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Green Manuring and Irrigation Strategies Positively Influence the Soil Characteristics and Yield of Coriander (*Coriandrum sativum* L.) Crop under Salinity Stress

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Abstract: This study shows the influence of soil salinity and irrigation dose on biomass production and its impact on some edaphic indicators and functions. For this purpose, an experiment was carried out in two representative soils from Murcia (SE Spain), one slightly saline (LS) and the other saline (S), where an oat–vetch green manure was intercalated between a spinach cycle and a coriander cycle; the latter being subjected to three different irrigation doses (deficient, optimum and surplus). Rapid response indicators (ECext, cations and anions in the soil solution, etc.) were monitored, as well as the material balances, in particular C and salts. Green manure and crop residues increased soil OC by 12.5% and reduced Na^+ and $NO_3{}^-$ concentrations. Total biomass production was also affected by salinity, both in oat–vetch, 35.9 and 31. 9 tm ha^{-1} in LS and S, respectively, and in the coriander crop, where the irrigation dose was decisive, obtaining around 29 tm ha^{-1} with the optimum and surplus doses and significantly lower amounts with the deficit dose: 20.4 tm ha^{-1} in LSD and 14. 0 in SD. Therefore, it is necessary to adjust the irrigation doses, since deficit irrigation significantly reduces production and the surplus does not lead to an increase with respect to the optimum, while also causing ions to leach to depth horizons, as is the case for $NO_3{}^-$, Cl^- and Na^+, with the consequent risk of contaminating the water table.

Keywords: sustainable management; coriander; CO_2 sink; saline soils; irrigation dose

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1. Introduction

The sustainable development objectives established by the UN General Assembly (UNGA, 2015) [1] recognize that the greatest challenge facing the world today is the eradication of poverty, which is why the 2030 Agenda has established 17 SDGs and 169 targets covering, among other areas, the preservation of nature and the rational use of its resources. In this context, agriculture cannot remain on the sidelines, especially because it has probably been the activity that has most degraded and polluted the soil and its associated ecosystems over the last 100 years [2]. Thus, in arid and semi-arid areas such as those in this study, 30% of irrigated agricultural soils have been rapidly degraded due to the excessive application of inorganic fertilizers [3], inadequate tillage [4,5] and the use of water for irrigation, either because of its poor quality or inappropriate doses [6,7]. All of this has led to episodes of nitrate pollution, soil erosion and desertification, eutrophication, etc. [8,9], degradation processes that can be mitigated or eliminated through sustainable agricultural management practices [10] to ensure the economic viability of agricultural enterprises and the conservation of natural resources, including soil and water [11].

In this regard, special mention should be made of the current agri-environmental problems in the Campo de Cartagena area (Murcia, Spain), where studies carried out by several authors [12–14] have demonstrated alterations in the properties of the soils in this region caused by the inadequate management of natural resources and of soil and irrigation water. The result of this inadequacy is evident in the degradation of the structure, decrease in porosity and erosion resistance [15] and increased salinity of the soils, as well as the loss of their ecological functionality, such as their ability to sequester greenhouse gases [16]. Physical and chemical degradation stages have also been observed in the soil and inland and marine waters of the Campo de Cartagena area, with consequent social alarm. This situation has worsened in recent years [17].

The ecological situation in Campo de Cartagena is characterized by the complex interaction of agricultural, environmental and water resource management issues, which require sustainable solutions to ensure the overall well-being of the region. There are no simple solutions to these problems, but we should not rule out other forms of agricultural management that are more respectful of the environment. This is why the European Union has defined a Strategic Plan in the regulatory framework of the Common Agricultural Policy 2023–2027 (CAP 2023–2027) where, in line with the 2030 Agenda, a relevant role is given to sustainable agricultural practices and the preservation of natural resources, including soil and water (Regulation (EU) 2021/2015), all to promote the transition to so-called "resilient agroecosystems" and promote the role of soil as a carbon sink [18] in these resilient systems; the role of soil in the carbon cycle is very important, as it stores about 75% of the total CO_2 captured in terrestrial media [19]. This aspect has been extensively studied in soils from humid climates, but not in those from Mediterranean climates, where, according to Huang et al. [20], the soils have a high potential to fix atmospheric carbon through the application of appropriate agricultural practices, which contribute positively to their ecological function as carbon sinks and minimize degradation [21].

As a result, it is becoming increasingly common for crop scheduling, particularly fertilization, including the addition of organic amendments, irrigation water management and phytosanitary treatments, to be carried out considering environmental factors, with the aim of increasing their overall efficiency. In this sense, it has been shown that proper crop management increases the accumulation of organic carbon (OC) in the soil and agricultural productivity [4,22,23], preserving a healthy ecological environment [24]. On the other hand, crop rotation and green manuring are strategies widely advocated for in agroecological models and are economically incentivized in the CAP Strategic Plan 2023–2027 (Regulation (EU) 202172015), as they affect the dynamics of nutrients in the soil [25], the chemistry of depth horizons [26] and, in general, soil quality. Likewise, the quality and quantity of water used in irrigation can induce changes in some of its properties; for example, when soil salinity is high, salinization processes are triggered that limit and even prevent the agricultural use of this resource, as has been widely described by several authors [27,28]. In addition, as carbonate waters, these irrigation water inputs are the main abiotic drivers of carbon stock changes [29,30].

Taking into account the problems described above, an investigation has been designed starting with green manuring, based on oats (*Avena sativa* L.) and vetch (*Vicia sativa* L.), immediately after a spinach (*Spinacia oleracea* L.) crop, the results of which have already been published [31]. After the green manuring stage, a coriander (*Coriandrum sativum* L.) crop was planted in a soil with different salinity levels and subjected to different irrigation doses. Coriander was chosen because it is a crop whose nutritional requirements are complementary to the preceding crop (spinach) and because it is widely demanded in the European market. Coriander is an aromatic herb with multiple health benefits. It contains anti-inflammatory, antiseptic and diuretic properties. It is also rich in antioxidants, vitamins C, K and A and minerals such as manganese, potassium, copper, iron and calcium [32]. Coriander can help lower blood sugar, benefit heart health, protect brain health, promote digestion and intestinal health and act as a powerful anticholesterol ally [33].

The hypotheses that justified this study were the following:

The current models of agricultural soil management in Campo de Cartagena are not sustainable, so other agricultural practices that are less aggressive towards the agricultural ecosystems should be implemented, such as green manuring, crop rotation and organic amendments, as well as the optimization of irrigation and fertilization doses. It is to be expected that this agronomic management will improve soil quality and, therefore, the indicators that define it, especially those of rapid response (EC_{ext}, EC of lysimeters, Cl^-, NO_3^-, etc.), as well as its functionality, particularly its role as a carbon sink. The second hypothesis is that the concentration of soluble salts in the soil affects the availability of nutrients and, therefore, the uptake capacity of plants and consequent biomass production. The third hypothesis is that the excessive supply of nutrients in the form of mineral fertilizer and excess irrigation doses can produce lateral nutrient flushing and/or leaching of nutrients into subway aquifers, which may be responsible for the eutrophication processes in nearby river and lake ecosystems.

The objectives of this study were as follows:

To study the agroenvironmental repercussions of green manuring as a sustainable agricultural practice in the management of vegetable crops under semi-arid climatic conditions, as well as the influence of soil salinity and irrigation dose on the behavior of some edaphic indicators, on biomass production and on the cycles of matter that affect the soil's functions as a carbon sink or source.

With regards to the innovative aspects of our study, it is worth highlighting the experimental model carried out in a farm dedicated to the cultivation of vegetables in the open air, where different sustainable agriculture techniques have been applied in line with the recommendations given by the EU in its CAP for the period 2023–2027. Therefore, the results obtained can contribute to mitigating the degradation of the agroecosystems of the region and can be transferred to the production sector of the area, which is strongly affected by the degradation of soil and water, partly attributable to the intensive agricultural activity of the last 40 years.

2. Materials and Methods

The study was carried out in an experimental plot located in Campo de Cartagena, SE Spain, in the municipality of Fuente Álamo (Murcia), coordinates 37°43′45.32″ N and 1°8′24.60″ E (Figure 1), in an area of 5019 m^2 and an altitude of 127 m above sea level. The soil in the study area is formed from polygenic quaternary sediments of limestone and dolomitic marbles, phyllites and quartzites [34]. The soil climate is an aridic humidity regime, with a mean annual rainfall of 320 mm and a thermal soil temperature regime, with an average annual temperature of 18.2 °C. The climatic data were supplied by the Fuente Álamo (Murcia) weather station. The potential vegetation in the area corresponds to the *Chamaeropo humilis–Rhamnetum lycioidis* association; however, at present, advanced stages of degradation predominate, with crops of horticultural, citrus and fruit species all under irrigation.

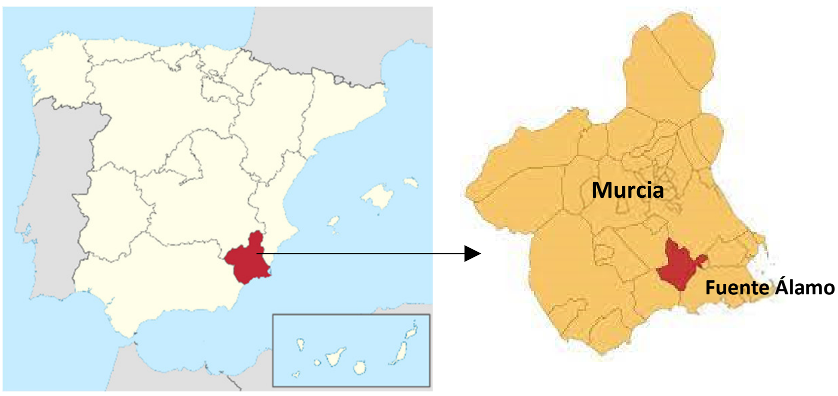

Figure 1. Geographical location of the study area.

The experiment was carried out on two soils with different salinity levels; the LS soil is a Haplic Calcisol (Loamic, Ochric) [35], Typic Haplocalcid [36], where the ECext is 3.8 dS m^{-1}, while soil S is a Haplic Calcisol (Loamic, Ochric, Salic) [35], Typic Haplocalcid [36] with an ECext of 8.5 dS m^{-1}. The general characteristics of both soils are summarized in Table 1.

Table 1. Characteristics of the soils at the beginning of the experiment.

	OC (g kg^{-1})	TN (g kg^{-1})	NO_3^- (mg kg^{-1})	C/N	$CaCO_3$ (g kg^{-1})	CEC (cmolc$_{(+)}$ kg^{-1})	pH_w	pH_k	ECext (dS m^{-1})
LS	10.2	1.4	456	7.3	422	11.6	8.10	7.54	3.8
S	10.4	1.5	465	6.9	435	11.7	8.25	7.53	8.5

OC—organic carbon; TN—total nitrogen; C/N—carbon–nitrogen ratio; $CaCO_3$—total calcium carbonate; CEC—cation exchange capacity; pH_w—pH in water solution; pH_k—pH in 1 M KCl solution; ECext—electrical conductivity in saturated paste.

2.1. Experimental Design and Sampling

The study presented here is part of a larger project where the monitoring of the parameters of a soil dedicated to the rotational cultivation of outdoor vegetables under irrigation, alternating with cover crops, green manuring and other sustainable agriculture techniques, has been carried out. Specifically, it has been developed between a spinach crop (December 2017–May 2018), the results of which are not part of this article, and a coriander crop (March 2019–May 2019) interspersed between them with green manuring based on oat—vetch (October 2018–March 2019). Sampling, both soil and plant material, was carried out on 18 blocks established according to the methodology described by Little and Hills [37], where 3 irrigation doses were applied to in each soil (LS and S), with 3 replications (Figure 2).

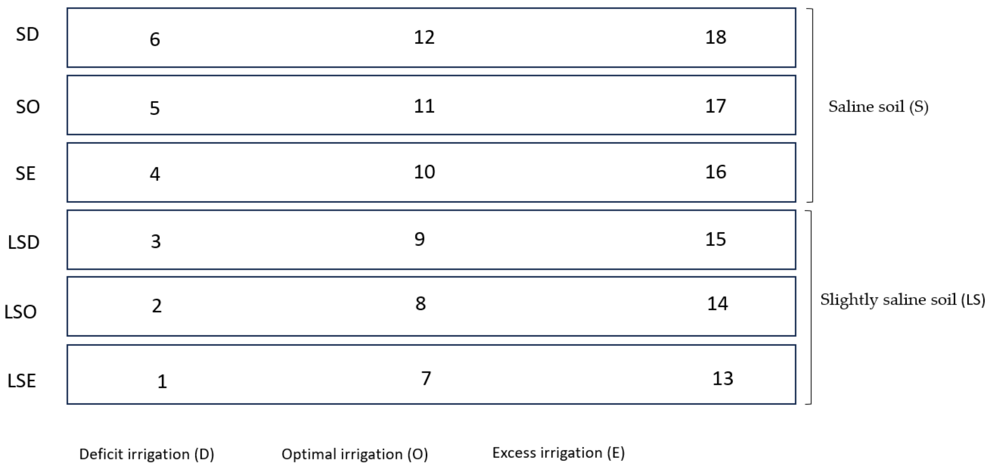

Figure 2. Experimental design. The different soil sampling sites where rain gauges, lysimeters and tensiometers were installed at different depths are numbered from 1 to 18.

The water requirements of the coriander crop were determined according to FAO recommendations for the calculation of evapotranspiration [38]; the optimum irrigation dose was obtained from them, increasing or reducing it proportionally for the surplus and deficit treatments. For each of the treatments, irrigation systems with different water flow rates were installed: deficit irrigation (LSD and SD), with a flow rate of 11.6 L m^{-2} h^{-1}; optimum irrigation (LSO and SO), with a flow rate of 15.3 L m^{-2} h^{-1}, and excess irrigation (LSE and SE), with a flow rate of 2.7 L m^{-2} h^{-1}. A sprinkler irrigation system was used. For this purpose, sprinklers for deficit (D), optimum (O) and excess (E) irrigation were installed 10 m apart and connected by 50 mm diameter polyethylene hoses.

The irrigation water had an ECext of 2.1 dS m^{-1}; SAR = 3.46; and a pH_w of 7.6, with the following salt contents: the HCO_3^-, Cl^- and SO_4^{2-} contents were 287, 250 and 357 mg L^{-1}, respectively, while Na^+ was the predominant cation (220 mg L^{-1}), followed by Ca^{2+}, Mg^{2+} and K^+, at 73.2, 46.4 and 10.0 mg L^{-1}, respectively. These parameters caused the water to be classified as C3S1 (Riverside Norms, U.S. Soil Salinity Laboratory), the use of which is only recommended for very permeable soils and using excess volumes to wash salts from the soil and using tolerant crops.

Water consumption during the vegetative cycle of coriander was 1651, 2201, 2759 1797, 2396 and 3030 m^3 ha^{-1} in LSD, LSO, LSE, SD, SO and SE, respectively, while during green manuring, the same irrigation rate was used with a total consumption of 918 m^3 ha^{-1}. Irrigation control was achieved with a set of Watermark electrical resistance blocks (Irrometer Inc., Riverside, CA, USA), which were installed about 15 cm from the plant row at a depth of 30 cm.

To monitor soil salinity (ECext), soil samples taken at each sampling point from two depths, i.e., shallow (0–30 cm) and depth (30–60 cm), were used. Four samplings were carried out throughout the crop cycle of coriander on 10 and 16 April 2019 and 7 and 22 May 2019. Lysimeters and tensiometers were installed at different depths at each of the 18 sampling sites (Figure 2). Every 15 days during the cultivation period, agronomic monitoring of the crop and characterization of the soil solution were carried out using lysimeters installed at different depths, including 25–30 cm (SSAT-LT-300) to determine the bioavailability of nutrients during the cultivation cycle and 55–60 cm (SSAT-LT-600) to quantify the leaching of nutrients to the deep soil horizons.

Regarding fertilization, an organic amendment based on composted sheep manure (Table 2) was added before sowing the oats, at a dose of 16,000 kg ha^{-1}. The nutritional needs of coriander were met with a background fertilization, before sowing, where 12 kg of N, 10 of P_2O_5 and 18 of K_2O were provided per hectare, complemented with a fertigation program including 35, 45 and 20 kg ha^{-1} of N, P_2O_5 and K_2O, respectively, incorporated between 31 March 2019 and 28 May 2019. For the analysis of plant material, samples of the coriander crop and oat–vetch, both the leaves and roots, were obtained from each of the six treatments. For this purpose, all plants were harvested in an area of 20 × 20 cm, washed with distilled water, and dried at 105 °C in a forced-air oven. The leaves were separated from the roots and these fractions were crushed and homogenized integrally in a Dito Sama K55 Cutter-Emulsifier 5.5 L mill (Aubusson, France). An aliquot of 3 g was taken from each sample and processed with an A10 Analytical Mill 50/60 Hz (IKA Works Inc., Wilimington, NC, USA) to obtain a fine grind suitable for acid digestion.

Table 2. Chemical analysis of sheep manure (SM) performed on a dry matter basis.

Amendment	M	pH_w	ECext	C/N	TOM	TN	P	K	Ca	Mg	Fe	Cu	Mn
SM	38.6	8.4	8.7	13.1	486	21.5	22.6	26.2	71.6	19.1	7.8	0.05	0.4

M—% moisture; pH_w—pH_{water} (1:2.5); ECext—electrical conductivity (1:10 and 1:5 *, dS m^{-1}); TOM—total organic matter (g kg^{-1}); TN—total nitrogen (g kg^{-1}); P—total phosphorus (g kg^{-1} of P_2O_5); K—total potassium (g kg^{-1} of K_2O); Ca—total calcium (g kg^{-1} of CaO); Mg—total magnesium (g kg^{-1} of K_2O); Fe—total iron (g kg^{-1}); Cu—total copper (g kg^{-1}); Mn—total manganese (g kg^{-1}).

2.2. Physical and Chemical Analysis of the Soil Samples, Soil Solutions and Plants

The air-dried soil samples were screened at 2 mm and the following analyses were carried out:

The organic carbon (OC) and total nitrogen (TN) contents were determined in an elemental analyzer (Leco, model CHNS-932, St. Joseph, MI, USA), while the pH was measured in a 1:1 suspension of soil in water (pHw) and a 1:1 suspension of soil in 1 M KCl (pHk) [39]. The total carbonates ($CaCO_3$) were determined by volumetric analysis using a Bernard calcimeter [39]. A soil-saturated paste was prepared for ECext determination [40]; in the extracts obtained, the contents of K^+, Na^+, Mg^{2+}, and Ca^{2+} were determined by ICP-OES (Varian Vista MPX, Palo Alto, CA, USA) and those of anions (NO_3^-, NO_2^- PO_4^{3-} and SO_4^{2-}) were determined by ion chromatography (METROHM 861 Advanced Compact IC; METROHM 838 Advanced Sampler, Herisau, Switzerland). CO_3^{2-} and HCO_3^- were measured by valuation [41]. The sodium adsorption ratio (SAR) was calculated from the concentrations of Na^{+}, Ca^{2+} and Mg^{2+} (meq L^{-1}) in the water and soil saturation extracts prepared for ECext determination [40] by applying the formula:

$$SAR = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}} \quad (1)$$

The soil solution samples obtained from the lysimeters were assessed for pH, EC and the ions K^{+}, Na^{+}, Mg^{2+}, Ca^{2+}, NH_4^{+}, NO_3^{-}, NO_2^{-}, PO_4^{3-}, SO_4^{2-}, CO_3^{2-} and HCO_3^{-} following the same methodology as that used for the samples obtained from the soil saturation extract mentioned in the previous paragraph.

Chemical characterization of the plant material was carried out by fine grinding and acid digestion (HNO_3 + $HClO_4$). The Na, K, Ca, Mg, P, Fe, Cu, Mn, Zn and Mo contents were determined by ICP-OES (Varian Vista MPX), while the TN, OC and S contents were determined using an elemental analyzer (Leco, model CHNS-932). Nutrient extractions by the crops are expressed in kg ha^{-1} and were calculated based on the total biomass production (aerial + roots) and the chemical composition obtained in the elemental analysis of the plant material.

The nutrient balance in the soil was calculated as the difference between the input and removal of elements, including amendments, irrigation water and the return of biomass (roots + aerial biomass) not harvested as inputs; in terms of removal, only the extractions by the crops that were finally taken as harvest were considered, as well as the percentage of OC mineralization calculated from the values found by Almagro et al. [42] in soils similar to those in this study, who set mineralization at 0.19 mg C (CO_2) g^{-1} OC day^{-1}.

2.3. Crop Yield

To quantify biomass production and characterize it chemically, oat-vegetable and coriander samples were obtained. In each of the six treatments, all plants were harvested in triplicate in an area of 20 × 20 cm and the parameters of total yield in kg ha^{-1} (Yt) and dry biomass (DB) were determined by drying at 105 °C.

2.4. Statistical Analysis

The data were analyzed using the general linear model of the SPSS Version 25 statistical package (SPSS, Chicago, IL, USA). The experimental data were subjected to analysis of variance (ANOVA) [43] using Tukey's multiple range test to estimate statistical differences among the mean values for the treatments (LSE, LSO, LSD, SE, SO and SD). Differences were considered significant at the 5% level (p = 0.05).

3. Results

3.1. Evolution of ECext in the Soil

As can be seen in Figure 3, soil salinity undergoes significant changes during the study period. Thus, in the soil less affected by salts (LS), a significant increase in salinity is observed in the first phase (December 2018–March 2019), which is corrected in the subsequent phase with coriander cultivation, recovering to ECext values similar to the starting point. However, in the saline soil (S), although there is apparently an increase in ECext in the first phase, such an increase is not significant, while in the second phase it evolves analogously to LS. On the other hand, the soil solution monitoring carried out during coriander cultivation shows that the EC values are lower at the surface than at depth, which indicates a net loss of salts in the surface horizons.

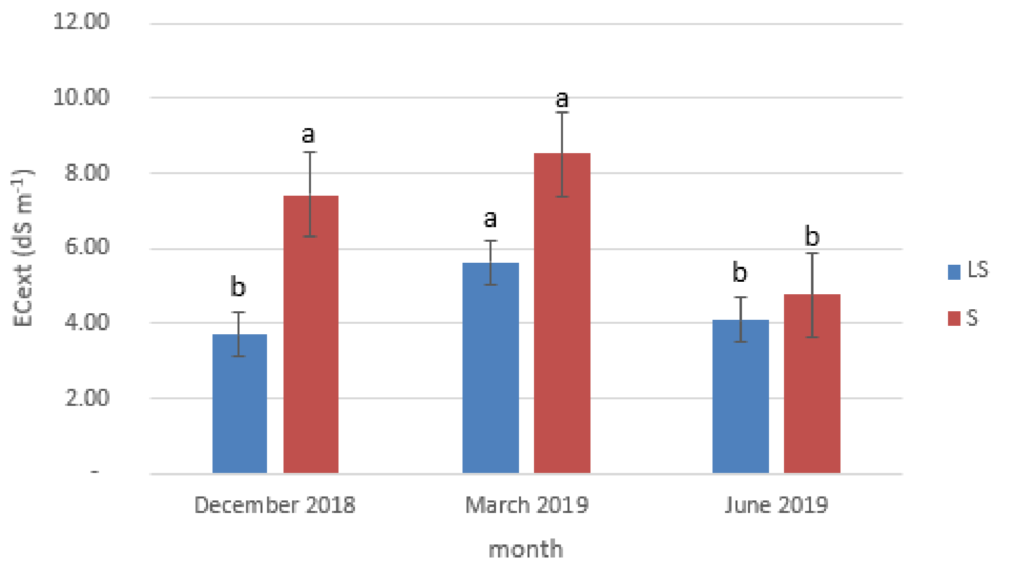

Figure 3. Evolution of ECext values for LS and S during green manuring and coriander cultivation. "a" and "b" indicate temporal significant differences in each soil at the 95% confidence level.

3.2. Ions in Soil Solution

The qualitative and quantitative analysis of the ions present in the saturation extract throughout the two crop cycles evidenced significant differences between LS and S. Thus, we found a pattern in the behavior of Cl^- (Figure 4) and SO_4^{2-} in both soils, so that, in general terms, both anions decrease in concentration as a consequence of the coriander crop cycle, i.e., between March and May, while in the green manuring period (December-March), their concentrations either do not change (S) or even increase (LS), a behavior that corresponds to that found in the ECext.

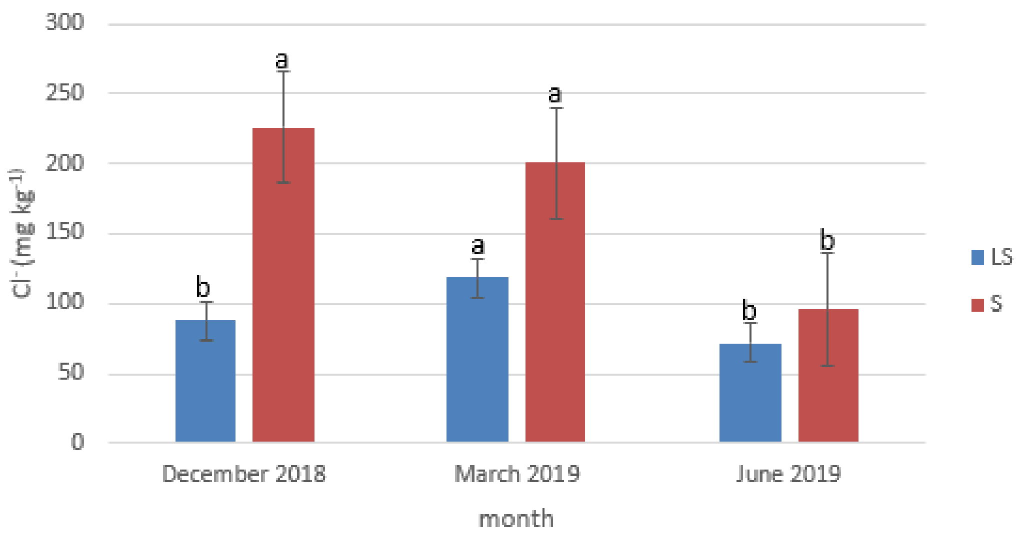

Figure 4. Cl^- concentration (mg kg^{-1}) in the saturation extract of the different treatments during green manuring and coriander cultivation. "a" and "b" indicate temporal significant differences in each soil at the 95% confidence level.

Regarding nitrogenous forms, a statistically significant decrease in NO_3^- was observed in S during green manuring, while in LS it remained constant (Figure 5). However, coriander cultivation caused a decrease in NO_3^- content in both soils, although without statistical significance in S, due to the lack of homogeneity in the variance. It should also be noted that, although at the starting point there is a statistically higher NO_3^- concentration in S than in LS, after green manuring and coriander cultivation, the concentrations in both soils are homogeneous and are around 10 mg kg^{-1}. Likewise, regarding the mobility during the study period through the soil horizons, it is noteworthy that the lysimeters installed at 60 cm in the deficit irrigation blocks did not record leachates, while in the optimum and surplus NO_3^- appear at this depth in concentrations ranging between 1072.8 and 185.5 mg L^{-1} in LSO and SE, respectively. On the other hand, the evolution throughout the vegetative cycle is clearly downward, with leaching also being observed in the samples taken on April 16 and May 24.

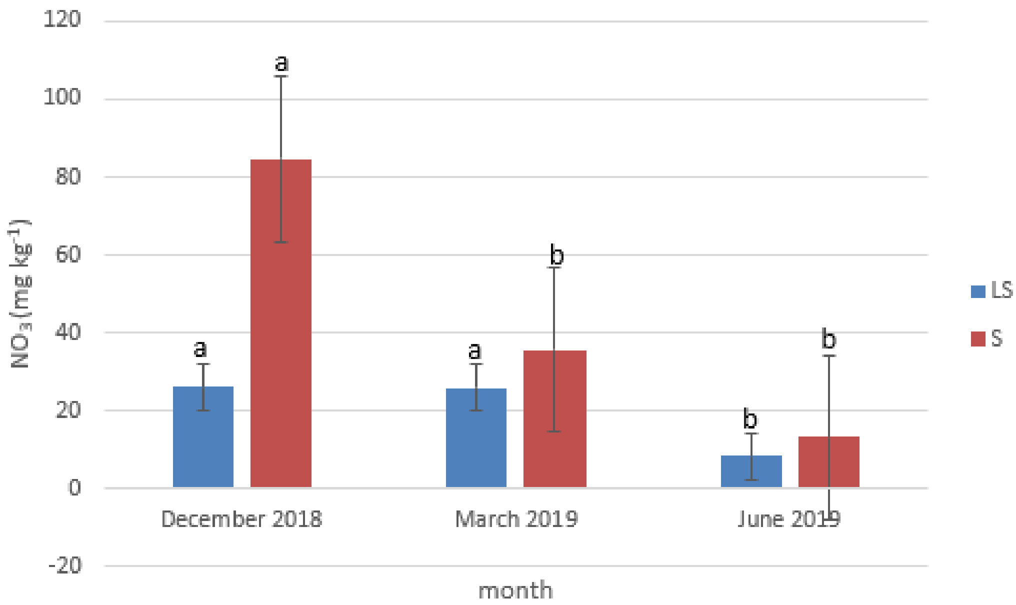

Figure 5. NO_3^- concentrations (mg kg^{-1}) in the different experimental phases of experiment on LS and S soil. "a" and "b" indicate temporal significant differences in each soil at the 95% confidence level.

With respect to NO_2^- content in soil, it is not detected in the initial phase, prior to green manuring, but it is detected at the end of green manuring and especially at the end of coriander cultivation, where it reaches levels close to 7 mg kg^{-1} in LS.

Regarding the rest of the anions we analyzed, carbonates and phosphates were not detected; bicarbonates did appear, but did not show significant differences, with average levels close to 40 mg kg^{-1} soil.

As for cations, both monovalent and divalent, they adopt a very similar behavior pattern throughout the experiment (Figure 6), observing a significant decrease in concentration in the soil solution in the green manuring stage, while, during the coriander crop, although the graphs show lower concentration at the end of the cycle, it does not have statistical significance. On the other hand, at the beginning of the trial (December 2018) statistically significant differences are observed in the cation content between LS and S, which disappear throughout the experiment, becoming equal in both soils, as we have also seen for anions.

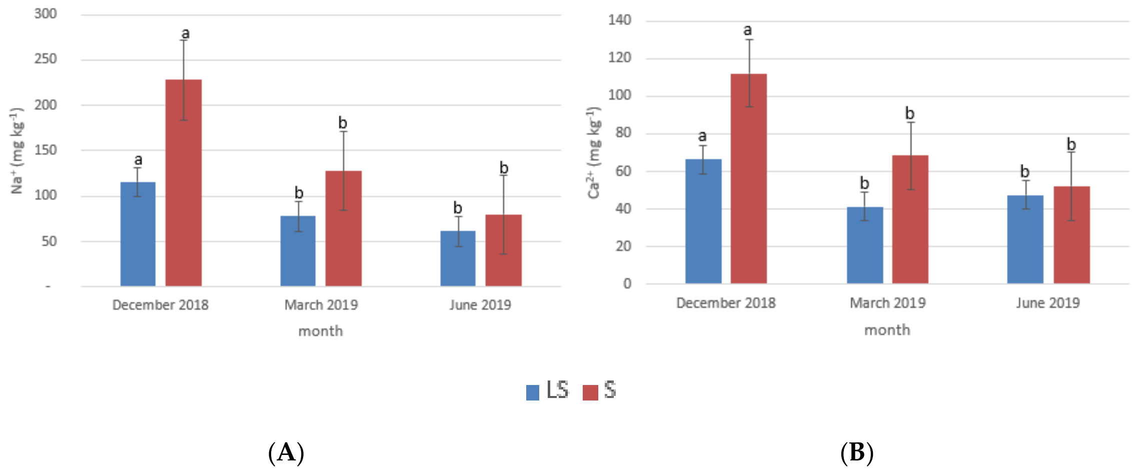

Figure 6. (**A**) Na^{+} concentration (mg kg^{-1}) and (**B**) Ca^{2+} concentration (mg kg^{-1}) in the different experimental phases on LS and S soil. "a" and "b" indicate temporal significant differences in each soil at the 95% confidence level.

3.3. Biomass Production and Bioelement Extraction

In the experimental design there are two stages of biomass generation. The first, which coincides with the green manuring, where the elements absorbed from the soil are returned to it in the form of fresh organic matter and, therefore, the mass balance, a priori, can be considered neutral; although, the availability or state of these elements is different, since before green manuring they are found as soluble salts in the soil solution and then those that are absorbed by the plant cover become part of the organic structures of the plants and are immobilized in them until they are degraded by soil microorganisms [43–45]. On the other hand, those absorbed from the atmosphere (C, H, O and N) contribute to enhancing the ecological function of the soil as a sink of matter and energy. Once the green manure was incorporated into the soil, coriander planting was carried out, a stage that involves a net extraction of matter and energy from the soil to transform it into food. The results of both phases are as follows.

3.3.1. Oat-Vetch Biomass

As shown in Figure 7, soil salinity influences oat–vetch biomass production (green manure), obtaining statistically higher values in LS than in S.

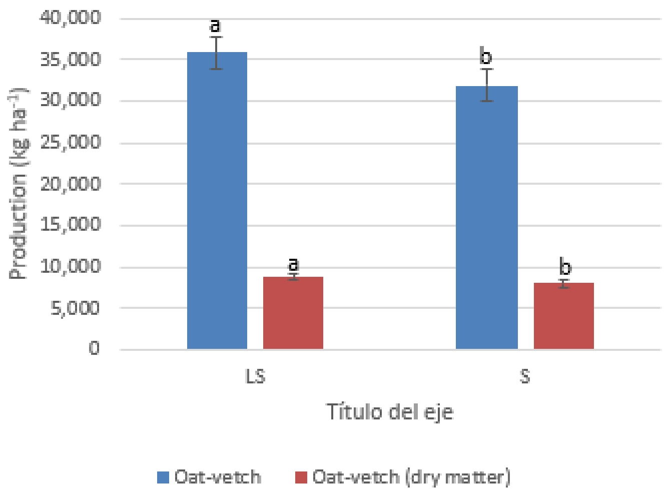

Figure 7. Oat–vetch biomass production as a function of soil salinity. "a" and "b" indicate significant differences between LS and S at the 95% confidence level.

3.3.2. Total Yield (Yt) and Dry Biomass (DB) in Coriander Crop

As can be seen in Figure 8, the highest yields are obtained in the optimum and surplus irrigation treatments, regardless of soil salinity, while the lowest yields are obtained in the deficit treatments, especially in SD. The percentage of moisture ranges from 72% in the S treatment to 75% in LS, but this difference is not statistically significant. Finally, dry biomass production (DB) adopted the same behavior as Yt.

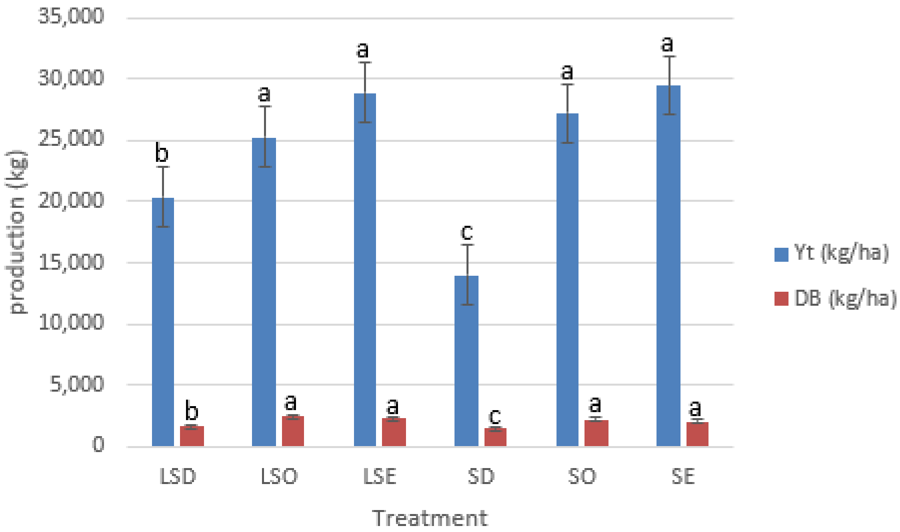

Figure 8. Total yield (Yt) and dry biomass (DB) for each treatment in coriander cultivation. "a", "b" and "c" indicate significant differences between treatments at the 95% confidence level.

Root biomass production was obtained in each of the treatments, showing the same behavior as seen for the aboveground biomass, but with much lower productions, ranging between 670 and 1205 kg ha^{-1} in SD and LSE, respectively, equivalent to 145–187 kg ha^{-1} of dry matter in the same two treatments. This biomass is incorporated into the soil, participating in the different biogeochemical cycles and enhancing the soil's function as a carbon sink.

3.4. Bioelement Extractions

3.4.1. Oat–Vetch Extractions

Except for Cu and Zn, where there are no differences between LS and S, statistically significant differences were detected in the quantitative absorption of the remaining nutrients (Table 3), so that, as expected, higher amounts of macronutrients and Mn are absorbed in LS soil, while in S, Fe and Ca are absorbed in greater quantities than in LS.

Table 3. Macroelements absorption (C, N, P_2O_5, K_2O, S, CaO, MgO and Na_2O) and microelements absorption (Fe, Cu, Mn and Zn) on kg ha^{-1} by green oat–vetch fertilization. "a" and "b" indicate significant differences between treatments at the 95% confidence level.

Treatment	C	N	P_2O_5	K_2O	S	CaO	MgO	Na_2O	Fe	Cu	Mn	Zn
LS	3431 a	211.3 a	40.9 a	354.0 a	19.4 a	61.4 b	30.3 a	124.0 a	4.78 b	0.09 a	0.78 a	0.44 a
S	3143 b	197.9 b	37.3 b	296.0 b	17.7 b	67.3 a	29.1 b	110.0 b	5.11 a	0.08 a	0.64 b	0.41 a

3.4.2. Coriander Crop Extractions

Nutrient extraction by crops is an indicator of soil fertility loss and, therefore, should be the basis for fertilization programs. On the other hand, considering that the accumulation of bioelements is not homogeneous among the different plant tissues and that some of these elements return to the soil as crop residues after harvest, the extraction of macro and micronutrients in the aerial biomass and in the root was determined separately; the results are shown below.

Macronutrients

The macronutrients extracted by the coriander crop (Table 4) are different depending on the part of the plant (aerial biomass or root) and on treatments in question. In the aerial part, significant differences were found between treatments in all the macronutrients analyzed, where the lowest values were obtained in the deficit irrigation dose, while no differences were found in the optimum and surplus irrigation doses. On the contrary, the extractions made by the roots do not adopt a defined pattern, except for S, whose behavior is similar to that described for the aerial biomass. Finally, it should be noted that macronutrient extractions made by the coriander crop are used in percentages close to 96% for the development of aerial biomass, while only about 4% is stored in the roots. This behavior has been observed in N, P_2O_5, K_2O and S, while in CaO and MgO the accumulation in the roots reaches 20.5% and 15.8%, respectively.

Table 4. Macronutrients extraction (N, P_2O_5, K_2O, S, CaO and MgO) (kg ha^{-1}) by aerial biomass and roots in a coriander crop subjected to different soil salinity on and irrigation treatments. "a" "b" and "c" indicate significant differences between treatments at the 95% confidence level.

Treatment	N	P_2O_5	K_2O	S	CaO	MgO
Aerial biomass	85.8	56.7	179.6	3.6	28.7	10.1
LSD	64.6 b	37.4 b	151.4 b	3.0 b	23.8 b	8.1 a
LSO	102.0 a	66.1 a	234.3 a	4.9 a	35.4 a	11.9 a
LSE	103.5 a	70.9 a	217.5 a	3.6 a	38.6 a	11.9 a
SD	54.7 b	36.0 b	107.5 b	2.5 b	18.3 b	6.9 b
SO	100.2 a	69.1 a	186.1 a	4.5 a	29.3 a	11.7 a
SE	89.9 a	60.1 a	150.4 a	3.3 a	26.6 a	10.0 a
Root	3.3	2.2	7.1	0.2	3.6	0.9
LSD	2.6 b	1.9 b	8.8 a	0.1 b	2.9 b	0.7 c
LSO	3.3 ab	2.2 ab	7.0 b	0.2 a	3.6 b	1.0 a
LSE	3.8 a	2.8 a	8.0 a	0.2 a	4.9 a	1.1 a
SD	3.2 b	1.6 b	5.5 c	0.1 b	2.5 a	0.7 b
SO	3.4 ab	2.5 a	6.2 c	0.2 a	5.4 b	1.1 a
SE	3.5 a	2.1 ab	6.9 b	0.2 a	2.5 a	0.7 b
Total plant	89.1	58.9	186.7	3.8	32.3	12.0
% (Aerial biomass)	96.3	96.3	96.2	94.7	79.5	84.2
% (Root)	3.7	3.7	3.8	3.3	20.5	15.8

Micronutrients

As can be seen in Table 5, micronutrient extractions by the aerial biomass of coriander adopt a behavior pattern like that of macronutrients, except for Fe. Thus, the lowest extractions are obtained with deficit irrigation doses (LSD and SD), with no difference between the two soils, while when irrigation is optimal, micronutrient extractions are at maximum in the two soils, with no statistical differences between them. Finally, in surplus irrigation, the extractions are similar to those in deficit irrigation, except for Zn, where levels are similar to those in optimum irrigation. As for Fe, the lowest values are obtained in the saline soil, regardless of the irrigation dose used, which, in turn, are homogeneous with those reached in LSD, then LSO and finally LSE, where the highest Fe extractions are obtained.

Table 5. Fe, Cu, Mn and Zn extraction (g ha^{-1}) by aerial biomass and roots in a coriander crop subjected to different treatments. "a", "b" and "c" indicate significant differences between treatments at the 95% confidence level.

Treatment	Fe	Cu	Mn	Zn
Aerial biomass	940.4	27.9	116.0	60.0
LSD	706.6 c	23.4 b	93.4 b	48.7 b
LSO	1185.9 b	33.6 a	135.0 a	69.8 a
LSE	1665.2 a	33.1 a	133.2 a	73.4 a
SD	636.3 c	21.4 b	82.0 b	40.4 b
SO	864.4 c	30.0 a	145.0 a	64.7 a
SE	584.0 c	25.7 b	107.6 b	63.2 a
Root	395.1	3.3	11.5	4.7
LSD	264.6 b	2.6 b	9.0 c	3.9 c
LSO	385.3 b	3.7 a	11.7 b	4.9 b
LSE	536.4 a	4.1 a	13.7 a	5.7 a
SD	300.1 b	2.9 b	9.5 c	3.7 c
SO	665.1 a	3.7 a	17.2 a	5.5 a
SE	219.0 b	2.9 b	8.0 c	4.4 b
Total plant	1335.5	31.2	127.5	64.7
% (Aerial biomass)	70.4	89.4	91.0	92.7
% (Root)	29.6	10.6	9.0	7.3

Regarding the extraction of micronutrients by the roots, the highest values were found for SO and LSE, while for the rest there was no defined trend.

3.5. Balance of Elements with Environmental Impact

In order to determine the impact of agricultural practices on the ecological function of the soil, it is very important to know the balance of the main bioelements that influence this function and, in particular, C, Cl^- and Na^+, which are the first to elements quantify the role of the soil as a sink or source of CO_2, while the rest can be used to measure certain processes of degradation or contamination, sometimes remarkable in these soils, such as salinization, alkalinization, leaching, etc.

Thus, if we look at Table 6, we can see that the OC inputs to the soil are constituted by the organic amendment, aerial and root biomass from the green manure, which is the most important contribution, especially in the slightly saline soil, where significantly higher amounts are incorporated than in the saline soil. Finally, the return of biomass in the form of roots from the coriander crop also contributes to soil OC, although in this case the amount is marginal with respect to the other two inputs. On the other hand, the extractions were obtained from the values of OC mineralization proposed by Almagro et al. [42] for soils similar to those on which the study was conducted and does not exceed in any case 10% of the inputs during the trial period (September 2018–May 2019), so the net balance per hectare, as far as OC is concerned, is higher than 4.7 tm ha^{-1} in LS and 4.4 tm ha^{-1} in S.

With respect to the elements that contribute most to the salinization of these soils, the balance of Cl^- and Na^+ was determined. Regarding the former, irrigation water is the main input for both elements, much higher than the organic amendment added to the soil before the oat–vetch cycle. Significant differences were also detected between the three irrigation doses for Cl^-, but not for Na^+, where the following sequence is observed in the balance: SE > SO, LSO > SD, LSD.

Table 6. C, Cl^- and Na^+ balance (kg ha^{-1}) in an oat–vetch–coriander crop subjected to different irrigation doses. "a", "b", and "c" indicate significant differences between treatments at the 95% confidence level.

				OC			
		LSD	**LSO**	**LSE**	**SD**	**SO**	**SE**
Inputs	Sheep manure	1745.1	1745.1	1745.1	1745.1	1745.1	1745.1
	Oat-vetch	3430.6 a	3430.6 a	3430.6 a	3142.7 b	3142.7 b	3142.7 b
	Biomass return	50.8 c	57.6 b	63.2 a	52.6 c	57.7 b	51.3 c
	Total inputs	5226.5	5233.3	5238.9	4940.4	4945.5	4939.1
Removals	OC mineralization	481.6	481.6	481.6	472.9	472.9	472.9
	Total Removals	481.6	481.6	481.6	472.9	472.9	472.9
	Balance	4744.9 a	4751.7 a	4757.3 a	4467.5 b	4472.6 b	4466.2 b
				Cl^-			
		LSD	LSO	LSE	SD	SO	SE
Inputs	Water irrigation	642.1 c	779.7 b	919.3 a	678.7 c	828.5 b	987 a
	Sheep manure	107.2	107.2	107.2	107.2	107.2	107.2
	Total inputs	749.3 c	886.9 b	1026.5 a	785.9 c	935.7 b	1094.2 a
				Na_2O			
		LSD	LSO	LSE	SD	SO	SE
Inputs	Water irrigation	762.0 c	925.0 b	1090.0 a	805.0 c	983.0 b	1171.0 a
	Sheep manure	81.5	81.5	81.5	81.5	81.5	81.5
	Biomass return	1.4	2.3	2.6	1.9	2.5	2.0
	Total inputs	969.0 c	1132.9 b	1298.2 a	998.7 c	1177.3 b	1364.8 a
Removals	Oat-vetch	124.1 a	124.1 a	124.1 a	110.3 b	110.3 b	110.3 b
	Coriander	12.5 c	24.8 a	23.5 a	22.9 a	25.5 a	23.2 a
	Total removals	136.6 b	148.9 a	147.6 a	133.2 b	135.8 b	133.5 b
	Balance	832.4 c	984.0 b	1150.6 ab	865.5 c	1041.5 b	1231.3 a

4. Discussion

4.1. Electrical Coductivity of Extract of Saturatión (ECext)

As already mentioned, during the green manuring stage, an increase in ECext was observed, which can be attributed to the decomposition of the organic amendment and biomass incorporated into the soil, as well as to the background manuring prior to coriander planting, while the decrease during the crop cycle (March 2019–May 2019) is due to nutrient uptake by cultivation and flushing to depth horizons, especially at the higher irrigation doses, as observed in the lysimeters installed at 60 cm, results that coincide with those obtained by [31] in studies carried out in a spinach culture, as well as those contributed by other authors [12,13].

4.2. Ions in Soil Solution

The calcareous nature of the parent material and the slightly basic pH of the soil, among other properties, were the main factors controlling the content and dynamics of ions in the soil solution. Thus, the absence of soluble phosphates and carbonates must be attributed to their precipitation in the forms of Ca_3PO_4 and $CaCO_3$, respectively, favored by the basic pH and the Ca^{2+} saturation of the soil solution.

On the other hand, anions tend to decrease during cilantro cultivation, an evolution that is logical considering the behavior of the ECext and is similar to that described by other authors [9,12,14], and that it is attributable to absorption to meet the nutritional needs of the coriander or to leaching and evacuation from the profile. This leaching process would be corroborated by the decrease in EC in the lysimeters throughout the coriander crop cycle, especially in treatments with higher doses of irrigation, where the anionic concentration in the lysimeters tends to equilibrate with that of the irrigation water. However, in the oat–vetch cycle, the concentration remains constant in S and increases slightly in LS, which indicates that the balance between extractions and inputs in this phase is neutral in the saline soil (S) and slightly positive (LS) in the slightly saline one. As a result, it can be said that the washing of salts in the irrigation water is more intense in S than in LS, a process that is entirely to be expected since these are highly soluble compounds such as Cl^- and NO_3^- (Figures 4 and 5).

The dynamics of NO_3^- in the soil dissolution system, essential to the ecological balance of the soils of the Campo de Cartagena region and its surroundings, is related to the vegetative development of the oat–vetch and especially of the coriander crop, whose strong demand for N justifies the decrease in NO_3^- concentration in both soils during their growth stages [41,42]. On the contrary, in the green manure there is a net decrease in NO_3^- in S, which is not observed in LS, where the concentration remains constant. This behavior is not as expected, since it does not agree with the N absorbed by the oat–vetch cover crop (Table 4), where similar extraction values are obtained in the two soils and close to 200 kg ha^{-1}. In short, in view of the results, it seems that the green manure has a different performance in terms of NO_3^- absorption depending on soil salinity, so that, under low salinity conditions (LS), the N needs of the plant cover are partially supplied by the Rhizobium–legume symbiosis and, therefore, the NO_3^- concentration in the soil is not altered [43]. However, in saline soils, it seems that the mentioned symbiosis would not work so well and, therefore, the plant cover absorbs NO_3^- from the soil and causes the decrease in concentration, although this decrease would only account for 50% of that found in the biomass, so that the other 50% must come from atmospheric N_2 incorporated into the plant tissues through the symbiotic process. Similar results were found by Benidire et al. [44]. On the other hand, the NO_3^- dynamics observed in the lysimeters confirm its decrease in the surface horizons during the coriander vegetative cycle, a trend clearly attributable to the absorption of this constituent, but also to leaching towards deeper horizons, which is confirmed by the increase in the lysimeters installed at 60 cm during some stages of cultivation in treatments with optimal and surplus irrigation, a process that may be behind the eutrophication observed in nearby aquatic ecosystems [45–47] and which satisfies the third hypothesis of this paper.

As for NO_2^-, its absence at the beginning of the study is in accordance with the soil aeration conditions, which make it an oxidizing medium where N predominantly undergoes a nitrification process, leading to its most oxidized forms (NO_3^-) [48], a trend already evident in the study area [31]. However, NO_2^- was detected at the end of the green manure cycle and especially at the end of the coriander crop, whose origin must be the oxidative degradation of the fresh organic matter incorporated into the soil [49] as green manure, where NO_2^- appears as an intermediate oxidation product before being fully oxidized to NO_3^-.

The dynamics of cations in soil dissolution during the experiment was strongly affected by the oat–vetch crop, but not by the coriander crop. In the former, the generalized decrease in cation concentration is a consequence of absorption, both in LS and S, whereas, in the coriander cycle, nutrient inputs in the form of fertilizer have compensated for the absorption of the crop and, therefore, their concentration in the soil solution has not been altered.

In summary, the net balance of ions in the soil, considering the green manuring and coriander cultivation phases together, is negative and, taking into account that during green manuring is when the greater consumption of salts is observed, we can consider that a process of phytoextraction is occurring during that stage, which is particularly important in saline soils, due to the considerable decrease in Na^+ and Cl^- [50–52]. These results confirm the initial hypothesis, since the combined management of green manuring and vegetables improves soil quality and is manifested in a decrease in soluble salts concentration, more pronounced in S than in LS, and in the improvement of quick response indicators, as is the case for soil dissolution ions.

4.3. Biomass Production

As already mentioned, biomass production, both in the green manuring stage and in the coriander crop, was affected by soil salinity and irrigation dose. Thus, oat–vetch production was lower in S, since, although oats are a relatively tolerant species to soil salinity, they are more tolerant to soil salinity than coriander [53,54], vetch is quite sensitive [55,56], so that the vegetative development has been lower, possibly due to the added difficulty of overcoming the osmotic force which exists in the soil solution under these high salinity conditions, as well as the partial inhibition of the symbiotic mechanism with bacteria from the Rhizobium genus [43,44]. Therefore, the germination of vetch seeds was strongly affected, as can be seen in Figure 9. Taking into account these results, the selection of species for green manure cover crops should be based, among other factors, on soil salinity levels, choosing more tolerant species in those cases that require it, as in the present case [57].

Figure 9. Panoramic view of the oat–vetch crop on 5 December 2018, 60 days after planting. In the foreground, soil S; in the background, LS.

During coriander cultivation, it has also been observed that, when the irrigation dose is increased (LSO, LSE and SO, SE), contrary to what might be expected, biomass production is independent of the soil salt concentration, reaching similar values in LS and S, while under deficit irrigation production decreases significantly, especially in the most saline soil. Plant growth is seriously affected by abiotic stress and water deficit is one of the most important limiting factors, especially during the initial phase of reproductive growth and usually causes a reduction in yield [58]. This fact confirms the hypothesis about the influence of osmotic forces on the capacity of nutrient absorption by crops, so that increasing the irrigation dose causes the dilution of the soil solution, decreases the osmotic pressure and, therefore, favors the absorption of nutrients by the crop [59,60]. These results coincide with those obtained by various authors [61,62], who agree that the establishment of adequate irrigation doses eliminates the situations mentioned above and allows the plant to find not only the water but also the oxygen and nutrients it needs with minimal energy costs, which can result in an improvement in crop yield when the rest of the production factors are controlled.

4.4. Macro and Micronutrient Extraction

Various authors [63–66] have found that nutrient extraction by horticultural crops is influenced by different factors, among which are the nature of the bioelement and the soil conditions and, in particular, soil salinity. Thus, in the case of green manure, the extractions of most macro and micronutrients are higher in slightly saline soil (LS) than in saline soil (S); results which are consistent with biomass production and are, therefore, related to the greater or lesser tolerance to salinity of the cultivated species [64,67]. Fe and Ca have an inverse behavior, so that a higher concentration was found in the oat–vetch from the S soil than that from the LS soil, an aspect that may be due to the less favorable soil conditions for plant development, where a higher transpiration and photosynthetic activity of the plants is encouraged to compensate the osmotic pressure of the soil [64,67].

However, this behavior changes in the coriander crop, due to the influence of the irrigation dose on the osmotic potential of the soil solution. Thus, we can observe that, when irrigation is optimal or surplus, there is a dilution of soil dissolution and, therefore, quantitatively, the same amounts of macronutrients are extracted in slightly saline soil (LS) as in saline soil (S), especially by the aerial biomass, which represents more than 95% of the total plant. However, at deficit irrigation doses, there is an increase in soil salt concentration and osmotic potential, which hinders nutrient uptake. In summary, the differences in concentration between treatments must have been related to transpiration and metabolic activity generated under the different salinity conditions in which the crop develops; results that coincide with those found by other authors [64,68] and confirm the second hypothesis of this research.

4.5. Balances

It is important to highlight that the agricultural management carried out in this study has allowed the OC content in the soil to be increased and, therefore, its functionality as a carbon sink also increased. In this sense, it is observed that the contribution of organic amendments as the basis of fertilization, common to all treatments, and especially the incorporation of biomass from the plant cover used as green manure, have resulted in a significant increase in OC which, together with the return of biomass from coriander crop residues, make the soil a net C sink during the two crop cycles, increasing from 34.4 tm ha^{-1} to more than 38.7 tm ha^{-1}, 12.5% of the initial level. Thus, although there is an accelerated mineralization of the organic matter as a consequence of the cultivation practices, estimated at 0.19 mg C (CO_2) g^{-1} OC day^{-1} [69], the crop management carried out makes it a C sink, thus contributing to the achievement of one of the goals set at the Paris Climate Conference (COP21), which was to increase the OC content of agricultural soils by 4 per 1000, as well as with the European guidelines on the CAP, as set out in Regulation (EU) 2021/2115 of the European Parliament and of the Council of 2 December 2021, which promotes these cultivation techniques as tools to mitigate climate change.

With respect to Na^+ and Cl^-, elements responsible for soil salinization, it is confirmed that the most important source of supply is irrigation water, meaning that its quality is essential in preventing this process. On the other hand, the evolution of these elements in the soil throughout the trial shows that there is a decrease in concentration, especially in S and during the green manuring stage, so it can be considered, therefore, as a valid phytoextraction tool for the recovery of soils affected by salts.

5. Conclusions

The agronomic management carried out on the experimental farm provided statistically different results for the treatments tested. Thus, the oat–vetch cover crop, interspersed between the vegetable crops, produced a very significant increase in soil organic matter and proved to be a viable alternative for reducing Na^+ and NO_3^- concentrations in saline soils. Both results are very important to take into account, especially in areas such as those where the study was carried out, where the organic matter content of soils is very low and processes linked to the contamination and alkalinization of soils and aquifers have been observed, due to the use of water of poor agronomic quality for irrigation and doses of agrochemicals, sometimes excessive ones, which are all catalyzed by an arid climate and the current scenario of climate change, in which these conditions are expected to be accentuated.

The agronomic practices carried out were also a determinant of the behavior of some fast response indicators, such as EC_{ext}, NO_3^-, Cl^- and Na^+. Thus, the concentration and availability of ions in the soil and their oxidation state were strongly influenced by pH and redox potential, causing the precipitation of carbonates and phosphates in the soil and the oxidation of their nitrogenous forms to NO_3^-. This explains the leaching of the most soluble ions (NO_3^-, Cl^- and Na^+) from the surface to the depth horizons, especially in the optimum and excess irrigation treatments, while no leaching occurred in the deficit irrigation.

The degree of salinity of the soil is a very important factor for its management, since it significantly influences biomass production, regardless of whether it is the plant cover or the coriander crop, which can be corrected in the latter case by using higher doses of irrigation, but at the same time causes undesirable effects, such as NO_3^- contamination of groundwater bodies that can end up in the nearby Mar Menor lagoon and increase its salinization.

Macro- and micronutrients extraction by the oat–vetch cover crop and by the coriander crop was very different depending on soil salinity and irrigation dose. Thus, in S, the extractions of most nutrients by the oat–vetch cover crop were statistically lower than in LS, while nutrient uptake in coriander was not sensitive to soil salinity and was affected by the irrigation dose used, obtaining the highest values in the optimum and excess doses.

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