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Effects of solar park construction and solar panels on soil quality, microclimate, CO₂ effluxes, and vegetation under a Mediterranean climate

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1 i. Manuscript Title

2 **Effects of solar park construction and solar panels on soil**
3 **quality, microclimate, CO₂ effluxes and vegetation under**
4 **Mediterranean climate**

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21 v. Short informative containing containing the major key words.

22 Effects of solar parks on soil quality, CO₂ effluxes and vegetation under Mediterranean
23 climate

24 Solar parks are expanding in Europe, but their impact on soil and vegetation is not well
25 studied yet. In the present study including three parks in the Mediterranean region, we show
26 that the construction of solar parks reduces the physical quality of the soil altering main soil
27 functions. Moreover, the presence of solar panels decreases CO₂ emissions and temperature
28 but does not change the structure of plant communities.

29 vi. Short running title

30 Effects of solar parks on soil quality, CO₂ effluxes and vegetation

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36 viii. Abstract and Keywords

37 Abstract:

38 Solar energy is increasingly used to produce electricity in Europe, but the environmental impact
39 of constructing and running solar parks (SP) is not yet well studied. Solar park construction
40 requires partial vegetation removal and soil leveling. Additionally, solar panels may alter soil
41 microclimate and functioning. In our study of three French Mediterranean solar parks, we
42 analysed 1) effects of solar park construction on soil quality by comparing solar park soils with
43 those of semi-natural land cover types (pinewood and shrubland) and abandoned croplands

44 (former vineyards) and 2) the effect of solar panels on soil microclimate, CO₂ effluxes and
45 vegetation. We measured 21 soil properties of physical, chemical, and microbiological soil
46 quality in one solar park and its surroundings to calculate integrated indicators of soil quality. We
47 surveyed soil temperature and moisture, CO₂ effluxes and vegetation below and outside solar
48 panels of three solar parks. Soil aggregate stability was reduced by SP construction resulting in a
49 degradation of soil physical quality. Soil chemical quality and a general indicator of soil quality
50 were lower in anthropogenic (SP and abandoned vineyards) than in semi-natural (pinewood and
51 shrubland) land cover types. However, differences between abandoned vineyards representing the
52 pre-construction land cover type and solar parks were not significant. Solar panels reduced the
53 soil temperature by 10% and soil CO₂ effluxes by 50% but did not affect early successional plant
54 communities. Long-term monitoring is needed to evaluate the effects of solar panels on
55 vegetation.

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

58 ix. Main text

59 1. Introduction

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

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

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

85 Velasquez *et al.* (2007) developed a single general indicator of soil quality (GISQ) that integrates
86 a set of physical, chemical, and biological soil properties. Such soil properties are chosen and
87 measured to evaluate multifaceted aspects of soil functions and further combined to calculate
88 sub-indicators of physical quality, chemical fertility, and biological functioning. The GISQ
89 combines the sub indicators to provide a global assessment of soil quality based on soil

90 ecosystem services and facilitates the comparison of soils between different sites/habitats. In a
91 comparative study on four land use types, (Raiesi & Salek- Gilani, 2020) showed, using an
92 adapted GISQ, that soil quality was 1.5 times lower in anthropogenic than in natural soils. Joimel
93 *et al.* (2016) observed a decrease in soil physico-chemical quality along an anthropization
94 gradient from forest to urban soils whereas Joimel *et al.* (2017) did not find any difference in
95 biological quality of these soils. The construction of solar parks on natural and semi-natural land
96 use types (e.g. forest, shrubland and abandoned vineyards) may reduce soil quality and affect
97 ecosystem functions such as infiltration and storage of water, fertility and plant reestablishment,
98 soil organic matter and nutrient cycling (Khare & Goyal, 2013; Romero-Díaz *et al.*, 2017;
99 Rutgers *et al.*, 2009; Scarpore *et al.*, 2019; Yin *et al.*, 2020).

100 Plant communities and soil functioning may also be affected by changes in microclimate under
101 solar panels. Solar panels reduce solar radiation, air humidity and soil temperatures, but in winter,
102 soil temperatures are generally higher under panels (Armstrong *et al.*, 2016). Adeh *et al.* (2018)
103 reported highest soil moisture and local heterogeneity of soil water conditions under solar panels.
104 Such changes in microclimate may alter plant community composition and soil respiration that
105 can be measured as CO₂ release. Mediterranean plant communities are dominated by heliophilous
106 plants (Bagella & Caria, 2012). The reduction of solar radiation under solar panels may thus
107 result in a plant community shift towards shade-tolerant species. Seed germination of
108 Mediterranean species may be limited by light reduction (Gresta *et al.*, 2010), and the mortality
109 of heliophilous plants increases in competition to shade-tolerant species. (Novara *et al.*, 2012; de
110 Dato *et al.*, 2010). The change in air and soil microclimate under panels reduced the soil
111 respiration under temperate oceanic climate (Armstrong *et al.*, 2016). Under Mediterranean
112 climate with higher annual temperatures and summer drought, changes in microclimate under

113 solar panels may be higher resulting in a strong disturbance of seasonal soil respiration dynamics
114 (González-Ubierna & Lai, 2019). Plant communities contribute to soil CO₂ release by respiration
115 of roots and rhizosphere microorganisms (Raich & Tufekciogul, 2000) but also by changes in soil
116 structure (Yang *et al.*, 2009; Zou *et al.*, 2005). Furthermore, plants are the principal carbon source
117 of decomposer microorganisms (Wall *et al.*, 2012). Thus, solar panels may also change soil
118 conditions indirectly by a shift in plant community composition since plants are very sensitive to
119 change in microclimate.

120 The aims of our study were to assess 1) the effect of solar park construction on soil quality in
121 comparing solar parks with semi-natural land cover types (pinewood and shrubland) and
122 abandoned vineyards and 2) the effects of solar panels on soil microclimate, CO₂ effluxes and
123 vegetation under Mediterranean climate. We expected that 1) solar park construction reduces
124 physical, chemical, and biological soil quality, 2) solar panels change soil microclimate and plant
125 community composition, and 3) solar panels change soil respiration according to the season.

126

127 2. Material and Methods

128 2.1. Study sites

129 Two studies were conducted in three solar parks (SP) located in Southern France (La Calade,
130 Pouzols-Minervois and Roquefort des Corbières, Figure 1A.) with a distance of 10 to 30 km from
131 one another (Table 1). These SP were constructed in 2011, 2014 and 2016, respectively, covered
132 between 8.5 and 16 Ha and used ground-fixed photovoltaic (PV) systems carrying the solar
133 panels at a fixed inclination. The solar panels are aligned to form rows (height of 0.6 m min and
134 2 m max) exposed to the South, with a gap of 4 m between rows. The study region is

135 characterized by typical Mediterranean climate with summer drought and mild, wet winters. The
136 SP are mainly bordered by pinewood (*Pinus halepensis*), shrublands and vineyards. The soils of
137 the SPs are characterized by carbonatic pedofeatures (i.e. fine calcareous silty clay soil).

138

139 2.2. Sampling designs

140 Study 1: effect of solar park construction

141 To study the effects of solar park construction on soil quality, four sampling plots (50 ×2 m)
142 separated by 150 m were randomly chosen within the SP at Roquefort des Corbières (inter-rows
143 between solar panels). In the surroundings of the SP, we randomly selected four sampling plots
144 (100 m²) for each of the three dominant habitat types in the study region: pinewood, shrubland
145 and abandoned vineyards (Figure 1B). These three land cover types are also representative of
146 regional land use (forestry, ancient pastures and viticulture), and the studied SP was constructed
147 on an abandoned vineyard. The plots were at least 200 m apart from each other and not more than
148 400 m from the SP. The pinewood is essentially composed of *Pinus halepensis* and *Quercus*
149 *coccifera*. The shrublands are dominated by *Quercus coccifera*, *Pistacia lentiscus*, *Rosmarinus*
150 *officinalis*, *Myrtus communis*, *Genista scorpius*, *Brachypodium retusum* and *Cistus*
151 *monspelliensis*. The vineyards had been abandoned for five years before solar park construction
152 and were dominated by grapevine, *Anisantha rubens*, *Dittrichia viscosa* and *Lysimachia arvensis*.
153 In March 2016, ten soil samples were randomly collected (10 cm depth) within each plot, mixed
154 to one composite sample per plot. Composite samples were sieved (mesh size: 2 mm) prior to
155 analyses. An aliquot of samples was air-dried (1 week, 30 °C). For each sample, another aliquot
156 was stored at 4 °C for microbial analyses.

157 Study 2: effect of solar panels

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

162

163 2.3. Measurements of soil physico-chemical and microbiological quality

164 Soil physical properties

165 Water content (g.kg⁻¹) was determined after drying samples (24 hours, 105 °C). Water holding
166 capacity (WHC) was analyzed according to Saetre (1998) but using a modified protocol. 10 g of
167 dried soil were weighted in a PVC cylinder and saturated with water. WHC was defined as the
168 water content remaining in the soil after 12 h (4 °C). The different soil fractions (*i.e.* sand, silt,
169 clay) were determined using the Robinson's pipette method (Olmstead *et al.*, 1930) after organic
170 matter removal by oxidation with H₂O₂ (30%, 48 hours). Bulk density (BD) was determined by
171 measuring dried soil mass sampled in a Siegrist's cylinder. According to Huang *et al.*, (2004), a
172 value of 2.65 g.cm⁻³ was assumed for real soil density (RD). Soil porosity was calculated using
173 the following equation.

$$174 \quad \text{Soil porosity} = 100 \times \frac{RD-BD}{RD} \text{ (Equation. 1)}$$

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

177

178 Soil chemical properties

179 The soil pH was measured in distilled water and KCL (1M) (Aubert, 1978). Total Carbon (TC)
180 and Nitrogen (TN) content were determined by combustion in an elemental analyzer CN FlashEA
181 1112 (ThermoFisher) (NF ISO 10694, NFISO 13878). Calcium carbonate (CaCO_3) content was
182 measured using a Bernard calcimeter (Müller & Gastner, 1971) and the percentage of C in
183 CaCO_3 (C- CaCO_3) was determined as: $\text{C-CaCO}_3 = 11.991 / 100 \times \text{CaCO}_3$. Inorganic nitrogen
184 (NH_4^+ and NO_3^-) was extracted in KCL solution (1 M) and analysed calorimetrically using the
185 nitroprusside-salicylate and nitrosalicylic acid method according to Mulvaney (1996) and Keeney
186 and Nelson (1983), respectively.

187

188 Soil microbiological properties

189 Microbial Biomass (MB) was measured using substrate induced respiration (SIR) rates
190 (Anderson and Domsch, 1978). Basal respiration was determined without adding glucose to
191 calculate the metabolic quotient $q\text{CO}_2$ (the ratio of basal respiration to microbial biomass), which
192 is a sensitive ecophysiological indicator of soil stress (Anderson, 2003). Three enzyme activities
193 (*i.e.* fluorescein diacetate hydrolase, phosphatase and tyrosinase) involved in carbon and
194 phosphorous cycles were assessed (n=3 per sample) to determine the catabolic potential of
195 microbial communities. Fluorescein diacetate hydrolase (FDase, U.g^{-1} dry weight) was measured
196 according to Green *et al.* (2006), phosphatase (U.g^{-1} dry weight) according to Tabatabai and
197 Bremner (1969) and the activity of tyrosinase ($\mu\text{mol.min}^{-1}.\text{g}^{-1}$ dry weight) according to Saiya-
198 Cork *et al.* (2002).

199

200 2.4. Measurements of solar panel effects on soil moisture, temperature and *in situ* respiration

201 Soil respiration, temperature and moisture were recorded in March and June 2017 in each
202 sampling plot of the study on solar panel effects. *In situ* CO₂ release (g.CO₂.m⁻¹.h⁻¹) from soils,
203 plant roots, soil organisms and chemical oxidation of C compounds was measured after removal
204 of aboveground vegetation, using a portable gas analyser (IRGA, EGM-4, PP-system). The
205 device was connected to a closed soil respiration chamber (SRC-1, PP systems Massachusetts,
206 USA). To prevent leakage of CO₂ when placing the chamber on the soil, a PVC tube (10 cm x 11
207 cm) was buried 1 cm deep into the soil prior to measurements. Soil temperature was recorded in a
208 depth of 7 cm using the soil temperature probe (STP-1, PP-system) connected to the
209 respirometer. Soil moisture was recorded on four points at 7 cm depth using a portable time-
210 domain reflectometry (TDR) device (Delta-T Devices, ML2 Theta Probes).

211

212 2.5. Measurements of solar panel effects on vegetation

213 In the sampling plots of the study on solar panel effects, vegetation surveys were carried out in
214 2016 and 2017. Three rectangular sub-plots of 10 m² (2 m × 5 m) were placed at the ends and the
215 center of each plot. Percentage cover of all occurring vascular plant species was estimated as the
216 vertical projection of aboveground plant organs. A ratio of shadow-tolerant (sciaphilous) to hemi-
217 heliophilous and heliophilous plant species (Julve, 2020) was calculated .

218

219 2.6. Statistical analyses

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

234
$$Iq_i = \sum_{i=1}^n w_i v_i \text{ (Equation 2.)}$$

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

239

240
$$p, c \text{ or } mSQ = 0.1 + \frac{Iq_i - b}{a - b} \times 0.9 \text{ (Equation 3.)}$$

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

$$245 \quad GISQ = 0.29 pSIq + 0.28 cSIq + 0.33 mSIq \text{ (Equation 4.)}$$

246

247 All data were analysed using R software (3.6.1, R Core Team, 2020). Effects of land cover type
248 on soil physical, chemical and microbiological properties, sub-indicators of soil quality and GISQ
249 were assessed using one way-analysis of variance (ANOVA). In the case of a significant land
250 cover type effect, a Tukey HSD post hoc test was used to analyze differences between specific
251 land cover types. To analyze the effect of solar panels on soil temperature, water content, CO₂
252 effluxes and vegetation, linear mixed-effect models (LMMs) (R package “lme4”) were applied
253 including month and treatment (below vs outside panels) as fixed factors and solar park identity
254 as random factor. Assumptions of ANOVA were checked by Shapiro-Wilks test for normality
255 and by Levene test for homoscedasticity. When necessary, data were transformed using the
256 “bestNormalize” package (Peterson, 2019) to meet these assumptions. Effects of solar panels on
257 plant communities were visualized by non-metric multidimensional scaling (nMDS) based on the
258 Bray-Curtis dissimilarity. Differences in plant community composition were tested using
259 permutational multivariate analysis (PERMANOVA) in R package “vegan” (Oksanen *et al.*,
260 2019). A subsequent pairwise post hoc test was conducted to analyze differences between factor
261 levels. False discovery rate (fdr) was used to correct for multiple comparisons.

262

263

264 3. Results

265 3.1. Effects of solar park construction on soil properties

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

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

284 ranged between 8.02 and 8.11 and showed a small but significant difference between shrubland
285 and abandoned vineyards.

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

292 3.2. Effects of solar park construction on soil quality

293 The first two axes of the PCA run on physical properties explained 80.56 % of the total variance
294 (see A.1.A). The semi-natural land cover types are separated from the anthropogenic soils along
295 the first axis. Silt, water content, water holding capacity and mean weight diameter of aggregates
296 had the highest score on the first PCA axis, while soil porosity was strongly correlated with the
297 second axis (see A.1.A). The highest physical quality index of 0.92 was measured in pinewood
298 and shrubland being two times higher than in abandoned vineyards ($p < 0.001$). The pSQ (Figure
299 2A) was two times and four times lower in SP than in the abandoned vineyards and semi-natural
300 land cover types, respectively ($p < 0.01$).

301 The first two axes of the PCA used to calculate the sub-indicator of soil chemical quality (cSQ)
302 explained 80.98% of the total variance (see A.1.B). The semi-natural land cover types are
303 separated from the anthropogenic soils along the first axis. Total carbon, organic carbon, total
304 nitrogen and ammonium were most correlated with the first axis and nitrate with the second axis

305 (see A.1.B). With a value of 0.18, the cSQ was four times lower in the SP and abandoned
306 vineyards than in shrubland and pinewood ($p < 0.001$, Figure 2B).

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

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

314

315 3.3. Effects of solar panels on soil temperature, water content and *in situ* CO_2 effluxes.

316 Soil temperature and water content were significantly different between months ($p < 0.05$; Figure
317 3A and 3B). Solar panels significantly decreased soil temperature in March and June (Figure 3A)
318 but did not affect soil water content ($p = 0.79$). Soil CO_2 effluxes did not change between months
319 but were twice as high outside solar panels than below solar panels ($p < 0.001$).

320

321 3.3. Effects of solar panels on plant communities

322 Neither the species richness nor the total cover of plant community was significantly affected by
323 the solar panels (Table 4). A marginally significant difference was detected for the ratio
324 ‘Sciaphile: Heliophile plants’, being higher below than outside solar panels. The NMDS and
325 PEMANOVA did not reveal any significant solar panel effect on plant community composition
326 ($p = 0.3461$, Figure 4). However, community composition was significantly different between

327 the solar parks ($p < 0.001$). No significant difference was detected between observation years (data
328 not shown).

329

330 4. Discussion

331 Solar Park (SP) construction reduced physical and chemical soil quality compared with semi-
332 natural land cover types (forest and shrubland) but not biological soil quality. A change in soil
333 temperature and CO₂ effluxes also demonstrated a negative solar panel effect on soil
334 microclimate and functioning. However, in early stages of plant succession following solar park
335 construction, plant community composition below and outside solar panels was not significantly
336 different.

337

338 4.1 Effects of solar park construction on soil quality

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

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

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

366 In contrast to our expectations, the SP construction did neither increase soil bulk density nor
367 decrease porosity compared to the abandoned vineyards (Table 2). In our study, soil bulk density
368 was found to be lower in abandoned vineyards than in semi-natural land cover types. The past
369 land management of vineyards may have degraded these properties before SP construction
370 limiting effects of construction work. It is well known that the use of agricultural machinery
371 considerably increases the soil bulk density (Dunjó *et al.*, 2003) . Under similar Mediterranean

372 climate and land use history in Spain, the bulk density was 30% higher in vineyards than in
373 pinewood (Dunjó *et al.* 2003). Such changes in soil physical properties can reduce the infiltration
374 and storage of water. To improve the process of water infiltration and the capacity of water
375 storage, a decompaction of the soil surface may be useful in particular if soils were already
376 compacted by previous land management. Such decompaction also facilitates the germination
377 and establishment of plant species (Bassett *et al.*, 2005). The resulting improved revegetation
378 may limit erosion and protect functions supported by soil physical quality (Beatty *et al.*, 2017).

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

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

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

417 The key processes involved in degradation of soil quality were soil tillage, partial topsoil removal
418 increasing erosion (Quinton *et al.*, 2010) and organic matter mineralization. Reduced organic
419 matter content and increase of soil compaction decrease water holding capacity (Mujdeci *et al.*,
420 2017) and soil stability (Simansky *et al.*, 2013). Soil restoration by revegetation may improve soil
421 physical and microbiological qualities of solar parks (Hernandez *et al.*, 2019). Revegetation may
422 increase the stability of aggregates by increasing root biomass and the production of binding
423 agents (Erktan *et al.*, 2016). The root exudates can also stimulate microbial biomass and activity
424 and thus improve nutrient cycling (Eisenhauer *et al.*, 2010 ; Feng *et al.*, 2019).

425

426 4.2 Effects of solar panels on soil microclimate, vegetation, and *in-situ* CO₂ effluxes

427 Climatic conditions influence both soil microbial activities (Shao *et al.*, 2018) and plant
428 communities (García- Fayos & Bochet, 2009). In our study, solar panels reduced the soil
429 temperature in spring and in summer by about 5 °C (Figure 3A). Similarly, Armstrong *et al.*
430 (2016) found a soil temperature reduction of 2 °C under solar panels during the summer (UK).
431 The lower temperature under solar panels was the direct effect of shading although night
432 temperatures may be higher (Tanner *et al.*, 2020). Solar panels also intercept precipitation, and
433 Tanner *et al.* (2020) found a significant reduction in soil humidity under solar panels in the
434 Mojave desert. However, we did not find any significant soil humidity difference under solar
435 panels and outside (Figure 3B). The result may be explained by a lower evapotranspiration
436 limiting humidity losses during drought periods as suggested by Tanner *et al.* (2020).
437 Mediterranean vegetation is dominated by heliophilous plants (Bagella & Caria, 2012). So we
438 expected that light reduction by solar panels strongly affects plant communities. However, we did
439 not find a significant effect of solar panels on plant community composition and structure (Figure

440 4). The effect of solar panels on the ratio of shadow-tolerant to heliophilous species was only
441 marginally significant and no influence on plant species richness was detected (Table 3). Other
442 studies showed, however, a reduction in plant cover and species richness under solar panels
443 resulting from lower germination and higher mortality (Armstrong *et al.* 2016). Due to light
444 limitation, heliophilous plants are expected to be less competitive under solar panels (Chen *et al.*,
445 2004). However, protection against strong solar radiation and drought during Mediterranean
446 summer may have compensated for reduction of light and precipitation in our study. Accordingly,
447 Tanner *et al.* (2020) observed that in a desert plant richness was marginally greater under their
448 solar panels than in the control. In our study, the absence of a solar panel effect on the vegetation
449 (Figure 4, table 3) may also be explained by the low age of our solar parks limiting differential
450 effects on the vegetation. In early successional stages, the vegetation is dominated by ubiquitous
451 annual species germinating and developing under a great variety of environmental conditions.
452 Responses to the specific microclimate under solar panels may be slow in Mediterranean
453 vegetation types (Coiffait-Gombault *et al.*, 2012; Kinzig *et al.*, 1999). Long-term monitoring is
454 required to finally evaluate the influence of solar panels on plant communities.

455 A lower soil respiration is an indicator of lower litter decomposition and nutrient cycling
456 suggesting that these ecosystem functions may be reduced under solar panels (Incerti *et al.*,
457 2011). In our study, soil respiration was highly affected by solar panels (Figure 3C). Half of the
458 CO₂ fluxes from soils are produced by heterotrophic organisms (Bond-Lamberty *et al.*, 2004).
459 Heterotrophic respiration, but also plant respiration, are driven by environmental factors, mainly
460 temperature and moisture, explaining the strong influence of solar panels (Francioni *et al.*, 2020,
461 Moinet *et al.*, 2019). Accordingly, Armstrong *et al.* (2016) found a reduction of soil CO₂ effluxes
462 under solar panels in May and June. We already detected a reduced CO₂ efflux from March

463 onwards suggesting that the warm Mediterranean spring results in earlier temperature differences
464 between soils under and outside solar panels compared to temperate oceanic climate. This early
465 decrease in temperature under solar panels compared to controls outside solar panels may have
466 reduced microbial activity and thus heterotrophic respiration. The reduction of CO₂ effluxes
467 under solar panels may also be the result of light reduction reducing plant growth and root
468 respiration.

469

470 4.4 Conclusions

471 Physical, chemical, and general soil quality indexes were lower in a solar park than in semi-
472 natural land cover types. Clearing and grading the soil surface during solar park construction
473 resulted in a strong degradation of soil physical quality, especially of soil structure, but did
474 neither disturb soil chemical quality nor global quality compared to abandoned vineyards. These
475 results suggest that solar parks should be preferably constructed on anthropogenic soils or that
476 construction must be accompanied by environmental compensation measures and/or ecological
477 restoration. At our Mediterranean study sites, solar panels reduced soil temperature from spring
478 onwards. Neither light nor spring temperature reduction under solar panels altered plant
479 communities in early stages of plant succession but reduced CO₂ effluxes. Our study
480 demonstrated that solar park construction and solar panels changed soil quality and microclimate
481 to a magnitude known to affect key soil functions. Long-term monitoring including different
482 seasons is required to evaluate the final response of soil properties and vegetation to solar panels.

483

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715 xi. Table

716 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

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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 ($\mu\text{g } \mu\text{g N-NO}_3^+ \cdot \text{g}^{-1}$)	1.34 (0.32)	1.06 (0.80)	0.72 (0.26)	1.71 (0.61)	0.12
	Ammonium ($\mu\text{g N-NH}_4^+ \cdot \text{g}^{-1}$)	2.90 (0.17) ^a	2.92 (0.19) ^a	2.65 (0.14) ^b	2.65 (0.04) ^b	0.03
	BR ($\mu\text{g C-CO}_2 \cdot \text{g}^{-1} \cdot \text{h}^{-1}$)	1.28 (0.33) ^a	1.31 (0.61) ^a	0.61 (0.36) ^b	0.60 (0.07) ^b	0.03
	MB ($\mu\text{g C-CO}_2 \cdot \text{g}^{-1} \cdot \text{h}^{-1}$)	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
Microbiological	FDAse ($\text{u} \cdot \text{g}^{-1}$)	0.0007 (0.0001) ^{ab}	0.0008 (0.0003) ^a	0.0004 (0.0001) ^b	0.0004 (0.0002) ^b	0.02
	Tyrosinase ($\text{u} \cdot \text{g}^{-1}$)	0.0526 (0.0144)	0.0321 (0.0061)	0.0504 (0.0084)	0.0438 (0.0154)	0.11
	Phosphatase ($\text{u} \cdot \text{g}^{-1}$)	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 CO₂ 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 ($p < 0.05$).





