

## Article

# Global Warming Potential of the Change in Land Use from Citrus Fields to Solar Parks

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## Abstract

The current trend towards decarbonization has increased the pressure towards land use change through the installation of solar parks on agricultural fields. The usefulness of RothC to model the evolution of soil carbon after the installation of the solar park has been validated in a field with historic data. The model has been applied to evaluate the impact of a large-scale modification of land use in Valencia (Spain), a mediterranean region with an ambitious plan for the installation of renewable energy. The removal of the orange trees for the installation of a solar park would generate a carbon release in CO<sub>2</sub> eq to 72 Mg ha<sup>−1</sup>. If the soil is left vacant of vegetation, another 28 Mg ha<sup>−1</sup> would be emitted in 30 years. By contrast, if the soil is covered by scrubland, an overall CO<sub>2</sub> capture of −226 Mg ha<sup>−1</sup> could be achieved, including the impact of the initial plant removal. If we consider the Valencia region, the installation of 12.000 hectares of solar parks could generate up to  $1.2 \times 10^6$  Mg of CO<sub>2</sub> emissions or capture  $2.7 \times 10^6$  Mg of CO<sub>2</sub>. Also, a sensitivity analysis to evaluate the effect of the main labels has been performed, revealing that the original carbon content is the most relevant label, followed by plant input and the % of soil covered by the solar panels. The limited availability in experimental data means that this study should be considered an exploratory evaluation of the impact of including plantations in solar parks.

**Keywords:** RothC; solar park; soil carbon; Valencia; land use change; citrus crops

## 1. Introduction

Soil is a crucial component of ecosystem functionality, serving as a home for a multitude of species. It also acts as a significant carbon reservoir, containing more carbon than the atmosphere and terrestrial vegetation combined, but it is presently contributing substantially towards greenhouse gas emissions [1]. Changes in land use can have a profound impact on this soil carbon pool, influencing the balance between carbon sequestration and emissions. When forests or grasslands are converted to agricultural lands, the disturbance often leads to a loss of soil organic carbon, resulting in increased emissions of carbon dioxide. Conversely, restoring degraded lands, converting agricultural lands back to forests, or practices such as cover cropping, reduced tillage, or organic farming can increase the amount of organic matter in the soil, thereby increasing soil carbon storage and reducing carbon dioxide (CO<sub>2</sub>) emissions, helping to mitigate climate change [2–4].

Photovoltaic (PV) installations have seen significant growth in recent years. The political push for renewable energy and the reduction in the costs of PV installations,



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which has reached up to 95% in the last 15 years, have been key factors in this growth [5]. According to the International Energy Agency, 240 GW of new global capacity was installed in 2022 [5]. The European Union became the second most important player in the world, with an 18% increase of the global capacity or 271 GW, and a world leader in KWh per capita, led by Germany and then Spain in terms of installed capacity. Forecasts for the future are that the installations will continue to grow in the coming years [6].

Considering the limitations of rooftop installations, the greatest possibilities for expansion are in centralized PV parks. In economic terms, solar farms offer an attractive return for landowners. However, this trend has also led to certain tensions. On the one hand, farmers complain that they cannot compete with the rental rates offered by solar farm developers. On the other hand, there are concerns about the environmental impact of the installation of large fields of solar panels in rural areas [7]. A middle path is agrivoltaics, which seeks the coexistence of solar energy production and agriculture on the same land; however, its current adoption is limited to some pilot initiatives [8,9].

According to the regional government, by 2030 the Valencia region must have an installed capacity of 6000 MW of PV capacity, which means the occupation of 12,000 hectares; 8% of the surface is currently occupied by the main crop, citrus fruits [10]. Given that forest areas and natural parks have higher levels of protection, it is to be expected that their installation will take place mainly on agricultural land. However, the study of the impact derived from the implementation of solar panels on agricultural land is an understudied field [11–13] and so any study that offers information about the evolution of the soil in solar parks in the following years will be of interest.

After the seminal opinion paper by Armstrong et al. [14] examining the potential for the microclimatic effects of solar parks to alter plant–soil carbon cycling, most of the research into the effect of solar parks on soils based on experimental measures have been developed in recent years. It has been observed that solar panels influence the annual mean net radiation in the soil of the solar farms, inducing changes in the air and soil average temperatures, amplitude of the temperature variation during the day, photosynthesis, net ecosystem exchange, and the complexity of microbial communities [15–21]. Photovoltaic (PV) modules not only affect the soil by shading, but also affect the soil moisture distribution, with a reduction in erosion under heavy rainfall, and precipitation accumulating along the lower edges of panels, which generates vegetation heterogeneity in the solar park [22]. Despite the growing body of research on the impacts of photovoltaic (PV) parks on soil properties, important knowledge gaps remain. Most existing studies have focused on short-term field observations, soil moisture dynamics, vegetation responses, and changes in soil biochemical properties under PV installations. While these studies have demonstrated that PV panels can substantially modify soil physicochemical and microbiological properties, their findings are often site-specific and difficult to extrapolate across different climatic and environmental conditions.

The vegetated solar areas have significantly higher soil moisture, carbon, and other nutrients compared to bare solar areas [23], but a reduction in the photosynthetically active radiation and emissions of CO<sub>2</sub> is also observed [24]. Moscatelli et al. [25] observed in a solar park in Italy that seven years of soil coverage modified soil fertility with a significant reduction in water holding capacity, while electrical conductivity and pH increased. In addition, soil organic matter was greatly reduced under the panels (61% and 50% for total organic carbon and total nitrogen, respectively, compared to the gap area), inducing a parallel decrease in microbial activity assessed either by respiration or enzymatic activity. Similarly, in a solar park in France, reduced soil physical quality was observed under PV panels [26]. The direction and strength of the effect of PV panels is largely dependent on ecosystem type; for example, PV panels can impact microhabitats in arid sandy areas and

accelerate vegetation recovery progress and quality [27]. In areas that already have a solar park, some initiatives have been developed to restore the soil. However, the area under the PV panels offered lower restoration rates, and carbon and nitrogen remained lower and contained a greater fraction of coarse particles [28,29].

Recently Wu et al. [30,31] published two studies exploring the possibility of applying diverse models to understand the evolution of the soil in solar parks. In the first one, they integrated processes of energy budget and water cycle in a model able to quantify the eco-hydrological effects of PVs on soil microclimate and moisture regimes. They evaluated the effect at different locations (zones) near individual PVs. The evolution of soil microclimate and moisture was calculated using simulations run with a 100-year climate time series. The results indicated that soil moisture content would duplicate, and soil temperature would decrease by around 1.5 °C under the PV panels. This behavior is assigned to the presence of 6 times more available water and ~27% less available radiation compared with the control zone. In the second, they applied the SOFAR model in China in an arid area. Results indicated that the soil carbon sink capacity increased in all the cases, but there was a correlation with the total amount of rain. The increase was especially relevant for highly arid areas (6.7%), reaching up to 10% in other climatic conditions. Enhanced water availability for plants located under the drip lines of PV panels has been identified as the primary factor responsible for increasing soil carbon sink capacity. It is necessary to increase the applicability of these models to Mediterranean agroecosystems. The potential of process-based models to simultaneously assess changes in soil carbon stocks, greenhouse gas emissions, and soil quality indicators under large-scale PV deployment remains underexplored.

To address these gaps, the present study uses a process-based soil model to estimate the long-term impacts of solar parks on soil carbon dynamics and greenhouse gas emissions in the Valencia region. The limited number of studies using process-based soil modeling to understand the effect of solar parks on soils highlights the need to test the potential of current soil models as tools to analyze and predict the content of carbon in the soil and the emissions of greenhouse gases. The novelty of this work lies in the integration of local soil, climate, and land-use conditions within a modeling approach capable of assessing future soil trajectories under PV installations. The application of such models to a real area, such as the Valencia region, could be a valuable tool to quantify the effects of the current and projected solar parks in the Valencia region on the properties of the soil in the long term, and suggest practices to reduce the deterioration of the soil and the emissions of greenhouse gases while increasing the soil carbon content.

## 2. Methods

### 2.1. RothC Model

According to the International Modeling Soil Consortium there are more than 40 models that simulate soil organic matter turnover [32]. The Rothamsted carbon model (RothC) [33] is particularly suitable for our study due to its relative simplicity, its focus on soil carbon, the possibility of applying it in large areas and it being a widely used and tested model [34].

A version of RothC implemented in Microsoft Excel was used to model the impacts of solar parks on soils. The RothC model simulates the dynamics of organic carbon in non-waterlogged topsoil. One of the strengths of this model is its minimal input requirements. It considers the impacts of soil type, temperature, soil moisture and plant cover, providing a comprehensive view of the turnover process of organic carbon.

The RothC model assumes that carbon decomposition follows first-order kinetics (Equation (1)), where  $Y_t$  is the carbon content at time  $t$  ( $\text{Mg ha}^{-1}$ ),  $Y_0$  is the original carbon

content ( $\text{Mg ha}^{-1}$ ),  $a$  is the temperature rate modifier (no units),  $b$  is the moisture rate modifier (no units), and  $c$  is the soil cover modifier (no units). It operates on a monthly time step, using five types of carbon pools: inert organic matter (IOM), decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO) and humified organic matter (HUM). It can be applied at different scales, depending on the input data provided; at the plot level, it provides detailed insights into small-scale dynamics while at the field level, it can be used to help farmers understand and manage soil health, and at the regional level, it can be used to inform policy and conservation efforts. In this case it has been applied to a typical agricultural field to quantify the effect and the results extrapolated to the Valencia region (province scale), considering the demand of solar farms in the regions in the coming years.

$$Y_t = Y_0 \left( 1 - e^{-abck\Delta t} \right) \quad (1)$$

The model operates in two modes: ‘forward’ and ‘inverse’. In the ‘forward’ mode, known inputs are used to calculate changes in soil organic matter. In ‘inverse’ mode, inputs are calculated based on known changes in soil organic matter.

## 2.2. Calibration of the Model to Estimate Carbon Variations Derived from the Land Use Change in Solar Parks with the RothC Model

The implementation of a solar park involves a significant modification of land use. In general, it is characterized by the removal of all vegetation and the installation of structures with which to fix the panels to the ground. From this point on, soils can undergo different adaptations, from minimal modification to soil compaction, the removal of the upper layers in processes of transformation and leveling of the land, or even the covering of the entire soil with concrete [28].

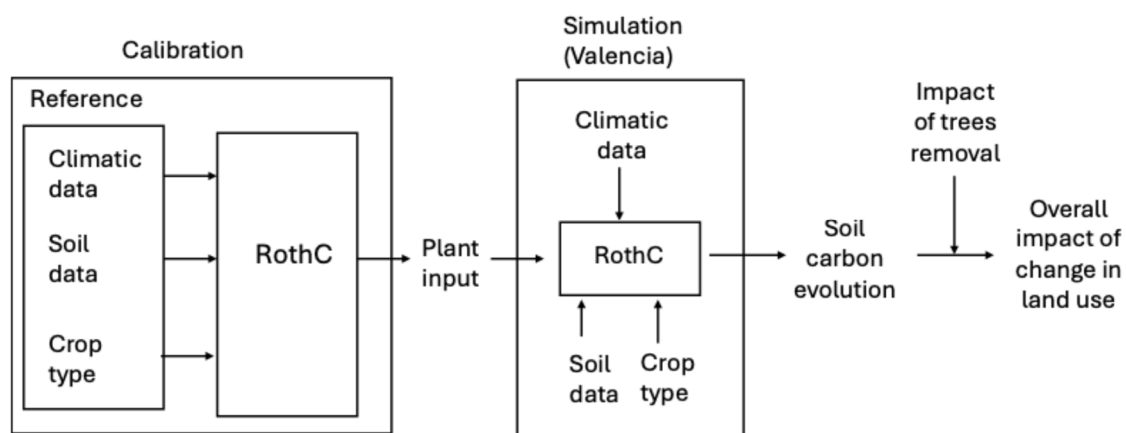
First, we performed a bibliographic search to identify examples of soils that were analyzed prior to their transformation into a solar park and monitored for long periods of time to assess the evolution of carbon in soils. Unfortunately, although there have been diverse studies that evaluate the effect of various treatments in already established solar parks, or the heterogeneity in different sections of the field, they generally make a one-off assessment, rather than a follow-up of the assessment over time. In other cases, although the evolution of the soil in the solar park over time was monitored, the state of the soil before the transformation, or the existence of possible treatments in the process, was not indicated. Undoubtedly, the novelty of this type of change in land use makes it a little-explored field of work and highlights the relevance of this type of study. Only one study, by Moscatelli et al. [25], provided all the data needed to run simulations and estimate soil carbon content before and after transformation both between and beneath the panels. This will be used to establish the parameters needed to run the model, so we lack independent data to evaluate the model; future work should collect additional data to allow a thorough model evaluation.

Most of the citrus fields were pre-leveled to prevent runoff and facilitate irrigation work. To minimize costs, the entire ground was not covered with concrete, but only the vegetation was removed and the support pillars for the solar panels were introduced. This is typical of the most common model of solar parks in the Valencian region [25]. The solar park is situated in Montalto di Castro (Italy) and is 5.6 km away from the sea. The park is located on flat land with moderately acidic soil that varies in texture from clayey to sandy loam. Prior to the installation of the plant, the land was used for agriculture, with a rotation of wheat, barley and alfalfa crops. No significant mechanical excavation that could disrupt the soil profile was performed before the plant was installed. The power plant was established in 2011, and the samples were collected in 2018, seven years later. Under the

PV panels, only *Sonchus oleraceus* L. was present, while in the gap area, this species was mixed with *Cicorium intybus* L. and *Portulaca oleracea* L.

The soil of the solar park was markedly different composition in the spaces between and under the panels. In the gap there is a significant increase in total carbon reaching 3.3%, but the carbon content in the soil under the panels is similar, although slightly higher, to that of the control (around 1.4%). These observations are not surprising given that the solar irradiation, temperature and humidity is markedly different under and between the panels.

A representation of the calibration–simulation process to estimate the carbon emissions can be found in Figure 1. The soil and weather data used to run the model are shown in Table 1, Tables S1 and S2 respectively. Meteorological data were obtained from NASA [35]. First, the model was initialized to the spring barley control by iteratively adjusting plant inputs until the simulated soil C matched the measured soil C as described by Smith et al. [36]. As defined in the RothC model, this uses plant inputs with a DPM:RPM ratio of 1.44 [33]. The changes in soil C after the installation of the solar farms were simulated by assuming land use changed to shrubland, as this is the most similar to the type of vegetation present in the gap between solar panels. This changed the proportion of DPM:RPM to 0.25, and full coverage/production over the year (i.e., no fallow period) was assumed [33]. With these parameters, average plant inputs after the land use change were calculated by fitting to the values measured by Moscatelli et al. [25] after seven years.



**Figure 1.** Representation of the calibration–simulation process to estimate the carbon emissions.

**Table 1.** Data used for the verification of the RothC model.

| Parameter         | Value                   |
|-------------------|-------------------------|
| Latitude          | 42.22°                  |
| Soil thickness    | 20 cm                   |
| Clay content      | 23%                     |
| Silt content      | 43%                     |
| Sand content      | 34%                     |
| Carbon content    | 0.95%                   |
| Soil bulk density | 1.35 g cm <sup>−1</sup> |
| Soil pH           | 5.7                     |

### 2.3. Simulation of Carbon Dioxide Emissions Due to the Conversion of Citrus Fields into Solar Parks in the Valencia Region

To assess the impact on carbon emissions of the solar park, we considered two factors: the removal of trees prior to the installation of the panels, and the evolution of soil carbon after installation. Other factors, such as the larger carbon footprint derived from the use of machinery, the impact of the stone/concrete supports, the aluminum pillars and the solar

panels, or the reduction in carbon footprint of the renewable electricity generated in the solar park, were not included in the analysis.

The plant inputs in soils after the installation of solar panels simulated using the data from Moscatelli et al. [25] were used to estimate changes in soil carbon following the installation of a solar park in a typical farm in the Valencian region. The example farm is located in the municipality of Albalat de la Ribera (W 0°22'59.99" N 39°12'0") (Spain). It features mature orange trees with an age of more than 10 years in full production. Soil data of the Spanish farm were analyzed by a certified laboratory (Verchilab S.L.). The soil type is loam (clay 25%, silt 30%, and sand 45%) with a carbon content of 0.6% and a soil bulk density of 1.4 g cm<sup>-3</sup>. The climate is temperate in winter and hot in summer, with average temperatures throughout the year around 16.5 °C, but with oscillations that can vary between 6.5 and 28.4 °C. The rainfall pattern is variable throughout the year and between years, but summers are usually dry, and the average is around 36 mm month<sup>-1</sup>. Since this is a permanent crop, we used scrubland as a crop type to determine the key parameters in the steady state. The DPM:RPM ratio was set to the standard value within RothC for scrubland (0.25), and the plant inputs were adjusted to that the steady state simulation matched the soil organic carbon content measured before land use change as described by [36]. This then allowed the forward run with no land use change from citrus to be directly compared to land use change to a solar park, simply by modifying the plant inputs from the citrus plant inputs. A 50% coverage of the soil by solar panels was established for the simulations.

#### 2.4. Sensitivity Analysis

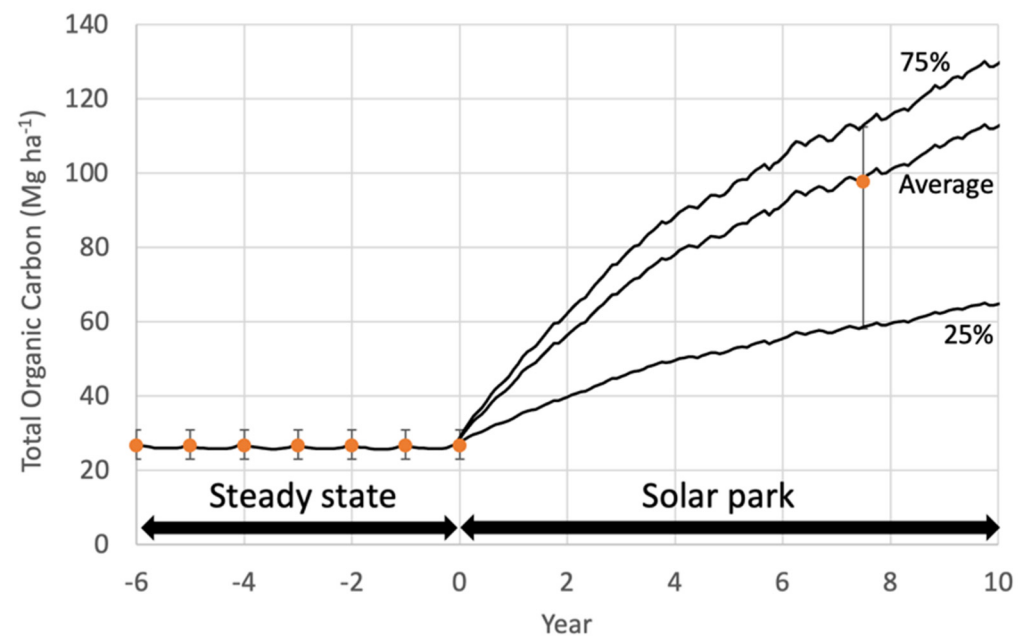
The results of the study are illustrative of the effect that the installation of solar parks can have on C emission and C content in the soil, and even allow for quantifying their effect. However, it is based on measurements and assessments that could undergo significant variations. Therefore, to understand the robustness of the results, a sensitivity analysis was carried out, in which the values of the variables were modified and the CO<sub>2</sub> emissions evaluated. The variables that were considered were planting scheme (6 × 3), mass of the trees (±20%), initial soil organic carbon (SOC) (1 and 2%), temperature (+2 °C), rainfall (−20%), plant input (±20%), and the % of surface covered by the solar panels (40% and 60%). The first three variables refer to the characteristics of the land on which the solar park would be installed. The next three refer to environmental aspects and plant growth, which is indirectly related to the plant species used in the replanting. The last refers to the characteristics of the solar park.

### 3. Results and Discussion

#### 3.1. Calibration of the Model to Estimate Carbon Variations Derived from the Land Use Change in Solar Parks with the RothC Model

The model initialization estimated a plant input under barley of 1.84 Mg ha<sup>-1</sup> y<sup>-1</sup> of carbon. This results in steady-state carbon pools of 0.42, 3.85, 0.54, 19.73 and 2.06 C Mg ha<sup>-1</sup> for DPM, RPM, BIO, HUM and IOM respectively. Most of the carbon is in the form of resistant pool (HUM) whose degradation and accumulation require long periods of time.

The evolution of total carbon at steady state and after transformation can be seen in Figure 2. Plant inputs for shrubland to achieve the average measurement provided by Moscatelli et al. [25] after 7 years (98 Mg ha<sup>-1</sup>) were calculated to be 1.81 Mg ha<sup>-1</sup> month<sup>-1</sup>. For the 25–75% range of soil analysis (58 to 112 Mg ha<sup>-1</sup>), plant inputs were calculated to be from 0.87 to 2.15 Mg ha<sup>-1</sup> month<sup>-1</sup>. As discussed above, overestimation of plant inputs cannot be ruled out, in particular for long-term scenarios, due to the conversion of the scrubland to a mature plantation, with lower rates of plant growth.



**Figure 2.** Evolution of the total organic carbon modeled with RothC in a farm, before and after its conversion into a solar park.

Over the 7-year period, the increase in soil C is concentrated in RPM (increases from 3.9 to 60.4 Mg ha<sup>-1</sup>) followed by HUM (increases from 19.7 to 31.0 Mg ha<sup>-1</sup>). The increase in the pools with longer residence time means that the soil carbon stock is becoming more recalcitrant. This is largely due to the change in land use type from arable to shrubland, revealing the importance of the type of vegetation when considering strategies to maximize carbon sequestration in the soil of solar farms.

As discussed above, solar parks have a great heterogeneity in the terrain due to the shade generated by the panels. We have assumed that the value after 7 years is representative of the average changes over that period. Thus, no estimation of dynamic changes in shade-induced moisture and temperature modifiers over time have been included. The soil below the surface of the panels had a C content of 37.0 Mg ha<sup>-1</sup> 7 years after the transformation, clearly lower than the value calculated by the model for the gap between the panels. This is to be expected due to the shading effect of the panels that reduces rainfall and solar irradiation, hindering the growth of vegetation. To account for this effect, reduced plant inputs of only 0.38 Mg ha<sup>-1</sup> month<sup>-1</sup> would be required: this is 5 times lower than the plant inputs in the gap. This proportion will be used to simulate the change in plant inputs that will be used to define the overall behavior of the land in the analysis of the Valencian farm.

### 3.2. Simulation of Carbon Dioxide Emissions Due to the Conversion of Citrus Fields into Solar Parks in the Valencia Region

A plant input of 1.08 Mg ha<sup>-1</sup> year<sup>-1</sup> was obtained under citrus, and values of 0.05, 3.97, 0.30, 11.01 and 1.20 Mg ha<sup>-1</sup> for DPM, RPM, BIO, HUM and IOM, respectively, giving a total of 16.5 Mg ha<sup>-1</sup> of SOC. These low values agree with the low rainfall, high temperatures and the common agricultural practices in the region, focused on the use of chemical fertilizers applied in the irrigation system, and the removal of the grass by tillage to maintain clean fields most of the year. Apart from the carbon in the soil, we must consider the carbon stock in the trees, which in this case is equivalent to 104 kg of dry matter per tree, 77 kg on the surface, and 27 kg under the ground for mature orange trees [37].

The removal of the orange trees for the installation of the solar park would remove 41.6 Mg of dry matter  $\text{ha}^{-1}$  assuming a plantation scheme of  $5 \times 5$  (400 trees  $\text{ha}^{-1}$ ) [38]. The amount of carbon released in  $\text{CO}_2$  eq would be 72 Mg  $\text{ha}^{-1}$  [39,40]. Since orange wood does not have the necessary qualities for a later industrial application, this type of wood is usually burned in the field, and the larger logs become wood that is burned in the following months. Therefore, the process of removing trees for the installation of solar parks results in a significant net emission of  $\text{CO}_2$  to the atmosphere.

After the installation of the solar park, we considered different scenarios, each with its corresponding impact on the evolution of C in soil and  $\text{CO}_2$  emission into the atmosphere. For clarity, the main results have been summarized in Table 2. In the first scenario, we assumed that the land would become vacant of vegetation after the implementation of the PV panels. This is currently the case with most of the wind farms installed in our region (see Figure 3). Due to the removal of plant inputs, a reduction in soil carbon immediately begins to occur, going from a value of C stock of 16.5 Mg C  $\text{ha}^{-1}$  prior to the installation of the solar park to 13.2, 11.7, and 8.9 Mg C  $\text{ha}^{-1}$  at 5, 10, and 30 years after, respectively. This reduction is more important for active pools. If we study the evolution of the RPM as the most relevant at a quantitative level, we go from 3.03 Mg C  $\text{ha}^{-1}$  in the steady state to 0.95 Mg C  $\text{ha}^{-1}$  at 5 years and 0.29 Mg C  $\text{ha}^{-1}$  at 10 years, which represents losses of 69 and 90%, respectively. For resistant pools, the decline of HUM is slower, with reductions of 4% and 9% in the same time frame.

**Table 2.** Evolution of C content in soil and total  $\text{CO}_2$  emissions in the period. Note: SOC = soil organic carbon.

| Scenario      |                               |                                                   |                               |                                                   |
|---------------|-------------------------------|---------------------------------------------------|-------------------------------|---------------------------------------------------|
| 1- Bare Field |                               |                                                   | 2- Vegetated <sup>a</sup>     |                                                   |
| Year          | SOC<br>(Mg $\text{ha}^{-1}$ ) | $\text{CO}_2$ Emissions<br>(Mg $\text{ha}^{-1}$ ) | SOC<br>(Mg $\text{ha}^{-1}$ ) | $\text{CO}_2$ Emissions<br>(Mg $\text{ha}^{-1}$ ) |
| 0             | 16.5                          | 71.7                                              | 16.5                          | 71.7                                              |
| 5             | 13.2                          | 83.5                                              | 55.8 (34.4–64.4)              | −72.4 (5.9/−104.0)                                |
| 10            | 11.7                          | 89.3                                              | 70.8 (41.3–82.8)              | −127.7 (−19.4/−171.4)                             |
| 15            | 10.7                          | 92.7                                              | 77.3 (44.1–90.7)              | −151.3 (−29.6/−200.5)                             |
| 20            | 10.1                          | 95.1                                              | 82.3 (46.3–96.8)              | −169.6 (−37.6/−223.0)                             |
| 25            | 9.5                           | 97.3                                              | 90.2 (49.9–106.4)             | −198.6 (−51.1/−258.1)                             |
| 30            | 8.9                           | 99.7                                              | 97.8 (53.5–115.6)             | −226.3 (−64.1/−291.9)                             |

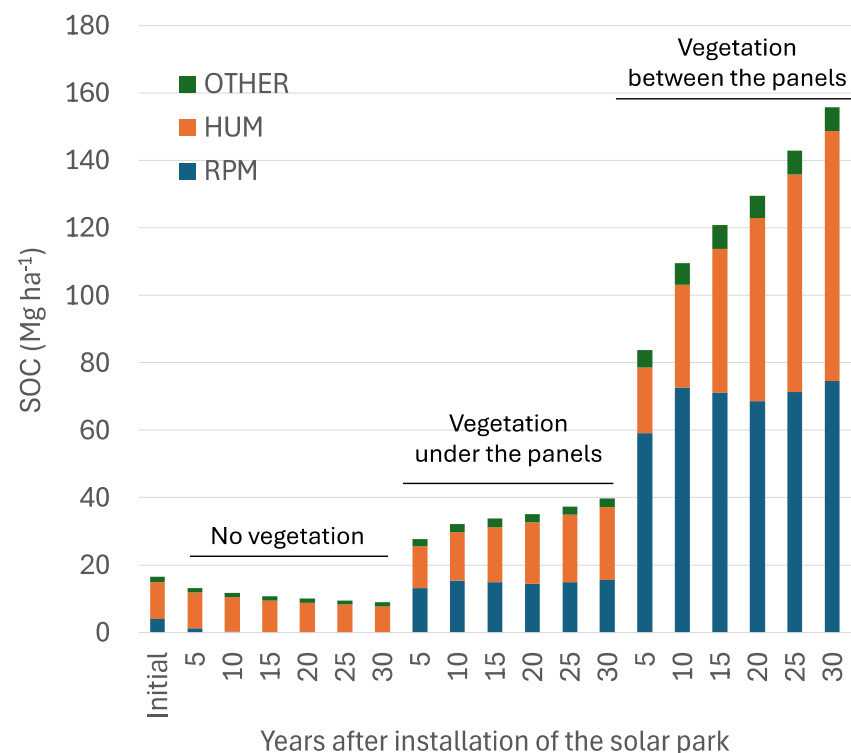
<sup>a</sup> Average (25/75%).

The second scenario evaluates the possibility of carrying out revegetation activities, or at least letting the wild flora grow. In this case we must consider that approximately 50% of the ground is covered by solar panels. Thus, we can propose a scenario in which 50% would be scrubland, and the other 50% would present a 5-fold reduction in plant input. As can be seen in Figure 4, despite the heterogeneity in the area covered and uncovered by both types of panel, an increase in the carbon content in the soil is observed for both types of vegetated areas, under the panel and in the gap between them. Of course, the gap, which receives the influence of the sun, and the rainfall offers faster growth in agreement with the higher plant input. Again, the main changes just after the creation of the solar parks are observed for the RPM pool, reaching a new equilibrium around 10 years after installation, with values of around 43 Mg C  $\text{ha}^{-1}$ , although the total carbon continues to increase due to the growth of the resistant pools, in particular HUM during the full lifetime

of the solar park (30 years) (see Figure 3). We can expect soil organic carbon of 58, 71, 82, and 98 Mg C ha<sup>-1</sup> at 5, 10, 20, and 30 years, respectively (Table 2).



**Figure 3.** Example of an orange farm transformed into a solar park in the Valencia region (source Google maps).



**Figure 4.** Evolution of the soil organic carbon after the installation of the solar part as a function of the soil treatment. RPM: resistant plant material (RPM). HUM: humified organic matter.

Once the effect of changing land use from agricultural to solar park has been defined, we are able to evaluate the effect that the installation of PV parks may have on the emission of CO<sub>2</sub> and carbon in soil in the Valencian Community over the lifetime of the solar park, 30 years. We have considered again the two scenarios indicated above (bare and vegetated surface) and evaluated the impact of the installation of the 12,000 hectares of solar parks planned for 2030 in orange groves. It should be borne in mind that, according to the European Union's forecasts, the installation of solar parks is expected to continue

to increase in the period 2030–2050, so although in the coming years not all installations will probably be carried out on this type of land, it is expected that in the long term there will be a change in land use of this magnitude. As can be seen in Table 3, the conversion of orange orchards into solar parks can have a significant impact on the emission of CO<sub>2</sub> into the atmosphere, which can exceed  $1.1 \times 10^6$  Mg within 20 years. A significant part of these emissions come from the change in the uprooting of trees and the release of the carbon contained in them ( $0.86 \times 10^6$  Mg). This is especially important as it is an immediate release. Although it is out of the scope of this study, for the start-up of the solar park, the emissions derived from the manufacture of the panels and auxiliary materials (e.g., aluminum profiles, or cement for the pillars), the installation of the panels and the development of the electrical infrastructure to transmit electricity, etc., should be added in future studies.

**Table 3.** Emitted CO<sub>2</sub> from predicted conversion of orange groves to solar parks across the full region of Valencia.

| Year | Scenario 1                                         | Scenario 2                                                  |
|------|----------------------------------------------------|-------------------------------------------------------------|
|      | Non Vegetated ( $\times 10^3$ Mg CO <sub>2</sub> ) | Vegetated ( $\times 10^3$ Mg CO <sub>2</sub> ) <sup>a</sup> |
| 0    | 860                                                | 860                                                         |
| 5    | 1.003                                              | −869 (71/−1249)                                             |
| 10   | 1.072                                              | −1532 (−233/−2056)                                          |
| 15   | 1.113                                              | −1816 (−356/−2406)                                          |
| 20   | 1.142                                              | −2036 (−451/−2676)                                          |
| 25   | 1.168                                              | −2383 (−613/−3097)                                          |
| 30   | 1.191                                              | −2716 (−769/−3502)                                          |

<sup>a</sup> Average (25/75%).

Once the solar park is commissioned, the emissions will depend on the treatment we do to the soil. The worst-case scenario is the maintenance of vacant land (the most common practice) that facilitates the loss of soil C in a process that will lead to decades of net CO<sub>2</sub> emissions and exposes the soil to the elements favoring erosion. The alternative is to encourage the combination of solar panels with vegetation growth, which, in any case, would replace the C lost from tree removal during installation, while protecting the soil. Depending on the type of vegetation and climatic conditions, this strategy could lead to an increase in C sequestration in the soil, helping to combat climate change by decreasing the concentration of CO<sub>2</sub> in the atmosphere, while renewable energy generation avoids the consumption of fossil fuels. In any case, it is necessary to develop additional long-term field studies that allow us to establish the best conditions and quantify the effect of this strategy to confirm the results.

### 3.3. Sensitivity Analysis

The main results in relation to CO<sub>2</sub> emissions derived from land use change at 30 years are summarized in Table 4. The average plant input values have been used as a reference in Scenario 2.

As can be seen, none of the modifications studied can change the trend in CO<sub>2</sub> emissions. Leaving the ground empty results in net emissions under all conditions. If plants are planted, a net adsorption of C occurs in all cases. However, all the variables evaluated affect the emissions associated with the solar park, which reaches up to 70% higher emission values. The variable that seems to have the greatest influence, whether the land is left without vegetation or revegetated, is the percentage of soil organic carbon. In our case, we worked with agricultural land that has been impoverished in carbon after decades of intensive agriculture. When we increase the soil organic carbon, the tendency to produce additional carbon losses increases, and the additional capture capacity decreases

significantly. This effect is greater the higher the initial carbon content. Other factors, such as the planting frame or the weight of each tree, are more relevant in Scenario 1 since the removal of the trees has a greater relevance in it.

**Table 4.** Thirty years after the installation of the solar park.

| Label                            | CO <sub>2</sub> Emissions ( $\times 10^3$ Mg) |            | Variation (%) |            |
|----------------------------------|-----------------------------------------------|------------|---------------|------------|
|                                  | Scenario 1                                    | Scenario 2 | Scenario 1    | Scenario 2 |
| Planting scheme ( $6 \times 3$ ) | 1526                                          | −2381      | 28.1          | 12.3       |
| Tree weight (+20%)               | 1363                                          | −2545      | 14.4          | 6.3        |
| Tree weight (−20%)               | 1020                                          | −2888      | −14.4         | −6.3       |
| SOC (1%)                         | 1432                                          | −2476      | 20.2          | 8.8        |
| SOC (2%)                         | 1999                                          | −1889      | 67.9          | 30.4       |
| Air T (+2 °C)                    | 1216                                          | −2410      | 2.1           | 11.3       |
| Rainfall (−20%)                  | 1184                                          | −2915      | −0.6          | −7.3       |
| Plant input (+20%)               | -                                             | −3497      | -             | −28.8      |
| Plant input (−20%)               | -                                             | −1932      | -             | 28.9       |
| PV coverage (60%)                | -                                             | −2203      | -             | 18.9       |
| PV coverage (40%)                | -                                             | −3225      | -             | −18.8      |

Considering environmental conditions, the temperature was raised, and rainfall was lowered, considering the effect derived from climate change. Although a 2-degree growth has a minor effect on the emissions, a further reduction in the water available reduces plant growth, and so also reduces carbon fixation. Plant growth has an important effect, with carbon sequestration being greater the higher the plant input. It will therefore be necessary to work with plants specially adapted to the climatic conditions in which the farm is located. It should be considered that although the RPM reaches equilibrium within about 10 years, the total equilibrium requires a much longer period since there is an accumulation of the HUM fraction of the SOC.

Finally, the percentage of land covered with solar panels can also have an important influence. A variation of 10% has an incidence of almost 20% in carbon sequestration. However, this is one of the aspects on which there may be less influence since, seeking the highest energy production and profitability of the farms, the owners of the solar farms will seek to achieve an optimal coverage of the solar panels in which energy production is maximized and shadows are minimized, including sufficient passage for maintenance work. What can be promoted is planting with different types of plants. Species with greater vigor and adaptation to direct sunlight can be planted between the PV panels, and under the panels, species that are more efficient in the use of light and water, but which develop better in the shade.

#### 4. Conclusions

The installation of solar parks in citrus fields represents a significant change in land use, with a strong influence on soil organic carbon and global CO<sub>2</sub> emissions. However, the effect is highly dependent on the type of vegetation adopted after the installation of the solar park. Because this result is based on limited experimental data, calculations should be considered as an indicator of the potential for C sequestration but not used quantitatively. Leaving soil under solar parks bare could result in emissions of 100 Mg CO<sub>2</sub> ha<sup>−1</sup> or  $1.2 \times 10^6$  Mg CO<sub>2</sub> across the Valencia region. This could be countered by planting scrubland-type plants and increasing the space between panels, even in scenarios with lower rainfall and higher temperatures. These strategies could achieve a net capture higher than  $3 \times 10^6$  Mg of CO<sub>2</sub> across the region. Even considering the effect of variations in plant inputs, the sensitivity analysis suggests that including plantations in solar parks could offer

additional benefits to the emission reductions associated with the use of renewable energy. However, further experimental data are needed to verify these findings, and a full life cycle analysis of the solar park should be included in future studies.

**Supplementary Materials:** The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/cleantechnol8040106/s1>. Table S1: Total rainfall values used for the verification of the RothC model.; Table S2: Average air temperature values used for the verification of the RothC model.

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