: an assessment of soil microbial and plant communities. *Front. Microbiol.* p. 14.
- Mackay, A.D., Klavivko, E.J., 1985. Earthworms and rate of breakdown of soybean and maize residues in soil. *Soil Biol. Biochem.* 17, 851–857.
- Magnusson, A., Skaug, H., Nielsen, A., Berg, C., Kristensen, K., Maechler, M., van Bentham, K., Bolker, B., Brooks, M., Brooks, M.M., 2017. Package 'glmmtmb'. R Package Version 02, 25.
- Marinissen, J.C.Y., De Ruiter, P.C., 1993. Contribution of earthworms to carbon and nitrogen cycling in agro-ecosystems. *Agric. Ecosyst. Environ.* 47, 59–74.
- Marrou, H., Guillion, L., Dufour, L., Dupraz, C., Wery, J., 2013. Microclimate under agrivoltaic systems: Is crop growth rate affected in the partial shade of solar panels? *Agric. for. Meteorol.* 177, 117–132.
- Mathew, R.P., Feng, Y., Githinji, L., Ankumah, R., Balkcom, K.S., 2012. Impact of no-tillage and conventional tillage systems on soil microbial communities. *Appl. Environ. Soil Sci.* 2012.
- Menta, C., Remelli, S., 2020. Soil health and arthropods: From complex system to worthwhile investigation. *Insects* 11, 54.
- Menta, C., Remelli, S., Andreoni, M., Gatti, F., Sergi, V., 2023. Can Grasslands in Photovoltaic Parks Play a Role in Conserving Soil Arthropod Biodiversity? *Life* 13, 1536.
- Morris, M.G., 1978. Grassland management and invertebrate animals—a selective review.
- Moscatelli, M.C., Marabottini, R., Massaccesi, L., Marinaro, S., 2022. Soil properties changes after seven years of ground mounted photovoltaic panels in Central Italy coastal area. *Geoderma Reg.* 29, e00500.
- Noirot-Cosson, P., Riou, T., Bugny, Y., 2022. Towards assessing photovoltaic trackers effects on annual crops growth and building optimized agrivoltaics systems based on annual crops. Presented at the Agrivoltaics2021 Conference.
- Panwar, N.L., Kaushik, S.C., Kothari, S., 2011. Role of renewable energy sources in environmental protection: A review. *Renew. Sustain. Energy Rev.* 15, 1513–1524.
- Perez, G., Decaens, T., Dujardin, G., Akpa-Vinceslas, M., Langlois, E., Chauvat, M., 2013. Response of collembolan assemblages to plant species successional gradient. *Pedobiologia* 56, 169–177.
- Ponge, J.-F., Pères, G., Guernion, M., Ruiz-Camacho, N., Cortet, J., Pernin, C., Villenave, C., Chaussod, R., Martin-Laurent, F., Bispo, A., 2013. The impact of agricultural practices on soil biota: a regional study. *Soil Biol. Biochem.* 67, 271–284.
- Powlson, D.S., Gregory, P.J., Whalley, W.R., Quinton, J.N., Hopkins, D.W., Whitmore, A. P., Hirsch, P.R., Goulding, K.W., 2011. Soil management in relation to sustainable agriculture and ecosystem services. *Food Policy* 36, S72–S87.
- R. Core Team, 2024. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing; 2014.
- Sanchez, G., 2013. PLS path modeling with R. Berkeley Trowchez Ed. 383, 551.
- Schweiger, A.H., Pataczek, L., 2023. How to reconcile renewable energy and agricultural production in a drying world. *PLANTS PEOPLE PLANET* 5, 650–661. <https://doi.org/10.1002/ppp3.10371>.
- Stinner, B.R., House, G.J., 1990. Arthropods and Other Invertebrates in Conservation-Tillage Agriculture. *Annu. Rev. Entomol.* 35, 299–318. <https://doi.org/10.1146/annurev.en.35.010190.001503>.
- Sutton, S., 2013. Woodlice. Elsevier.
- Suuronen, A., Muñoz-Escobar, C., Lensu, A., Kuitunen, M., Guajardo Celis, N., Espinoza Astudillo, P., Ferrú, M., Taucare-Ríos, A., Miranda, M., Kukkonen, J.V., 2017. The influence of solar power plants on microclimatic conditions and the biotic community in Chilean desert environments. *Environ. Manage.* 60, 630–642.
- Tanner, K.E., Moore-O'Leary, K.A., Parker, I.M., Pavlik, B.M., Hernandez, R.R., 2020. Simulated solar panels create altered microhabitats in desert landforms. *Ecosphere* 11, e03089. <https://doi.org/10.1002/ecs2.3089>.
- Tenenhaus, M., Tenenhaus, A., 2011. Comparaison entre l'analyse canonique généralisée régularisée et l'algorithme PLS pour l'analyse des tableaux multiples. Mardi 24 Mai 2011 221.
- Tsiafouli, M.A., Thébault, E., Sgardelis, S.P., De Ruiter, P.C., Van Der Putten, W.H., Birkhofer, K., Hemerik, L., De Vries, F.T., Bardgett, R.D., Brady, M.V., Bjornlund, L., Jørgensen, H.B., Christensen, S., Hertefeldt, T.D., Hotes, S., Gera Hol, W.H., Frouz, J., Liiri, M., Mortimer, S.R., Setälä, H., Tzanopoulos, J., Uteseny, K., Pizl, V., Stary, J., Wolters, V., Hedlund, K., 2015. Intensive agriculture reduces soil biodiversity across Europe. *Glob. Change Biol.* 21, 973–985. <https://doi.org/10.1111/gcb.12752>.
- Uldrijan, D., Černý, M., Winkler, J., 2022. Solar park: opportunity or threat for vegetation and ecosystem. *J. Ecol. Eng.* p. 23.
- Vervloesem, J., Marcheggiani, E., Choudhury, M.A.M., Muys, B., 2022. Effects of Photovoltaic Solar Farms on Microclimate and Vegetation Diversity. *Sustainability* 14, 7493.
- Wei, T., Simko, V., Levy, M., Xie, Y., Jin, Y., Zemla, J., 2017. Package 'corrplot'. *Statisticians* 56, e24.
- Weselek, A., Bauerle, A., Hartung, J., Zikeli, S., Lewandowski, I., Högy, P., 2021. Agrivoltaic system impacts on microclimate and yield of different crops within an organic crop rotation in a temperate climate. *Agron. Sustain. Dev.* 41, 59. <https://doi.org/10.1007/s13593-021-00714-y>.
- Wild, J., Kopecký, M., Macek, M., Šanda, M., Jankovec, J., Haase, T., 2019. Climate at ecologically relevant scales: A new temperature and soil moisture logger for long-term microclimate measurement. *Agric. for. Meteorol.* 268, 40–47.
- Yue, S., Guo, M., Zou, P., Wu, W., Zhou, X., 2021. Effects of photovoltaic panels on soil temperature and moisture in desert areas. *Environ. Sci. Pollut. Res.* 28, 17506–17518.