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LETTER

# Plant and soil responses to ground-mounted solar panels in temperate agricultural systems

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## Abstract

In the move to decarbonise energy supplies to meet Net Zero targets, ground-mounted solar farms have proliferated around the world, with uncertain implications for hosting ecosystems. We provide some of the first evidence on the effects of ground-mounted solar panels on plant and soil properties in temperate agricultural systems. We sampled 32 solar farms in England and Wales in summer 2021. Plant cover and aboveground biomass, as well as soil nutrients and physiochemical properties, were quantified on land underneath solar panels, in the gaps between rows of solar arrays, and in control land (pasture) adjacent to three solar farms. Plant cover and aboveground biomass were significantly lower under solar panels than in the gaps between solar arrays and in pastures. Soil compaction was 14.4% and 15.5% higher underneath solar panels than in gaps and pastures, respectively. Soil organic carbon was 9% lower under solar panels than in gaps, while particulate organic matter was 29.1% and 23.6% lower under solar panels than in gaps and pastures, respectively. Soil mineral nitrogen was 30.5% higher under solar panels than in gaps, while soil (plant-available) phosphorus was approximately 60% higher in solar farm soils than in pasture soils. Reductions in solar radiation and changes to microclimate caused by solar panels may be driving lower plant productivity and growth, with consequences for nutrient cycling and soil properties. However, impacts must be considered in light of the previous land use and the total land area under solar panels, in the gaps between solar arrays, and around the margins of the solar farm. Our findings can inform solar farm design and management options (e.g. increase the proportion of land unaffected by solar panels, enhance plant cover under solar panels) to ensure the long-term provision of ecosystem services (e.g. soil carbon storage) within this fast-growing land use.

## 1. Introduction

The global deployment of renewable energy technologies has accelerated in the last decade in response to expanding policy support, growing energy security concerns, and the need to meet Net Zero targets to mitigate climate change (IEA 2024). Solar photovoltaic (PV) technologies are currently leading this growth in renewable energy (Ember 2024), mostly in the form of ground-mounted solar farms due to policy incentives for large-scale developments and declining module prices (IEA 2023). The increase in solar farm development is expected to continue in the coming decades (Nijsse *et al* 2023) and is likely to intensify competition for land to produce food, generate energy, and conserve nature (Capellán-Pérez *et al* 2017). It is thus becoming increasingly important to quantify and understand solar farm impact on ecosystems, especially considering the potential to manage solar farms for positive environmental outcomes (Randle-Boggis *et al* 2020).

Solar farms are commonly built on agricultural land (Tinsley *et al* 2024) and managed as grasslands in temperate regions (Carvalho *et al* 2023, 2024a), offering both risks and opportunities for ecosystem health (Randle-Boggis *et al* 2020). Existing data indicate effects on microclimate and ecosystem processes (Armstrong *et al* 2016) and on plant and soil properties (Lambert *et al* 2021). For instance, the installation of PV arrays may have negative environmental impacts by disrupting soil aggregate stability and the native vegetation, resulting in topsoil erosion (Hernandez *et al* 2014). The removal of topsoil during construction can also reduce soil carbon (Choi *et al* 2020), nitrogen, and phosphorus (Geissen *et al* 2013), as well as increase soil bulk density and affect the soil's structural and hydraulic properties (Geissen *et al* 2013, Udom *et al* 2018). However, solar farms can also have positive environmental impacts, and have the potential to deliver several co-benefits beyond low-carbon electricity when compared to conventional fossil fuel sources (Turney and Fthenakis 2011). For instance, construction and land management techniques conducive to providing local biodiversity benefits (e.g. allocating space for semi-natural habitats) can help restore degraded habitats (Gazdag and Parker 2019, Semeraro *et al* 2020) and result in enhanced ecosystem services (Randle-Boggis *et al* 2020). Despite this recent evidence, relatively little is known of the effects of solar farms on plant and soil properties in temperate agricultural systems. This is an important knowledge gap since solar farms are expected to become increasingly common features of agricultural landscapes in coming decades as part of the low-carbon energy transition (IEA 2023).

The aim of this study was to investigate the effects of ground-mounted solar panels on plant and soil properties across solar farms in England and Wales. We compared plant (cover and aboveground biomass) and soil (organic carbon, mineral-associated organic matter (MAOM), particulate organic matter (POM), total nitrogen, C/N ratio, mineral nitrogen, nitrate, plant-available phosphorus, bulk density, and pH) properties from areas underneath solar panels to areas between rows of solar arrays and to control land adjacent to solar farms (permanent pasture) representing the previous land use. These properties are thought to broadly capture complex plant-soil interactions that drive the functioning of terrestrial ecosystems and the delivery of numerous ecosystem services (Bardgett and Wardle 2010) and are commonly used as primary indicators of soil quality in national monitoring programmes (e.g. Emmett *et al* 2010).

## 2. Methods

### 2.1. Plant, soil, and climate data

We sampled 32 operational solar farms in England and Wales (figure 1) between June and September 2021 following standard protocols (Carvalho *et al* 2023). At each site, four replicate plots were randomly placed on land underneath solar panels ('under') and in between the rows of solar arrays ('gaps'; figure 1). In three sites (where permission was granted by landowners; figure 1), four additional plots were sampled in permanent pastures adjacent to these solar farms ('control'). Total plant cover (visual percentage estimation of vegetation cover within a quadrat as seen from above) and plant aboveground biomass (AGB) harvested at the soil surface with a pair of shears were sampled within 30 × 30 cm quadrats at each plot. Soils were sampled within the same quadrats to 10 cm depth and 5 cm diameter with a cylindrical metal corer. Four replicate soil samples were collected from each quadrat; three samples were homogenised in the laboratory for soil analyses and one sample was kept separate for bulk density measurements. Plant and soil properties directly linked to the delivery of multiple ecosystem services (e.g. biomass production, soil carbon storage, nutrient cycling) were estimated following standard published methods (table 1).

We adopted the soil classification system derived by Feeney *et al* (2023), based on the NATMAP vector dataset by Cranfield University (National Soil Resources Institute 2001), to characterise our sites by soil class. This soil classification captures key structural properties of soils, including texture, drainage, organic carbon/matter content, depth, flood risk, and the degree of modification from human activity (see supplementary material in Feeney *et al* 2023). Site-specific air temperature and rainfall data (annual averages for the 1991–2020 period provided on a 12 km British National Grid) were sourced from the UK's Met Office Climate Data Portal (https://climatedataportal.metoffice.gov.uk/).

### 2.2. Data analyses

All numerical analyses were performed in R 4.4.1 (R Core Team 2024). Plant and soil properties were either arcsine- (percentage variables converted to proportions; table 1) or $\log_{10}$- (continuous variables; table 1) transformed to reduce skewness and the effect of outliers prior to analyses, which largely followed the ten-step protocol outlined in Zuur *et al* (2009) to implement model selection in linear mixed modelling

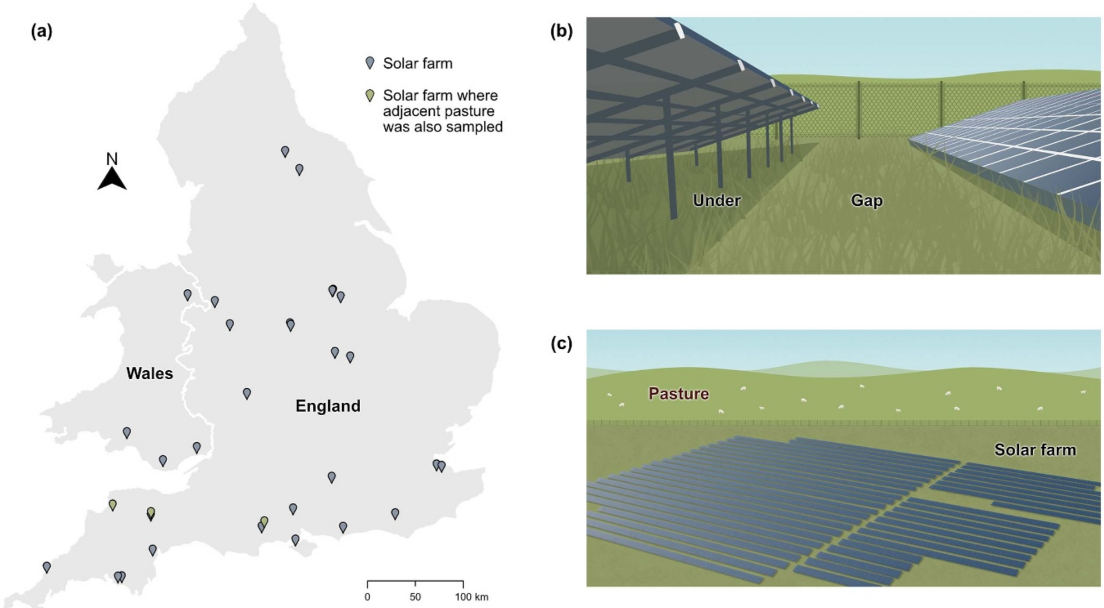

**Figure 1.** Location of the 32 solar farms sampled in England and Wales in summer 2021 (a) alongside visual representations of the treatments where plant and soil data were collected (b) and (c). Sites coloured in green denote the three solar farms where the adjacent pasture was sampled as a control treatment.

**Table 1.** Plant and soil properties measured on 32 solar farms in England and Wales in summer 2021. AGB = plant aboveground biomass, SOC = soil organic carbon, MAOM = mineral-associated organic matter, POM = particulate organic matter, N = nitrogen, P = phosphorus, BD = bulk density.

| Property | Unit | Method | References |
|---|---|---|---|
| Plant cover | % cover | Visual plot-level estimation | Damgaard (2014) |
| AGB | Tonnes ha$^{-1}$ | Destructive harvesting & oven-drying (60°C to constant mass) | Sala and Austin (2000) |
| SOC | % dry soil | Dry combustion (Vario EL Cube Elemental Analyser, Elementary, Stockport, UK) after acid (HCl) treatment | Harris *et al* (2001)<br>Nayak *et al* (2019) |
| MAOM | % dry soil | Organic matter fractionation by size | Cotrufo *et al* (2019) |
| POM | % dry soil | Organic matter fractionation by size | Cotrufo *et al* (2019) |
| Total soil N | % dry soil | Dry combustion (Vario EL Cube Elemental Analyser, Elementary, Stockport, UK) | Emmett *et al* (2008) |
| Soil C/N ratio | NA | Soil organic carbon divided by total soil nitrogen | Emmett *et al* (2008) |
| Soil mineral N | mg N kg$^{-1}$ dry soil | 2 M KCl-extraction ($NH_4$ + $NO_3$ estimation in an Auto Analyser, Seal-Analytics©, Southampton, UK) | Emmett *et al* (2008) |
| Soil nitrate | Proportion of mineral N | 2 M KCl-extraction ($NO_3$ estimation in an Auto Analyser, Seal-Analytics©, Southampton, UK) | Emmett *et al* (2008) |
| Soil Olsen P | mg P kg$^{-1}$ dry soil | $NaHCO_3$-extraction (Auto Analyser, Seal-Analytics©, Southampton, UK) | Emmett *et al* (2008) |
| Soil BD | g dry soil cm$^{-3}$ | Dried sample mass (110 °C for 24 h) over volume | Emmett *et al* (2008) |
| Soil pH | NA | Fresh soil pH in water (soil-water suspension) | Emmett *et al* (2008) |

and address heterogeneity of variance and spatial correlation by testing different combinations of variance and auto-correlation structures.

We determined the effects of solar panels on plant and soil properties by testing the differences between the under and gap treatments ($n = 256$ per property; 32 sites × 4 replicates × 2 treatments) with linear mixed effects models fitted with the *nlme* package (Pinheiro and Bates 2023). Furthermore, we compared the two solar farm treatments (under and gap) to a control treatment (pasture outside the boundaries of the solar farm) for three sites where data were available ($n = 36$ per property; 3 sites × 4 replicates × 3 treatments).

In addition to *treatment*, the fixed effects included variables to account for local conditions (*soil class*), differences in climate between sites (*mean annual air temperature* and *rainfall*), and time since land use conversion (*age* of solar farms). The variable *site* was fitted as a random effect. The models that used data from the three sites with adjacent pasture (control) only included *treatment, mean annual rainfall* and the *age* of solar farms, since *site* and *soil class* were colinear and *air temperature* showed low variability (coefficient of variation = 2.1%). Marginal means and pairwise differences between treatments were then estimated with the *emmeans* package (Lenth 2023) after back-transforming plant and soil properties to their original units.

Finally, for the three sites with data available for the adjacent pasture, we weighted the marginal means of the under and gap treatments to provide a solar farm weighted mean of plant and soil properties by accounting for the proportion of land within the under and gap treatments. Weighted means were calculated by summing the product of the weights (i.e. the proportions of the under and gap areas to the total solar farm area) times the marginal mean value of each variable and divided by the sum of the weights. The under and gap treatments accounted, on average, for 33% ± 0.06% (±1 SD) and 37% ± 0.09% (±1 SD) of the land between the three sites, respectively.

## 3. Results

### 3.1. Effects of solar panels on plant and soil properties

Areas under solar panels showed lower plant cover and AGB, lower soil carbon—when measured as soil organic carbon (SOC) and POM—and lower soil C/N ratio than areas in the gaps between solar arrays (figure 2). Soils under solar panels were more compacted and lower in total nitrogen than in gap areas, while (plant-available) mineral nitrogen and nitrate were higher under solar panels than in the gaps (figure 2). There were no statistical differences in MAOM, soil (plant-available) phosphorus (Olsen P), and soil pH between the two treatments (figure 2).

Older solar farms (ages ranged between 0.3 and 10.1 years old) tended to show higher plant cover, MAOM, POM, and soil nitrate than younger sites, though most differences were only marginally significant (table A1). Wetter sites showed higher plant AGB and higher soil carbon and nitrogen (measured in their different forms) than drier sites, while wetter soils were less compacted and lower in pH than drier soils (table A1). Measures of soil carbon and nitrogen varied among soil classes, but differences in air temperature between the sampled sites had no influence on the measured plant and soil properties (table A1).

### 3.2. Solar farms vs pasture

In the three sites where data for the adjacent pasture were available (figure 1), there were few statistical differences in plant and soil properties between gap areas and pastures (figure 3(b)), but areas under solar panels revealed higher soil compaction and lower plant cover, AGB, and POM than pastures (figure 3(a)). Solar farms generally showed higher soil (plant-available) nutrients than pastures, particularly Olsen P (figures 3(a) and (b)), though differences in mineral nitrogen and nitrate were only marginally significant (table A2). Rainfall had no influence on the results, but older sites showed marginally higher soil carbon and nitrogen (and marginally lower soil compaction) than younger sites (table A2).

When comparing solar farm weighted means (i.e. by accounting for the proportion of land under solar panels and in gap areas) to pasture means (table 2), SOC was slightly higher in solar farms than in pastures. In addition, the differences between the solar farm weighted means and the pastures were lower for plant cover, AGB, POM, and soil bulk density compared to the differences between the under areas and pasture (figure 3(a) and table 2).

## 4. Discussion

Our analyses are the first to demonstrate solar farm impacts on a suite of plant and soil properties across a range of sites and offer important insights into the effects of ground-mounted solar panels on plants and soils. Below, we discuss our results by grouping them into measures of plant (plant cover and AGB) and soil properties, including soil carbon and nitrogen (SOC, MAOM, POM, total nitrogen, and C/N ratio), soil (plant-available) nutrients (mineral nitrogen, nitrate, and Olsen P), and soil physiochemical properties (bulk density and pH).

### 4.1. Plant properties

Our findings, covering a range of solar farms with different design and site characteristics, indicate that plant cover and AGB are lower underneath solar panels than in gaps and pasture. However, effects may be context-dependent as plant cover has also been found to be unaltered by solar panels in some cases (Lambert *et al* 2021). Solar panels have been found to reduce plant photosynthetic rates and biomass by altering soil temperature and lowering receipts of photosynthetically active radiation (Vervloesem *et al* 2022) in temperate (Armstrong *et al* 2016) and Mediterranean (Lambert *et al* 2021, 2023) systems. Lambert *et al* (2023) found reduced plant biomass under solar panels to be due to higher allocation of resources to chlorophyll production to offset shading conditions, which in turn compromised resource allocation for biomass production of aboveground parts. However, the relationship between chlorophyll and biomass production is likely complex and highly variable between species (Paliwal *et al* 1986).

Management practices adopted by some operators may also have an impact on plant cover and biomass, including herbicide spraying to control weeds (often prominent under solar panels in summer; personal observation) and the sowing of low-statured

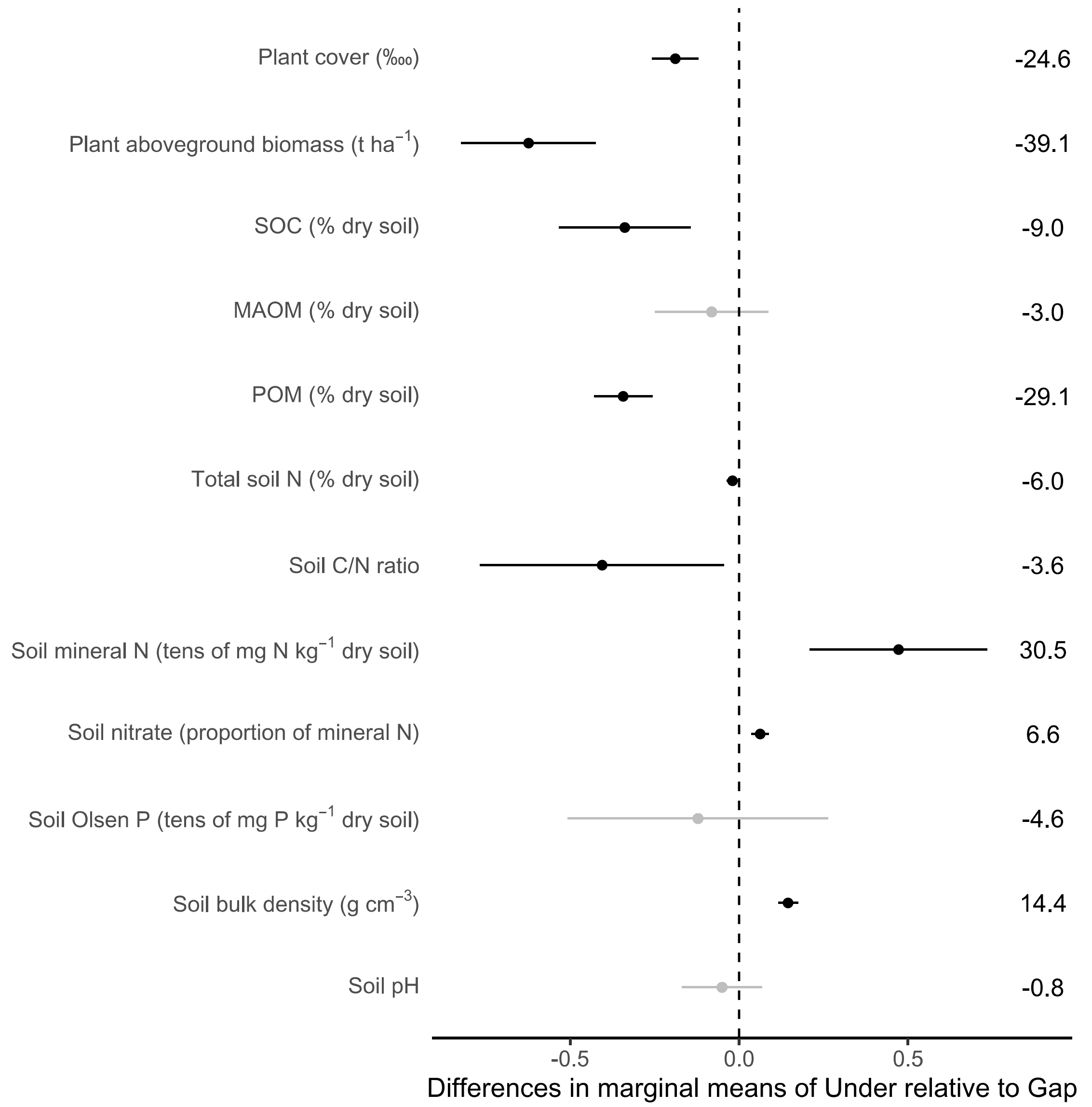

**Figure 2.** Pairwise differences in plant and soil properties between the under (land underneath solar panels) and gap (land between the rows of solar arrays) treatments. Error bars are 95% confidence intervals and circles depict differences between marginal means. Differences between treatment pairs are significant ($p < 0.05$) when the bars (highlighted black) do not overlap the vertical (dashed) zero line. If a difference is positive (i.e. to the right of the zero line), the under treatment has a higher marginal mean than the gap treatment (positive % difference shown on the right). If a difference is negative (i.e. to the left of the zero line), the under treatment has a lower marginal mean than the gap treatment (negative % difference shown on the right). Some results were scaled to 0 ± 1 by dividing them by 100 or 10 (see *y* axis labels). SOC = soil organic carbon, MAOM = mineral-associated organic matter, POM = particulate organic matter, N = nitrogen, P = phosphorus.

species to avoid shading of solar panels. The regular use of areas under solar panels for shelter by grazing sheep (personal observation on several sites) may also impact plant establishment and growth through heavy trampling.

The effect of solar panels on microclimate, coupled with land management decisions, also seem to influence plant community composition, diversity, and abundance, as well as the presence of indicator species (Armstrong *et al* 2016, Schindler *et al* 2018, Uldrijan *et al* 2021, 2022, Lambert *et al* 2022), by recruiting species tolerant to specific microclimatic, soil, and management conditions (Uldrijan *et al* 2021). This filtering may have implications for plant cover and AGB and affect ecosystem functioning (Hernandez *et al* 2014), trophic interactions (Uldrijan *et al* 2022), and the development of fire prone vegetation (Vaverková *et al* 2022).

### 4.2. Soil carbon and nitrogen

The lower soil carbon found for areas underneath solar panels compared to gap areas and pastures may be directly linked to the effects of solar panels on microclimate, solar radiation, and photosynthetic rates mentioned above. These effects can negatively impact plant establishment and growth, and reduce plant-derived carbon input to soils through altered plant tissue chemistry and litter quality and

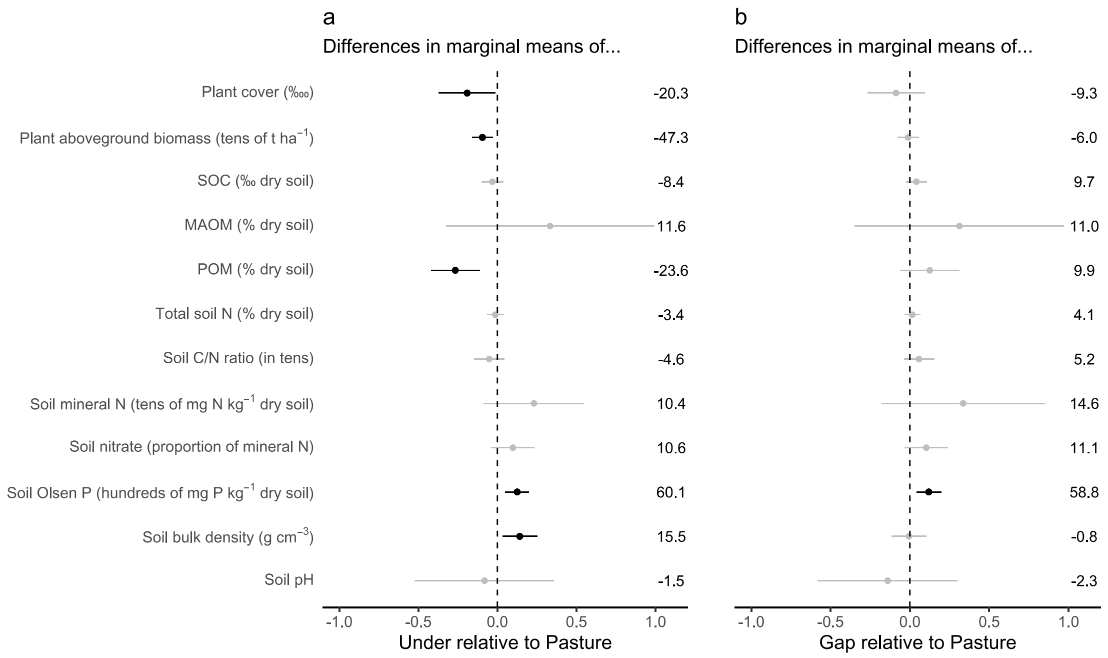

**Figure 3.** Pairwise differences in plant and soil properties between pasture (control treatment) and (a) the under treatment (land underneath solar panels) and (b) the gap treatment (land between the rows of solar arrays). Tukey adjustment was used to correct the $p$ values for comparing three estimates (under, gap, and control), but only comparisons between under and pasture (a) and gap and pasture (b) are shown. Error bars are 95% confidence intervals and circles depict differences between marginal means. Differences between treatment pairs are significant ($p < 0.05$) when the bars (highlighted black) do not overlap the vertical (dashed) zero line. If a difference is positive (i.e. to the right of the zero line), the under (a) and gap (b) treatments showed a higher marginal mean than the pasture treatment (positive % difference shown on the right). If a difference is negative (i.e. to the left of the zero line), the under (a) and gap (b) treatments showed a lower marginal mean than the pasture treatment (negative % difference shown on the right). Some results were scaled to $0 \pm 1$ by dividing them by 100 or 10 (see $y$ axis labels). SOC = soil organic carbon, MAOM = mineral-associated organic matter, POM = particulate organic matter, N = nitrogen, P = phosphorus.

**Table 2.** Mean differences in plant and soil properties between solar farms and pastures. Means are the marginal means of pairwise tests following mixed linear models fitted to the three sites where data were available for the adjacent pasture, but solar farm means were weighted by the proportion of land taken by the under and gap treatments. If a difference is negative in the final column, solar farms showed a lower mean than pastures.

| Variable | Solar farm weighted mean | Pasture marginal mean | % Difference |
|---|---|---|---|
| Plant cover (%) | 80.94 | 94.58 | −14.4 |
| Plant aboveground biomass (AGB) (t ha$^{-1}$) | 1.50 | 2.01 | −25.2 |
| Soil organic carbon (SOC) (%) | 3.88 | 3.81 | 1.8 |
| Mineral-associated organic matter (MAOM) (%) | 2.84 | 2.52 | 11.3 |
| Particulate organic matter (POM) (%) | 1.07 | 1.13 | −5.2 |
| Total soil nitrogen (%) | 0.38 | 0.38 | 0.6 |
| Soil C/N ratio | 10.97 | 10.90 | 0.6 |
| Soil mineral nitrogen (mg kg$^{-1}$) | 22.78 | 19.91 | 12.6 |
| Soil nitrate (proportion of mineral nitrogen) | 0.92 | 0.82 | 10.9 |
| Soil (plant-available) phosphorus (Olsen P) (mg kg$^{-1}$) | 20.54 | 8.34 | 59.4 |
| Soil bulk density (g cm$^{-3}$) | 0.83 | 0.77 | 7.7 |
| Soil pH | 5.94 | 6.06 | −1.9 |

quantity (Gill *et al* 2002). Similarly, the lower total soil nitrogen recorded underneath solar panels compared to gap areas may be due to relatively low levels of plant-soil feedbacks (e.g. nitrogen fixation through N-fixing bacteria; van der Putten *et al* 2013) and nutrient cycling under reduced levels of plant-derived organic matter input and microbial activity (Lambert *et al* 2023), as recorded in soils under solar panels elsewhere (Choi *et al* 2020, Lambert *et al* 2021, Moscatelli *et al* 2022). In addition, vegetation removal and soil disturbance due to tillage, levelling, trenching works, machinery compaction, and/or topsoil removal before or during solar farm construction may increase erosion and mineralisation rates of organic matter and also result in reduced SOC (Quinton *et al* 2010, Gregory *et al* 2015) and nitrogen (Lambert *et al* 2021, Moscatelli *et al* 2022) content.

The lower POM observed underneath solar panels compared to gaps and pasture could be a direct result of lower plant biomass, since POM is mostly plant-derived, fast-cycling, and relatively vulnerable to disturbance (Cotrufo *et al* 2019). Reductions in POM may have important implications for long-term changes in SOC considering temperate grasslands can store significant fractions of organic carbon in POM pools (Denef *et al* 2013), making construction and management practices that reduce soil disturbance and maximise carbon input to soils particularly important. Lower POM can also have consequences for soil aggregate stability (Zech *et al* 2022) and negatively impact soil infiltration and erosion rates (Abu-Hamdeh *et al* 2006). In addition, despite being predominantly of microbial origin and relatively slow-cycling, MAOM can receive substantial carbon contributions from plant-derived organic matter and be closely related to short-term SOC cycling (Yu *et al* 2022). Therefore, despite no differences in MAOM between treatments found here, MAOM could be negatively affected over time under solar panels if plant-derived carbon inputs remain low. Moreover, MAOM tends to rapidly saturate under organic fertilisation (Stewart *et al* 2007, Just *et al* 2023), after which the continuous sequestration and storage of soil carbon is only possible through additional POM accrual (Cotrufo *et al* 2019). This could have consequences for long-term soil carbon storage under solar panels, since MAOM is a more persistent form of carbon than POM. Reductions in POM and MAOM could also have consequences for microbial growth and the soil food web by affecting supply of labile carbon and nutrients to plants and microbiota (Lavallee *et al* 2020), as evidenced elsewhere by lower microbiological activity and nutrient cycling under solar panels due to low soil organic matter (Lambert *et al* 2021, 2023, Moscatelli *et al* 2022). Given the potential for temperate grasslands to uptake carbon (Ostle *et al* 2009), there is ample evidence of the importance of land management on soil carbon (Carvalho and Armstrong 2021), and these should be carefully considered in relation to local conditions.

### 4.3. Soil (plant-available) nutrients

Given solar farms are rarely fertilised, the persistence of plant-available nutrients (nitrogen and phosphorus) in solar farm soils after construction, particularly underneath solar panels, may be a legacy of previous land fertilisation regimes under agricultural production since declines in inorganic nutrients may take several years to occur after cessation of agricultural activities (Parkhurst *et al* 2022a, 2022b), especially if they are not continually removed through harvesting (McLauchlan 2006). Vervloesem *et al* (2022) attributed higher nutrient content in soils underneath solar panels to their relatively low exposure to sun and rain compared to gap areas that could result in nutrient accumulation over time due to reduced leaching. In addition, the microbial carbon deficiency commonly found under solar panels (Lambert *et al* 2021, 2023) triggered by relatively low plant carbon inputs (rhizodeposition) may be driving microbial targeting of MAOM carbon pools with relatively low C/N ratio to result in excess nitrogen release into the soil via nitrogen mineralisation (Mooshammer *et al* 2014). These effects could lead to negative outcomes for biodiversity and ecosystem functioning long after land use change given the well-documented relationships between soil nutrients and plant species richness and abundance (Isbell *et al* 2019).

Despite the differences in soil nutrients among treatments described above, comparisons between sites under varying conditions and of different ages are difficult since the legacy of agricultural effects on soil properties can be highly variable and dependent on several factors, including time since land use change, post-agricultural management, climate, and mineralogy (McLauchlan 2006).

### 4.4. Soil physiochemical properties

Compaction of agricultural soils is typically associated with regular trafficking of agricultural machinery or the presence of grazing livestock, and its effects have been well documented (Gregory *et al* 2015), including increased risk of flooding and soil erosion (Batey 2009) and reduced biodiversity (Roovers *et al* 2004). The higher soil compaction under solar panels compared to gap areas and pastures is likely the result of a mixed legacy of previous (and current) agricultural practices (notably livestock grazing) and the use of heavy machinery during construction. Soils in the gaps showed similar levels of compaction to pasture, possibly due to largely successful revegetation efforts after solar farm construction and relatively low levels of disturbance during solar farm operation. In contrast, low levels of vegetation establishment and growth under solar panels may be directly related to high soil compaction due to reduced plant root penetration and water cycling that would help increase soil porosity and aeration, and reduce compaction (Correa *et al* 2019).

There were no statistical differences in soil pH between treatments, but soils under solar panels were slightly more acidic than in gap areas and pastures. Previous research found lower soil pH under solar panels compared to other land use types (Vervloesem *et al* 2022), which was attributed to low soil carbon and nitrogen (Aciego Pietri and Brookes, 2008, Chen *et al* 2016) and high (plant-available) nutrient concentrations (Chen *et al* 2015) under solar panels affecting soil fauna and the concentration of mineral cations. Soil pH will vary considerably from site to site though depending on several factors, including soil type and texture, climate, topography, mineralogy, and water availability (Slessarev *et al* 2016).

## 5. Implications

The results presented here showed that, across a range of solar farms within temperate agricultural systems, the most marked impact of ground-mounted solar panels is on vegetation, with cascading effects on soil properties. This indicates that solar farms in temperate systems with a past agricultural legacy should be actively managed (e.g. by seeding diverse native species mixtures and maintaining structured habitats) to maximise delivery of plant- and soil-related ecosystem services. This is particularly true for biomass production and long-term soil carbon storage and sequestration, given the observed effects of solar panels on vegetation and their consequences for soil properties (e.g. soils being deprived of plant carbon inputs due to relatively low plant biomass under solar panels). However, our results suggest that past biotic and abiotic agricultural legacies can be overcome to allow solar farms to deliver environmental benefits other than low carbon electricity, given plant and soil properties in the gaps between solar arrays were generally similar to control conditions, suggesting no deterioration of ecosystem functioning in solar farms if converted from agricultural land. In fact, plant cover and soil carbon showed signs of improvement as solar farms aged (tables A1 and A2), meaning plant- and soil-related ecosystem services could improve over time if solar farms were managed accordingly (Randle-Boggis *et al* 2020) and offered the right policy incentives (Carvalho *et al* 2024b).

Solar farms can be designed and managed to deliver positive plant and soil outcomes. Regarding design, increasing the height of solar panels over the ground to offset the negative effects of shading and changes to microclimate on plant productivity, or increasing the proportion of gap areas (and other areas within solar farms such as margins) to favour plant development and consequently benefit soils through enhanced carbon inputs would be beneficial. Areas under solar panels account for approximately 39% of land in an average solar farm in the UK (but it could be as high as 70% in some cases; Blaydes, unpublished digitised solar farm data), offering scope to manage the remainder to deliver net positive outcomes for nature. In fact, differences in plant and soil properties between solar farms and pastures were lower than differences between under and pasture when accounting for the proportion of land in the different treatments (under and gap), while soil carbon was slightly higher in solar farms than in pastures on average (table 2), even if margins were not considered in this study. These results suggest solar farms can deliver net environmental gains across the site if enough area is set-aside for conservation away from solar arrays. However, increasing the proportion of land not over sailed by solar panels may result in higher land take for solar farms, meaning overall outcomes will depend on the type of land use being converted.

Finding management solutions to enhance vegetative cover under solar panels in temperate systems will be challenging, given the relative novelty of this type of land use and the fact plant and soil responses to active land management are highly dependent on local conditions. Management options may include the use of low impact machinery during construction to reduce soil compaction, the reduction in soil (plant-available) nutrients to promote species diversity (Isbell *et al* 2013, Midolo *et al* 2019), the regular monitoring of soil pH to formulate soil remediation measures if needed (Neina 2019), the sowing of generic all-purpose seed mixes that can establish on a range of soils and contain shade-tolerate species, and the use of conservation cutting and grazing to promote structured and diverse habitats to benefit wildlife. Frequent monitoring using standardised approaches (Carvalho *et al* 2023) will ensure the delivery of land management objectives and the collection of data that are comparable across sites. This will be key in guaranteeing the long-term provision of ecosystem services and in offering a broad picture of the ecosystem effects of this rapidly expanding novel land use.

## 6. Conclusions

Solar energy, especially in the form of ground-mounted solar farms, is set to play an important role in decarbonising electricity supplies worldwide. To address both the climate and biodiversity crises, the effects of ground-mounted solar panels on plants and soils must be considered before, during, and after solar farm development and contextualised to local conditions. In addition, the overall impact of a solar farm must be appropriately scaled to account for net environmental change across the site after land development given contrasting effects experienced by areas under solar panels to those in the gaps between solar arrays.

Given the relative youth of solar farms and their anticipated growth, it is critical that ecosystem responses to solar farm development and management are continually monitored to maximise positive biodiversity outcomes. The development of solar farms on agricultural land may lead to benefits for some ecosystem services over time (considering time lags in soil response to land use change), but developing ways to address the legacy of previous agricultural land use and enhancing plant cover under solar panels should be the focus of future research.

Other explanatory variables not included here (e.g. previous land use, land management, gap width, solar panel height and angle) should be considered in upcoming studies as they may also drive plant and soil responses to solar farm development and can be altered to maximise positive biodiversity outcomes. In addition, the expected growth in solar farms may be accompanied by integrated battery storage facilities, introducing other environmental impacts (Simpa *et al* 2024). Consequently, the effects of battery storage facilities on soils should be considered in future research as they become increasingly more common.

Plant and soil properties may offer foundational indicators to investigate the impacts of solar farms on ecosystem services, but better understanding of the potential effects of solar farms on wider biodiversity (e.g. invertebrates, birds, mammals) is also needed to develop ways to manage solar farms that can benefit nature recovery in the fullest sense.

## Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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## Author contributions

Fabio Carvalho, Alona Armstrong, Hannah Montag, Tom Clarkson, Stuart P Sharp, and Piran C L White conceived the ideas and designed the methodology. Fabio Carvalho conducted field work and Rosanne C Broyd, Miranda Burke, Fabio Carvalho, Marta Cattin, Sammani Ramanayaka, Radim Sarlej, and Abby Wallwork performed laboratory work. Hollie Blaydes produced the map and graphics in figure 1. Laura Bentley advised on the use of soil classes and performed data selection. Fabio Carvalho analysed the data and led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for submission.

## Conflict of interest

Fabio Carvalho was co-funded by Clarkson & Woods Ltd, Hannah Montag is employed by Clarkson & Woods Ltd, Hollie Blaydes was co-funded by Low Carbon Investment Management Ltd, and Tom Clarkson is Managing Director of Clarkson & Woods Ltd. Marta Cattin is currently employed by the Environment Agency; the views expressed are hers and those of the authors and are not formal positions of the Environment Agency.

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