Effects of solar park construction and solar panels on soil quality, microclimate, CO 2 effluxes, and vegetation under a Mediterranean climate

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i. Manuscript Title

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Effects of solar parks on soil quality, CO_2 effluxes and vegetation under Mediterranean climate

Solar parks are expanding in Europe, but their impact on soil and vegetation is not well studied yet. In the present study including three parks in the Mediterranean region, we show that the construction of solar parks reduces the physical quality of the soil altering main soil functions. Moreover, the presence of solar panels decreases CO_2 emissions and temperature but does not change the structure of plant communities.

vi. Short running title

Effects of solar parks on soil quality, CO_2 effluxes and vegetation

vii. Acknowledgements

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viii. Abstract and Keywords

Abstract:

Solar energy is increasingly used to produce electricity in Europe, but the environmental impact of constructing and running solar parks (SP) is not yet well studied. Solar park construction requires partial vegetation removal and soil leveling. Additionally, solar panels may alter soil microclimate and functioning. In our study of three French Mediterranean solar parks, we analysed 1) effects of solar park construction on soil quality by comparing solar park soils with those of semi-natural land cover types (pinewood and shrubland) and abandoned croplands (former vineyards) and 2) the effect of solar panels on soil microclimate, CO_2 effluxes and vegetation. We measured 21 soil properties of physical, chemical, and microbiological soil quality in one solar park and its surroundings to calculate integrated indicators of soil quality. We surveyed soil temperature and moisture, CO_2 effluxes and vegetation below and outside solar panels of three solar parks. Soil aggregate stability was reduced by SP construction resulting in a degradation of soil physical quality. Soil chemical quality and a general indicator of soil quality were lower in anthropogenic (SP and abandoned vineyards) than in semi-natural (pinewood and shrubland) land cover types. However, differences between abandoned vineyards representing the pre-construction land cover type and solar parks were not significant. Solar panels reduced the soil temperature by 10% and soil CO_2 effluxes by 50% but did not affect early successional plant communities. Long-term monitoring is needed to evaluate the effects of solar panels on vegetation.

Keywords: renewable energy, soil functions, land cover, microclimate, soil respiration, plant communities

ix. Main text

1. Introduction

The use of solar energy to produce electricity is increasingly common in Europe and requires large areas in order to be cost-effective (Murphy *et al*., 2015 ; Ong *et al*., 2013). Solar park construction involves clearing and grading the soil surface, burying of electric cables, vegetation removal and soil compaction increasing runoff and erosion. Grading, compaction, and erosion change the physical and chemical properties of the soil and thus reduce its quality. Since solar park construction destroys the vegetation and affects the soil, a careful analysis of the environmental impact of solar parks is needed (Armstrong *et al.*, 2016; Hernandez *et al.*, 2015).

Although soil quality is an important indicator of ecosystem functioning, the effect of solar park construction on soil quality has not yet been reported elsewhere. After the installation of solar panels, the vegetation is regularly mown or grazed limiting vegetation height to prevent shading of panels. The solar panels also change the microclimate such as temperature, humidity, solar radiation (Tanner *et al.*, 2020; Armstrong *et al.*, 2016). Such changes in microclimate may affect soil processes and plant communities under panels, in particular in the European Mediterranean with high solar irradiation compared to temperate regions.

Soil quality is “the capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality and support human health and habitation” (Karlen *et al.*, 1997). Three soil quality indicator groups are commonly used: physical, chemical and biological soil properties (Bünemann *et al*., 2018 ; Costantini *et al*., 2016 ; Maurya *et al*., 2020). Physical properties, such as bulk density and texture influence water holding capacity and plant communities by modulating root growth (Scarpare *et al*. 2019 ; Lampurlanés, Cantero-Martínez 2003). Chemical properties such as inorganic N, total C and pH control plant nutrition and microbiological activity. Biological indicators include the activity of decomposers such as invertebrates or microorganisms. These organisms control organic matter decomposition and nutrient cycling (Maurya *et al.*, 2020).

Velasquez *et al*. (2007) developed a single general indicator of soil quality (GISQ) that integrates a set of physical, chemical, and biological soil properties. Such soil properties are chosen and measured to evaluate multifaceted aspects of soil functions and further combined to calculate sub-indicators of physical quality, chemical fertility, and biological functioning. The GISQ combines the sub indicators to provide a global assessment of soil quality based on soil ecosystem services and facilitates the comparison of soils between different sites/habitats. In a comparative study on four land use types, (Raiesi & Salek- Gilani, 2020) showed, using an adapted GISQ, that soil quality was 1.5 times lower in anthropogenic than in natural soils. Joimel *et al*. (2016) observed a decrease in soil physico-chemical quality along an anthropization gradient from forest to urban soils whereas Joimel *et al*. (2017) did not find any difference in biological quality of these soils. The construction of solar parks on natural and semi-natural land use types (e.g. forest, shrubland and abandoned vineyards) may reduce soil quality and affect ecosystem functions such as infiltration and storage of water, fertility and plant reestablishment, soil organic matter and nutrient cycling (Khare & Goyal, 2013; Romero-Díaz *et al.*, 2017; Rutgers *et al.*, 2009; Scarpare *et al.*, 2019; Yin *et al.*, 2020).

Plant communities and soil functioning may also be affected by changes in microclimate under solar panels. Solar panels reduce solar radiation, air humidity and soil temperatures, but in winter, soil temperatures are generally higher under panels (Armstrong *et al*., 2016). Adeh *et al*. (2018) reported highest soil moisture and local heterogeneity of soil water conditions under solar panels. Such changes in microclimate may alter plant community composition and soil respiration that can be measured as CO_2 release. Mediterranean plant communities are dominated by heliophilous plants (Bagella & Caria, 2012). The reduction of solar radiation under solar panels may thus result in a plant community shift towards shade-tolerant species. Seed germination of Mediterranean species may be limited by light reduction (Gresta *et al.*, 2010), and the mortality of heliophilous plants increases in competition to shade-tolerant species. (Novara *et al.*, 2012; de Dato *et al.*, 2010). The change in air and soil microclimate under panels reduced the soil respiration under temperate oceanic climate (Armstrong *et al.*, 2016). Under Mediterranean climate with higher annual temperatures and summer drought, changes in microclimate under solar panels may be higher resulting in a strong disturbance of seasonal soil respiration dynamics (González-Ubierna & Lai, 2019). Plant communities contribute to soil CO_2 release by respiration of roots and rhizosphere microorganisms (Raich & Tufekciogul, 2000) but also by changes in soil structure (Yang *et al.*, 2009; Zou *et al.*, 2005). Furthermore, plants are the principal carbon source of decomposer microorganisms (Wall *et al.*, 2012). Thus, solar panels may also change soil conditions indirectly by a shift in plant community composition since plants are very sensitive to change in microclimate.

The aims of our study were to assess 1) the effect of solar park construction on soil quality in comparing solar parks with semi-natural land cover types (pinewood and shrubland) and abandoned vineyards and 2) the effects of solar panels on soil microclimate, CO_2 effluxes and vegetation under Mediterranean climate. We expected that 1) solar park construction reduces physical, chemical, and biological soil quality, 2) solar panels change soil microclimate and plant community composition, and 3) solar panels change soil respiration according to the season.

2. Material and Methods

2.1. Study sites

Two studies were conducted in three solar parks (SP) located in Southern France (La Calade, Pouzols-Minervois and Roquefort des Corbières, Figure 1A.) with a distance of 10 to 30 km from one another (Table 1). These SP were constructed in 2011, 2014 and 2016, respectively, covered between 8.5 and 16 Ha and used ground-fixed photovoltaic (PV) systems carrying the solar panels at a fixed inclination. The solar panels are aligned to form rows (height of 0.6 m min and 2 m max) exposed to the South, with a gap of 4 m between rows. The study region is characterized by typical Mediterranean climate with summer drought and mild, wet winters. The SP are mainly bordered by pinewood (*Pinus halepensis*), shrublands and vineyards. The soils of the SPs are characterized by carbonatic pedofeatures (i.e. fine calcareous silty clay soil).

2.2. Sampling designs

Study 1: effect of solar park construction

To study the effects of solar park construction on soil quality, four sampling plots (50 ×2 m) separated by 150 m were randomly chosen within the SP at Roquefort des Corbières (inter-rows between solar panels). In the surroundings of the SP, we randomly selected four sampling plots (100 m²) for each of the three dominant habitat types in the study region: pinewood, shrubland and abandoned vineyards (Figure 1B). These three land cover types are also representative of regional land use (forestry, ancient pastures and viticulture), and the studied SP was constructed on an abandoned vineyard. The plots were at least 200 m apart from each other and not more than 400 m from the SP. The pinewood is essentially composed of *Pinus halepensis and Quercus coccifera.* The shrublands are dominated by *Quercus coccifera, Pistacia lentiscus, Rosmarinus officinalis, Myrtus communis, Genista scorpius, Brachypodium retusum* and *Cistus monspelliensis*. The vineyards had been abandoned for five years before solar park construction and were dominated by grapevine, *Anisantha rubens, Dittrichia viscosa* and *Lysimachia arvensis.* In March 2016, ten soil samples were randomly collected (10 cm depth) within each plot, mixed to one composite sample per plot. Composite samples were sieved (mesh size: 2 mm) prior to analyses. An aliquot of samples was air-dried (1 week, 30 °C). For each sample, another aliquot was stored at 4 °C for microbial analyses.

Study 2: effect of solar panels

To study the effect of solar panels on soil respiration, temperature, and moisture and on plant communities, we randomly selected within each of the three SP four sampling plots (50 ×2 m) below the solar panels, both separated by at least 100 m, and four adjacent sampling plots (50 ×2 m) in the inter-rows between the solar panel.

2.3. Measurements of soil physico-chemical and microbiological quality

Soil physical properties

Water content ($g.kg^{-1}$) was determined after drying samples (24 hours, 105 °C). Water holding capacity (WHC) was analyzed according to Saetre (1998) but using a modified protocol. 10 g of dried soil were weighted in a PVC cylinder and saturated with water. WHC was defined as the water content remaining in the soil after 12 h (4 °C). The different soil fractions (*i.e.* sand, silt, clay) were determined using the Robinson's pipette method (Olmstead *et al.*, 1930) after organic matter removal by oxidation with H_20_2 (30%, 48 hours). Bulk density (BD) was determined by measuring dried soil mass sampled in a Siegrist's cylinder. According to Huang *et al.*, (2004), a value of 2.65 $g.cm^{-3}$ was assumed for real soil density (RD). Soil porosity was calculated using the following equation.

$$Soil\ porosity\ = 100 \times \frac{\mathrm{RD-BD}}{RD} \quad \text{(Equation. 1)}$$

Mean weight diameter (MWD) of soil aggregates was measured according to Kemper and Rosenau (1986).

Soil chemical properties

The soil pH was measured in distilled water and KCL (1M) (Aubert, 1978). Total Carbon (TC) and Nitrogen (TN) content were determined by combustion in an elemental analyzer CN FlashEA 1112 (ThermoFisher) (NF ISO 10694, NFISO 13878). Calcium carbonate ($CaCO_3$) content was measured using a Bernard calcimeter (Müller & Gastner, 1971) and the percentage of C in $CaCO_3$ (C-$CaCO_3$) was determined as: C-$CaCO_3$ = 11.991 / 100 x $CaCO_3$. Inorganic nitrogen (NH_4^+ and NO_3^-) was extracted in KCL solution (1 M) and analysed calorimetrically using the nitroprusside-salicylate and nitrosalicylic acid method according to Mulvaney (1996) and Keeney and Nelson (1983), respectively.

Soil microbiological properties

Microbial Biomass (MB) was measured using substrate induced respiration (SIR) rates (Anderson and Domsch, 1978). Basal respiration was determined without adding glucose to calculate the metabolic quotient qCO_2 (the ratio of basal respiration to microbial biomass), which is a sensitive ecophysiological indicator of soil stress (Anderson, 2003). Three enzyme activities (*i.e.* fluorescein diacetate hydrolase, phosphatase and tyrosinase) involved in carbon and phosphorous cycles were assessed (n=3 per sample) to determine the catabolic potential of microbial communities. Fluorescein diacetate hydrolase (FDase, $U.g^{-1}$ dry weight) was measured according to Green *et al*. (2006), phosphatase ($U.g^{-1}$ dry weight) according to Tabatabai and Bremner (1969) and the activity of tyrosinase ($\mu mol.min^{-1}.g^{-1}$ dry weight) according to Saiya-Cork *et al*. (2002).

2.4. Measurements of solar panel effects on soil moisture, temperature and *in situ* respiration

Soil respiration, temperature and moisture were recorded in March and June 2017 in each sampling plot of the study on solar panel effects. *In situ* CO_2 release ($g.CO_2.m^{-1}.h^{-1}$) from soils, plant roots, soil organisms and chemical oxidation of C compounds was measured after removal of aboveground vegetation, using a portable gas analyser (IRGA, EGM-4, PP-system). The device was connected to a closed soil respiration chamber (SRC-1, PP systems Massachusetts, USA). To prevent leakage of CO_2 when placing the chamber on the soil, a PVC tube (10 cm x 11 cm) was buried 1 cm deep into the soil prior to measurements. Soil temperature was recorded in a depth of 7 cm using the soil temperature probe (STP-1, PP-system) connected to the respirometer. Soil moisture was recorded on four points at 7 cm depth using a portable time-domain reflectometry (TDR) device (Delta-T Devices, ML2 Theta Probes).

2.5. Measurements of solar panel effects on vegetation

In the sampling plots of the study on solar panel effects, vegetation surveys were carried out in 2016 and 2017. Three rectangular sub-plots of 10 m² (2 m × 5 m) were placed at the ends and the center of each plot. Percentage cover of all occurring vascular plant species was estimated as the vertical projection of aboveground plant organs. A ratio of shadow-tolerant (sciaphilous) to hemi-heliophilous and heliophilous plant species (Julve, 2020) was calculated .

2.6. Statistical analyses

We calculated a General Indicator of Soil Quality (GISQ) according to Velaquez *et al*. (2007). Information on 21 variables of physical, chemical, and microbiological soil properties was used to create three sub-indicators related to main soil functions: 1) physical properties that determine the infiltration and storage of water, 2) chemical properties that affect fertility and plant reestablishment in solar parks, 3) microbiological properties that drive soil organic matter decomposition and nutrient cycling. For each group of variables (physical, chemical and microbiological), a principal component analysis (PCA) with data scaled to unit of variance was run using “FactoMineR” (Husson *et al.*, 2020) and “Factoextra” (Kassambara & Mundt, 2020) packages. The Kaiser–Meyer–Olkin measure (>0.50). Bartlett’s test of sphericity (0.05) were used to test the sampling adequacy of variables included in the PCA. Variables with communality values <0.05 were removed and main components were identified using the latent root criterion (eigenvalues >1.0). A synthetic index of quality for each group of variables at a plot i (Iq_i) was calculated as the sum of n variables (vi) multiplied by their respective weight (wi) in the determination of axes 1 and 2 of the PCA (Equation 2.).

$$Iq_i = \sum_{i=1}^{n} w_i v_i \text{ (Equation2.)}$$

The values of Iq_i were then reduced to a common range (0.1 to 1.0) using a homothetic transformation to obtain the sub-indicators of physical, chemical and microbiological soil quality (hereafter pSQ, cSQ and mSQ respectively, Equation 3.). In this equation, a is the maximal and b the minimal Iq value for the plot i.

$$p, c \text{ or } mSQ = 0.1 + \frac{Iq_i - b}{a - b} \times 0.9 \text{ (Equation 3.)}$$

Finally, a PCA was run with the 3 sub-indicators. The GISQ was obtained by summing the products of the respective contributions of variables to factors 1 and 2 by the % inertia explained by factors, respectively. Finally, the sum of these products gave the following formula for the GISQ (Equation 4.):

$$GISQ = 0.29\ pSIq + 0.28\ cSIq + 0.33\ mSIq$$ (Equation 4.)

All data were analysed using R software (3.6.1,R Core Team, 2020). Effects of land cover type on soil physical, chemical and microbiological properties, sub-indicators of soil quality and GISQ were assessed using one way-analysis of variance (ANOVA). In the case of a significant land cover type effect, a Tukey HSD post hoc test was used to analyze differences between specific land cover types. To analyze the effect of solar panels on soil temperature, water content, CO_2 effluxes and vegetation, linear mixed-effect models (LMMs) (R package "lme4") were applied including month and treatment (below vs outside panels) as fixed factors and solar park identity as random factor. Assumptions of ANOVA were checked by Shapiro-Wilks test for normality and by Levene test for homoscedasticity. When necessary, data were transformed using the "bestNormalize" package (Peterson, 2019) to meet these assumptions. Effects of solar panels on plant communities were visualized by non-metric multidimensional scaling (nMDS) based on the Bray-Curtis dissimilarity. Differences in plant community composition were tested using permutational multivariate analysis (PERMANOVA) in R package "vegan" (Oksanen *et al.*, 2019). A subsequent pairwise post hoc test was conducted to analyze differences between factor levels. False discovery rate (fdr) was used to correct for multiple comparisons.

3. Results

3.1. Effects of solar park construction on soil properties

Seven of the eight tested physical soil properties were significantly different between land cover types (Table 2). Among these seven properties, only two showed a significant difference between the two semi-natural (pinewood and shrubland) land cover types and the SP. Soil water content was 5.5% lower in the SP ($p<0.01$) than in shrubland. The mean weight diameter of aggregates was twice as high in abandoned vineyards as in SP, and three times higher in pinewood and shrubland than in SP ($p<0.001$). Organic carbon was about 2.5 times higher in semi-natural than in anthropogenic land cover types ($p<0.001$). Sand and silt content, soil porosity and bulk density were significantly different between abandoned vineyards and pinewood (Table 2). Silt content and soil porosity were 1.4 and 1.3 times lower in abandoned vineyards than in pinewood, respectively. Sand content and BD were about 1.5 times higher in abandoned vineyards than in pinewood. Pinewood and shrubland showed similar physical properties without significant differences.

For most soil chemical properties, SP showed significant differences to pinewood and shrubland but not to abandoned vineyards (Table 2). Total carbon contents were 1,44 times higher in semi-natural land cover types than in anthropogenic land cover types ($p <0.01$). Organic carbon contents were about 2,76 times higher in semi-natural land cover types than in anthropogenic land cover types ($p<0.01$). Total nitrogen (TN) content showed the same pattern. TN was twice as high in pinewood and shrubland as in the SP and abandoned vineyards ($p<0.001$). The water pH ranged between 8.02 and 8.11 and showed a small but significant difference between shrubland and abandoned vineyards.

Two microbiological properties were significantly different between land cover types (Table 2). Land cover type had a significant influence on basal respiration ($p<0.03$) being two times lower in the SP and abandoned vineyards than in forest and shrubland. The FDAse activity was two times higher in shrubland and pinewood than in the SP and abandoned vineyards. Microbial biomass was twice as low (marginally significant) in SP and abandoned vineyards as in the semi-natural land cover types.

3.2. Effects of solar park construction on soil quality

The first two axes of the PCA run on physical properties explained 80.56 % of the total variance (see A.1.A). The semi-natural land cover types are separated from the anthropogenic soils along the first axis. Silt, water content, water holding capacity and mean weight diameter of aggregates had the highest score on the first PCA axis, while soil porosity was strongly correlated with the second axis (see A.1.A). The highest physical quality index of 0.92 was measured in pinewood and shrubland being two times higher than in abandoned vineyards ($p<0.001$). The pSQ (Figure 2A) was two times and four times lower in SP than in the abandoned vineyards and semi-natural land cover types, respectively ($p<0.01$).

The first two axes of the PCA used to calculate the sub-indicator of soil chemical quality (cSQ) explained 80.98% of the total variance (see A.1.B). The semi-natural land cover types are separated from the anthropogenic soils along the first axis. Total carbon, organic carbon, total nitrogen and ammonium were most correlated with the first axis and nitrate with the second axis (see A.1.B). With a value of 0.18, the cSQ was four times lower in the SP and abandoned vineyards than in shrubland and pinewood ($p<0.001$, Figure 2B).

The first two axes of the PCA used to calculate the sub-indicator of soil microbiological quality explained 80.28 % of the total variance (see A.1.C). Basal respiration, microbial biomass, FDAse and phosphatase were highly correlated with the first PCA axis, while the qCO_2 was correlated with the second one (see A.1.C). The mSQ was not significantly different between land cover types ($p=0.74$) (Figure 2C).

The General Indicator of Soil Quality was four times lower in the SP and abandoned vineyards than in the pinewood and shrubland ($p<0.001$).

3.3. Effects of solar panels on soil temperature, water content and *in situ* CO_2 effluxes.

Soil temperature and water content were significantly different between months ($p<0.05$; Figure 3A and 3B). Solar panels significantly decreased soil temperature in March and June (Figure 3A) but did not affect soil water content ($p=0.79$). Soil CO_2 effluxes did not change between months but were twice as high outside solar panels than below solar panels ($p<0.001$).

3.3. Effects of solar panels on plant communities

Neither the species richness nor the total cover of plant community was significantly affected by the solar panels (Table 4). A marginally significant difference was detected for the ratio ‘Sciaphile: Heliophile plants’, being higher below than outside solar panels. The NMDS and PEMANOVA did not reveal any significant solar panel effect on plant community composition ($p = 0.3461$, Figure 4). However, community composition was significantly different between the solar parks ($p<0.001$). No significant difference was detected between observation years (data not shown).

4. Discussion

Solar Park (SP) construction reduced physical and chemical soil quality compared with semi-natural land cover types (forest and shrubland) but not biological soil quality. A change in soil temperature and CO_2 effluxes also demonstrated a negative solar panel effect on soil microclimate and functioning. However, in early stages of plant succession following solar park construction, plant community composition below and outside solar panels was not significantly different.

4.1 Effects of solar park construction on soil quality

Soil quality assessments require the measurement of a wide range of physical, chemical, and biological properties involving a high complexity of potential analyses (Maurya *et al.*, 2020). In this study, we assessed soil quality using a multi-proxy approach including 21 soil properties. The reduction of the number of variables using PCA to group these properties allows an integrated evaluation of soil quality based on their main functions, such as infiltration and storage of water, soil fertility, plant reestablishment and soil organic matter and nutrient cycling. We found that two of three integrated sub-indicators and the general indicator of soil quality were lower in SP than in the semi natural land cover types.

Among the physical soil properties, the aggregate MWD was 1.5 times lower in the SP than in the semi-natural land cover types (Table 2). A low MWD may result in a low aggregate stability.

Similarly, Kabir *et al.*, (2017) showed that the MWD decreases in anthropogenic soils associated with a degraded vegetation. In our study, soil levelling and vegetation removal prior to SP construction may have decreased soil organic matter (SOM) content reducing MWD. By binding colloids and stabilizing soil structure, SOM plays a key role in soil physical properties and nutrient cycling (Six *et al.*, 2004). Telak and Bogunovic (2020) showed a decrease in SOM and MWD in a vineyard of Croatia after intensive and frequent tillage. Such mechanical disturbance for many years may have affected soil structure of the vineyard on which the studied SP (Roquefort des Corbières) was constructed. Accordingly, overall physical soil quality of SP was lower than that of abandoned vineyards which was in turn lower than that of semi-natural land cover types. The physical soil quality index (Figure 2A) revealed that the construction of a SP increased the degradation of the physical soil quality of habitats already degraded by land management (abandoned vineyards). In particular, the stability of the soil, key factor of soil functioning, was lower in SP than in abandoned vineyards. Moreover, a lower SOM affects microbial activity and production of mucus resulting in a decrease of aggregate MWD and thus a soil more sensitive to erosion (Blavet *et al.*, 2009; Le Bissonnais *et al.*, 2018). The soil levelling and vegetation removal during SP construction may have increased surface runoff and soil erosion (Rabaia *et al.*, 2021).

In contrast to our expectations, the SP construction did neither increase soil bulk density nor decrease porosity compared to the abandoned vineyards (Table 2). In our study, soil bulk density was found to be lower in abandoned vineyards than in semi-natural land cover types. The past land management of vineyards may have degraded these properties before SP construction limiting effects of construction work. It is well known that the use of agricultural machinery considerably increases the soil bulk density (Dunjó *et al.*, 2003) . Under similar Mediterranean climate and land use history in Spain, the bulk density was 30% higher in vineyards than in pinewood (Dunjó *et al.* 2003). Such changes in soil physical properties can reduce the infiltration and storage of water. To improve the process of water infiltration and the capacity of water storage, a decompaction of the soil surface may be useful in particular if soils were already compacted by previous land management. Such decompaction also facilitates the germination and establishment of plant species (Bassett et al., 2005). The resulting improved revegetation may limit erosion and protect functions supported by soil physical quality (Beatty *et al.*, 2017).

Soil chemical properties, such as total and organic carbon and total nitrogen are directly linked to soil fertility and plant growth (Liu *et al.*, 2014). In our study, these properties showed lower values in anthropogenic soils than in semi-natural land cover types (Table 2). Joimel *et al*. (2016) obtained similar results along a gradient from natural to anthropogenic habitats in which total carbon and nitrogen decreased significantly from forests to vineyards. Soil disturbance such as soil tillage in vineyards or construction activities increases mineralization of organic matter reducing organic C and N (Brantley & Young, 2010). Accordingly, Choi *et al*. (2020) found a significantly lower C and N content in SP than in grassland soil. In our study, SP construction did not reduce neither C and N content nor soil chemical quality compared to degraded vineyard soil (Table 2). Consequently, the construction of SP did not further degrade the soil chemical properties. The low index of chemical quality (Figure 2B) is thus most likely related to the past vineyard management. Low C and N content suggest that nutrient cycling was lower in vineyards and SP soils and that several SP soil functions (carbon sequestration, soil structure, biological processes) were hampered compared to semi-natural soils. Appropriate site selection may limit such a loss of key soil functions by SP construction (Choi et al. 2020).

Soil microorganisms (*i.e.* bacteria and fungi) contribute actively to soil nutrient cycling (Schimel and Schaeffer, 2012). Thus, their genetic and physiologic characteristics are important indicators of ecosystem functioning such as nutrient cycling (Ranjard *et al.*, 2011). Microbiological soil properties showed differences between land cover types for fluorescein diacetate hydrolase (FDAse) activity and basal respiration. FDAse is an appropriate proxy to evaluate soil microbial activities because the ubiquitous esterase enzymes (e.g. lipase, protease) are involved in the hydrolysis of FDA (Schnürer & Rosswall, 1982). In our study, the FDAse was two times lower in anthropogenic soils (Table 2) suggesting a reduction of microbiological activity and nutrient cycling. Soil basal respiration showed the same pattern confirming a degradation of soil functions compared to semi-natural soils (Sparling 1997). Under a similar Mediterranean climate in Italy, basal respiration was three to four times lower in vineyards than in coniferous forests, mixed forests and shrublands (Marzaioli *et al.* (2010). The decrease in soil respiration may be related to the lower organic carbon and nitrogen content or the decrease in microbial biomass (Fernandes *et al.*, 2005). Previous vineyard management, in particular soil tillage, may have severely decreased microbial biomass resulting in low microbial activity. Five years abandonment were probably not sufficient to entirely reestablish microbial communities (Quintana et al., 2020). Despite the reduction of microbial properties in abandoned vineyards and solar park soils, the microbiological soil quality index (mSiQ) was not significantly different between land cover types (Figure 2C). Other microbiological properties (BM and phosphatase) mainly contributing to the first PCA axis were hardly affected by land cover type and thus overruled significant response variables in mSiQ calculation.

As a consequence of lower physical and chemical sub-indicators, the general indicator of soil quality was about three times lower in SP compared to semi-natural land cover types (Figure 2D).

The key processes involved in degradation of soil quality were soil tillage, partial topsoil removal increasing erosion (Quinton *et al.*, 2010) and organic matter mineralization. Reduced organic matter content and increase of soil compaction decrease water holding capacity (Mujdeci *et al.*, 2017) and soil stability (Simansky *et al.*, 2013). Soil restoration by revegetation may improve soil physical and microbiological qualities of solar parks (Hernandez *et al.*, 2019). Revegetation may increase the stability of aggregates by increasing root biomass and the production of binding agents (Erktan *et al.*, 2016). The root exudates can also stimulate microbial biomass and activity and thus improve nutrient cycling (Eisenhauer et al., 2010 ; Feng *et al.*, 2019).

4.2 Effects of solar panels on soil microclimate, vegetation, and *in-situ* CO_2 effluxes

Climatic conditions influence both soil microbial activities (Shao *et al.*, 2018) and plant communities (García- Fayos & Bochet, 2009). In our study, solar panels reduced the soil temperature in spring and in summer by about 5 °C (Figure 3A). Similarly, Armstrong *et al*. (2016) found a soil temperature reduction of 2 °C under solar panels during the summer (UK). The lower temperature under solar panels was the direct effect of shading although night temperatures may be higher (Tanner *et al.*, 2020). Solar panels also intercept precipitation, and Tanner *et al*. (2020) found a significant reduction in soil humidity under solar panels in the Mojave desert. However, we did not find any significant soil humidity difference under solar panels and outside (Figure 3B). The result may be explained by a lower evapotranspiration limiting humidity losses during drought periods as suggested by Tanner *et al*. (2020).

Mediterranean vegetation is dominated by heliophilous plants (Bagella & Caria, 2012). So we expected that light reduction by solar panels strongly affects plant communities. However, we did not find a significant effect of solar panels on plant community composition and structure (Figure

4). The effect of solar panels on the ratio of shadow-tolerant to heliophilous species was only marginally significant and no influence on plant species richness was detected (Table 3). Other studies showed, however, a reduction in plant cover and species richness under solar panels resulting from lower germination and higher mortality (Armstrong *et al*. 2016). Due to light limitation, heliophilous plants are expected to be less competitive under solar panels (Chen *et al.*, 2004). However, protection against strong solar radiation and drought during Mediterranean summer may have compensated for reduction of light and precipitation in our study. Accordingly, Tanner *et al*. (2020) observed that in a desert plant richness was marginally greater under their solar panels than in the control. In our study, the absence of a solar panel effect on the vegetation (Figure 4, table 3) may also be explained by the low age of our solar parks limiting differential effects on the vegetation. In early successional stages, the vegetation is dominated by ubiquitous annual species germinating and developing under a great variety of environmental conditions. Responses to the specific microclimate under solar panels may be slow in Mediterranean vegetation types (Coiffait-Gombault *et al.*, 2012; Kinzig *et al.*, 1999). Long-term monitoring is required to finally evaluate the influence of solar panels on plant communities.

A lower soil respiration is an indicator of lower litter decomposition and nutrient cycling suggesting that these ecosystem functions may be reduced under solar panels (Incerti *et al.*, 2011). In our study, soil respiration was highly affected by solar panels (Figure 3C). Half of the CO_2 fluxes from soils are produced by heterotrophic organisms (Bond-Lamberty *et al.*, 2004). Heterotrophic respiration, but also plant respiration, are driven by environmental factors, mainly temperature and moisture, explaining the strong influence of solar panels (Francioni *et al.*, 2020, Moinet *et al.*, 2019). Accordingly, Armstrong *et al*. (2016) found a reduction of soil CO_2 effluxes under solar panels in May and June. We already detected a reduced CO_2 efflux from March onwards suggesting that the warm Mediterranean spring results in earlier temperature differences between soils under and outside solar panels compared to temperate oceanic climate. This early decrease in temperature under solar panels compared to controls outside solar panels may have reduced microbial activity and thus heterotrophic respiration. The reduction of CO_2 effluxes under solar panels may also be the result of light reduction reducing plant growth and root respiration.

4.4 Conclusions

Physical, chemical, and general soil quality indexes were lower in a solar park than in semi-natural land cover types. Clearing and grading the soil surface during solar park construction resulted in a strong degradation of soil physical quality, especially of soil structure, but did neither disturb soil chemical quality nor global quality compared to abandoned vineyards. These results suggest that solar parks should be preferably constructed on anthropogenic soils or that construction must be accompanied by environmental compensation measures and/or ecological restoration. At our Mediterranean study sites, solar panels reduced soil temperature from spring onwards. Neither light nor spring temperature reduction under solar panels altered plant communities in early stages of plant succession but reduced CO_2 effluxes. Our study demonstrated that solar park construction and solar panels changed soil quality and microclimate to a magnitude known to affect key soil functions. Long-term monitoring including different seasons is required to evaluate the final response of soil properties and vegetation to solar panels.

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xi. Table

Table 1 Environmental and technical characteristics of solar parks.

	La Calade	Pouzols-Minervois	Roquefort des Corbières
Altitude (m)	77	100	62
Slope (%)	5	5	5
Temperature (annual mean, °C)	15.5	13.6	15.5.
Precipitation (annual mean, mm)	557	648	557
Sunshine duration (annual mean, hours)	2465	2119	2324
Soil texture	Loamy soil	Loamy soil	Loamy soil
Land cover before construction	Shrubland	Abandoned Vineyards and shrublandsQ	Abandoned Vineyards
Commissioning of the SP	2011	2014	2016
Maximum power (Kwc)	5102	4950	11152
Solar panel soil localisation		Ground-fixed	
Solar panel cell technologies		Crystalline	
A Solar panel power (Wc)	180	250	260
Number of solar panels	26856	19800	46473
Area of the SP (ha)	8.5	10.7	16

Table 2: Soil physical, chemical, and microbiological properties in each type of land cover. Mean values with standard errors in parentheses. Different letters indicate significant differences between land cover types (significant P-values in bold). BD: bulk density, WC: water content; WHC : water holding capacity; MWD : mean weight diameter; OC : organic carbon; TC: Total carbon, TN: total nitrogen; BR : basal respiration; MB : microbial biomass; qCO2 : metabolic quotient; FDAse : Fluorescein diacetate hydrolase.

	Properties	Pinewood	Shrubland	Abandoned Vineyards	Solar park	p value
Physical	Sand (%)	35.13 (5.07)[a]	45.91 (8.96)[ab]	47.78 (4.34)[b]	42.68 (2.58)[ab]	**0.04**
	Silt (%)	47.32 (8.63)[a]	35.81 (6.67)[ab]	33.16 (2.97)[b]	35.97 (1.03)[ab]	**0.03**
	Clay (%)	17.54 (4.70)	18.28 (6.33)	19.06 (1.37)	21.35 (1.57)	0.59
	BD ($g.cm^{-3}$)	1.11 (0.18)[a]	1.13 (0.17)[a]	1.47 (0.10)[b]	1.32 (0.13)[ab]	**0.02**
	WC (%)	19.55 (3.78)[ab]	22.14 (3.15)[a]	16.67 (2.01)[ab]	16.36 (0.44)[b]	**0.03**
	WHC (%)	65.66 (12.46)	70.81 (15.30)	51.93 (13.03)	59.24 (9.06)	0.23
	Porosity (%)	58.15 (6.95)[a]	57.54 (6.38)[a]	44.69 (3.92)[b]	50.19 (4.88)[ab]	**0.02**
	MWD (mm)	2626.47 (260.47)[a]	2618.40 (223.73)[a]	1593.30 (194.09)[b]	879.22 (271.43)[c]	**<0.001**
Chemical	OC (%)	4.92 (0.62)[a]	4.13(0.70.64)[a]	1.46(0.19)[b]	1.61 (0.17)[b]	**<0.001**
	TC (%)	8.59 (0.35)[a]	8.07 (1.28)[a]	5.63 (0.46)[b]	5.93 (0.71)[b]	**<0.001**

	TN (%)	0.22 (0.06)[a]	0.20 (0.07)[a]	0.09 (0.03)[b]	0.10 (0.02)[b]	**<0.01**
	Soil pH in water	8.03 (0.04)[ab]	8.02 (0.03)[b]	8.11 (0.05)[a]	8.06 (0.04)[ab]	**0.03**
	Soil pH in KCl	7.45 (0.04)	7.48 (0.06)	7.52 (0.06)	7.49 (0.05)	0.38
	Nitrate (µg µg $N\text{-}NO_3^{+}.g^{-1}$)	1.34 (0.32)	1.06 (0.80)	0.72 (0.26)	1.71 (0.61)	0.12
	Ammonium (µg $N\text{-}NH_4^{+}.g^{-1}$)	2.90 (0.17)[a]	2.92 (0.19)[a]	2.65 (0.14)[b]	2.65 (0.04)[b]	**0.03**
Microbiological	BR (µg $C\text{-}CO_2.g^{-1}.h^{-1}$)	1.28 (0.33)[a]	1.31 (0.61)[a]	0.61 (0.36)[b]	0.60 (0.07)[b]	**0.03**
	MB (µg $C\text{-}CO_2.g^{-1}.h^{-1}$)	0.40 (0.10)	0.37 (0.15)	0.24 (0.12)	0.20 (0.07)	0.07
	qCO2	3.20 (0.26)	3.48 (0.56)	3.33 (2.68)	3.38 (1.28)	0.99
	FDAse ($u.g^{-1}$)	0.0007 (0.0001)[ab]	0.0008 (0.0003)[a]	0.0004 (0.0001)[b]	0.0004 (0.0002)[b]	**0.02**
	Tyrosinase ($u.g^{-1}$)	0.0526 (0.0144)	0.0321 (0.0061)	0.0504 (0.0084)	0.0438 (0.0154)	0.11
	Phosphatase ($u.g^{-1}$)	0.0067 (0.0004)	0.0058 (0.0015)	0.0046 (0.0024)	0.0053 (0.0005)	0.28

Table 3: Effects of solar panels on plant communities. Mean values with standard errors in parentheses.

Parameters	Below solar panels	Outside solar panels	p
Species richness	12.56 (5.92)	13.25 (5.49)	0.29
Total cover (%)	351.2 (165.12)	379.97 (183.31)	0.22
Hemi-heliophilous: Heliophilous ratio	0.12 (0.14)	0.10 (0.10)	0.09

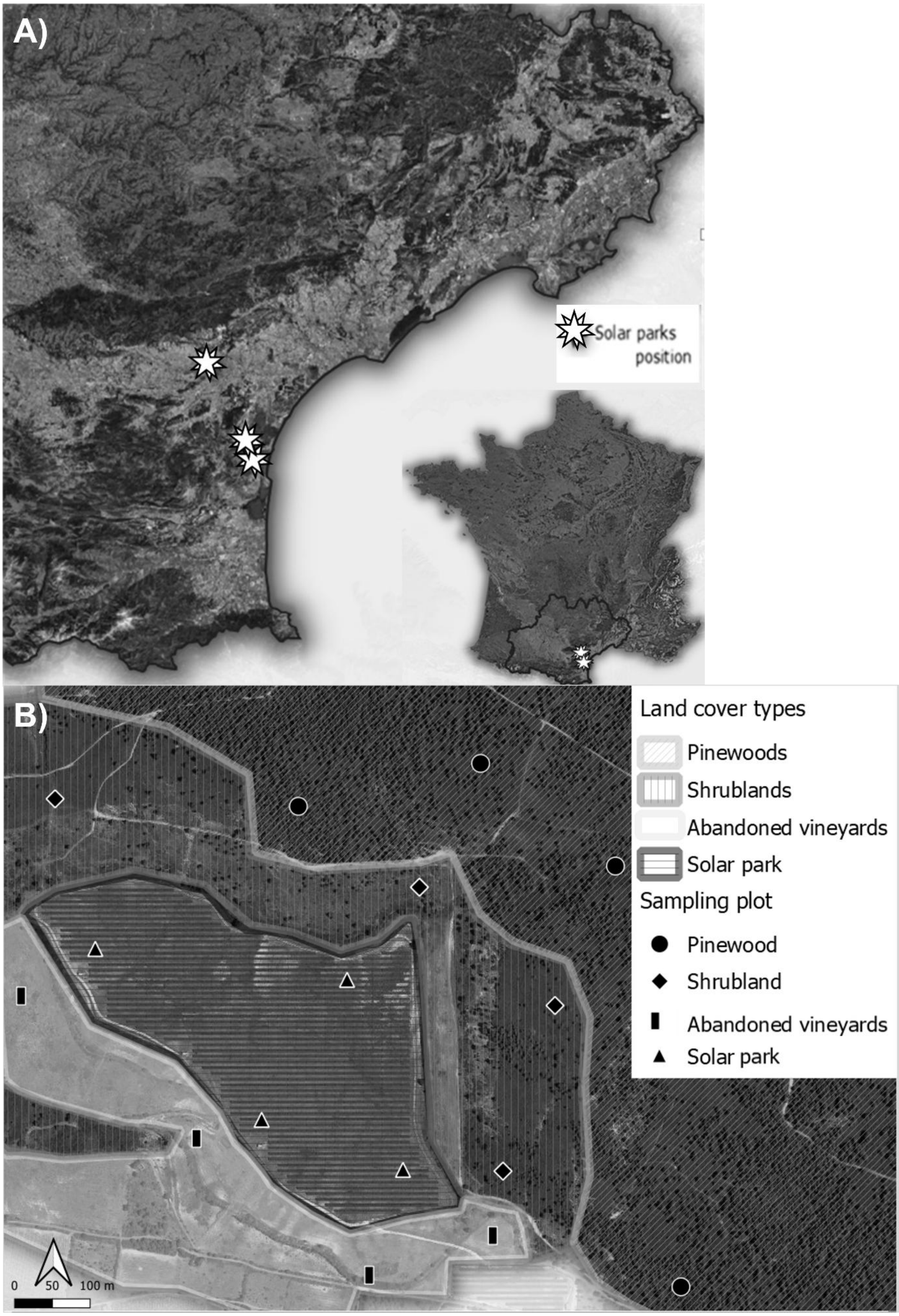
xii. Figure legend:

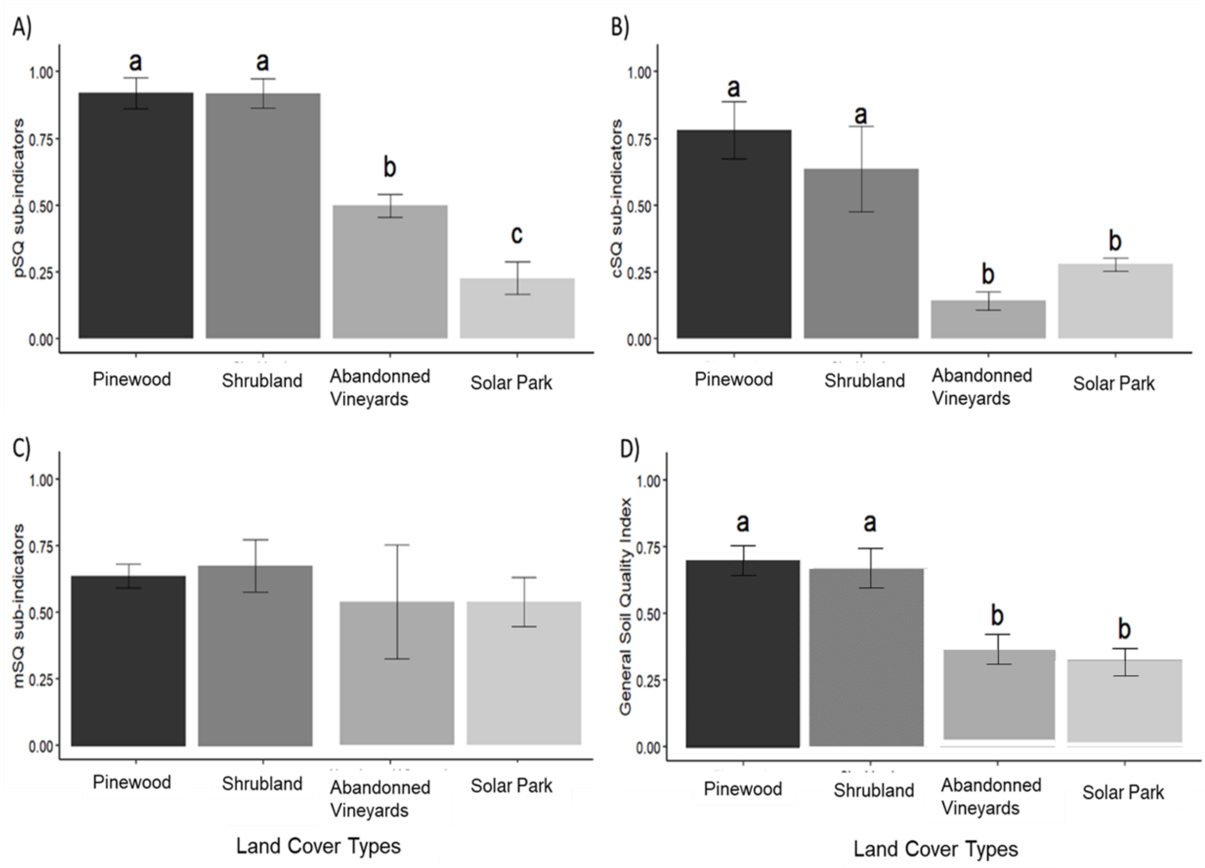
Figure 1: (A) Position of the three solar parks with 1 : Pouzols-Minervois, 2 : Roquefort-des-Corbières 3: La Calade (A) (B) The Roquefort-des-Corbières solar park in detail with surrounding land use types and sampling points.

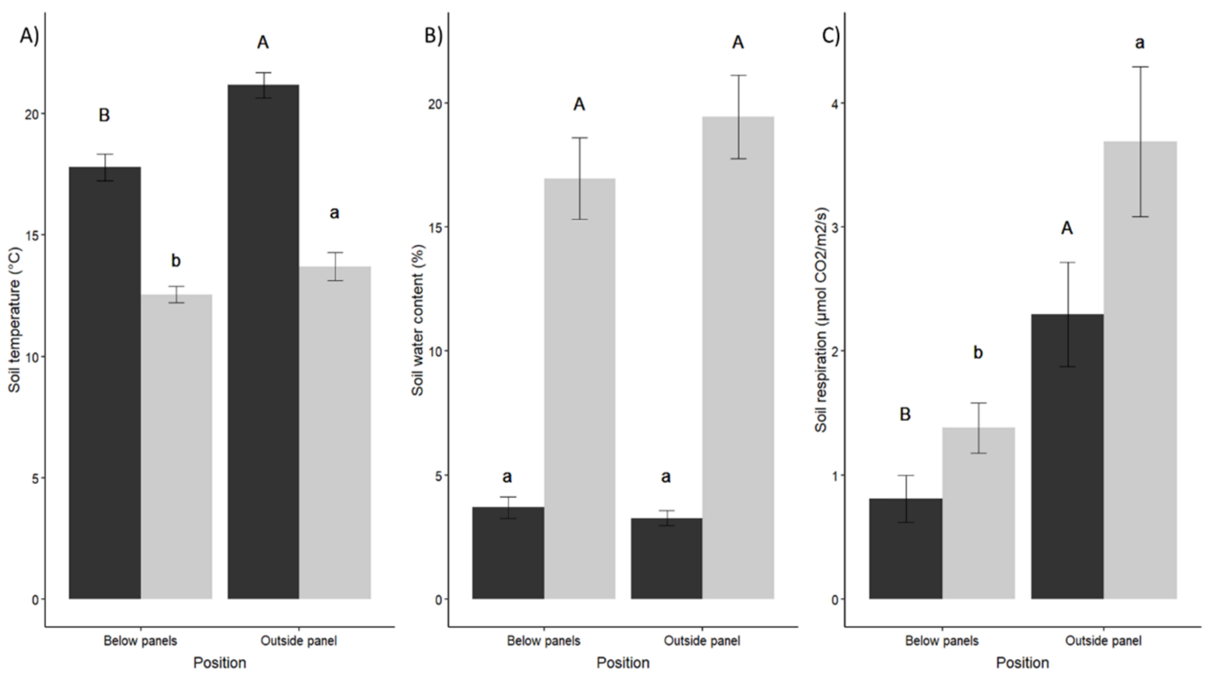
Figure 2: Sub-indicators of soil physical (A), chemical (B), and microbiological (C) quality and general soil quality indicator (D) for different types of land cover. Error bars are means +/- standard error. Different letters indicate significant differences ($p < 0.05$).

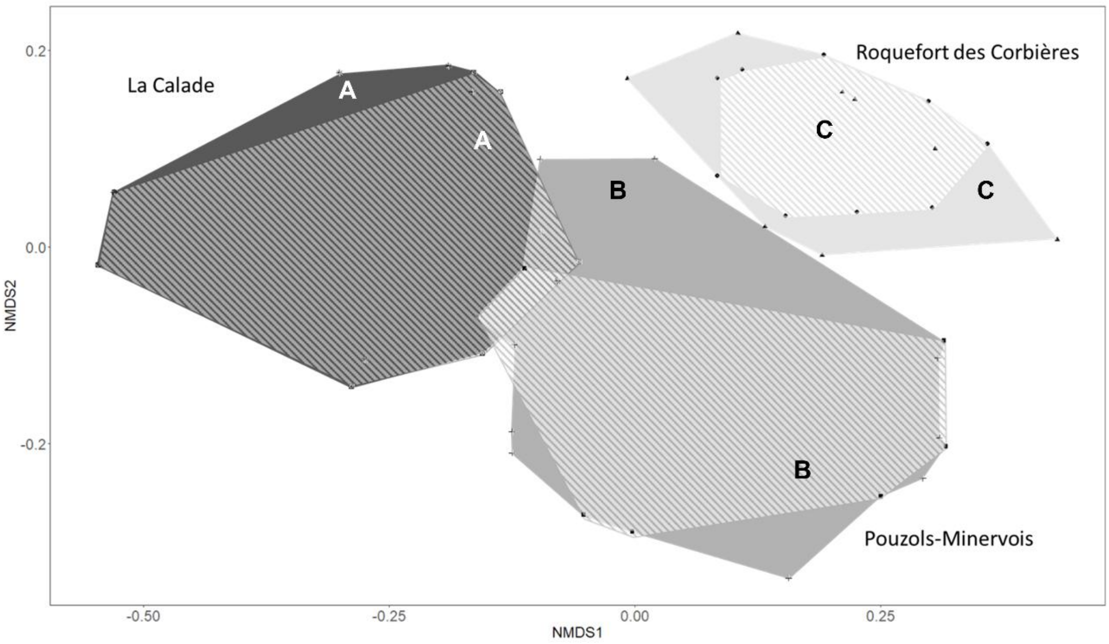
Figure 3: Soil temperature (A), water content (B) and CO_2 effluxes in March (black bars) and June (grey bars) below and outside solar panels. Error bars are means +/- standard error; different capital and lowercase letters indicate significant differences under and outside panels in March and June, respectively.

Figure 4: NMDS plot with polygons indicating the plant species composition of the three solar parks under (hatched polygon) and outside (solid polygon) solar panels, NMDS stress: 0.084. Different letters indicate significant differences after pairwise post hoc test ($p < 0.05$).


A)
Solar parks position
B)
Land cover types
Pinewoods
Shrublands
Abandoned vineyards
Solar park
Sampling plot
Pinewood
Shrubland
Abandoned vineyards
Solar park
0
50
100 m


A)
B)
C)
D)
pSQ sub-indicators
cSQ sub-indicators
mSQ sub-indicators
General Soil Quality Index
Pinewood
Shrubland
Abandonned Vineyards
Solar Park
Land Cover Types


A)
B)
C)
Soil temperature (°C)
Soil water content (%)
Soil respiration (µmol CO2/m2/s)
Below panels
Outside panel
Position



La Calade
A
A
B
Roquefort des Corbières
C
C
B
Pouzols-Minervois
0.2
0.0
-0.2
-0.50
-0.25
0.00
0.25
NMDS1
NMDS2