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Spontaneous Plants Improve the Inter-Row Soil Fertility in a Citrus Orchard but Nitrogen Lacks to Boost Organic Carbon

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Abstract: The inter-row soils in conventionally run citrus orchards in Eastern Spain lose fertility, either physically, chemically, or biologically, as a consequence of machinery traffic and the use of herbicides. In order to regain inter-row soil fertility, two grass-cover management alternatives to the commonly used herbicide-kept bare management, namely, spontaneous plants and fescue, were established and left for four years until their effects on several physical, chemical, and biological parameters were monitored for two years more. The fescue ground cover exhibited lower average and maximum soil temperatures due to higher evapotranspiration rates but also higher annual soil water content on average and, additionally, higher rhizodeposition. Despite the fact that these new beneficial conditions helped enhance the soil's biological fertility under fescue, the physical or chemical fertilities did not improve and neither did the organic carbon (SOC). The spontaneous plants also enhanced the biological fertility, but in this case, beneficial conditions were reflected by improvements in the chemical fertility, particularly the exchangeable potassium, and in the physical fertility by increasing the surface hydraulic conductivity and decreasing the bulk density. In the inter-rows of this citrus orchard, a seeded grass cover does not seem able to provide any soil fertility enhancement in comparison to a spontaneous one; rather the opposite. However, a lack of natural or man-driven nitrogen inputs poses a constraint to SOC gains. For this aim, the annual surface application of organic nitrogen-rich materials or even better, the fostering of N-fixing organisms would be recommended.

Keywords: soil quality; cover crops; enzymatic activity; CO_2 emission; Mediterranean climate; carbon sequestration; bulk density; hydraulic conductivity; *Hordeum murinum*

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1. Introduction

In agriculture, soil fertility is the soil's ability to provide crops with a favorable environment where they can optimally develop and yield. Soil fertility is made up of interdependent chemical, physical, and biological factors [1,2]. The soil's chemical fertility is the soil's ability to provide crops with the amounts of nutrients their genetic potential requires as readily absorbable ions and molecules. The soil's physical fertility is the soil's ability to provide crops with a porous ground material that their roots can explore to anchor to and obtain oxygen, water, and nutrients at the pace that these are required according to the plants' growth and weather conditions. Finally, the soil's biological fertility is the soil's ability to provide crops with a community of overall mutualistic organisms, i.e., ones that help plants to obtain the oxygen, water, and nutrients their roots look for, with no harm induced by competition, parasitism, or (micro)predation.

Nowadays, conventional agriculture is characterized as follows. It tries to maximize soil chemical fertility through the application of synthetic fertilizers that exceed the crop's needs. It tries to maintain the soil's physical fertility, often by means of harsh tillage operations, e.g., moldboard plowing. Finally, it constrains the soil's biological fertility to the control of competing organisms, parasites, and plant (micro)predators by using tillage and/or xenobiotic chemicals. All of these practices ignore the interdependence among chemical, physical, and biological fertility and thus lead to land degradation [3–6]. In addition, in the case of drip irrigation systems, the need for fertility is only circumscribed to the emitter-dampened soil volume. Lastly, considering the inter-rows as little more than alleyways for machinery traffic further damages soil fertility [7].

In Spain, there is currently 5,340,000 ha with woody crops, among which 307,000 ha, i.e., ≈6%, are with citrus, over half in the Valencian Community (Eastern Spain) [8]. Spanish citrus soils are mostly drip irrigated (≈84%) [8] and subjected to herbicide applications for weed control (≈75%) [9]. Conventionally managed Spanish citrus soils not only feature low organic carbon [10,11] but also high bulk density because of the constant agricultural machinery traffic on the inter-rows [12]. The soil compaction experienced by citrus soils under conventional management practices harms their physical fertility, which appear as decreased topsoil water infiltration [13] and, as a consequence, higher runoff and erosion rates [12,14].

High compaction is strongly related to low soil organic carbon (SOC) [15–18], and therefore, the deterioration of physical fertility worsens chemical fertility. Fortunately, the converse has been observed, as ameliorating one fertility aspect improves the other and vice versa [19,20]. In this regard, there are several soil-management practices that may be applied to the inter-rows of citrus plantations so as to increase their SOC and decrease their compaction, e.g., the use of cover crops [21] including spontaneous plants and mulching with agricultural by-products such as rice straw [22].

These management practices, especially cover crops, improve the soil's chemical fertility by increasing SOC, and the soil's physical fertility by increasing porosity, water infiltration, available water capacity, and structural stability. Additionally, they improve the soil's biological fertility in woody crop orchards (i) by increasing enzyme activity [23–25], (ii) controlling weeds [26,27], and by controlling harmful insects [28], therefore becoming an alternative to the use of xenobiotic chemicals.

Among cover crops, seeded ones, either with Poaceae or Leguminosae or mixtures of both, are the standard [29]. However, since they are genuine crops, they have to be cultivated, which includes seeding, cutting, and even watering and fertilizing [30]. This way, they become an expense to the farmer. The question is whether they make up for this expense in terms of soil fertility and SOC increase and, moreover, how they compare with spontaneous plants, which due to their nature, are more easily managed.

To the best of our knowledge, in citrus orchards, the alternative inter-row soil management of spontaneous plants has not been compared against the conservative treatment using Poaceae cover crops and conventional bare-soil treatment by means of herbicide application. In the framework of the soil and climate conditions of the citrus orchards from the Valencian coastal plain (Eastern Spain), the tested hypothesis is that in the short-to-medium term, the use of grass cover crops, specifically, spontaneous plants, on the inter-rows, enhances the soil's physical, chemical, and biological fertility more than keeping the soil bare.

2. Materials and Methods

2.1. Study Site

A citrus orchard located at the Centro de Experiencias Cajamar in the municipality of Paiporta (coordinates 39°25′2′′ N, 0°25′4′′ W, altitude of 17 m, slope < 1%) was selected as the study site (Figure 1). This emplacement is at the bottom of a Pleistocene accumulation piedmont immediately contiguous to the Valencian coastal plain. The climate of the area is semiarid hot-summer Mediterranean (Csa), according to the Köppen–Geiger classification [31], and the soils are Typic calcixerepts, according to the Soil Taxonomy [32].

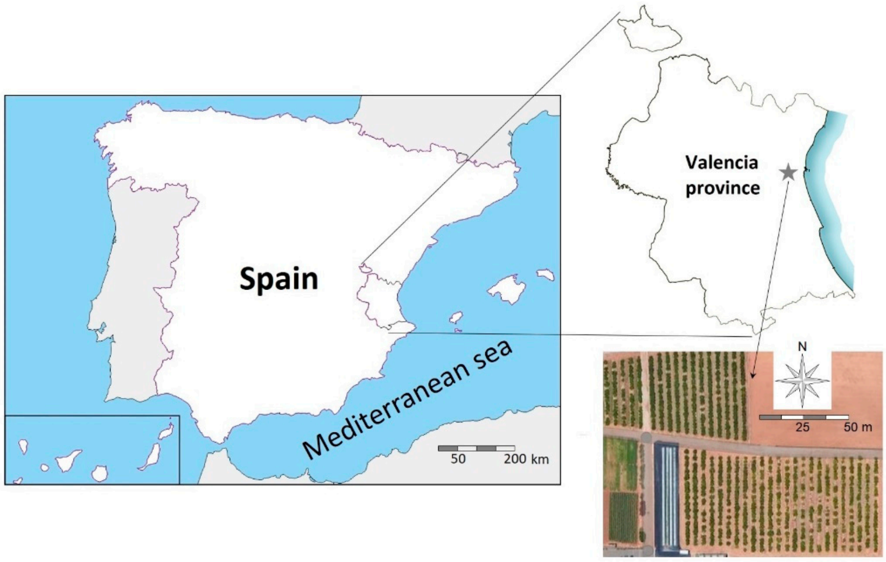

Figure 1. Location of the study site.

2.2. Crop and Irrigation Characteristics

The site was planted between 2013 and 2014 with clementine (*Citrus clementina*) grafted onto Cytrange carrizo with a 5 × 2 m^2 spacing, and the irrigation system was trickle on the tree lines with a double hose per plant row. Fertigation was carried out according to the usual practices in the surrounding Valencia area.

2.3. Treatments and Trial Plots

Three management methods for the soil on the inter-rows were set up as treatments with two trial plots that were 10-to-15-m-long per each one: (i) the soil kept bare as a control using weed killers (bare), (ii) the soil left with no weed control (spontaneous), and (iii) the soil planted with fescue (*Festuca* spp.) as a cover crop (fescue). Both the establishment and maintenance of these treatments are described in some detail below.

In the control treatment, a broad-spectrum herbicide (glyphosate) plus minor quantities of other more weed-specific herbicides, following the conventional practices in the citrus production of the Valencia area, were applied to keep the soil bare throughout the experiment time stretch. Before the winter of 2015, the soil under all treatments had been subjected to this same treatment with herbicides. From the winter of 2015 onwards, the soil on the inter-rows in the spontaneous treatment was left to freely grow local weeds, whereas, in the fescue treatment, the grass was sown.

Following the setup of the treatments, all plants on the inter-row, either sowed or spontaneous, were reaped on a regular basis each spring, summer, and winter. Importantly, the residues were not mixed with the soil but left on it. The rest of the agricultural operations were the same in all treatments. Furthermore, no other fertilizers or management practices different from the ones just described were applied to the inter-rows. Starting from the winter–spring of 2019, the trials were monitored for two years.

2.4. Weather Measurements

Rainfall was measured with an ECRN-50 (METER Group, Inc., Pullman, WA, USA) rain gauge installed at a 1 m height in a clear spot near the center of the study site, and the data were recorded by means of a ZL6 m (METER Group, Inc., Pullman, WA, USA). The atmospheric pressure (P) data were measured and saved by means of one ZL6 m per treatment. The air temperature and relative humidity were measured and recorded with one HOBO MX2301 (Onset Computer Corp., 470, Bourne, MA, USA) installed at a 1 m height in the middle of one trial plot per treatment.

2.5. Soil Measurements and Samplings

All of the soil measurements and samplings were performed on the inter-rows, avoiding the areas near the drip emitters.

2.6. Soil Temperature and Water Content Measurements

For the monitoring of the soil temperature and water content, two 5TM (METER Group, Inc., Pullman, WA, USA) capacitance probes per trial plot were installed between 5 and 10 cm depths.

2.7. Soil Saturated Hydraulic Conductivity

The soil-surface saturated hydraulic conductivity (*K*s) was assessed by using a single-ring infiltrometer with a 12.5 cm diameter and a 6.5 cm height, filled with water with a 400 µS/cm electrical conductivity at 25 °C [33]. Two batches of *K*s measurements composed of four repetitions per trial plot were made, one at the beginning and another at the end of the monitoring.

During each infiltration measurement, a constant hydraulic head (H) of 1 cm was kept on the soil surface and the cumulative infiltration values (I) were taken against time (t) for 20 min. In order to calculate *K*s, first of all, it was determined from which time the infiltration rate reached a steady state. This minimum time to reach steadiness in water infiltration (t_{min}) was determined in the laboratory through the visual inspection of the I against t graph and calculation of the coefficient of determination (R^2) of the following equation:

$$I = \mathrm{a}\, f\, K\mathrm{s}\, t + \mathrm{c} \tag{1}$$

where a is a dimensionless constant with a 0.9084 value, c is an empirical parameter, and f is a geometric parameter that depends on the hydraulic head and the single-ring dimensions according to:

$$f = 1 + (H + 12.5)/(d + r/2) \tag{2}$$

where d is the depth of the ring insertion and r is its radius [34]. Once t_{min} was known, Equation (1) was considered to represent the water infiltration into the soil from there onwards, and *K*s can be assessed from its slope.

2.8. Soil Carbon Dioxide Emission Rate

Polyvinyl chloride (PVC) collars of 10 and 4.5 cm in, respectively, inner radius (r) and height, were driven 3.5 cm into the soil in two places across the inter-row of each trial plot and left for the entire project time span. Then, the soil CO_2 emission was measured once every one or two months in the collar-delimited areas.

To measure the soil CO_2 emission rate every time it was made, a measurement chamber was constructed over the PVC collars by tightly fitting a steel cylinder with a 10 cm outer radius and a 16 cm height and a PVC cover on top. This lid was equipped with a K-30 (SenseAir AB, Delsbo, Sweden) dispersive infrared CO_2 sensor and, additionally, an HS-2000V (Kele Precision Manufacturing, Memphis, TN, USA) air temperature (T) and relative humidity (RH) sensor.

The chamber cover was connected by means of a multi-wire cable to an Arduino UNO (Smart Projects S.R.L., Scarmagno, Italy) microcontroller, which was also connected to a real-time clock (RTC), a 16 × 2 liquid crystal display (LCD), a 4 GB secure digital (SD) card recorder, and a 12 V battery. A program in the C language was written in the Arduino Development Environment (ADE) and loaded into the microcontroller to take measurements in the chamber headspace of the CO_2 volumetric fraction (x_{CO2}), T and RH every five seconds for 30 min.

In order to calculate the soil C-CO_2 emissions, firstly, the C-CO_2 volumetric mass content in the chamber ($\rho_{\mathrm{C\text{-}CO2}}$) was calculated from the x_{CO2}, T, and P data according to the following equation:

$$\rho_{C-CO2} = \frac{x_{CO2} M_C P}{R(T + 273.15)} \tag{3}$$

where M_C is the C molar mass and R is the gas constant. Then, a polynomial was tried to fit the data of $\rho_{C\text{-}CO2}$ against time (t), and, in general, a fourth-degree one was found to be quite representative of the C-CO_2 evolution in the chamber:

$$\rho_{C\text{-}CO2} = \alpha + \beta t + \gamma t^2 + \delta t^3 + \varepsilon t^4 \tag{4}$$

The polynomial coefficients were estimated by means of least squares fitting. Since covering the soil with a closed measurement chamber is known to alter the previous natural flux of soil CO_2 [35], a pre-deployment soil C-CO_2 emission rate per unit surface ($E_{C\text{-}CO2}$) was estimated from the derivative of Equation (4) at t = 0 [36]. This initial rate equals the β coefficient in Equation (4), and thus, the $E_{C\text{-}CO2}$ was estimated by multiplying the β coefficient in Equation (4) by the chamber height (h):

$$E_{C\text{-}CO2} = \beta\ h \tag{5}$$

2.9. Undisturbed Soil Sampling for Bulk Density

Undisturbed soil core samples with a 5 cm diameter and height were taken using steel cylinders and a 0753SA (Eijkelkamp, Giesbeek, The Netherlands) volumetric sampler at two depth intervals: 0–5 and 20–25 cm. During the experiment, three batches of core samples from three points per trial plot were collected.

These core samples of known volume (V) were hermetically closed in the field and, once in the laboratory, dried at 105 °C for 24 h and weighed (m_{ss}). Then, the soil was extracted from the cylinders and disaggregated. The coarse fragments (>2 mm) were separated and weighed to find their mass (m_{cf}), whereas their volume (V_{cf}) was estimated assuming a standard particle density of 2.65 g cm^{-3} and applying $V_{cf} = m_{cf}/2.65$. Then, the apparent density of the fine earth (<2 mm) (ρ_b) was calculated by means of:

$$\rho_b = (m_{ss} - m_{cf})/(V - V_{cf}) \tag{6}$$

2.10. Undisturbed Soil Sampling for Roots

Using the aforementioned volumetric equipment, undisturbed core samples were taken in four points per trial plot but only at a 0–5 cm depth for the root-weight mass fraction assessment only once during the experiment time span. The core samples were again hermetically closed, and once in the laboratory, they were weighed to find the field soil mass (m_{fs}). Then, the soil was extracted from the steel cylinders, and one rootless sub-sample per core was taken, weighed, dried at 105 °C for 24 h, then reweighed to assess the gravimetric field water mass fraction (w_{fs}), and finally, the dry mass of the whole undisturbed soil (m_{ds}) was calculated. The roots were separated from the rest of the soil by sieving and flotation, dried at 65 °C for 48 h, and weighed to find their mass (m_{root}). Then, the mass fraction of the roots in the soil (w_{root}) was calculated by using this equation:

$$w_{root} = m_{root}/m_{ds} \tag{7}$$

2.11. Disturbed Soil Sampling

Disturbed soil samples were also taken with a steel sampling tube. Following sampling, the extracted soil material was thoroughly mixed, and one subsample was separated, transferred to a plastic pot, and kept in an ice chest at 5–10 °C, whereas the rest of the sample was simply sealed in a plastic bag and kept at air temperature. Three places per trial plot were drilled every three months throughout the experiment at depths of 0–20 cm. However, at the beginning of the experiment, the 20–40 and 40–60 cm layers were also sampled.

Once in the laboratory, the low-temperature-preserved subsamples were kept at 4 °C until the field water content, dehydrogenase activity (DHA), and β-D-glucosidase (GLA) activity could be determined. The field water content was determined by oven-drying a subsample at 105 °C for 24 h, whereas DHA and GLA were determined according to the methods of, respectively, Casida et al. [37] and Tabatabai and Bremner [38].

The non-refrigerated soil was spread onto polyethylene trays, which were bottom-covered with ashless filter paper sheets and left to air-dry. Then, the hygroscopic water content was determined by oven-drying a subsample at 105 °C for 24 h. The soil nitrogen mass fraction (w_N) was determined using the Kjeldahl method [39]. The SOC mass fraction (w_{SOC}) was determined by the Walkley–Black method [40] using 1.33 as the Walkley–Black coefficient [41]. The available soil phosphorus (w_P) was estimated using the Olsen–Watanabe method [42]. The extractable potassium (n_K) was determined by displacement with 1 N ammonium acetate and measurement by emission flame spectrophotometry. Finally, texture, according to the USDA, was assessed using a Bouyoucos densimeter [43].

2.12. Statistical Analyses

Before the comparisons among treatments, each batch of data was analyzed to ascertain if it satisfactorily fulfilled the requirements of normality. The adjusted Fisher–Pearson standardized moment coefficient (G1) and the Kolmogorov–Smirnov test were used to assess normality. In case this could not be accepted, then a logarithm to base 10 or even a square root transformation were tried in this order, and the G1 and the Kolmogorov–Smirnov test were reassessed. Then, Pearson's product–moment correlation coefficients among all of the normalized variables were calculated by using the mean values of each season and subplot. Next, it was ascertained if the variables significantly changed among the soil treatments by means of two-way ANOVAs, where an additional variable, i.e., sampling or measurement time, was included along with the treatments. Regarding this, if the interaction between the treatment and sampling or measurement time could be considered significant, then as many one-way ANOVAs as sampling or measurement times were carried out instead. Two-way ANOVA and, if necessary, one-way ANOVAs for each sampling or measurement time, were followed by orthogonal comparisons, in which the following a priori hypotheses were tested: (i) the joint bare and spontaneous treatments against the fescue and (ii) the bare soil against the spontaneous plants. In this work, a p-value below 0.05 has been regarded as revealing significant differences, and all average values have been expressed as the arithmetic mean plus its 95% confidence interval according to the Student's t distribution.

3. Results

3.1. General Observations

The soil in the study site is not stony ($m_{cf}/m_{ss} < 2\%$), clay loam, and moderately calcareous (Table 1). In addition, at the beginning of the monitoring in the bare inter-rows, the soil was also found to be poor in organic matter and moderately compacted (Table 1). In the spontaneous treatment, the soil covering attained between 50 and 90% in spring due to a mixture of, primarily, false barley (*Hordeum murinum*) and, secondarily, horseweed (*Conyza canadensis*), whereas soil covering decreased to between 10 and 20% in winter, summer, and autumn when the horseweed dominated. The fescue treatment attained a more homogeneous soil covering, which ranged between 60 and 80%.

Table 1. Summary of the main soil characteristics [1] in the citrus orchard at the beginning of the study.

Depth/cm	Texture USDA				w_{SOM}(%)	w_{CCE}(%)	ρ_b/g cm^{-3}
	Clay (%)	Silt (%)	Sand (%)	Class			
0–20	30	42	29	Clay loam	1.4	27	1.63
20–40	26	42	32	Loam	1.0	29	–
40–60	29	41	31	Clay loam	0.6	30	–

[1] Depth: depth interval; w_{SOM}: mass fraction of organic matter; w_{CCE}: mass fraction of calcium carbonate equivalent; ρ_b: fine earth (<2 mm) bulk density.

3.2. Soil Temperature

The differences in soil temperature between the treatments were remarkable. The mean daily temperature was the lowest under fescue with 19.1 ± 0.3 °C whereas the spontaneous plants and bare soil had the highest with a joint of 19.8 ± 0.2 °C. Therefore, the treatments may be arranged in the following order from lower to higher soil temperature: fescue < spontaneous plants ≈ bare soil.

As can be seen in Figure 2, the differences in mean daily temperature among the treatments were primarily caused by the differences in maximum daily temperature and not by the differences in the minimum one. Specifically, the maximum mean daily temperature was again the lowest under fescue at 21.1 ± 0.3 °C, and then, under the spontaneous plants and bare soil, which again featured the highest with a joint of 22.8 ± 0.2 °C. Contrary to the maximum temperature, there were no differences in the minimum mean daily temperature between the treatments, and a joint of 17.5 ± 0.1 °C could be calculated for all three.

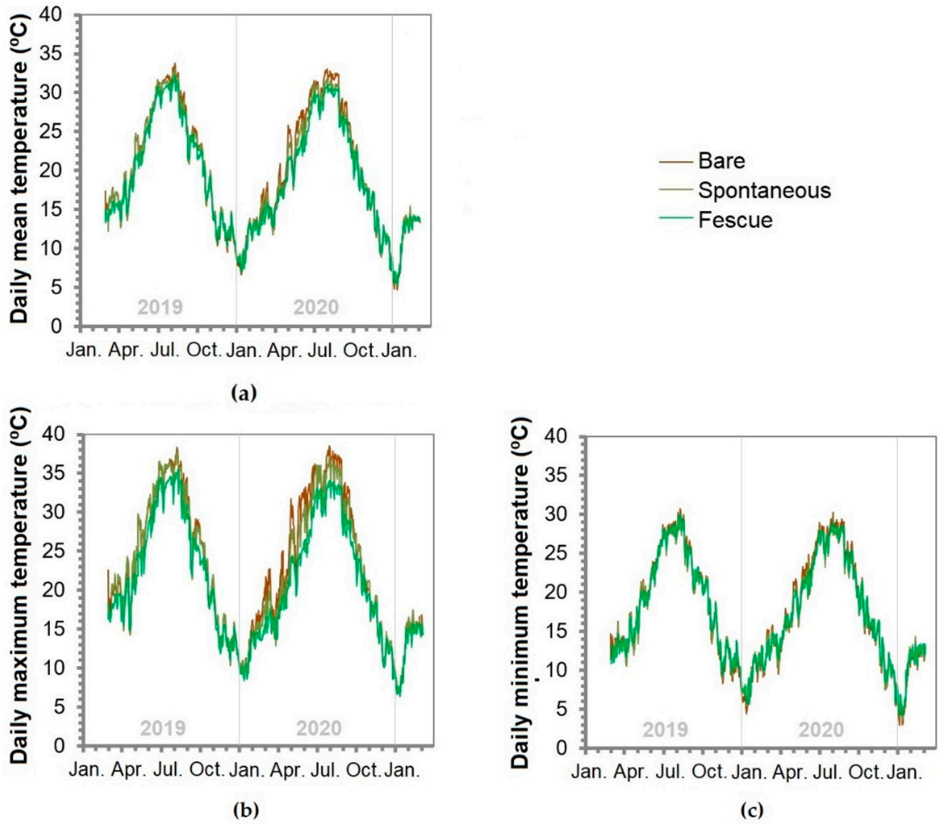

Figure 2. (**a**) Daily mean temperature at 5–10 cm depth in the different treatments; (**b**) daily maximum temperature; (**c**) daily minimum temperature.

3.3. Soil Water Content

In addition to temperature, there were also remarkable differences in the soil water content between the treatments. The mean daily water content was the lowest in both the bare soil and spontaneous plants, which had a joint of 0.199 ± 0.001, followed by the fescue with 0.205 ± 0.002. Therefore, the treatments may be arranged in the following order from lower to higher annual average water content: bare soil ≈ spontaneous plants < fescue. This order reverses the soil temperature one. Notwithstanding this, the fescue left the soil drier than the other treatments during spring and, particularly, summer, likely because of the plant evapotranspiration during those seasons (Figure 3).

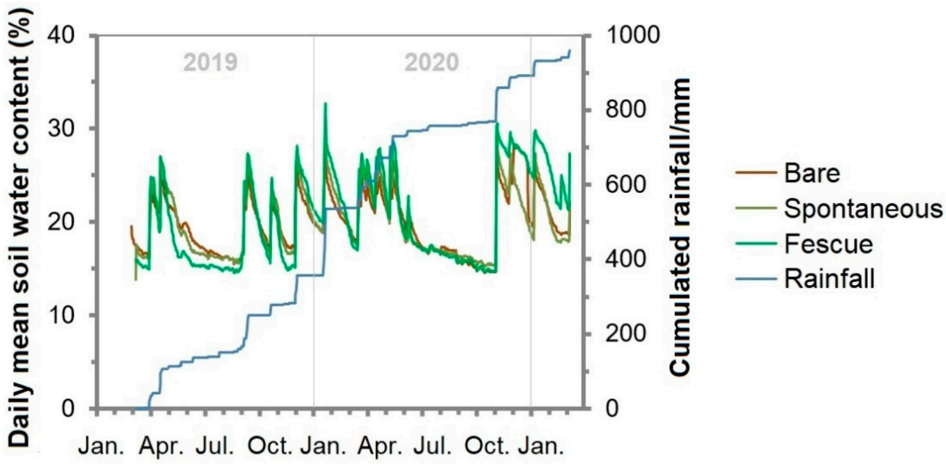

Figure 3. Daily mean soil water content at 5–10 cm depth in the different treatments along with the cumulated rainfall during the monitoring time.

3.4. Statistical Characteristics of the Soil Properties

The general statistical features of the soil variables were evaluated (Table S1). Additionally, the adjusted Fisher–Pearson standardized moment coefficient (G1) and the Kolmogorov–Smirnov test parameters were calculated (i) to assess the normality of their distributions and (ii) to study the adequate transformation to attain normality.

The saturated hydraulic conductivity data presented a G1 coefficient equal to 1.5, which means that *K*s followed a distribution with a heavy tail to the right, which, notwithstanding, could be accepted as normal according to the Kolmogorov–Smirnov test ($p = 0.45$) (Table S1). However, a logarithm-to-base-10 transformation led to a G1 very close to zero, specifically −0.1, and a *p*-value for the Kolmogorov–Smirnov test of 0.82 (Table S1). Therefore, the log *K*s data were used for the statistical analyses instead of *K*s.

The bulk density (ρ_b) data presented a G1 coefficient equal to −0.4, which means that ρ_b followed a distribution with no heavy tails, that could be accepted to come from a normal-like distribution according to the Kolmogorov–Smirnov test ($p = 0.83$) (Table S1). Therefore, the ρ_b data could be used with no transformation for the ensuing statistical analyses.

The soil root mass fraction (w_{root}) data presented a G1 coefficient equal to 2.4, which means that this property followed a distribution with a very heavy tail to the right that significantly departed from normality according to the Kolmogorov–Smirnov test ($p = 0.027$) (Table S1). A logarithm-to-base-10 transformation failed to fulfill both the G1 and the Kolmogorov–Smirnov normality criteria, and neither satisfactorily could a square root transformation. However, this last one, i.e., $w_{root}^{1/2}$, with a G1 equal to 1.3 and a *p*-value of 0.11 for the Kolmogorov–Smirnov test (Table S1), was finally used for the statistical analyses instead of w_{root}.

The dehydrogenase activity (DHA) data presented a G1 coefficient equal to 1.4, which means that it followed a distribution with a remarkable tail to the right (Table S1). Although the non-normality was not corroborated by the Kolmogorov–Smirnov test ($p = 0.22$), the logarithm to base 10 transformation was tried, and it led to a more normal-like distribution, with a G1 coefficient equal to −0.5 and a *p*-value for the Kolmogorov–Smirnov test of 0.63 (Table S1). Therefore, the log DHA data were used for the statistical analyses instead of the DHA data.

The β-D-glucosidase activity (GLA) data presented a G1 coefficient equal to 1.3, which means that the GLA followed a distribution with a remarkable tail to the right, which, according to the Kolmogorov–Smirnov test, significantly departed from normality ($p = 0.015$) (Table S1). A logarithm-to-base-10 transformation led to a G1 equal to 0.05 that did not depart from normality ($p = 0.83$) (Table S1). Therefore, the log GLA data were used for the statistical analyses instead of the GLA data.

The soil C-CO_2 emission ($E_{C\text{-}CO2}$) data presented a G1 coefficient equal to 2.7, which means that the $E_{C\text{-}CO2}$ data followed a distribution with a very heavy tail to the right that did not fulfill the requirements for normality according to the Kolmogorov–Smirnov test ($p < 0.001$) (Table S1). A logarithm-to-base-10 transformation led to a G1 equal to −0.8 that did fulfill the requirements for normality according to the Kolmogorov–Smirnov test ($p = 0.64$) (Table S1). Therefore, the log $E_{C\text{-}CO2}$ data were used instead of the $E_{C\text{-}CO2}$ for the statistical analyses.

The soil organic carbon mass fraction (w_{SOC}) data presented a G1 coefficient equal to −0.04, which means that the w_{SOC} followed a distribution with no tails to the right or left that could be accepted as normal according to the Kolmogorov–Smirnov test ($p = 0.25$) (Table S1). Therefore, the w_{SOC} data as such were used for the statistical analyses.

The soil nitrogen mass fraction (w_N) data presented a G1 coefficient equal to 1.3, which means that w_N followed a distribution with a remarkable tail to the right that could not be accepted as coming from a normally distributed population according to the Kolmogorov–Smirnov test ($p = 0.003$) (Table S1). A logarithm-to-base-10 transformation was tried, and the log w_N data presented a G1 coefficient equal to 0.77, which according to the Kolmogorov–Smirnov test could be accepted to come from a normal-like distribution ($p = 0.03$) (Table S1). Therefore, the log w_N data were used instead of the w_N for the statistical analyses.

The soil extractable potassium (n_K) data presented a G1 coefficient equal to 3.0, which means that the n_K followed a distribution with a very heavy tail to the right that did not fulfill the requirements for normality according to the Kolmogorov–Smirnov test ($p < 0.001$) (Table S1). A logarithm-to-base-10 transformation led to a G1 equal to 1.50 that characterizes a distribution with a heavy tail to the right. However, according to the Kolmogorov–Smirnov test, the normality of this distribution was closes to normal ($p = 0.022$, Table S1), and, therefore, the log n_K data were used instead of the n_K for the statistical analyses.

The available soil phosphorus mass fraction (w_P) data presented a G1 coefficient equal to 0.41, which means that w_P has a slight tail to the right that was not heavy enough to make the w_P data depart from the normality according to the Kolmogorov–Smirnov test ($p = 0.81$) (Table S1). Therefore, the data analyses were carried out with the w_P data.

3.5. Associations among the Soil Properties

The associations among the variables were revealed by Pearson's product–moment correlation coefficients that were found to be significantly different from zero, at least at the 95% confidence level. These were 11 out of 66, i.e., 17% (Table 2).

The association between T and θ_w featured a significant r of −0.65, which was driven by the annual Mediterranean weather cycle in which, particularly, the hottest and driest season match, i.e., summer. Additionally, w_N and DHA were significantly correlated with T and θ_w, with the r between 0.42 and 0.67 in absolute value.

The w_{root} was expected to be associated with T and θ_w and with the nutrient contents and enzymatic activities. These expectations were partially fulfilled since w_{root} exhibited high correlations with θ_w, ρ_b, GLA and w_P, and w_N. However, r was only significant with w_N since the scarce data that were collected for w_{root} prevented its correlation coefficients from attaining statistical significance regardless of their high values.

Remarkably, w_{SOC} was not significantly associated with any other soil variable, featuring correlation coefficients between 0.02 and 0.27 in absolute value. Besides, neither DHA nor GLA were associated, thus suggesting that these two enzymatic activities take account of two independent aspects of the metabolism of the soil organisms. Interestingly, however, $E_{C\text{-}CO2}$ was found to be significantly associated with GLA but not DHA. Finally, another relevant and expected association was found between ρ_b and Ks, which featured an r of −0.77.

Table 2. Pearson's product-moment correlation coefficients among the soil variables [1] along with an indication of their significance at the 95% (*), 99% (**), and 99.9% (***) confidence level.

	T	θ_w	Log Ks	ρ_b	$w_{root}^{1/2}$	Log DHA	Log GLA	Log $E_{C\text{-}CO2}$	w_{SOC}	Log w_N	Log n_K
θ_w	−0.65 ***										
Log Ks	0.59	−0.28									
ρ_b	0.01	0.25	−0.77 **								
$w_{root}^{1/2}$	−0.43	0.70	−0.33	0.70							
Log DHA	0.50 ***	−0.42 **	0.02	0.09	0.38						
Log GLA	−0.04	0.23	−0.25	−0.31	0.82	0.04					
Log_ $E_{C\text{-}CO2}$	−0.11	0.36 *	0.60	−0.18	0.00	−0.09	0.44 *				
w_{SOC}	−0.03	0.12	0.19	0.02	0.20	0.27	0.18	−0.15			
Log w_N	0.67 ***	−0.59 ***	−0.25	0.36	−0.84 *	0.41 **	0.18	−0.26	0.21		
Log n_K	−0.28	0.24	0.16	−0.15	−0.21	0.21	−0.25	−0.05	0.14	−0.18	
w_P	−0.06	−0.11	−0.00	−0.09	0.65	−0.07	−0.18	−0.16	−0.07	−0.17	−0.08

[1] T: temperature; θ_w: water content; Ks: saturated hydraulic conductivity; ρ_b: fine earth (<2 mm) bulk density, w_{root}: soil root mass fraction; DHA: dehydrogenase activity; GLA: β-D-glucosidase activity; $E_{C\text{-}CO2}$: carbon dioxide emission; w_{SOM}: organic carbon mass fraction; w_N: nitrogen mass fraction, n_K: exchangeable potassium; w_P: available phosphorus mass fraction.

3.6. Soil Saturated Hydraulic Conductivity

According to the two-way ANOVA (Table 3), in general, the soil treatment did not have a significant effect on log Ks, but the measurement time did drop the Ks from spring 2019 to autumn 2020 (p = 0.03). However, since the effect of the soil treatments did not change in magnitude or direction from the first measurement to the second according to the non-significant interaction effect (p = 0.69, Table 3), the orthogonal contrasts among the soil treatments could be assessed on the basis of the two-way ANOVA results. As a consequence, it was found that between the combined bare soil and spontaneous plants, on the one hand, and fescue, on the other, there were no significant differences of log Ks at all (p = 0.28) (Figure 4), but that more remarkable differences, though still non-significant, appeared between bare soil and spontaneous plants (p = 0.12) with spontaneous on top.

Table 3. Two-way analyses of variance of the properties studied in this work [1], except for $w_{root}^{1/2}$ for which the one-way ANOVA is shown.

Property	Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	p-Value
Log Ks	Treatment	2	0.3553	0.1777	1.869	0.1846
	Measurement time	1	0.5538	0.5538	5.827	0.0273
	Treat. × Meas.	2	0.0731	0.0365	0.384	0.6866
	Residual	17	1.6157	0.095		
ρ_b	Treatment	2	0.00889	0.004443	1.461	0.2537
	Sampling time	2	0.02897	0.014487	4.763	0.0191
	Treat. × Samp.	4	0.01479	0.003698	1.216	0.3325
	Residual	22	0.06691	0.003042		
$w_{root}^{1/2}$	Treatment	2	2.30754	1.15377	17.303	0.000824
	Sampling time	–	–	–	–	–
	Treat. × Samp.	–	–	–	–	–
	Residual	9	0.6001	0.0667		

Table 3. *Cont.*

Property	Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F-Value	*p*-Value
Log *DHA*	Treatment	2	0.294	0.1472	3.184	0.0453
	Sampling time	7	4.812	0.6874	14.865	1.85×10^{-13}
	Treat. × Samp.	14	0.621	0.0443	0.959	0.4998
	Residual	108	4.995	0.0462		
Log *GLA*	Treatment	2	1.9993	0.9997	38.027	3.96×10^{-12}
	Sampling time	4	1.4132	0.3533	13.44	2.63×10^{-8}
	Treat. × Samp.	8	0.8462	0.1058	4.023	0.000512
	Residual	75	1.9716	0.0263		
$E_{C\text{-}CO2}$	Treatment	2	0.356	0.1779	1.822	0.166
	Measurement time	15	11.206	0.7471	7.652	6.29×10^{-12}
	Treat. × Meas.	30	3.694	0.1231	1.261	0.189
	Residual	127	12.399	0.0976		
w_{SOC}	Treatment	2	0.0056	0.00279	0.266	0.767
	Sampling time	9	0.6758	0.07509	7.15	2.49×10^{-8}
	Treat. × Samp.	18	0.2094	0.01163	1.108	0.353
	Residual	126	1.3232	0.0105		
Log w_N	Treatment	2	0.0024	0.0012	0.512	0.601
	Sampling time	7	0.18809	0.02687	11.471	1.02×10^{-10}
	Treat. × Samp.	14	0.05042	0.003602	1.538	0.111
	Residual	104	0.24361	0.002342		
Log n_K	Treatment	2	0.2278	0.11391	12.178	0.0000177
	Sampling time	7	0.4001	0.05716	6.11	0.00000544
	Treat. × Samp.	14	0.1858	0.01327	1.419	0.157
	Residual	104	0.9728	0.00935		
w_P	Treatment	2	370	185	0.763	0.469
	Sampling time	7	56819	8117	33.497	$<2 \times 10^{-16}$
	Treat. × Samp.	14	49095	3507	14.472	$<2 \times 10^{-16}$
	Residual	104	25201	242		

[1] *T*: temperature; θ_w: water content; *Ks*: saturated hydraulic conductivity; ρ_b: fine earth (<2 mm) bulk density, w_{root}: soil root mass fraction; DHA: dehydrogenase activity; GLA: β-D-glucosidase activity; $E_{C\text{-}CO2}$: carbon dioxide emission; w_{SOM}: organic carbon mass fraction; w_N: nitrogen mass fraction, n_K: exchangeable potassium; w_P: available phosphorus mass fraction.

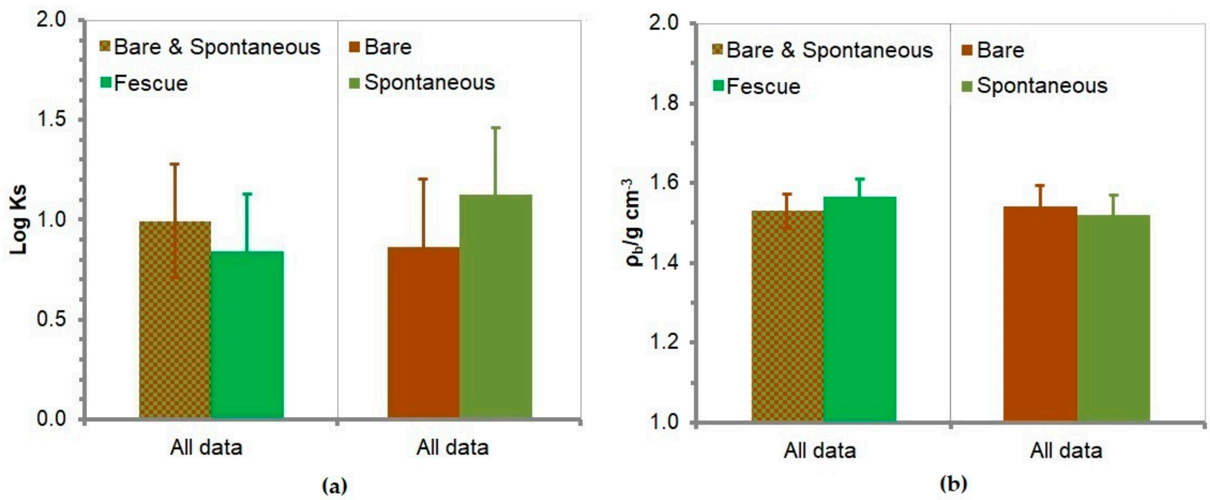

Figure 4. (**a**) Logarithm to base 10 of the soil surface saturated hydraulic conductivity (*Ks*) in the different treatments alongside the 95% confidence interval for the means according to the orthogonal contrasts based on the two-way ANOVA results; (**b**) bulk density (ρ_b) at 0–5 cm in the different treatments alongside the 95% confidence interval for the means according to the orthogonal contrasts based on the two-way ANOVA results.

3.7. Soil Bulk Density

According to the two-way ANOVA (Table 3), in general, the soil treatment did not have any significant effect on ρ_b, but again the sampling time did (p = 0.02). In addition, since, again, there were no significant changes in the magnitude or direction of the effect of the treatments on ρ_b from one sampling to the other according to the non-significant interaction (p = 0.33), the orthogonal contrasts were subsequently performed using all data. As a consequence, it was found that the combined bare and spontaneous treatments featured somewhat lower ρ_b than fescue, though non-significantly (p = 0.10) (Figure 4). Regarding the differences of ρ_b between bare and spontaneous, they were non-significant at all (p = 0.39). Note that these differences of ρ_b among treatments inversely reflect the ones obtained for log Ks (Figure 4). This result reveals the association between both physical fertility properties, which already showed up in the correlation analysis (Table 2).

3.8. Soil Root Mass Fraction

According to the ANOVA (Table 3), there were very significant differences among the treatments ($p < 0.001$). Then, since only data for one measurement time were available, the orthogonal contrasts were readily assessed. As a consequence, it was found that the combined bare and spontaneous treatments featured significantly lower soil root mass than fescue ($p < 0.001$) and that there were no significant differences between bare soil and spontaneous plants (p = 0.15) (Figure 5).

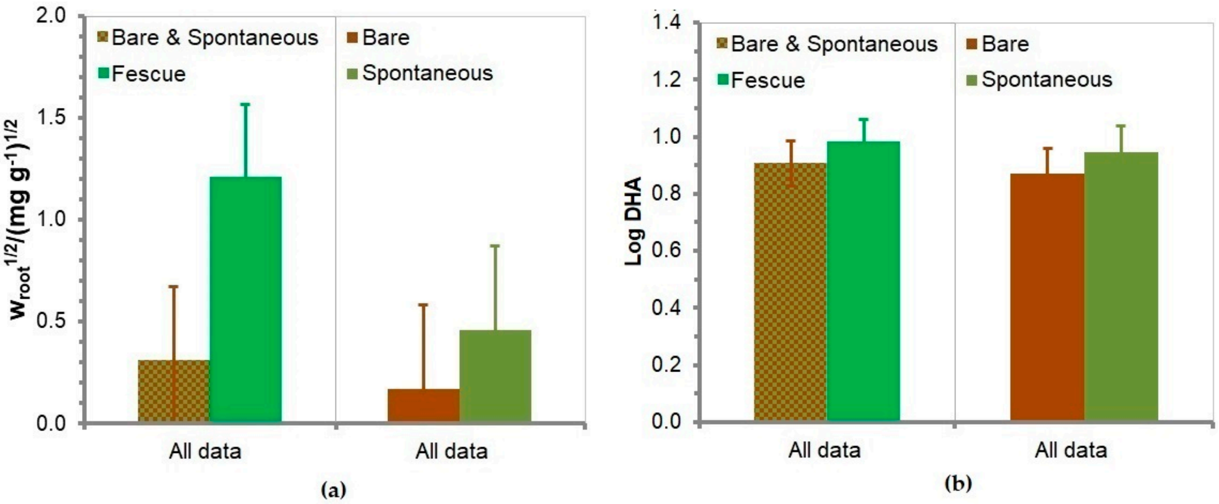

Figure 5. (**a**) Square root of the soil root mass fraction ($w_{root}^{1/2}$) at 0–5 cm in the different treatments alongside the 95% confidence interval for the means according to the orthogonal contrasts based on the two-way ANOVA results; (**b**) logarithm to base 10 of the dehydrogenase activity (DHA) at 0–20 cm in the different treatments alongside the 95% confidence interval for the means according to the orthogonal contrasts based on the two-way ANOVA results.

3.9. Soil Dehydrogenase Activity

According to the two-way ANOVA (Table 3), the most significant differences were among the different seasons ($p < 0.001$) and then among the soil treatments (p = 0.045). However, since the effect of the treatments did not change in magnitude or direction from one season to the other according to the non-significant interaction effect (p = 0.50), the orthogonal contrasts among the soil treatments were assessed on the basis of all data. As a consequence, it was found that between the combined bare soil and spontaneous plants, on the one hand, and fescue, on the other, there were no significant differences in DHA for a narrow margin (p = 0.06) and that there were even fewer differences between bare soil and spontaneous plants (p = 0.10) (Figure 5). Note that these differences in DHA among treatments smoothly reflect the ones obtained for the w_{root} (Figure 5), which is in accordance with the dim association between DHA and w_{root}, as seen in the correlation analysis (Table 2).

3.10. Soil β-D-Glucosidase Activity

According to the two-way ANOVA (Table 3), there were highly significant differences among the different soil treatments ($p < 0.001$) and sampling times ($p < 0.001$). Additionally, the effects of the soil treatments changed from one sampling to the other ($p < 0.001$). According to this significant interaction between the soil treatment and sampling time, five one-way ANOVAs and five batches of orthogonal contrasts, one per sampling time, were carried out. As a consequence, it was found that the combined bare and spontaneous treatments featured significantly lower GLA than fescue ($p < 0.05$) three out of five times. Conversely, there were non-significant differences in GLA between the bare soil and spontaneous plants (Figure 6).

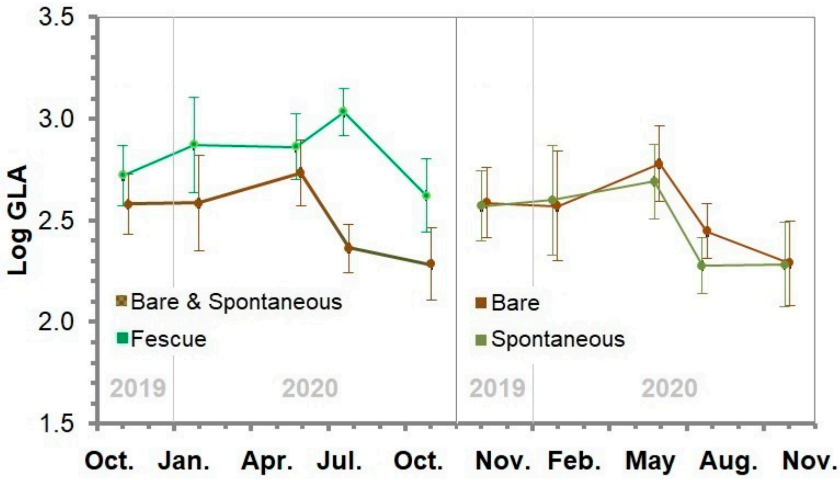

Figure 6. Logarithm to base 10 of the β-D-glucosidase activity (GLA) at 0–20 cm in the different treatments throughout five sampling dates during the monitoring time alongside the respective 95% confidence intervals according to the orthogonal contrasts based on the one-way ANOVAs results.

3.11. Soil Carbon Dioxide Emission

According to the two-way ANOVA (Table 3), there were significant differences among the measurement times ($p < 0.001$) but not among the treatments ($p = 0.17$), and the measurement time effects neither changed in magnitude nor direction from one treatment to the other according to the non-significant interaction effect ($p = 0.19$). According to this negligible interaction effect, and regardless of the non-significant treatment effects, the orthogonal contrasts among the soil treatments were assessed. As a consequence, it was found that between the combined bare soil and spontaneous plants, on the one hand, and fescue, on the other, there were no significant differences in $E_{C\text{-}CO2}$ at all ($p = 0.82$) (Figure 7). However, the $E_{C\text{-}CO2}$ in the spontaneous plants' soil was higher than in the bare soil, though non-significantly by a very narrow margin ($p = 0.06$) (Figure 7).

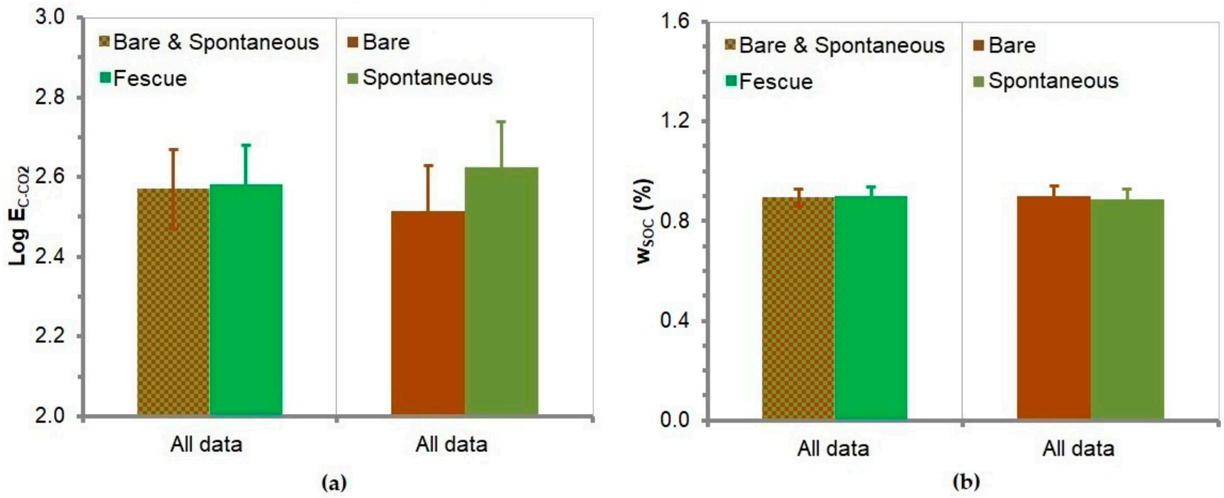

Figure 7. (**a**) logarithm to base 10 of the soil carbon dioxide emission ($E_{C\text{-}CO2}$) in the different treatments alongside the 95% confidence interval for the means according to the orthogonal contrasts based on the two-way ANOVA results; (**b**) soil organic carbon mass fraction (w_{SOC}) at 0–20 cm in the different treatments alongside the 95% confidence interval for the means according to the orthogonal contrasts based on the two-way ANOVA results.

3.12. Soil Organic Carbon

According to the two-way ANOVA (Table 3), there were highly significant differences among the different sampling times ($p < 0.001$) but not among the soil treatments ($p < 0.77$); additionally, the effect of the sampling time did not change from one treatment to the other ($p = 0.35$). According to this negligible interaction effect, and regardless of the non-significant treatment effects, the orthogonal contrasts among the soil treatments were assessed. As a consequence, it was found that the combined bare and spontaneous treatments featured the same w_{SOC} as the fescue ($p = 0.68$) and that no w_{SOC} differences existed between bare and spontaneous ($p = 0.55$) (Figure 7). Notwithstanding, some effects throughout time were discovered that eventually led to higher w_{SOC} (Figure 8).

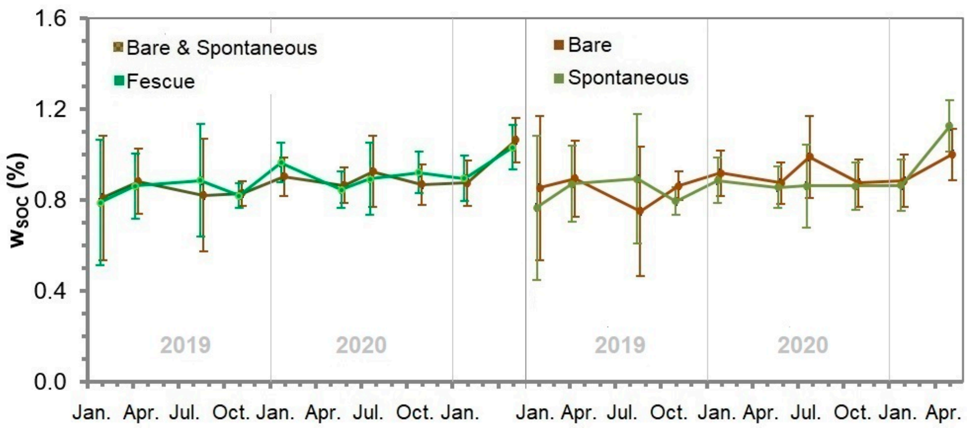

Figure 8. Soil organic carbon mass fraction at 0–20 cm in the different treatments throughout all sampling dates during the monitoring time alongside the respective 95% confidence intervals according to the orthogonal contrasts based on the one-way ANOVAs results.

3.13. Soil Nitrogen

According to the two-way ANOVA (Table 3), there were highly significant differences among the different sampling times ($p < 0.001$) but not among the soil treatments ($p = 0.60$). This strong dependence of w_N upon time may be driven by the root cycle throughout the year, as suggested by the high and significant correlations among ${w_{root}}^{1/2}$, the weather cycle variables, i.e., T and θ_w, and w_N (Table 2). Additionally, on the basis of the non-significant interaction (p = 0.11) between the treatments and sampling times found in the two-way ANOVA (Table 3), it was shown that the magnitude or direction of the treatments' effects did not change from one sampling time to the other. According to this negligible interaction, the orthogonal contrasts among the soil treatments were assessed to graphically put forth the absence of significant differences between all three treatments (Figure 9).

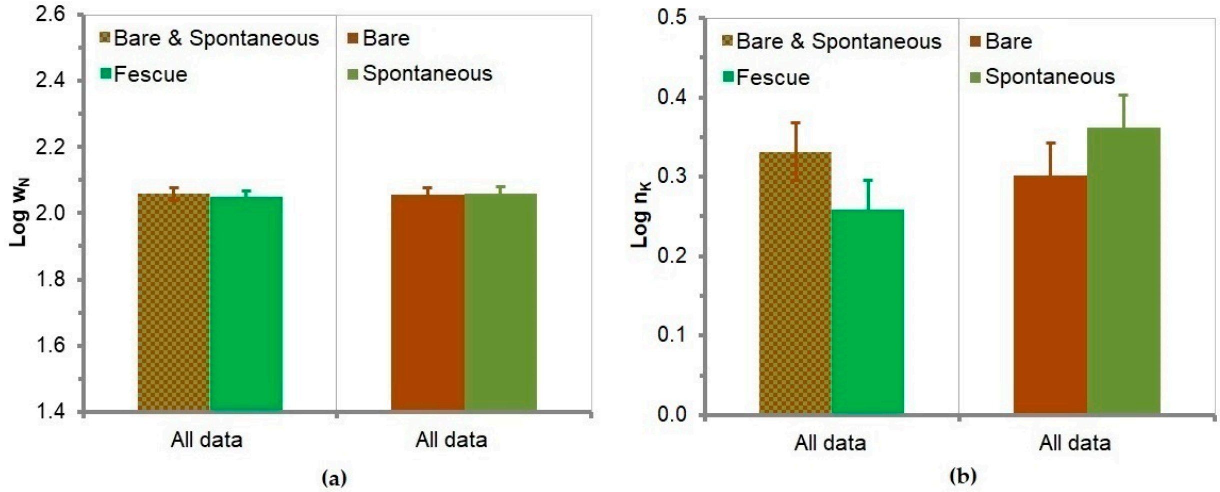

Figure 9. (**a**) logarithm to base 10 of the soil nitrogen mass fraction (w_N) at 0–20 cm in the different treatments alongside the 95% confidence interval for the means according to the orthogonal contrasts based on the two-way ANOVA results; (**b**) logarithm to base 10 of the soil exchangeable potassium concentration (n_K) at 0–20 cm in the different treatments alongside the 95% confidence interval for the means according to the orthogonal contrasts based on the two-way ANOVA results.

Related to soil organic carbon and nitrogen, there is the soil carbon to nitrogen ratio, i.e., w_{SOC}/w_N or C/N for short, which is presented in Figure 10. As can be seen, the fescue treatment tends to present higher C/N than the combined bare soil and spontaneous plants one, whereas the spontaneous plants' treatment tends to feature lower C/N than the bare one. Interestingly, the C/N under the spontaneous plant treatment drops faster from winter to summer than the others, which would be in accordance with the higher mean $E_{C\text{-}CO2}$ under this treatment (Figure 7) thus suggesting a higher biological activity in the spontaneous plants' soil.

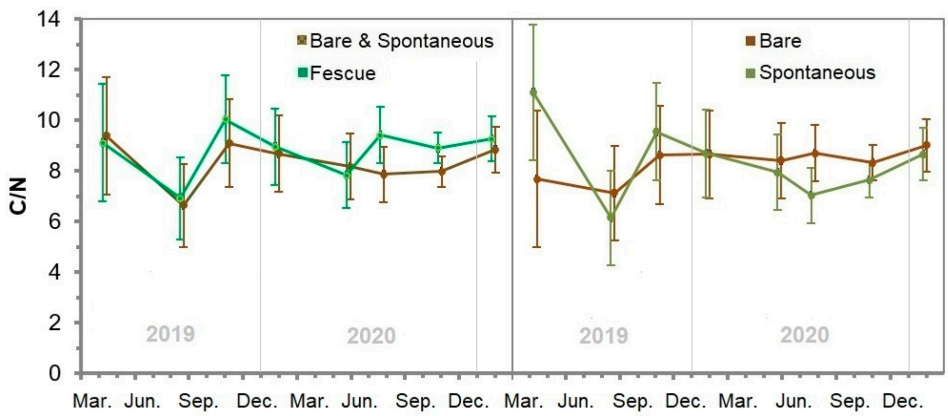

Figure 10. Soil carbon to nitrogen ratio, i.e., w_{SOC}/w_N (C/N), at 0–20 cm in the different treatments throughout the monitoring time alongside the 95% confidence interval for the means according to the orthogonal contrasts based on the one-way ANOVA results for each sampling time.

3.14. Soil Potassium

According to the two-way ANOVA (Table 3), there were highly significant differences among the different sampling times ($p < 0.001$) and also among the soil treatments ($p < 0.001$). However, the magnitude or direction of the treatments' effects did not change from one sampling time to the other on the basis of the non-significant interaction ($p = 0.16$). In accordance with this non-significant interaction, the orthogonal contrasts among the soil treatments were assessed. As a consequence, it was found that the combined bare and spontaneous treatments featured significantly higher n_K than the fescue one ($p < 0.001$). In addition, the spontaneous plants' soil presented significantly more n_K than the bare soil ($p = 0.004$) (Figure 9).

3.15. Soil Phosphorus

According to the two-way ANOVA (Table 3), there were highly significant differences among the different sampling times ($p < 0.001$) but not among the soil treatments ($p = 0.47$). However, since the magnitude or the direction of the treatments' effects changed from one sampling to the other on the basis of the significant interaction ($p < 0.001$), eight one-way ANOVAs and eight batches of orthogonal contrasts were carried out to find if specific differences could be found. As a consequence, it was found that, in general, there were no differences between the combined bare and spontaneous treatments, on the one hand, and fescue, on the other, but that, interestingly, the spontaneous plants' soil showed significantly lower available phosphorus than the bare soil in three out of the four last sampling times (Figure 11).

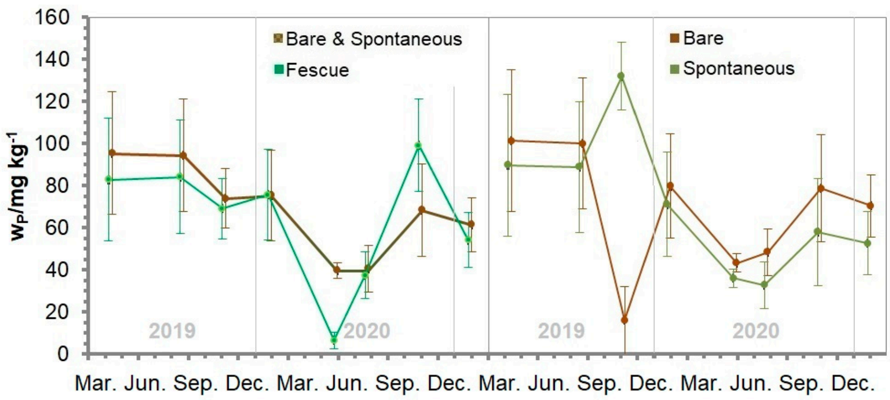

Figure 11. Soil available phosphorus (w_P) at 0–20 cm in the different treatments throughout eight sampling dates during the monitoring time alongside the respective 95% confidence intervals according to the orthogonal contrasts based on the one-way ANOVAs results.

4. Discussion

4.1. Soil Characteristics

The soil in the study site has developed on a Middle Pleistocene marl runoff blanket [44,45]. Therefore, the soil in the study site is quite young, which is revealed by the fact that only an incipient decarbonation can be observed in the shallower 20 cm layer (Table 1). In addition, according to its bulk density, the topsoil was moderately compacted, featuring a pore space between 36 and 40% at the beginning of the monitoring. This compaction is a disturbance condition typically shared by most Valencian citrus plantations because of the agricultural vehicle traffic [12], leading to the low physical fertility of the inter-row soils.

The soil organic matter was also low according to the amount of clay and calcium carbonate equivalent following Rémy and Marin-Laflèche [46]. The optimum w_{SOC} in the shallower 20 cm layer would be over 4.1%, according to these authors. Consequently, the soil in the study site shows damaged chemical fertility. However, it presents a potential carbon sequestration capacity of 1.5% of w_{SOC}, which in case it was fulfilled, the w_{SOC} would increase by 163%. Therefore, assuming a 4‰ annual rate of reasonable accumulation of SOM in agricultural soils following conservative practices [47], this increase of 163% may be achieved in 65 years.

4.2. Soil Fertility Drivers: Temperature and Water Content

Soil temperature and water content are the main drivers of soil fertility because they strongly regulate the vital functions of plants and soil organisms [48,49]. In this work, this was reflected by the significant correlations of T and θ_w with some biological activity indicators and nutrient contents (Table 2). Therefore, it is important to understand how the differences in the average daily topsoil temperature between the treatments depend on the magnitude of the energy inputs and outputs alongside the topsoil heat capacity. The topsoil temperature variation down to a depth of d can be assessed from (Appendix A):

$$\Delta T = \frac{R_s(1-\alpha) - R_{lw} - h_v ET - S - J_H}{(\rho_b C_s + \rho_w \theta_w C_w)d} \tag{8}$$

where the main warming-up ($\Delta T > 0$) factor is the incident solar radiation (R_s). Conversely, the main cooling-down ($\Delta T < 0$) factor is the reflected solar radiation, i.e., α R_s, the long-wave net radiation (R_{lw}), heat convection as latent heat, i.e., h_v ET, sensible heat (S), and the heat conduction towards the subsoil (J_H). In addition to these, there is the heat-buffering factor; this is the topsoil heat capacity in the denominator of Equation (8).

The soil temperature differences between the treatments may be understood, at least qualitatively, from Equation (8) by additionally considering that the average T values mostly reflected the maximum T values and not the minimum ones, which presented no variations between the treatments (Figure 2). The treatment that lowered the topsoil temperature the most was fescue. This is in accordance with Pradel and Pieri [50], who also observed lower soil temperatures under grass cover in comparison to plowing. Several processes may cause this T-lowering effect of fescue. First, there is the dimming of the warming-up factor, i.e., the solar radiation balance expressed by R_s $(1 - \alpha)$ in Eq. 8. Additionally, there is the increase in the cooling and heat-buffering factors, i.e., h_v ET and ρ_b C_s + ρ_w θ_w C_w. Finally, there is the heat conduction factor (J_H), as shown by Pradel and Pieri [50].

Which of these aforementioned effects dominate may be discovered by assessing their respective relative importance. Therefore, first, the soil's surface albedo was estimated from its corresponding color value in the Munsell Color System [51] by using the relationship calibrated by Post et al. [52]. The soil surface color in the study site was visually estimated to be 7.5YR 5/5.5 in the Munsell Color System, thus giving an albedo of 23%, whereas grass covers present an albedo ranging between 20 and 27% [53], featuring an acceptable average of 23% [54]. Therefore, all three treatments can be regarded as having presented the same albedo, and, consequently, the albedo effect cannot explain why fescue decreased the topsoil temperature more than both the bare and spontaneous plants treatments. On the contrary, higher evaporation from the grass cover may explain the temperature decrease regarding the control due to the loss of latent heat through water transpiration, i.e., the h_v ET. Note that the consequent decrease in the topsoil water content because of higher evapotranspiration in the fescue could decrease its heat capacity, thus fostering higher T, but also decrease its heat conduction, thus fostering lower T. Since soil T was not measured at different depths, these effects cannot be further disentangled. In the case of the spontaneous plants, the scarce covering of 10–20% during most of the year did not likely give rise to appreciable evapotranspiration differences in comparison to the bare treatment, and thus the T differences between the spontaneous and bare treatments did not consistently appear.

The average topsoil water content depends on the water inputs and outputs and, additionally, on its water holding capacity, which depends, in turn, on the texture and bulk density. Based on a simplified water balance down to a depth d, the following equation holds for assessing the topsoil water content ($\Delta\theta_w$) differences between the inter-row soils subjected to different water inputs and outputs:

$$\Delta\theta_w = R - ET - P \tag{9}$$

where R is the rainfall infiltration, ET is the evapotranspiration, and P is the percolation to the underlying soil layers.

In accordance with this simplified water balance (Equation (9)), the main wetting factor ($\Delta\theta_w > 0$) is R. Conversely, the main drying ($\Delta\theta_w < 0$) factors are ET and P. Therefore, from Equation (8), the differences in the topsoil water content between the treatments can be explained, at least qualitatively.

Although fescue left the topsoil drier than the other treatments in summer, on average, fescue increased the water content by the most. However, fescue also featured a somewhat higher ρ_b and lower Ks than the other two treatments and, furthermore, it was the treatment with higher ET, in accordance with the lower temperature of the topsoil. Therefore, the topsoil under fescue lost more water by ET and did not develop the extra macroporosity that would have been needed to ease rainfall infiltration. Accordingly, the higher annual average, θ_w, cannot be credited to a lower water loss through ET and neither to a higher rainfall infiltration rate. On the contrary, the higher annual average, θ_w, may be attributed (i) to a lower loss of water through percolation and (ii) to an overall higher amount of infiltrated water. In the first case, a lower Ks in the topsoil can not only slow down rainfall infiltration but also water percolation to the underlying soil layers, thus increasing the annual average, θ_w, whether the second overcomes the first. In the second case, it can be hypothesized that the grass increased the effective rainfall by shielding the fallen water from solar radiation and wind. This way, the evaporation rate of the soil water slowed down; it had more time left to infiltrate into the soil, and the effect of the infiltration rate (Ks) lost relevance.

Interestingly, under the spontaneous plants, the soil presented somewhat lower ρ_b and higher Ks. It seems that this treatment increased macroporosity sufficiently to rise Ks. The microporosity increases under spontaneous plants in comparison to the seeded one, which was likely a consequence of the different ecology of one plant compared to the other, as is discussed next.

4.3. Soil Organic Carbon

No organic materials were intentionally incorporated into the soil in any treatment because tillage was completely avoided in all three. Therefore, the most important contribution to enhancing the SOC in all treatments was the rhizodeposition from the plants' roots. Regarding this, fescue was the treatment that featured the highest topsoil root mass fraction. Then, the spontaneous treatment presented the second-most root mass fraction. However, under the spontaneous plants, the topsoil root mass fraction was not high enough to stand out significantly over the bare treatment. Even more interestingly, regardless of the magnitude and differences in the root mass fraction among the treatments, no differences in SOC were consistently found between them. Notwithstanding, differences in SOC increase during the monitoring time were found. Specifically, under the spontaneous plants, SOC increased the highest from the first until the last sampling (+47%), whereas the other two treatments led to lower increases: fescue (+30%) and bare (+17%) (Figure 8).

The higher root mass fraction under fescue supports the likely higher ET under this treatment, as the low average annual T and low summer θ_w suggested (Figure 3). The higher root mass fraction under fescue is, moreover, able to explain the lower topsoil exchangeable potassium that was observed under this treatment, which was absorbed by the fescue. Interestingly, the contrary was noticed under the spontaneous plants, which, somewhat surprisingly, were able to maintain exchangeable potassium not only higher than the fescue but also higher than the bare treatment. This significantly high exchangeable potassium under spontaneous plants regarding the bare soil may be caused by the ability of these native plants to foster an indigenous K-solubilizing microorganism community [55], which may have weathered the soil hydrated micas (illites) and feldspars and thus have mobilized some K^+ ions from the crystal lattices of these major minerals in the soils of the Valencian province. Then, the high soil exchangeable potassium under the spontaneous plants regarding the fescue reflects that this grass, perhaps due to its allochthonous nature, does not foster an indigenous K-solubilizing microorganisms in the same way as spontaneous plants do. A similar effect was observed in the inter-rows of a coffee plantation where exchangeable potassium, magnesium, and calcium increased in the topsoil more below the spontaneous plants than below a cover crop [56]. Therefore, spontaneous plants, due to their own unforced nature, adapt better to the harsh environmental conditions in the inter-rows. The good adaptation of false barley to the high year-to-year rainfall variability in semi-arid Mediterranean areas has already been shown [57], and this adaptation ability may also appear in the soil exchangeable potassium, as is further discussed next.

Under the Mediterranean climate conditions of the study site, spring is rainy, and summer is dry (Figure 3). Therefore, during early to mid-spring, both fescue and spontaneous plants grow and absorb potassium from the soil. Then, as spring passes by and summer comes, fescue dries but a relevant part of its material does not decay, and hence some potassium is preserved in its dry tissues, and, as a consequence, it does not return to the soil. Contrary to this, the spontaneous plants dry, and their tissues extensively decay, thus returning the potassium they absorbed in early spring to the soil. This fits the pronounced soil cover change from spring to summer of 50–90% to 10–20% under spontaneous plants, which is mainly led by the false barley life cycle. Conversely, the magnitude of the cover change for fescue fluctuated much less, specifically from 80% to 60% at most. Note that the almost significantly higher soil CO_2 emission rate under the spontaneous plants fits the higher decaying activity under this treatment, which stands up over the bare soil and, particularly, over the fescue. The faster decomposition rate of spontaneous ground covers in comparison to seeded ones has also been found in coffee plantations [58]. Furthermore, the specific difference in the soil CO_2 emissions between the spontaneous plants and fescue in the present study, indicates that under the spontaneous plants, the CO_2 emissions came more from heterotrophic than from autotrophic respiration. In this regard, note that the contribution from the autotrophic respiration under the spontaneous plants must be much less than under fescue on average during the season, as the remarkable differences in ground-cover changes along the year suggest.

Regarding the other major nutrients, the exchangeable potassium differences among the treatments were not replicated either by phosphorus or nitrogen. In the phosphorus case, no differences between the treatments were clearly observed. This may be because the K-solubilizing microorganism community is not able to weather the soil P minerals, e.g., apatite, as much as the K minerals or either the P-Olsen extractant is not able to reveal the differences in the available soil P among treatments [59]. In the nitrogen case, the differences between the treatments were not observed. Nitrogen was not provided in the form of either mineral or organic fertilizers to the inter-rows, and neither by symbiotic-living bacteria, since legumes were absent. Therefore, the only way nitrogen could have reached the soil under these conditions would have been through aerial wet or dry deposition and also by means of free-living nitrogen-fixing microorganisms. Both processes seem to have been hardly relevant in the study site, and, more interestingly, if present, they affected all the treatments to the same extent. Additionally, the average C/N ratio in the inter-row soils presented values between 6 and 11 along the season, with the spontaneous plants presenting the highest of these in early spring and the lowest in mid-summer. A C/N ratio of 6 is very low and typical of the last stages of soil organic matter evolution. The rapid transition from 11 to 6 under the spontaneous plants' cover further supports the high rate of SOM mineralization under these conditions. Evidence indicates that for SOC build-up, nitrogen must be provided to the soil system, either through N-fixing organisms or by N-fertilizers [60–63], and that the absence of nitrogen supply to the soil eventually leads to SOC loss and land degradation [64,65]. Therefore, the absence of any nitrogen supply to the inter-row soil under both herbaceous covers can explain why these consistently exhibited the same SOC as the bare soil.

In the study site, the development of spontaneous plants triggered higher biological activity than the other treatments. This was reflected by the dehydrogenase activity, which was comparable to under fescue (Figure 5), by the CO_2 emission, which was the highest

(Figure 7), and by the C/N ratio, which changed the fastest in addition to attaining the lowest eventual value (Figure 10), but not by the β-D-glucosidase activity (Figure 6). This higher biological activity certainly included some soil macrofauna blooming, which fed on the plant debris and drilled burrows into the soil, which can explain the comparatively higher hydraulic conductivity and the lower bulk density of the spontaneous plants' soil regarding the other two. The boost in the soil macrofauna populations, particularly earthworms, and the subsequent increase in macroporosity is commonplace in the transition to no-tillage, as reviewed by Kay and VandenBygaart [66]. Although the spontaneous ground cover had positive effects on the physical fertility, this amelioration was barely reflected in the SOC build-up, likely because of the scarce nitrogen. According to Novara et al. [67], at least five years are needed in this kind of Mediterranean citrus orchards for changes in SOC to appear. When soil nutrients are scarce, however, they may be delayed longer or not take place at all.

Although the inter-row soil in the study site was very physically degraded at the onset of the treatments and, moreover, the time throughout, to which the herbaceous covers were applied, is not too long, some practical recommendations can be already drawn. First, the positive behavior of the spontaneous ground cover regarding the seeded one in the study site makes the former the recommendable choice. Second, the soil management of the spontaneous cover should go beyond the mere "let it grow and cut from time to time" in order to enhance the inter-row SOC. It may be the annual winter application of N-rich amendments on the surface with minimum to no-tillage or, better, the fostering of N-fixing soil organisms. The effects of these recommendations should be investigated.

5. Conclusions

The changes in the topsoil energy and water balances, and not less importantly, the ecological characteristics of the seeded and spontaneous plants, affected the physical, chemical, and biological soil fertility in the inter-rows of the citrus orchard featured in this investigation. The fescue ground cover boosted biological activity, but no improvements were reflected by the physical fertility, which was kept essentially equal to the bare soil treatment. Conversely, though the spontaneous plants' effects on the topsoil temperature and water content were scarcely distinguishable from the bare soil and, moreover, they contributed fewer rhizodepositions than fescue, they also increased the enzymatic activities and, additionally ameliorated the chemical fertility, particularly the exchangeable potassium. In addition, they enhanced physical fertility. Regarding this, presumably, the burrows drilled by the development of a macrofauna community, which effectively fed on the spontaneous plants' debris, acted as vectors. The topsoil organic carbon slightly increased in all of the grass ground covers during the two-year monitoring, but no significant changes among the treatments were found overall. This may be due to the scarce soil nitrogen content, which is likely constraining primary productivity in the inter-rows, hence limiting topsoil organic carbon increase. In this citrus orchard, the seeded ground cover does not seem to contribute any benefit, rather the opposite, over the spontaneous plants. To enhance the effects of the spontaneous ground cover, an annual surface application of organic nitrogen-rich materials or the fostering of soil N-fixing organisms would be recommended alongside the "let it grow and cut from time to time" management method. More research is needed to know the possibilities for SOC enhancement of these recommendations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments9120151/s1, Table S1: Statistical summary of the properties studied in this work.

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Appendix A

On the basis of the classical soil energy balance equation [68], the following equation for assessing the soil energy differences (ΔH) leading to temperature changes throughout one time span can be suggested:

$$\Delta H = R_s\,(1-\alpha) - R_{lw} - h_v\,ET - S - J_H \tag{A1}$$

where R_s is the incident solar radiation, both direct and diffuse short-wave, α is the surface albedo, R_{lw} is the net soil long-wave radiation, h_v is the latent heat of water evaporation, ET is the evapotranspiration, S is the combined heat conduction and convection to the atmosphere as a sensible heat, and J_H is the heat transfer to the underlying soil layers. Second, the soil heat capacity is provided by Jury and Horton [68] as follows:

$$C = \rho_b\,C_s + \rho_w\,\theta_w\,C_w \tag{A2}$$

where θ_w is the soil water content, ρ_w the water density, and C_s and C_w are the heat capacities of, respectively, the soil solids and water. Then, by combining both equations, the soil temperature variation down to a depth of d can be assessed as follows:

$$\Delta T = \frac{\Delta H}{Cd} = \frac{R_s(1-\alpha) - R_{lw} - h_v ET - S - J_H}{(\rho_b C_s + \rho_w \theta_w C_w)d} \tag{A3}$$

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