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Soil properties changes after seven years of ground mounted photovoltaic panels in Central Italy coastal area

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ABSTRACT

Land use change is a major driver of soils' properties variation and potential degradation. Solar photovoltaic plants installed on the ground represent a key to mitigating global climate change and greenhouse gas emissions. However, it could represent an emerging source of land consumption, although reversible, which prevents the use of soils for agricultural purposes and may affect crucial ecosystems services. Despite the large widespread deployment of photovoltaic plants, their potential effect on soil properties has been poorly investigated. The aim of this study was to assess changes of soil physical, chemical and biochemical properties seven years after the installation of the panels. For this purpose, the soil under photovoltaic panels was compared with the GAP area between the panels' arrays and with an adjacent soil not affected by the plant.

The main results showed that seven years of soil coverage modified soil fertility with the significant reduction of water holding capacity and soil temperature, while electrical conductivity (EC) and pH increased. Additionally, under the panels soil organic matter was dramatically reduced (−61% and − 50% for TOC and TN, respectively compared to GAP area) inducing a parallel decrease of microbial activity assessed either as respiration or enzymatic activities.

As for the effect of land use change, the installation of the power plant induced significant changes in soils' physical, chemical and biochemical properties creating a striped pattern that may require some time to recover the necessary homogeneity of soil properties but shouldn't compromise the future re-conversion to agricultural land use after power plant decommissioning.

1. Introduction

Solar photovoltaics (PV) installation grew exponentially and is supposed to represent the dominant form of renewable energy by 2050 (Randle Boggis et al., 2020).While PV can provide clean, renewable energy, there is uncertainty regarding ground-mounted photovoltaic panels (GMPP) and their potential effect on the local natural environment in terms of visual impact on the landscape, pollution (Tsoutsos et al., 2005) and, mainly, land consumption of fertile soil. Solar power installations are considered a form of no-permanent land consumption (reversible artificial cover) (ISPRA, 2018; Strollo et al., 2020) and their impact on soil sealing, shading and general degradation processes have been identified but require further investigation (Delfanti et al., 2016). Between 2018 and 2019 Italy experienced an increase in GMPP rising from 65 ha to 195 ha of soil surface consumed (ISPRA, 2020) and, in particular, Lazio region is the fourth in national ranking accounting for 57% ground mounted vs. 43% on other surfaces (e.g. rooftops). In the scenarios where agricultural and/or natural land is lent for the lifetime of a solar project, the soil quality, linked to ecological functions and sustainable agriculture, may be negatively influenced thus impacting the reintroduction of native vegetation or crops. Hence, the impact of solar arrays on the soil underneath and vegetation needs to be investigated either for site preservation or for the likely introduction of crops or native vegetation within large solar infrastructures. A crucial problem concerning ground-mounted PV plants is represented by land use competing with crop production. Trade-off analyses consider the importance of site characteristics as soil fertility, type of agricultural land (arable land, marginal land etc.) showing different degrees of suitability for PV energy production/crop cultivation (Calvert and Mabee, 2015). Many authors claim for further investigation in order to assess any negative impact on the potential delivery of ecosystem services from this growing land use (Armstrong et al., 2014; Delfanti et al., 2016). Although Armstrong et al. (2014) reviewed the potential direct and indirect effects that solar parks may have on site microclimate,

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vegetation, soil C cycling and microbial community, as far as we know limited studies are available.

The recent literature was focused on: 1) amelioration of soil properties in desert areas where mitigation of soil temperature and moisture positively impacted vegetation coverage, biomass, and species richness alleviating crops climatic stress and water shortage (Liu et al., 2019; Zhou and Wang, 2019; Yue et al., 2021); 2) agrivoltaic systems where PV panels shading provided multiple additive and synergistic benefits including reduced plant drought stress (Marrou et al., 2013a, 2013b; Barron Gafford et al., 2019), 3) revegetation of a PV solar park that was affected by the spatial variation of soil properties (Seok Choi et al., 2020). Recently, Lambert et al. (2021) provided a comprehensive study on the effect of solar parks on soil quality under Mediterranean climate.

The installation of GMPP may induce direct effects on soil increasing shading, thus surface albedo, reducing precipitation and atmospheric deposition, as well as modifying wind speed and turbulence in the area under the panel (Armstrong et al., 2016). Therefore, since key ecosystem services involving plant–soil processes may be altered by this land use change, proper and focused investigations are required.

This study represents, therefore, a pilot attempt using an integrated methodological approach aimed to assess a variety of soil physical, chemical and biochemical properties.

This research aims to answer the following questions: 1) How do soil physico-chemical and biochemical properties vary between the soil under photovoltaic (PV) panels and the soil of GAP area within a GMPP? 2) How does land use change, due to the installation of GMPP, affect soil properties? We hypothesized that the soil physical, chemical and biochemical properties were affected by the presence of PV panels, and that those effects were more evident in the soil under PV panel, followed by GAP area.

2. Materials and methods

2.1. Site description

The study area of the present work is located at Montalto di Castro, Viterbo province, central Italy (42°22′52.93″N–11°35′08.37″E), 42 m a.s.l. and 5.6 km from the sea shore (Fig. 1). It is in a flat territory with moderately acid soils (Cambic Phaeozem, Haplic Vertisols and Chromic Luvisols) originated from marine or volcanic deposits. In this area soils texture ranged from clayey to sandy loam. The average annual temperature is 10 °C min and 16 °C max.

The power plant considered in this study is one of the small ones within a larger area of about 350 ha affected by GMPP and produces 99.36 kW. It was installed in 2011, covers an area of 1620 m^2 and started its regular functioning in 2012 (Fig. 2). Each panel, of rectangular shape, measures 0.99 m wide x 1.64 m length, its inclination is 30° S, 2 m wide GAP area separates two rows of panels. The previous land use was agricultural with a wheat-barley-alfalfa rotation. No deep mechanic excavation with consequent disturbance of soil profile was done prior to the plant installation. Regular mowing in spring period is the only activity regularly carried out within the plant, apart from maintenance and care of panels and instruments. An adjacent field, belonging to the same owner, and still used as arable land, has been considered as control and was bare at sampling time, October 2018. Under PV only *Sonchus oleraceus* L. was present while in the GAP area this species was mixed with *Cicorium intybus* L. and *Portulaca oleracea* L. Plant species composition was determined only for living biomass.

2.2. Soil and plant material sampling

Sampling procedure for soils, litter and plant biomass was performed in October 2018 following Armstrong et al. (2016) (Fig. 2). For the aim of this study, three areas were selected: one beneath the photovoltaic panels (PV), another one between photovoltaic panels rows (GAP) and the third in the adjacent bare arable field not interested by the solar plant installation (Control).

For soil sampling, nine plots (1.5x20m), three for each area, were chosen (Fig. 2). The six plots within the power plant were selected in the middle of the plant to avoid any edge effect. Three plots were identified below the panels (PV), the other three in the GAP areas between them (GAP). Lastly, three plots were chosen in the agricultural field (Control); these consisted in three transects running parallel to the power plant at 12 m distance. Within each plot three composite samples, originated

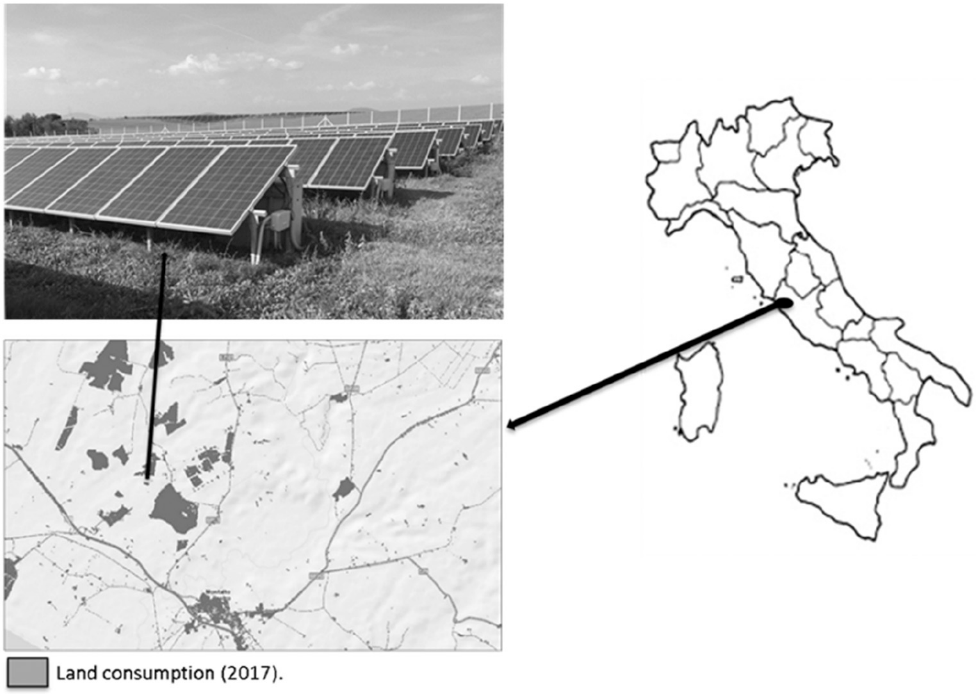


Fig. 1. Land consumption, in dark grey, in the municipality of Montalto di Castro, 2017.
Source ISPRA *(www.isprambiente.gov.it)*.

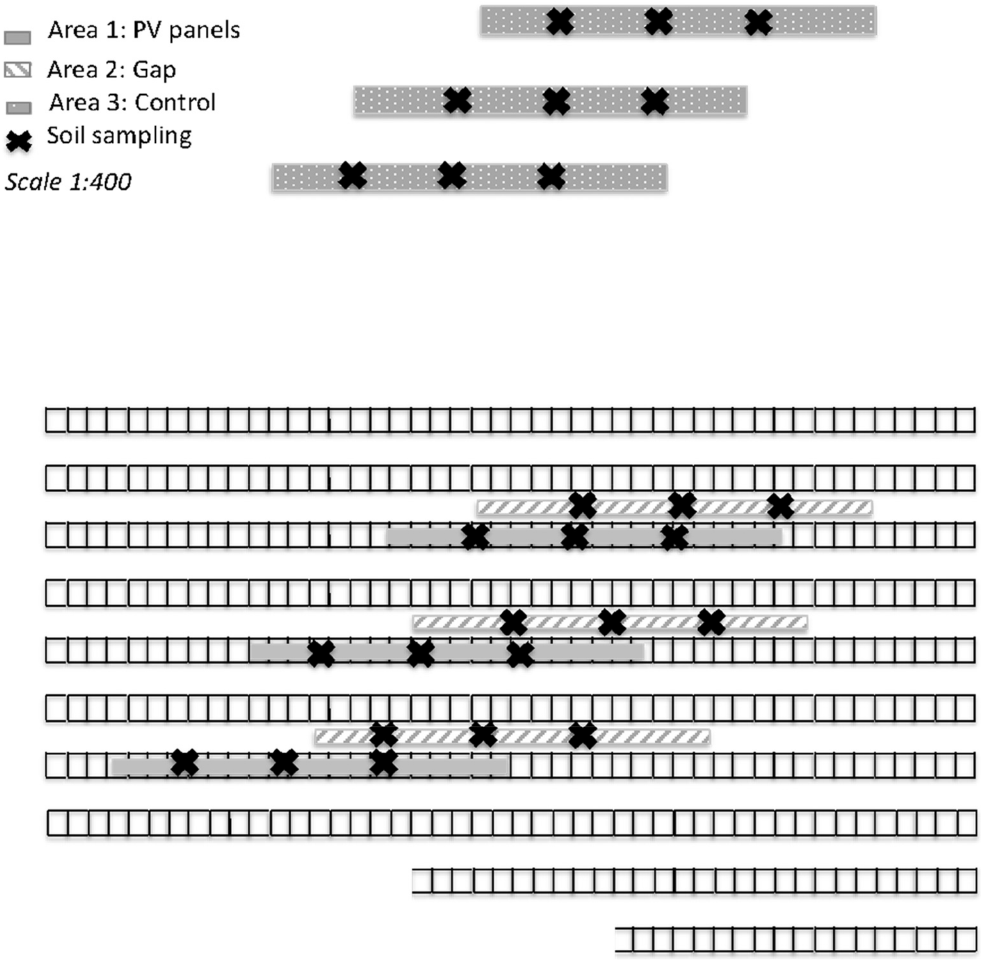


Fig. 2. Power plant structure and soil sampling scheme. More detailed information is provided in the text.

pooling 3 single cores, were collected for a final amount of 27 soil samples. Each soil sample was collected at 6 m distance from the next one (Fig. 2). Soil cores were collected with the help of an auger at 20 cm depth after removing any vegetation, when present, at the surface. Soil samples were thus collected at 0–20 cm of depth and were stored in a portable fridge. During the sampling campaign air (above soil level), temperature, irradiation and soil temperature were assessed by means of a probe *E*-RAY - XF002 (Microtronics). The measurements were performed in the afternoon at 4 pm.

Once in the laboratory, the soil was sieved through a 2 mm-mesh and air-dried at room temperature. Air dried soil samples were remoistened at 60% of their maximum water holding capacity and incubated at room temperature for five days prior to biochemical analyses.

Aboveground biomass was collected in the same plots except in the control, as no vegetation was present at sampling time. Litter and plant biomass were collected in 50 × 50 cm frame. Plant and litter samples were collected within each square in three replicates for a total number of 18 litter and 18 plant samples. The dominant species and the total weigh of plant biomass were assessed. Plant samples were collected in plastic bags, carried in the laboratory and immediately placed in aluminium trays to be oven dried at 50 °C.

2.3. *Physical and chemical analyses*

Physical and chemical analyses (texture, soil water holding capacity (WHC), water content (SWC), and electrical conductivity (EC)) were carried out in accordance with the Soil Survey Laboratory Methods Manual (Soil Survey Staff, 2014). Soil pH was measured potentiometrically in a 1:2.5 (*w/v*) soil-deionised water suspension or KCl 1 M for active and exchangeable acidity, respectively (van Reeuwijk, 2002). Available phosphorus was assessed after acid extraction with 1 M NH_4F (Bray and Kurtz, 1945). Cation exchange capacity (CEC) was measured after extraction with $BaCl_2$ pH 8.1. Total organic C (TOC) and nitrogen content (TN) were determined using the dry combustion method with Thermo Soil NC—Flash EA1112 elemental analyser (Tiessen and Moir, 1993).

2.4. *Biochemical analyses*

Microbial basal respiration (R_{mic}) was measured by incubating 10 g of soil at controlled temperature and humidity for 25 days (Badalucco et al., 1992). The CO_2 evolved was trapped, after 1, 3, 7, 10, 15 days of incubation, in 2 ml 1 M NaOH and determined by titration of the excess NaOH with 0.1 M HCl. The total CO_2 evolved at the end of the experiment is considered the cumulative respiration (MR_{cum}) while the average hourly CO_2 output is the basal respiration (BR). The mineralization quotient (qM) is represented by the ratio of the cumulative CO_2 released during the incubation period (MR_{cum}) to the total organic carbon content. It represents a measure of the quality of soil organic matter being decomposed during the incubation.

The enzymatic activities were measured in samples of bulk soil using the fluorogenic methylumbelliferyl (MUF)-substrates method (Marx et al., 2001). The following hydrolytic enzymes, involved in C, N, P and S biogeochemical cycles (Nannipieri et al., 2012), were analysed: β-cellobiohydrolase (CELL; EC 3.2.1.91), *N*-acetyl-β- glucosaminidase (NAG; EC 3.2.1.30), β-glucosidase (β-GLUC; EC 3.2.1.21), α-glucosidase (α-GLUC; EC 3.2.1.20), β-xylosidase (XYL; EC 3.2.2.27), acid phosphatase (AP; EC 3.1.3.2), arylsulphatase (ARYL; EC 3.1.6.1), butyrate estherase (BUT; EC 3.1.1.1) and leucine aminopeptidase (LAP; EC 3.4.11.1). The respective substrates were 4-MUF β-D-cellobioside, 4-MUF-*N*-acetyl-β-glucosaminide, 4-MUF β- D-glucoside, 4-MUF α-D-glucoside, 4-MUF-7-β-D-xyloside, 4-MUF-phosphate, 4-MUF-sulphate, 4-MUF-butyrate and L-leucine-7-amino-4-methylcoumarin (AMC). Fluorescence (excitation 360 nm; emission 450 nm) was measured with an automated fluorimetric plate-reader (Fluoroskan Ascent, Labsystem, Frankfurt, Germany) after 0, 30, 60, 120 and 180 min (Marinari et al., 2013). The results were expressed as nmoles of product (MUF or AMC) of each enzymatic reaction released per g of soil per unit of time in relation to a standard curve performed with increasing MUF or AMC concentrations and incubated at the same experimental conditions. The SEI (Synthetic Enzymatic Index), expressed as sum of all enzymatic activities, has been calculated for all soils as a synthetic measure of microbial functional capacity. Synthetic enzymatic index for the C-cycle (SEI_C) was calculated by the sum of the enzymatic activity values of CELL, β-GLUC, α-GLUC and XYL. Microbial functional diversity was assessed by calculating the Shannon diversity index (H′) defined as: $H' = -\Sigma\, pi * \ln pi$ where pi is the ratio of the activity of a particular enzyme to the sum of all enzymatic activities (Shannon and Weaver, 1949). The Shannon index helps to highlight differences due to the functional capacity of soil microbial biomass in the use of the available organic substrates and to activate specific metabolic processes (Moscatelli et al., 2018). The ecoenzymatic C/N and N/P acquisition activities were measured by the ratios of β-glucosidase/(chitinase+leucine) [β-gluc/(NAG+L.AP)] and (chitinase+leucine)/phosphatase activities [(NAG+L.AP)/Phosph], respectively (Sinsabaugh et al., 2009). These ratios represent the microbial limitation for N with respect to C and P, respectively.

The relative contribution to overall enzyme activity was calculated after expressing each enzymatic activity as percentage of SEI.

2.5. *Statistical analysis*

Differences in soil properties were tested for significance using one-way ANOVA with a Tukey multiple comparison post-hoc test at $p < 0.05$. Before carrying out the ANOVA the normal distribution and the homogeneity of variances of the data was verified by graphical analysis of residuals. Plant biomass differences were tested using Student *t*-test. All analyses, included correlation, were performed using GraphPad Prism 8.0 and significance was determined at $P \leq 0.05$.

3. Results

3.1. *Climatic and plant biomass data*

Soil temperature and irradiation are presented in Fig.s 3a and 3b, respectively. Within the power plant soil temperature did not differ between bare and vegetated soil, while it was significantly lower with respect to control (−9 and − 16%, in PV and GAP respectively, $P < 0.001$). In the GAP area it was further decreased with respect to PV (−7.3%, $P < 0.05$). Analogously, irradiation showed the highest values in the control soil with 314 W m^{-2} and the lowest values under the PV.

Litter and plant biomass contents are reported in Fig. 3e. The total biomass did not differ significantly between PV and GAP area. However, litter biomass was significantly higher under PV with respect to GAP area showing an almost doubled amount (541 vs 279 g dry biomass m^{-2}, respectively, $p < 0.01$). Consequently, there was more live biomass in GAP area than under PV (459 vs 192 g dry biomass m^{-2}, respectively, $p < 0.05$).

3.2. *Soil physical and chemical properties*

Soil water content (SWC) and water holding capacity (WHC) are reported in Fig.s 3c and 3d, respectively. SWC showed significant

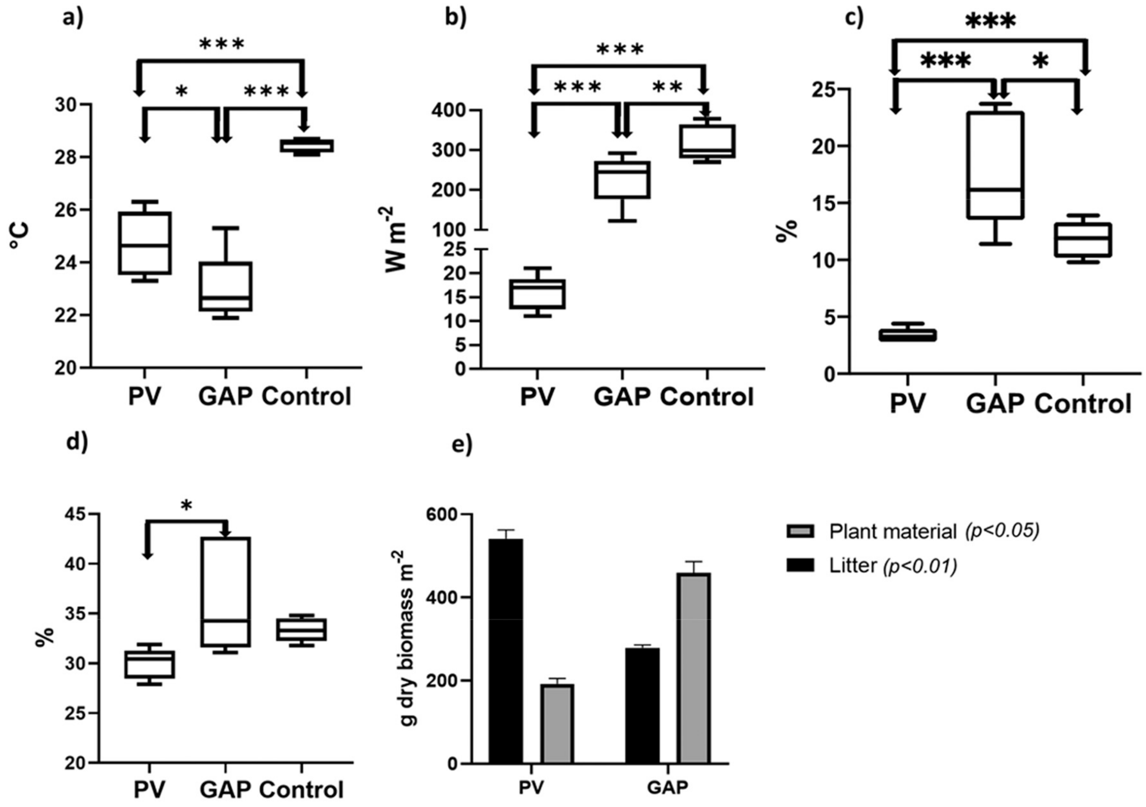


Fig. 3. a) soil temperature, b) irradiation, c) SWC: soil water content, d) WHC: water holding capacity, e) plant biomass and litter. PV: photovoltaic panel, GAP: gap area between panels rows, Control: adjacent agricultural soil. * = $p < 0.05$, ** = p < 0.01, *** = p < 0.001, **** = 0.0001.

differences among the three soils (PV, GAP and control soils) with the lowest value under PV (3.4%) ($p < 0.001$). Soil water holding capacity (WHC) was also lower under PV (30%) if compared to either GAP or control soils (36 and 33%, respectively) but significantly only with respect to GAP. Soil reaction (pH_{H2O} and pH_{KCl}) is reported in Fig. 4a and b, respectively. Land use change significantly increased soil pH_{H2O} with respect to control (6.5 for PV-GAP and 5.7 for control). Also, a significant increase for pH_{KCl} was evident either under PV or in GAP area with respect to control (6.1 and 6.0 vs. 5.0). The power plant, either PV or GAP, significantly increased EC with respect to control soil pointing to excessive salinity under PV (5300 μs cm^{-1}) (Fig. 4c). Available P decreased strongly and significantly in control soil with respect to PV and GAP area reaching nearly 2 μg g^{-1} (Fig. 4d). Total organic C and total nitrogen were both largely and significantly increased after land use conversion only in GAP areas as shown in Fig. 4e and f, respectively. In these soils, in fact, TOC reached 33 g kg^{-1} while TN accounted for 3 g kg^{-1}. Under PV total organic carbon and nitrogen drastically decreased reaching control soil values ($p < 0.001$ and $p < 0.01$, respectively). The C:N ratio was significantly higher in GAP area with respect to PV ($P < 0.001$) and control ($P < 0.05$) accounting for almost 12 (Fig. 4g).

3.3. Biochemical properties

Enzymatic activities, indexes and ratios are presented in Fig. 5. All enzymes showed a similar trend with the following ranking GAP>PV > control soils apart from AP that showed a different ranking: GAP>control>PV (Fig. 5d). The synthetic indexes (either SEI or SEI_C) showed, thus, a significantly higher value in the GAP area followed by PV and control (Fig.s 5a and b, $p < 0.001$). N microbial limitation with respect to P was significantly increased after conversion of land use exceeding the threshold value of 0.4 (Fig. 5f). Microbial functional diversity, measured by means of Shannon diversity index, showed a significant increase in the GAP soil followed by PV and Control (Fig. 5g).

In terms of relative contribution to overall enzymatic activity LAP and CELL were significantly enhanced in the power plant with respect to control while AP was decreased (Fig. 7). As for the effect of PV panel with respect to GAP area β-GLUC and LAP decreased while BUT was enhanced. (Fig. 7).

Microbial basal respiration, mineralization kinetics and the mineralization quotient are presented in Fig. 6a, b and c. BR was significantly increased in GAP areas with respect to PV ($P < 0.05$) and to control soil ($P < 0.01$), the mineralization kinetic model showed higher respiration rates for GAP followed by PV and control. At the end of the incubation period GAP soil showed the largest amount of CO_2 produced differing significantly from PV ($P < 0.05$) and Control ($P < 0.01$). Finally, the mineralization quotient (qM) showed the lowest release of CO_2 per unit of organic C in GAP areas, ($p < 0.05$) with respect to PV or Control.

Fig. 8 shows the heat map of Pearson correlation coefficient derived from the correlation analysis. pH_{H2O}, pH_{KCl}, EC, available P and P limitation were positively correlated to each other (supplementary materials Fig. S1) indicating that increase of soil pH recorded within the plantation affected soil conductivity, P availability and, consequently, microbial P limitation. Also, SWC and WHC were positively correlated to TOC, TN and all other parameters related to C cycling and microbial respiration.

4. Discussion

Notwithstanding the worldwide distribution of GMPP, and the need for further understanding their potential effects on soils and ecosystem services, the body of literature on the specific impacts of this form of reversible land consumption on soil chemical and biochemical properties is extremely scarce.

For this reason, the aim of this study was to add further knowledge to the likely effect of GMPP soil coverage by performing an integrated assessment of soil properties. In particular, the assessment of enzymatic activities, microbial functional diversity and C mineralization kinetics were chosen to infer additional information on key soil ecological features (C cycling and microbial diversity) that may be impacted by this growing land use change.

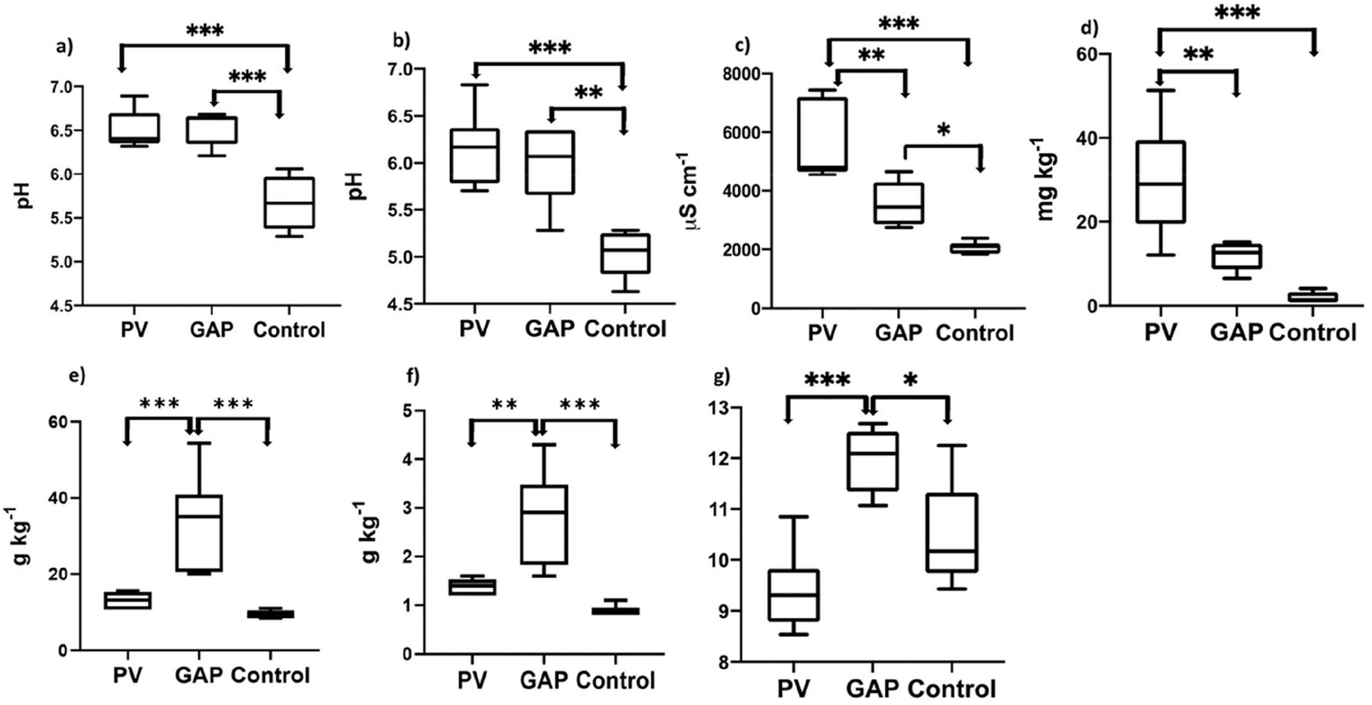


Fig. 4. a) soil pH_{H2O}, b) soil pH_{KCl}, c) EC = electrical conductivity, d) P = inorganic phosphorus, e) TOC = total organic C, f) TN = total nitrogen, g) C:N ratio. PV: photovoltaic panel, GAP: gap area between panels rows, Control: adjacent agricultural soil. * = p < 0.05, ** = p < 0.01, *** = p < 0.001, **** = 0.0001.

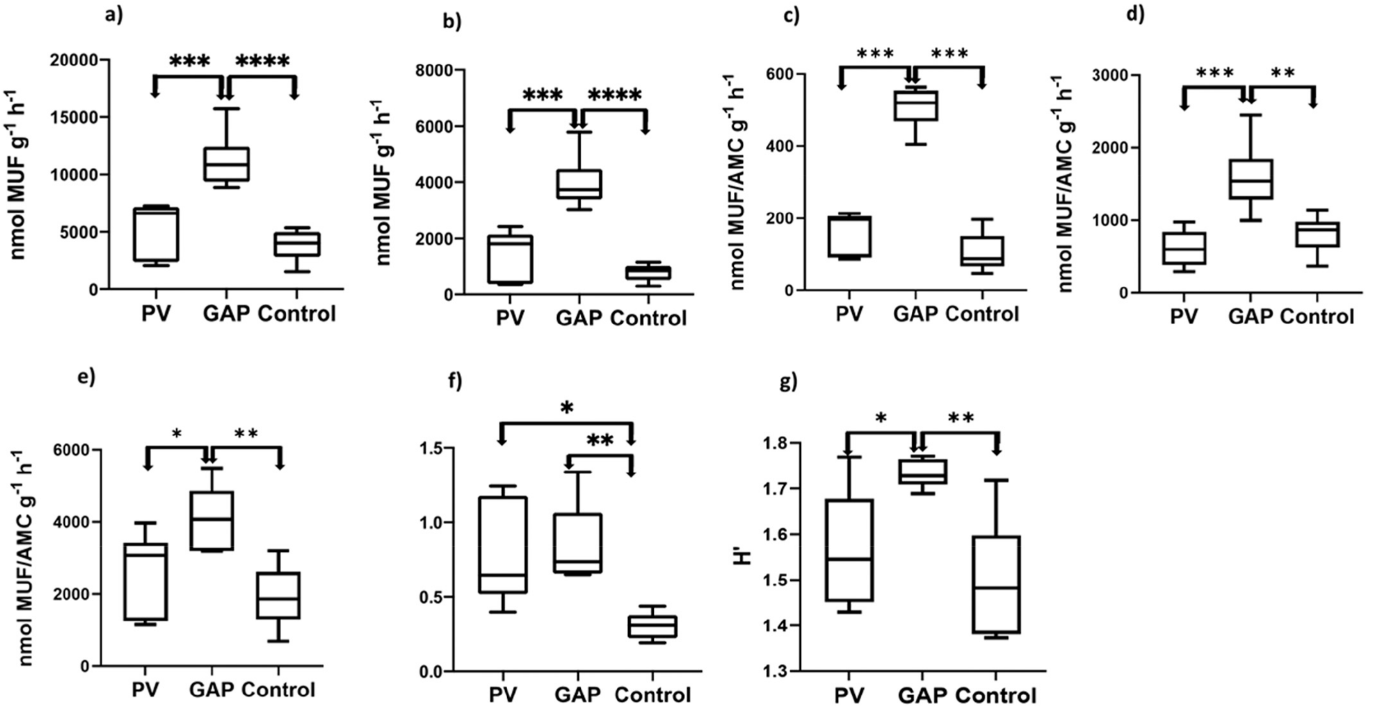


Fig. 5. Soil biochemical properties. Enzymatic activities: a) SEI = synthetic enzymatic index, b) SEI_C = synthetic enzymatic index for C cycling enzymes, c) leucine aminopeptidase (LAP), d) acid phosphatase (AP), e) butyrate estherase (BUT), f) (NAG+LAP)/AP = microbial N limitation with respect to P, g) Shannon diversity index (H′). PV: photovoltaic panel, GAP: gap area between panels rows, Control: adjacent agricultural soil. * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, **** = 0.0001.

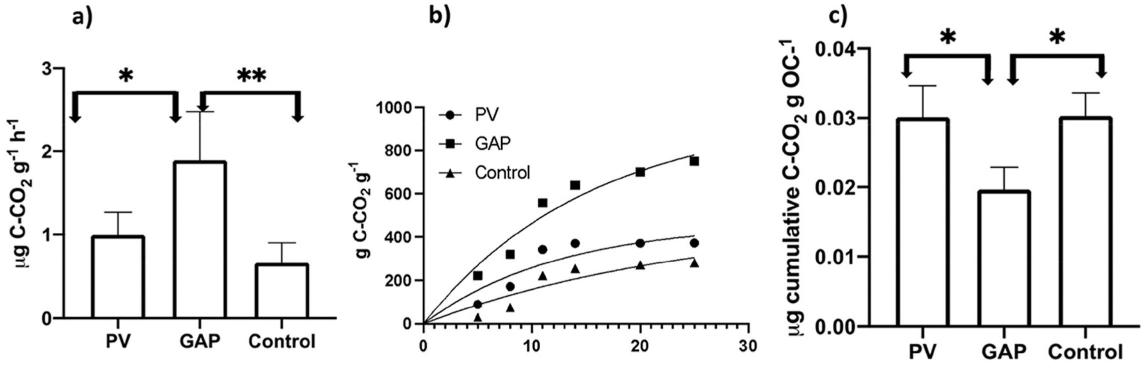
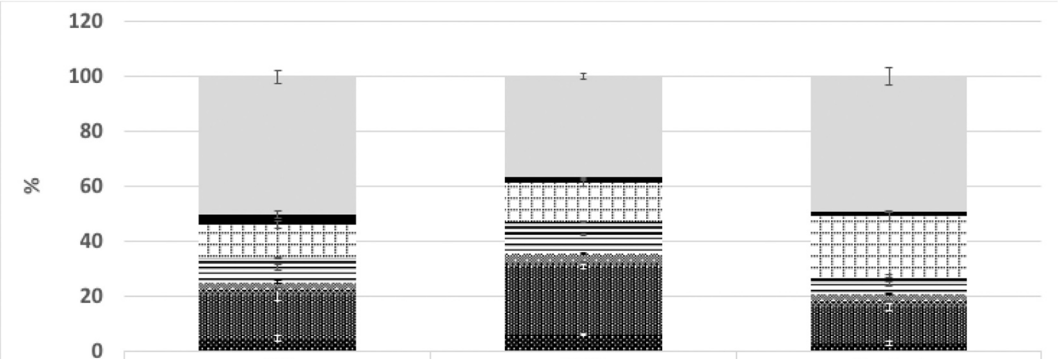


Fig. 6. Soil biochemical properties. a) Microbial basal respiration, b) C mineralization kinetic model, c) qM = mineralization quotient. PV: photovoltaic panel, GAP: gap area between panels rows, Control: adjacent agricultural soil. * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$, **** = 0.0001.

4.1. *Effect of PV panels' coverage within GMPP*

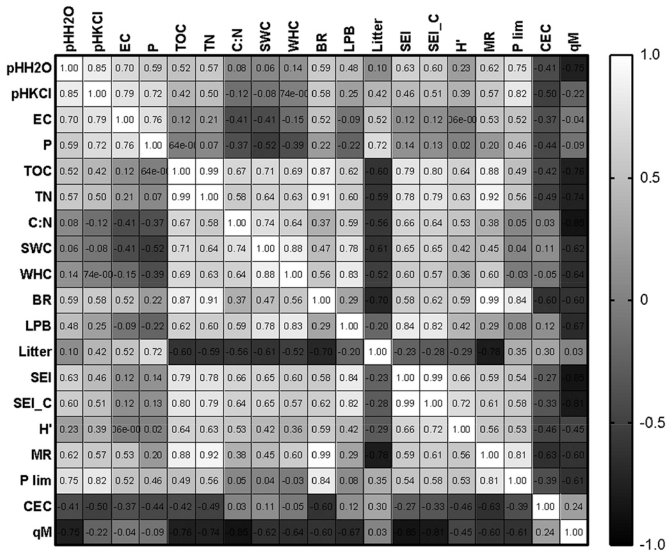
In this study, soil physical properties such as SWC, WHC and soil temperature were significantly modified by the presence of PV panels. Indeed, if we compare the PV soil with GAP soil the water content, either at sampling time or as potential retention, was reduced below the panels while soil temperature was increased. Since soil water holding capacity is promoted by the mineral phase, the organic matter content and their interactions (Brady and Weil, 2014) and as panels' coverage did not affect the mineral composition of the soils, the cause of the reduction of water content was attributed to changes in organic matter content which will be discussed below. Further, Armstrong et al. (2014) reported that GMPP installation might alter local microclimate in particular, changes in evapotranspiration and precipitation can potentially cause variations in soil moisture; even if the likely direction or magnitude of these changes is still unknown. Additionally, Marrou et al. (2013a) report a possible modification in rainfall flowing/dripping along PV surface hypothesizing a larger amount of water reaching the soil below the southern edge of the PV panels' strip.

Within the power plant the increase of electrical conductivity combined to the increase of soil pH, particularly in the soil under the PV was recorded. A possible explanation may be the likely long-range transportation of marine aerosol and interception exerted by the large panels' surfaces. In fact, it should be considered that the study area is only 5.6 km SW from the seashore, the panels orientation is 30° S and that the annual main winds direction is NE with an average speed of about 11 km h^{-1} (data referred to a site located 20 km W, data available at www.sir.toscana.it). Claeys et al. (2017) reported an average transport of 0.6 μg m^{-3} of primary marine aerosol (PMA) at 18 km h^{-1} wind speed in central Mediterranean basin. Although in this study no specific assessment of marine derived ions (eg. Na^+, Cl^- etc.) was performed, it may be assumed an accumulation of Na salts over the panels' surface that, leaching in the soil underneath, induced a salinization process (EC > 4 dS), ultimately, affecting soil reaction. Additionally, it may be



	PV	GAP	Control
░ BUT	50.4 *a*	36.8 *b*	49.3 *a*
■ ARYL	3.5 *a*	2.0 *a*	1.8 *a*
⊤ AP	12.3 *b*	14.2 *b*	21.7 *a*
= LAP	3.3 *b*	4.6 *a*	2.8 *b*
= NAG	5.4 *ab*	6.9 *a*	3.8 *b*
▩ XYL	2.8 *a*	3.1 *a*	2.5 *a*
▩ a-GLUC	2.2 *a*	1.5 *a*	2.1 *a*
▩ b-GLUC	15.6 *b*	24.8 *a*	13.2 *b*
▩ CELL	4.7 *ab*	6.1 *a*	2.9 *b*

Fig. 7. Relative contribution of enzymes categories to overall activity. Different letter indicate significant difference ($P < 0.05$).



	pHH2O	pHKCl	EC	P	TOC	TN	C:N	SWC	WHC	BR	LPB	Litter	SEI	SEI_C	H'	MR	P lim	CEC	qM
pHH2O	1.00	0.85	0.70	0.59	0.52	0.57	0.08	0.06	0.14	0.59	0.48	0.10	0.63	0.60	0.23	0.62	0.75	-0.41	-0.75
pHKCl	0.85	1.00	0.79	0.72	0.42	0.50	-0.12	-0.08	74e-00	0.58	0.25	0.42	0.46	0.51	0.39	0.57	0.82	-0.50	-0.22
EC	0.70	0.79	1.00	0.76	0.12	0.21	-0.41	-0.41	-0.15	0.52	-0.09	0.52	0.12	0.12	06e-00	0.53	0.52	-0.37	-0.04
P	0.59	0.72	0.76	1.00	64e-0	0.07	-0.37	-0.52	-0.39	0.22	-0.22	0.72	0.14	0.13	0.02	0.20	0.46	-0.44	-0.09
TOC	0.52	0.42	0.12	64e-0	1.00	0.99	0.67	0.71	0.69	0.87	0.62	-0.60	0.79	0.80	0.64	0.88	0.49	-0.42	-0.76
TN	0.57	0.50	0.21	0.07	0.99	1.00	0.58	0.64	0.63	0.91	0.60	-0.59	0.78	0.79	0.63	0.92	0.56	-0.49	-0.74
C:N	0.08	-0.12	-0.41	-0.37	0.67	0.58	1.00	0.74	0.64	0.37	0.59	-0.56	0.66	0.64	0.53	0.38	0.05	0.03	-0.85
SWC	0.06	-0.08	-0.41	-0.52	0.71	0.64	0.74	1.00	0.88	0.47	0.78	-0.61	0.65	0.65	0.42	0.45	0.04	0.11	-0.62
WHC	0.14	74e-00	-0.15	-0.39	0.69	0.63	0.64	0.88	1.00	0.56	0.83	-0.52	0.60	0.57	0.36	0.60	-0.03	-0.05	-0.64
BR	0.59	0.58	0.52	0.22	0.87	0.91	0.37	0.47	0.56	1.00	0.29	-0.70	0.58	0.62	0.59	0.99	0.84	-0.60	-0.60
LPB	0.48	0.25	-0.09	-0.22	0.62	0.60	0.59	0.78	0.83	0.29	1.00	-0.20	0.84	0.82	0.42	0.29	0.08	0.12	-0.67
Litter	0.10	0.42	0.52	0.72	-0.60	-0.59	-0.56	-0.61	-0.52	-0.70	-0.20	1.00	-0.23	-0.28	-0.29	-0.78	0.35	0.30	0.03
SEI	0.63	0.46	0.12	0.14	0.79	0.78	0.66	0.65	0.60	0.58	0.84	-0.23	1.00	0.99	0.66	0.59	0.54	-0.27	-0.85
SEI_C	0.60	0.51	0.12	0.13	0.80	0.79	0.64	0.65	0.57	0.62	0.82	-0.28	0.99	1.00	0.72	0.61	0.58	-0.33	-0.81
H'	0.23	0.39	06e-00	0.02	0.64	0.63	0.53	0.42	0.36	0.59	0.42	-0.29	0.66	0.72	1.00	0.56	0.53	-0.46	-0.45
MR	0.62	0.57	0.53	0.20	0.88	0.92	0.38	0.45	0.60	0.99	0.29	-0.78	0.59	0.61	0.56	1.00	0.81	-0.63	-0.60
P lim	0.75	0.82	0.52	0.46	0.49	0.56	0.05	0.04	-0.03	0.84	0.08	0.35	0.54	0.58	0.53	0.81	1.00	-0.39	-0.61
CEC	-0.41	-0.50	-0.37	-0.44	-0.42	-0.49	0.03	0.11	-0.05	-0.60	0.12	0.30	-0.27	-0.33	-0.46	-0.63	-0.39	1.00	0.24
qM	-0.75	-0.22	-0.04	-0.09	-0.76	-0.74	-0.85	-0.62	-0.64	-0.60	-0.67	0.03	-0.85	-0.81	-0.45	-0.60	-0.61	0.24	1.00

Fig. 8. Heat map of Pearson correlation coefficient derived from the correlation analysis. EC = electrical conductivity, P = available phosphorus, TOC = total organic C, TN = total N, C:N = C:N ratio, SWC = soil water content, WHC = water holding capacity, BR = basal respiration, LPB = living plant biomass, SEI = synthetic enzymatic index, SEI_C = synthetic enzymatic index C cycle, H′ = Shannon index, MR = cumulative microbial respiration, P lim = N microbial limitation with respect to P, CEC = cation exchange capacity, qM = mineralization quotient. *P* values of correlation analysis are available in supplemental material.

hypothesized that, as reported by Armstrong et al. (2016), wind speed and turbulence patterns in the area under the panel may have modified evapotranspiration rate thus increasing electrical conductivity.

The lower SWC and WHC combined to the increase in salinity and pH, under PV panels, affected plant biomass growth and turnover. In this study a higher amount of litter was in fact recorded under the PV panels if compared to GAP area.

In PV soils, the significantly higher amount of plant litter, with respect to total biomass, suggested the occurrence of unfavourable pedoclimatic conditions beneath the panels that may have hampered herbaceous plant species growth. Under PV panels, *Sonchus oleraceus* L. was the only plant species assessed; Mawalagedera and Gould (2015) and Jia et al. (2018) reported *S. oleraceus* L. efficiency to face soil salinity and drought stress producing low molecular weight antioxidants (LMWAs). The same authors encourage the cultivation of this species in arid environments. However, *Sonchus* spp. was almost completely present as litter at sampling time (October) suggesting a short growing season if compared to GAP area where it still showed a lush green living biomass. In GAP area, *Sonchus* spp. was also mixed with the genus *Portulaca* spp. that prefers exposed sunny locations (Zimmerman, 1976) and *Cycorium intybus* L.

The different amount and composition of plant biomass and living fine roots combined to the diverse soil physical and chemical properties in PV vs GAP soils deeply influenced soil carbon storage, C:N ratio and C cycling. Soil C and N storage were considerably affected by panels' coverage, which drastically reduced their content (by 61 and 50%, respectively). Soil organic matter was therefore dramatically lowered in PV soils after 7 years since the power plant installation. Conversely, in the GAP soil the higher amount of living plant biomass allowed a significant increase in organic matter that fuelled and enhanced microbial activity.

Although a larger amount of dry plant biomass was found below the panels, this neither contributed to the build-up of soil organic matter nor triggered microbial decomposition activity. Indeed, a general reduction of microbial activity either as C mineralization or nutrient acquisition (enzymatic activities) was observed in PV soils. Soil coverage by PV panels also induce changes of local microclimate (e.g. lowering of soil temperature and irradiation) that could result in a redistribution of plant biomass, shifts in vegetation composition and productivity as reported by Tanner et al. (2020). Consequently, this may affect the quantity and quality of plant products (litter and rhizodeposits) that ultimately fuel soil microorganisms (Armstrong et al., 2014). Additionally, Bahn et al. (2013) suggested the hypothesis that shading induces changes in C allocation with a preferential flow to belowground plant functions, to fungal communities and rhizosphere microbes thus affecting soil C turnover and storage. It may be assumed that a combined effect of unfavourable environmental conditions (e.g. low soil moisture, poor structure, high temperatures, increased salinity, and reduced soil organic substrates availability by low plant biomass) exerted a stress condition leading to a reduction of microbial activity. In addition, when considering the single enzymes, as relative contribution to total activity, a significant reduction of β-GLUC and LAP enzymes was observed in PV soils and was counterbalanced by a parallel increase of butyrate esterase activity which may be considered a proxy of endocellular activity (Wittmann et al., 2004). The general decrease of enzymes involved in nutrients uptake is further confirmed by the significant decrease of microbial functional diversity assessed in PV soils with respect to GAP. Finally, the reduction of enzymatic activity recorded in PV soils may also be ascribed to the decrease of organic matter content that prevented either enzymes immobilization process or the improvement of soil structure (formation of aggregates) that provides protection to extracellular enzymes (Burns and Dick, 2002; Nannipieri et al., 2012; Wang et al., 2015). Microbial C mineralization patterns measured either as basal respiration or as cumulative respiration showed an almost doubled respiration rate in GAP soil with respect to PV. It may be hypothesized that plant roots development and the lack of pedoclimatic constraints, such as drought, heat and salinity, allowed the establishment of a stabilized organic matter as the lower mineralization quotient demonstrates. All the above evidences pointed to a relevant inhomogeneity of soil fertility that may affect the immediate reconversion to agricultural land use after power plant decommissioning.

4.2. Effect of land use change

The installation of ground mounted photovoltaic power plants is considered a reversible form of land consumption (ISPRA, 2018). However, even if this transitory soil consumption will last until the panels will be kept on site (on average 20–25 years), the setback on soil quality will certainly have future consequences on agronomic practices. It is worth to note that the assessment of soil quality, after removal of GMPP, has been poorly investigated (Seok Choi et al., 2020, Lambert et al., 2021) and soil potential degradation addresses several doubts on the necessary recovery time to restore its original properties.

In this study many significant variations in soil properties (physical, chemical and biochemical) were observed comparing the soil within the power plant to the nearby arable land, which represented the original land use. Irradiation and soil temperature were reduced by the installation of the panels array in the whole area while soil moisture was significantly decreased in PV soils and increased in GAP soil with respect to control; therefore, the panels coverage modified light intensity and wind circulation in the whole area thus influencing some basic physical properties. Similar effects were reported by Marrou et al. (2013b), Yang et al. (2017), Liu et al. (2019) and Seok Choi et al. (2020). However, Liu et al. (2019) results were not all in the same direction than in this study; they observed positive effects in vegetation recovery within the power plant due to an increase of soil moisture, decrease of soil temperature, decrease of evaporation within the power plant with respect to a reference external site. It should be considered that the study was performed in the Mu Us desert in China, a mountain area characterized by strong winds, low precipitation, scarcity of natural vegetation, strong soil erosion. Under Mediterranean climate Lambert et al. (2021) found that the physical, chemical, and global soil qualities were lower in solar park than in the other semi-natural land cover types (pinewood and shrubland). Furthermore, the authors suggest that the solar parks should be constructed preferably on anthropogenic soils or that it must be accompanied by environmental reduction measures and ecological restoration.

Zhou and Wang (2019) reported very little difference in soil pH, total nitrogen, potassium, organic matter, and available phosphorus in the soil between the panels' rows and the undisturbed area outside the plant indicating that no influence was evident in soil nutrients. Conversely, in this study, after 7 years since the abandonment of agriculture and the installation of the power plant soil pH and EC were increased, being this process particularly enhanced in PV soil.

Soil pH raised, in fact, from moderately acid to slightly acid values thus allowing a higher availability of available P. Consequently, AP enzyme activity, expressed as relative contribution to the total, was significantly depressed in the soil within the power plant. The presence of a negative relationship between nutrient supply and enzyme activity has been observed in many studies (Sinsabaugh et al., 1993; Tadano et al., 1993; Moscatelli et al., 2005), supporting the idea that phosphatase production and activity are linked to biotic demand for P (Clarholm, 1993). This was also in accordance with the significant increase of microbial N limitation with respect to P in the control soils.

Finally, in contrast to what was hypothesized, the soil of the GAP area was found to be more influenced by GMPP establishment from the biochemical point of view than the soil under PV if compared with the adjacent agricultural soil.

5. Conclusions

In this paper changes in soil properties were recorded after seven years of GMPP installation. To our knowledge, for the first-time, soil changes were assessed using an integrated methodological approach. The obtained results showed that within a GMP plant existed a heterogenous distribution of soil physical, chemical and biochemical properties (e.g. salinity, temperature, water cycling and striped distribution of organic matter and microbiological properties) when the soil under the PV panels and that located between the rows of panels are compared. Hence, the peculiar microclimatic conditions occurring under the panels - alteration of albedo, precipitation patterns and air circulation – determined a cascade of processes that originated a patchy distribution of soil fertility. Furthermore, comparing the soil within the GMPP to the adjacent agricultural soil, some physical properties (EC and pH) were significantly impacted in PV soil and almost all biochemical properties were significantly increased in GAP soil. Therefore, the studied areas interested by the GMPP may require some time to recover the necessary homogeneity of soil properties and fertility but shouldn't compromise the future re-conversion to agricultural land use.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geodrs.2022.e00500.

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