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# Assessing Spatial and Temporal Variability for Some Edaphic Characteristics of Mediterranean Rainfed and Irrigated Soils

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**Abstract:** Mediterranean soils are particularly threatened by salinization and low levels of organic matter content. In order to assess an edaphic sustainable use, we need to study its characteristics and better understand the temporal and spatial evolution. In this study, a total of 14,852 ha located in a western Mediterranean basin were selected as the study site where 1417 and 1451 topsoil samples were analyzed in 2001/2002 and 2011/2012, respectively, for Soil Organic Matter (SOM) content, pH water ($pH_w$) and electrical conductivity (EC). Classical statistics and geostatistics techniques were used and the individual soil samples were related with the cultural system (CS) practiced–rainfed/irrigation–and the Reference Soil Group (RSG)–Cambisols, Calcisols, Luvisols, and Fluvisols. Predictive maps were created by interpolation using the Ordinary Kriging algorithm. The main results of this study were that, when transitioning from a rainfed to irrigation CS, SOM content is maintained in Cambisols but decreases in the other RSGs, $pH_w$ is maintained and EC increases in Fluvisols, Luvisols, and Cambisols. Over time in the rainfed CS all RSGs maintained SOM and $pH_w$ but EC increased in Fluvisols, Luvisols, and Calcisols and in the irrigation CS SOM decreased in Luvisols, $pH_w$ increased in Fluvisols and Calcisols and EC increased in all RSGs.

**Keywords:** soil organic matter; electrical conductivity; pH; Mediterranean sustainability; rainfed and irrigated soils

## 1. Introduction

The world population is increasing. The best estimations point towards 10,000 million inhabitants by 2050, a 33% increase when compared with the actual 7500 million, that will need to be fed and clothed. Proportionally, there is a registered decrease in arable land resources due to agricultural and urban intensification [1–3]. In the Mediterranean basin, food production depends today more than ever on cultural intensification through the practice of irrigation, as in this agroclimatic system, water is the limiting factor. This is especially true in the summer months, where temperature and solar radiation are at its peak and crop production can be maximized if irrigated.

Irrigation is a complex agricultural practice that is almost always related to other cultural aspects associated with intensification such as more frequent soil mobilizations and higher fertilization and phytopharmaceutical inputs, [4] and so, its study and management are of the utmost importance as this cultivation system (CS) is responsible for producing 2/5th of the world's food but also for the permanent deterioration of the soils due to salinization leading productive land towards complete unproductivity [5–8]. This raises important red flags related to the sustainability of the whole system, especially in the Mediterranean basin where human beings have been densely cultivating for 5000 years according to Yaalon [1] and traditional farming is declining for monoculture exploitation as noted by Siebert [9].

The studies of Calvo-Polanco, Sánchez-Romera & Aroca [10] and of Shrivastava & Kumar [11] state that we live in a world where 20% of the cultivated, and 33% of the irrigated, lands are affected by high salinity levels with the rate increasing by 10% per year, and that by 2050, about half of all arable land will be salinized with all the encompassing economic problems resulting therefrom.

Soil organic matter (SOM) is mostly composed of carbon and oxygen but also hydrogen and nitrogen, and although its net charge is always negative acting as a composite anion capable of adsorbing cations [12], charges are dependent on the soil solution pH. When pH increases, SOM develops more negative charges as the higher $OH^-$ availability in the soil solution dissociates the $H^+$ ion from the $OH^-$ that are adsorbed in the soil colloids (or in the carboxylic, phenolic and/or alcoholic functional groups) forming $H_2O$ [13]. When pH decreases, SOM develops fewer negative charges by the reverse action just described and, thus, the Cation Exchange Capacity (CEC) on the topsoil is interdependent with the pH of the soil.

Because SOM acts as a buffer for pH and EC [14,15] the three parameters have a key role in the soil, directly influencing its fertility, compaction, nutrient availability, water retention capacity, its conservation or degradation among other beneficial or prejudicial features depending if SOM, $H^+$, $OH^-$ and salt concentrations are increasing or decreasing [16,17].

It is, thus, very important to maintain, and if possible increase, SOM levels in the soils of the Mediterranean basin that are below 3.5% [18] and maintain the EC and pH at optimal levels.

Due to the intrinsic edaphic-climatic characteristics of the region, and the quality of the irrigation water, cultural intensification through irrigation in the soils of the Mediterranean basin have led to the base results in terms of SOM, EC and pH explained below [19].

Regarding SOM, the agro-climatic conditions responsible for optimum crop production are also the same conditions that cause its accelerated mineralization. The mineralization is increased because intensification processes, such as the greater number of soil mobilizations that increase soil aeration, further promote microbial life. These two aspects, combined with the low organic matter inputs to the soils, tend to decrease SOM concentrations over time [18,20–23].

Regarding soil EC, according to Pilatti & Buyatti [24], the edaphic-climatic characteristics of the Mediterranean basin are not sufficient for leaching the salts incorporated by irrigation water in its typical soils even when the water is of good quality leading to an observed increase in EC.

Regarding pH, as it depends on the aforementioned factors, on parent material composition and the nature of soil colloids, among others, investigation results are polarized with different authors presenting different results. In the studies of Nunes [25] and Zamora, Rodríguez, Torres, & Yendis [26], soil pH was found to be decreasing with irrigation while in the studies of Mancino & Pepper [27] and Rusan, Hinnawi & Rousan [28] soil pH was being maintained while in the studies of dos Reis et al. [29] and Ayoub, Al-Shdiefat, Rawashdeh & Bashabsheh [30] it was found to increase with irrigation practice. It is worth mentioning that there is some consensus, among scientists, that conservation agricultural practices, such as no-tillage, can lead to the soil acidification of the Mediterranean basin [31–34].

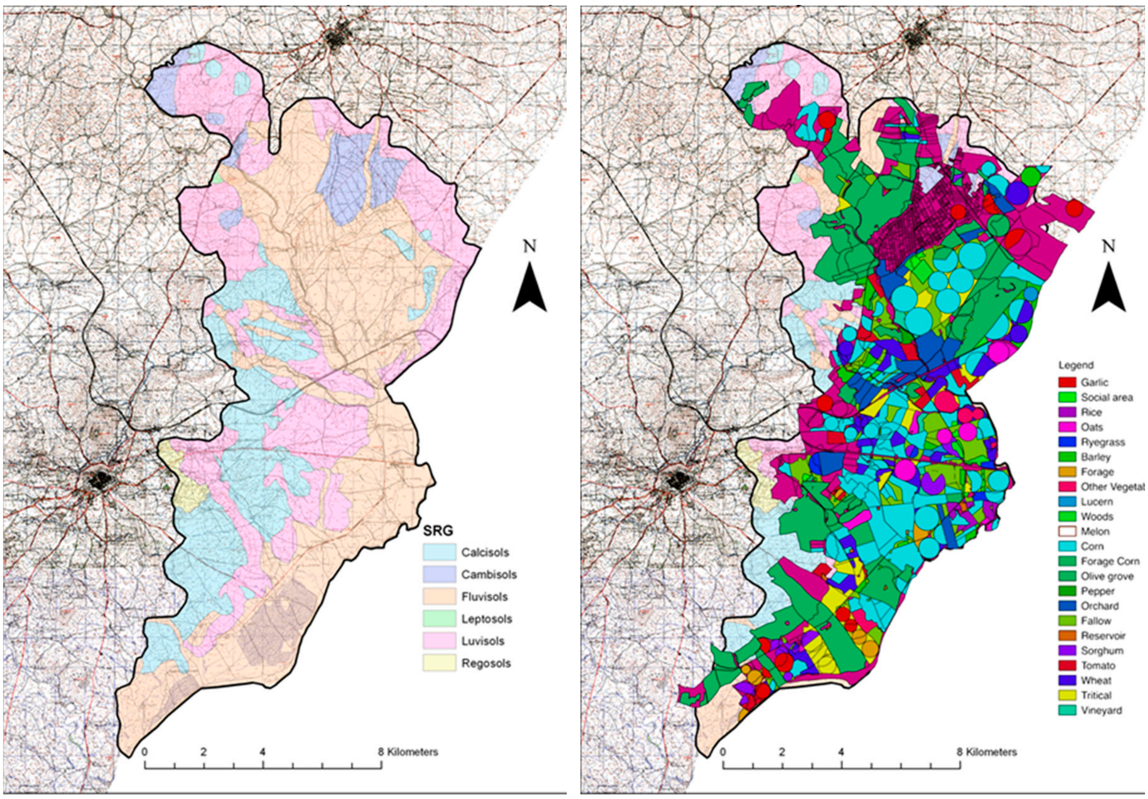
Soil pH is probably the single most informative measurement to determine the chemical and biological properties of the soils as it regulates the quantity, and informs the availability of essential nutrients and toxicity of others [24,35], it conditions the plant (and therefore to some extent, animal) species that predominate in a landscape, and it impacts the soil microorganisms which promotes soil sustainability [36] with a $5.8 \leq pH \leq 6.5$ directly related to the optimal productivity of most crops.

The main objective of this paper is, thus, to contribute to a better understanding of the sustainability of the rainfed and irrigation CS in the Mediterranean basin regarding SOM, soil EC and soil $pH_W$. This may be an important planning tool in relation to soil conservation practices since it will state which CS mostly affect soil potential and how the different reference soil group (RSG) behave over an 11 year time period.

## 2. Materials and Methods

### *2.1. Study Area and Sampling*

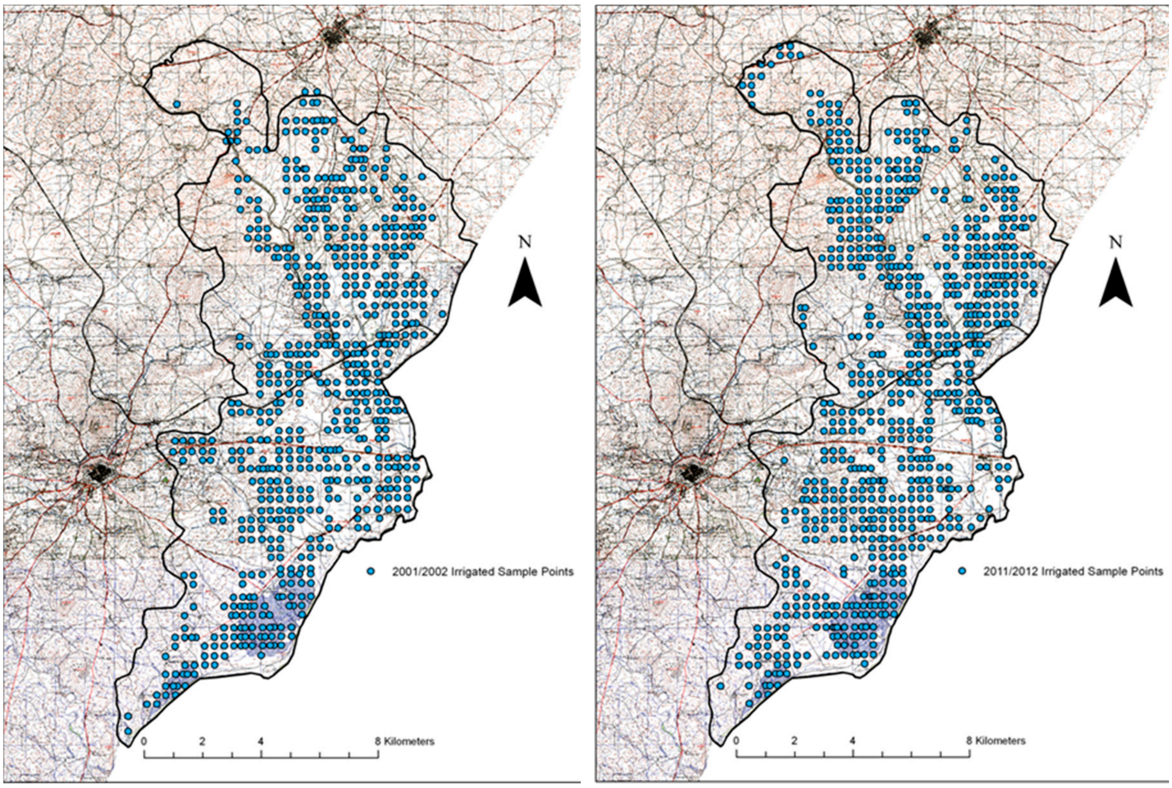
The study area was located in the western Mediterranean basin within the administrative townships of Elvas and Campo Maior, at the confluence of the Rivers Caia and Guadiana, near the Portuguese-Spanish border. The total area of the research accounted for 14,852 ha. The average annual rainfall is approximately 483 mm, most of which coincides with the coolest temperatures from October to March. The maximum average monthly temperature corresponds to July with 24.7 °C and the minimum to January with 8.8 °C. The Mediterranean region is characterized by its hot dry summers and cool wet winters and it's a Csa in the Koppen classification [12]. The geology is heterogeneous but mainly consisting of hiper-alkaline and basic rocks. The soils were classified according to the World Reference Base of Soil Resource (WRB) of the Food and Agriculture Organization of the United Nations (FAO) [37] and, from the six first level Reference Soil Groups (RSG) identified in the study area, four were analyzed: Fluvisols, Luvisols, Calcisols and Cambisols (Figure 1a), typical in the Mediterranean ecosystems [1,25,38]. The most important crops are olive (*Olea europea* L.) (35%), maize (*Zea mays* L.) (20%), tomato (*Lycopersicon esculentum* L.) (15%) and garlic (*Allium sativum* L.) (15%) (Figure 1b). The study area irrigation water is classified by FAO as C1S2 [25]—very good quality with low salinity and sodicity. Classification that has remained over the years but with a marked increase in bicarbonates ($HCO_3^-$) since 2001/2002 where the mean content in the study area was 68.6 mg $L^{-1}$ while in 2011/2012 was 101.0 mg $L^{-1}$ increasing the buffer capacity in the latter years and marking a transition from low to moderate $HCO_3^-$ levels in the irrigation water. In 2009 $HCO_3^-$ content in the study area was already at a mean of 92.0 mg $L^{-1}$.




(**a**) (**b**)

**Figure 1.** (**a**) Soils of the study area (WRB) and (**b**) Cropping system (data from 2012).

There was a 20% increase in the irrigated soils of the study area from 7500 ha in 2001/2002 to 9000 ha in 2011/2012 as illustrated by the irrigated sample points in Figure 2.




(**a**) (**b**)

**Figure 2.** Irrigated Sample Points Map in (**a**) 2001/2002 and (**b**) 2011/2012.

In 2001 we started by outlining the study area on the Portuguese military chart (scale 1:25,000) drawing the limits of the study area to be analyzed. We took as reference the cartographic coordinates of the military map, with each square representing 100 hectares, and divided it into nine equal sub-squares–each sub-square with an area of 11.11 ha–geo-referencing its center. In 2001/2002, with the coordinates on paper and a GPS system, we went to the study area, located each of the 1417 sites, and randomly collected 10 topsoil (0–20 cm) samples from scattered places within the land area to be represented, with a stainless-steel probe. The samples were carefully mixed in situ creating a single composite sample per site. In the laboratory all samples were airdried, crushed and sieved to <2 mm and stored. In 2011/2012, with the coordinates from the 2001/2002 samples already uploaded into a GPS system, we recollected the new samples with the same method earlier. In this sample collection, we divided some areas even further and ended up with a total of 1451 topsoil samples.

## *2.2. Soils of the Study Area*

In 2003, Nunes [25] studied the soils of the study area by opening and assessing 28 soil profiles that were categorized according to FAOs profile guide [39] and Munsell Color Chart [40]. The pedons chemical characteristics were analyzed leading to their categorization. The data from Table 1, that states the typical edaphic characteristics of the studied soils, was adapted from this analysis.

**Table 1.** Main edaphic properties of typical Mediterranean basin soils. Adapted from Nunes [25].

| | Depth | pH (water) | SOM (g kg$^{-1}$) | EC (dS m$^{-1}$) | C/N | $CaCO_3$ (%) | Sand | Silt (%) | Clay | Ca | Mg | K (cmol$_{(+)}$ Kg$^{-1}$) | Na | CEC | BSP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Fluvisols | 0–20 | 5.78 | 0.118 | 0.208 | 7.86 | 0.00 | 72 | 13 | 15 | 4.48 | 1.60 | 0.21 | 0.49 | 10.92 | 59.7 |
| | 20–40 | 6.26 | 0.102 | 0.06 | 6.34 | 0.00 | 76 | 11 | 13 | 2.24 | 0.84 | 0.06 | 0.50 | 7.46 | 48.6 |
| | 40–90 | 6.93 | 0.041 | 0.087 | 7.26 | 0.26 | 75 | 8 | 17 | 2.63 | 1.31 | 0.05 | 0.50 | 8.15 | 54.3 |
| | >90 | 7.41 | 0.023 | 0.086 | 3.46 | 0.77 | 62 | 9 | 29 | 3.83 | 1.24 | 0.12 | 0.57 | 9.59 | 59.8 |
| Luvisols | 0–20 | 6.80 | 0.159 | 0.05 | 10.93 | 0.57 | 70 | 12 | 18 | 6.41 | 3.00 | 0.20 | 0.40 | 14.33 | 68.76 |
| | 20–40 | 6.69 | 0.093 | 0.03 | 9.16 | 0.43 | 67 | 12 | 21 | 7.04 | 3.00 | 0.07 | 0.71 | 15.54 | 66.16 |
| | 40–70 | 7.07 | 0.059 | 0.05 | 7.26 | 0.49 | 60 | 14 | 26 | 7.9 | 4.20 | 0.08 | 0.60 | 16.24 | 74.71 |
| | 70–110 | 7.6 | 0.033 | 0.04 | 6.07 | 0.62 | 67 | 12 | 21 | 7.67 | 4.81 | 0.10 | 0.53 | 15.35 | 69.00 |
| | >110 | 7.61 | 0.024 | 0.05 | 2.69 | 0.91 | 70 | 13 | 17 | 6.81 | 4.51 | 0.05 | 0.38 | 13.67 | 82.26 |
| Calcisols | 0–20 | 7.44 | 0.204 | 0.170 | 6.94 | 15.14 | 50 | 21 | 29 | 11.68 | 1.18 | 0.57 | 0.34 | 14.82 | 73.14 |
| | 20–50 | 7.74 | 0.120 | 0.122 | 7.21 | 15.04 | 54 | 20 | 26 | 12.90 | 1.45 | 0.45 | 0.40 | 14.82 | 78.15 |
| | >50 | 8.15 | 0.036 | 0.112 | 8.53 | 24.58 | 66 | 18 | 16 | 10.76 | 1.28 | 0.10 | 0.45 | 10.32 | 78.90 |
| Cambisols | 0–20 | 6.03 | 0.133 | 0.195 | 11.83 | 0.20 | 71 | 13 | 16 | 5.83 | 2.25 | 0.08 | 0.47 | 11.98 | 68.7 |
| | 20–40 | 6.57 | 0.070 | 0.093 | 8.70 | 0.13 | 71 | 12 | 17 | 4.4 | 2.18 | 0.08 | 1.31 | 9.86 | 70.3 |
| | >40 | 8.38 | 0.030 | 0.295 | 7.33 | 2.05 | 71 | 11 | 18 | 4.03 | 4.20 | 0.08 | 3.81 | 12.82 | 78.5 |

pH: hydrogen potential; SOM: soil organic matter; EC: electrical conductivity; C/N: carbon/nitrogen ratio; CEC: cation exchange capacity (1 M $NH_4OAc$ at pH 7.0); BSP: base saturation percentage.

### 2.2.1. Fluvisols

This RSG represents 45.5% of the study area and is mainly comprised of distric, eutric and mollic Fluvisols. These are mineral soils developed from recent alluvial deposits consisting of fluvial, marine or lacustrine sediments deposited at regular intervals, or in the recent past, appearing in the first 25 cm and reaching a minimum depth of 50 cm. Fluvic material is recognized by the presence of a thin stratification in at least 25% of the soil volume. Stratification that can be recognized by an irregular decrease of SOM. These soils are geographically located near water lines that range from coarse sand, in levee soils, to heavy clay texture in basin areas. They generally have good permeability and aeration with low water retention capacity and so they are better used in irrigation CSs. Their CEC (1M $NH_4OAc$ at pH 7.0) is generally low and their degree of percentage base saturation (PSB) ranges from 40% to 60% with pH typically varying between 5.5 and 6.5 (Table 1). These are generally fertile soils of agricultural interest [25,37,41].

### 2.2.2. Luvisols

This RSG represents 30.1% of the study area and is characterized by pedogenetic clay differentiation (clay migration) having a higher clay content in the subsoil than in the topsoil, leading to an argic subsoil horizon with high-activity clays throughout it. Its CEC (1M $NH_4OAc$ at pH 7.0) is equal or greater than 24 $cmol^{(+)}$ $kg^{-1}$ soil either starting within 100 cm from the soil surface or within 200 cm from the soil surface if the argic horizon is overlain by loamy sand or coarser textures throughout. Its PSB is higher than 50% in the 50–100 cm depth and SOM levels are typically low but with a high degree of humification. The pH is neutral to slightly acidic (Table 1). These are deep soils with good water retention and, although not presenting high chemical fertility, the availability of nutrients is good. These soils do not present any important limitations from an agricultural perspective [25,37,42].

### 2.2.3. Calcisols

This RSG represents 18.9% of the study area and typically accommodates soils with substantial accumulation of secondary carbonates within 100 cm of the soil surface, often associated with highly calcareous parent materials, and diagnosed by a brown or pale brown surface horizon, ochric A horizon, a cambic B horizon or a calcium carbonate permeated B horizon. Calcisols have a neutral or slightly alkaline pH on the surface increasing with depth. Its CEC (1M $NH_4OAc$ at pH 7.0) is medium to high, ranging from 10 to 25 $cmol^{(+)}$ $kg^{-1}$ soil and slightly decreasing in depth, and the exchange complex is saturated due to an excess of calcium. Its SOM is in the low range, typically ranging from 0.1 to 0.2 g $kg^{-1}$ of soil, but it is rich in nutrients. Most Calcisols have medium to fine texture, poorly developed structure, and good water holding properties but slaking and crust formation may hinder the infiltration of precipitation and irrigation water where surface soils are silty (Table 1). Dryness and the presence of a petrocalcic horizon limit the soil agricultural use that only reaches full productive capacity when irrigated and drained carefully. These soils provide good yields when used for cereal crop and have adequate conditions to the vine and olive groves [25,37,43].

### 2.2.4. Cambisols

This RSG represents 5.5% of the study area and is characterized by slight or moderate weathering of parent material and by the absence of appreciable quantities of illuviated clay, organic matter, soluble salts, or aluminum and iron compounds having an incipient subsurface soil formation with, typically, a cambic horizon. These soils have good aeration, good water retention, and good internal drainage. Its textures range from loamy to clayey and are structurally stable with at least 8% clay. Its SOM content is low, and its pH is neutral to slightly acidic not reaching, typically, values below 5.5. The CEC (1M $NH_4OAc$ at pH 7.0) is moderate and the PSB varies with Cambisols type (Table 1). The thickness of these soils is also very variable. These soils are suitable for all crops, except in the case of being epileptic or skeletal, where they have strong limitations. They are often the most developed soils of the region resulting, in most cases, from recent soil erosion. Cambisols are generally comprised of satisfactory chemical fertility and active soil fauna making good agricultural lands and being used intensively for food production and oil crops on irrigated alluvial plains in the dry zone [25,37,44].

### 2.3. Analytical Methods

Soil organic matter was determined by the wet oxidation method with potassium dichromate, followed by dosing of the excess dichromate by titration with ferrous sulfate [45–47]. Soil pH water ($pH_W$) was determined in a mixture of soil and water. The ratio was one soil part to five parts of water (1:5 (*v/v*)). The measurement was performed by a METROHM 692 pH/Ion Meter potentiometer [47]. Electrical Conductivity was determined in an aqueous extract with a ratio of one soil part to five parts water (1:5 (*v/v*)) with a WPA CMD 8500 conductivity meter according to the Manual for soil and water analysis by Buurman, Van Lagen & Velthorst [47] and cation exchange capacity was analyzed from soil samples following methods of soil analysis part 2 by Rhoades [48].

### 2.4. Statistical and Geostatistical Analyses

All statistical analyses were performed using SPSS v.24 software package. Shapiro-Wilk tests of normality [49,50], inspection of skewness and kurtosis measures and standard errors [51–53] and a visual inspection of the histograms, normal quantile-quantile (Q-Q) plots and box plots were performed in order to assess if the data was normally distributed. Levene's tests for homogeneity of variances [54,55] were performed in order to assess the homoscedasticity/heteroscedasticity of the data and, thus, if it could be compared in their respective categories. Independent Sample *t*-Tests were performed on all normally distributed with homogeneity of variances data and, as we have more than 30 samples per subgroup, by the application of the Central Limit Theorem we consider that our non-normally distributed data approach the normal Bell curve and, thus, we also applied the aforementioned test in non-normally distributed, but with homogeneity of variances, data. Non-normal distributed, with no homogeneity of variances, data were analyzed by Mean Rank (MR) through the Mann-Whitney U Test (U) and a 1.000 sub-sample bootstrap was applied to the data in order to compare means–Bootstrapped Means (BM). All our results had a Confidence Interval (CI) $\geq$ 95%. All null hypothesis (H0) was rejected for a $p < 0.05$. All geo-statistical analyses were performed using the Esri ArcGIS v.10.2 software package (headquarters in 380 New York Street, Redlands, CA, USA.). The predictive maps were created following the studies of authors Behera & Shukla [56] and the indications of Esri ArcGIS v.10.2 tutorials [57]. The data were interpolated through spherical model semivariograms and, as there were no strong indication to remove data trends, Ordinary Kriging interpolation was performed, adjusted for a logarithmic factor equation, aided by ancillary variables when they were available.

## 3. Results and Discussion

### 3.1. Soil Organic Matter

There was a 2.24% general decrease in SOM mean content (Table 2a) during the period of this study which is mainly explained by the 20.00% decrease in SOM (Table 2b) when transitioning from the rainfed to the irrigation CS. As the SOM content is negatively correlated with the irrigation practice and all the intensification associated with it, the registered SOM decrease was expected and occurred mainly due to a) SOM decomposition being favored at the expense of its synthesis by aerobic organisms and b) the 20.00% increase in irrigated areas [8,12,58–61] (Figure 2).

**Table 2.** SOM, $pH_w$ and EC evolution (**a**) in time (from 2001/2002 to 2011/2012), (**b**) from rainfed to irrigation CS at present time (2011/2012) and (**c**) from rainfed to irrigation CS at present time (2011/2012) by RSG.

| | Parameter | Year | RSG | CS | Mean | N | Test | *p* |
|---|---|---|---|---|---|---|---|---|
| (a) | SOM (g kg$^{-1}$) | 2001/2002 | n.a. | all | 0.134 | 1276 | U: 776,612.500 | 0.019 |
| | | 2011/2012 | | | 0.131 | 1286 | | |
| | pH (water) | 2001/2002 | | | 6.8 | 1276 | U: 734,670.000 | 0.000 |
| | | 2011/2012 | | | 7.0 | 1285 | | |
| | EC (dS m$^{-1}$) | 2001/2002 | | | 0.118 | 1276 | U: 552,106.000 | 0.000 |
| | | 2011/2012 | | | 0.154 | 1285 | | |
| (b) | SOM (g kg$^{-1}$) | 2011/2012 | n.a. | rainfed<br>irrigated | 0.150<br>0.120 | 499<br>787 | U: 136,561.000 | 0.000 |
| | pH (water) | | | rainfed<br>irrigated | 6.93<br>7.00 | 499<br>786 | T (1283): −1.217 | 0.224 |
| | EC (dS m$^{-1}$) | | | rainfed<br>irrigated | 0.124<br>0.174 | 499<br>786 | U: 131,754.000 | 0.000 |
| (c) | SOM (g kg$^{-1}$) | 2011/2012 | Fluvisols | rainfed<br>irrigated | 0.148<br>0.111 | 221<br>196 | U: 26,038.500 | 0.000 |
| | | | Luvisols | rainfed<br>irrigated | 0.152<br>0.122 | 191<br>189 | T (332): 4.465 | 0.000 |
| | | | Calcisols | rainfed<br>irrigated | 0.165<br>0.146 | 99<br>132 | T (229): 2.382 | 0.000 |
| | | | Cambisols | rainfed<br>irrigated | 0.142<br>0.135 | 59<br>36 | T (93): 0.589 | 0.557 |
| | pH (water) | 2011/2012 | Fluvisols | rainfed<br>irrigated | 6.50<br>6.63 | 196<br>430 | T (624): −1.654 | 0.099 |
| | | | Luvisols | rainfed<br>irrigated | 7.10<br>7.29 | 145<br>189 | T (332): −1.871 | 0.062 |
| | | | Calcisols | rainfed<br>irrigated | 7.97<br>8.06 | 99<br>131 | U: 6193.000 | 0.560 |
| | | | Cambisols | rainfed<br>irrigated | 6.36<br>6.39 | 59<br>36 | T (93): −0.185 | 0.854 |
| | EC (dS m$^{-1}$) | 2011/2012 | Fluvisols | rainfed<br>irrigated | 0.143<br>0.185 | 196<br>430 | T (624): −3.805 | 0.000 |
| | | | Luvisols | rainfed<br>irrigated | 0.154<br>0.195 | 145<br>189 | T (332): −2.445 | 0.015 |
| | | | Calcisols | rainfed<br>irrigated | 0.153<br>0.157 | 99<br>131 | T (228): −0.386 | 0.700 |
| | | | Cambisols | rainfed<br>irrigated | 0.095<br>0.263 | 59<br>36 | U: 462.000 | 0.000 |

SOM: soil organic matter; $pH_w$: hydrogen potential; EC: electrical conductivity; RSG: Reference Soil Group; CS: Cultivation System; U: Mann-Whitney U test; T: Two-Sample *t*-Test; n.a.: non-applicable; all: rainfed plus irrigated cultivation system; *p*: *p*-value.

When analyzing the different RSGs and comparing them by CS (Table 2c) Fluvisols, Luvisols and Calcisols significantly decreased SOM contents by 25.00, 19.74 and 11.52%, respectively, when transitioning from CS. In Cambisols this decrease was not significant, which we believe happened because of the balance between the registered intensification in the RSG, since 2002, where fallow sites were being explored for maize (*Zea mays* L.) and olive groves (*Olea europaea* L.), due to increased productivity which lead to a greater organic content left in the soil and, as the low SOM contents in the rainfed CS (Figure 3b) suggests, this RSG is very resistant to decrease its passive pool content further due to the stabilization processes demonstrated by Heitkamp [62].

Over time, all RSGs in the rainfed CS maintained SOM contents (Table 3b) which is in accordance with the studies of Teixeira [63] and Francaviglia [64] whereas in the irrigation CS Fluvisols, Calcisols and Cambisols SOM contents remained constant. This constancy over time was patent in all of the study area (Table 3a) which we believe happened because the registered SOM belongs mainly to the more resistant passive pool, that usually takes centuries to deplete [65], with its active pool being nearly depleted. Thus, the relatively short time elapsed between sample collection, associated with the intrinsic low variability of the parameter in the Mediterranean basin edaphic-climatic conditions [32–34], have led to the general stabilization. The registered decrease (6.87%) of SOM content in the Luvisols probably occurred due to loss of content in its passive pool as this RSG, as the 15-year study by Solomon, Lehmann & Zech in chromic Luvisols demonstrated [66], has week SOM buffer capacities. This decrease was also noted by Saggar where they found out that gleyic Luvisol C stocks decreased by 58% when comparing permanent pastures with a 7-year crop of maize *Zea mays* L. (5 years) + barley, *Hordeum vulgare* L., (2 years) [67].

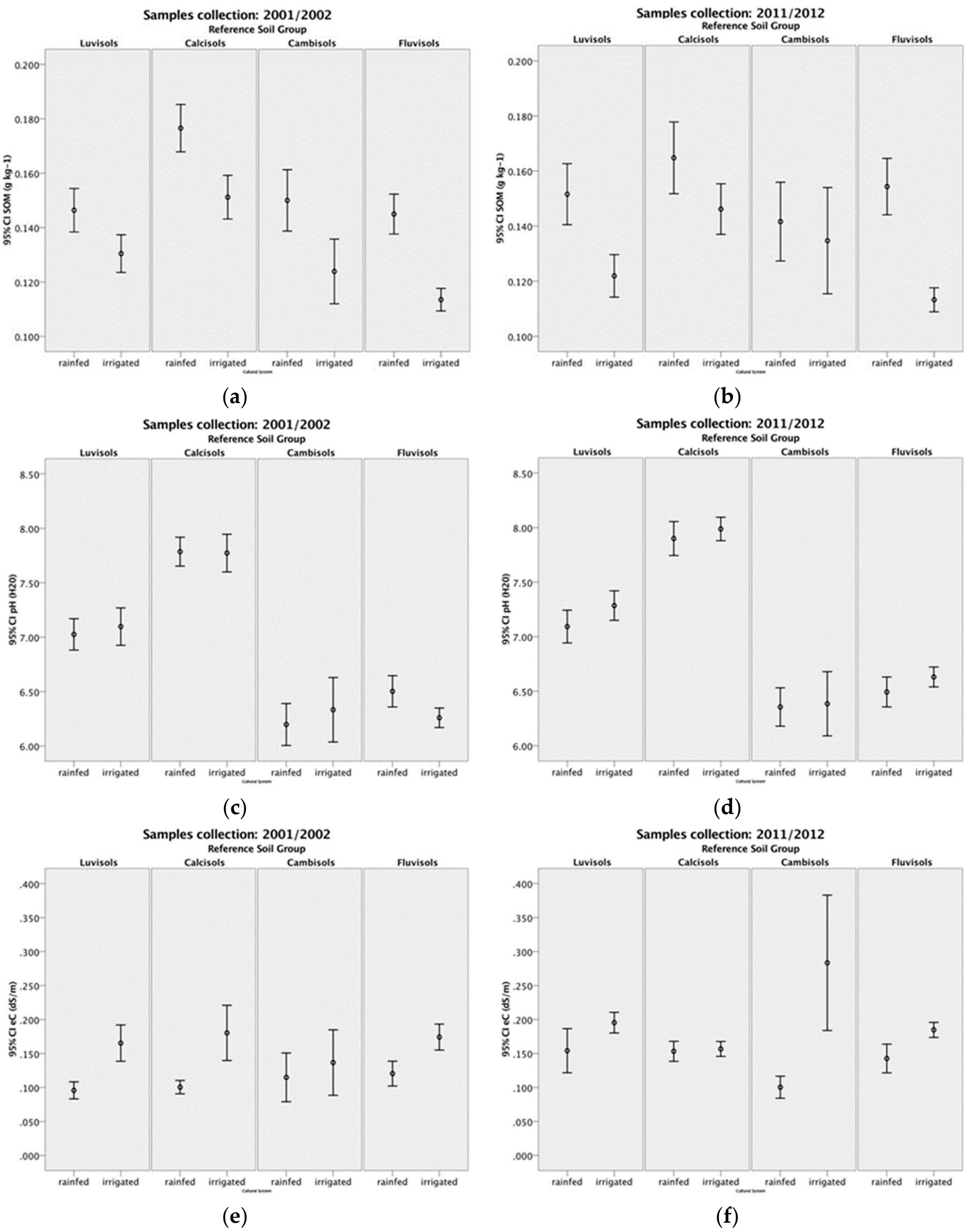



**Figure 3.** Error bar for SOM (g $kg^{-1}$) in (**a**) 2001/2002, (**b**) 2011/2012, pH (water) in (**c**) 2001/2002, (**d**) 2011/2012 and EC (dS $m^{-1}$) in (**e**) 2001/2002, (**f**) 2011/2012 by RSG and sample period.

**Table 3.** SOM, $pH_w$ and EC evolution in time (from 2001/2002 to 2011/2012) by (**a**) CS and (**b**) RSG by CS.

| | Parameter | RSG | Year | Rainfed Mean | Rainfed N | Rainfed Test | Rainfed *p* | Irrigated Mean | Irrigated N | Irrigated Test | Irrigated *p* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (a) | SOM (g kg$^{-1}$) | n.a. | 2001/2002<br>2011/2012 | 0.150<br>0.150 | 607<br>499 | U: 149,224.000 | 0.674 | 0.121<br>0.120 | 669<br>787 | U: 254,066.000 | 0.250 |
| | pH (water) | | 2001/2002<br>2011/2012 | 6.96<br>6.93 | 620<br>513 | U: 157,962.000 | 0.846 | 6.66<br>7.00 | 675<br>784 | T (1457): −6.115 | 0.000 |
| | EC (dS m$^{-1}$) | | 2001/2002<br>2011/2012 | 0.108<br>0.143 | 619<br>513 | T (933.472): −4.471 | 0.000 | 0.144<br>0.173 | 675<br>784 | U: 195,618.000 | 0.000 |
| (b) | SOM (g kg$^{-1}$) | Fluvisols | 2001/2002<br>2011/2012 | 0.145<br>0.155 | 222<br>198 | U: 20,595.000 | 0.265 | 0.114<br>0.114 | 222<br>198 | T (821): 0.130 | 0.897 |
| | | Luvisols | 2001/2002<br>2011/2012 | 0.147<br>0.151 | 194<br>152 | U: 13,755.000 | 0.284 | 0.131<br>0.122 | 160<br>188 | U: 12,697.000 | 0.012 |
| | | Calcisols | 2001/2002<br>2011/2012 | 0.176<br>0.167 | 143<br>98 | U: 6109.000 | 0.091 | 0.151<br>0.147 | 85<br>130 | U: 5270.000 | 0.567 |
| | | Cambisols | 2001/2002<br>2011/2012 | 0.155<br>0.142 | 61<br>64 | T (123): 1.461 | 0.146 | 0.124<br>0.135 | 36<br>36 | T (70): −0.968 | 0.897 |
| | pH (water) | Fluvisols | 2001/2002<br>2011/2012 | 6.50<br>6.49 | 221<br>196 | T (415): 0.092 | 0.927 | 6.22<br>6.64 | 390<br>430 | U: 63,231.500 | 0.000 |
| | | Luvisols | 2001/2002<br>2011/2012 | 7.03<br>7.10 | 191<br>145 | T (334): −0.628 | 0.530 | 7.13<br>7.32 | 158<br>189 | U: 13,636.000 | 0.164 |
| | | Calcisols | 2001/2002<br>2011/2012 | 7.79<br>7.90 | 142<br>99 | T (239): −1.097 | 0.274 | 7.83<br>8.07 | 85<br>131 | U: 4672.500 | 0.046 |
| | | Cambisols | 2001/2002<br>2011/2012 | 6.20<br>6.36 | 53<br>59 | T (110): −1.214 | 0.227 | 6.33<br>6.39 | 36<br>36 | T (70): −0.252 | 0.801 |
| | EC (dS m$^{-1}$) | Fluvisols | 2001/2002<br>2011/2012 | 0.099<br>0.120 | 221<br>196 | U: 16,889.500 | 0.000 | 0.149<br>0.173 | 390<br>430 | U: 64,190.500 | 0.000 |
| | | Luvisols | 2001/2002<br>2011/2012 | 0.083<br>0.129 | 191<br>145 | U: 6449.500 | 0.000 | 0.140<br>0.185 | 158<br>189 | U: 9895.000 | 0.000 |
| | | Calcisols | 2001/2002<br>2011/2012 | 0.095<br>0.145 | 142<br>99 | U: 2,587.000 | 0.000 | 0.149<br>0.151 | 85<br>132 | U: 4642.000 | 0.032 |
| | | Cambisols | 2001/2002<br>2011/2012 | 0.096<br>0.094 | 53<br>59 | U: 1364.500 | 0.246 | 0.114<br>0.245 | 36<br>36 | U: 364.000 | 0.001 |

SOM: soil organic matter; pH: hydrogen potential; EC: electrical conductivity; RSG: Reference Soil Group; U: Mann-Whitney U test; T: Two-Sample *t*-Test; *p*: *p*-value.

These results suggest that, while most of the Mediterranean basin soils are not able to support the transition from rainfed to irrigation CS without organic matter depletion, they will reach an equilibrium point where, even under irrigation, they will maintain SOM contents for at least a decade.

*3.2. pH*

Soil $pH_w$ significantly increased (Table 2a) during this study by 0.20 (2.94%) until reaching neutrality at around 7.00 but it was maintained when transitioning from the rainfed to the irrigation CS (Table 2b) even when considering the distinct RSGs (Table 2c).

Over time, there were no significant changes in the rainfed soils $pH_w$ (Table 3a) but in the irrigation CS, it increased by 0.34 (5.10%). This alkalinization occurred in the Fluvisols and Calcisols (Table 3b, Figure 3c,d) with an increase of 0.42 (6.75%) and 0.24 (3.07%) respectively which, although in accordance with dos Reis [29] are also contrary to the findings of other authors [26–28]. These results may be better explained in rainfed and irrigated soils separately.

In rainfed soils, $pH_w$ stabilization may occur due to (a) the low leaching and drainage capacity of most study area soils that caused the soil exchange complex (SEC) to be saturated with non-acid cations—mostly $Ca^{2+}$ and $Mg^{2+}$—released by mineral weathering [12] leading to a limited presence of acid cations—$Al^{3+}$ and $H^+$—in it and (b) the accentuated climatic changes that are rising exponentially causing lower precipitation and higher temperatures in the Mediterranean basin [68–71] whose soils tend to dry out at a faster rate, due to the higher evapotranspiration over precipitation causing the leaching rates to be increasingly lower and, thus, leaching ever fewer non-acid cations from the soil solution that accumulates in the SEC and, consequently, maintaining or raising $pH_w$ [65].

In irrigated soils, $pH_w$ increase may be explained by (a) all the aforementioned reasons for rainfed soils as the sum of precipitation and irrigation water are insufficient to leach the non-acid cations from the soil solution, that are then free to re-exchange places with the acid cations that had exchanged with them previously and were now in the SEC until an equilibrium is reached, b) the dissolution of calcite ($CaCO_3$) into $Ca^{2+}$ and carbonates ($CO_3{}^{2-}$) as, when the $CO_3{}^{2-}$ reacts with water, it generates $HCO_3{}^-$ and $OH^-$ raising pH and the $HCO_3{}^-$, that now accumulates in the soil solution, forms carbonic acid ($H_2CO_3$) by combining with $H^+$ and thus raising $pH_w$ further and c) the 47.23% increase in $HCO_3{}^-$ in the irrigation water that further promotes the reaction just explained. These results are in accordance with the studies of dos Reis [29] and Ayoub [30], to the point where $pH_w$ has increased, or at the very least maintained, its values in the irrigated soils.

The soil $pH_w$ here presented are expected for soils developed over calcareous substrata in the Mediterranean basin [72].

*3.3. Electrical Conductivity*

Mean EC content (Table 2a) significantly increased in the study period by 30.50% in the study area and increased 40.32% when transitioning from the rainfed to the irrigation CS (Table 2b). This increase was registered in the Fluvisols, Luvisols, and Cambisols (Table 2c, Figure 3) with an increment of 29.37, 26.62 and 76.84% respectively. This increase in EC is in line with the decrease in SOM levels [12,61,73,74].

Over time, there was also a significant increase in the rainfed and irrigated CSs (32.41 and 20.14% respectively) EC (Table 2a).In the rainfed system the Fluvisols, Luvisols, and Calcisols increased EC by 21.21, 55.42 and 52.63%, respectively, which we believe is a clear indicator of the effect the climatic changes are perpetrating in the basin soils, in line with the pH indicator, and that are leading to increasingly lower precipitation and higher temperatures in the area soils [68,69,71,75] which dry out at bigger rates due to the increased evaporation over rainfall causing the leaching rates to be increasingly lower and thus fewer ions being washed from the soil.

In the irrigated CS there was a significant increase over time in EC in all studied soils. Fluvisols, Luvisols, Calcisols, and Cambisols incremented its EC by 16.11, 32.14, 1.34 and 114.91%, respectively, results that are generally accepted by the scientific community [12,61,74,76,77] and that highlight the high correlation between EC values and the CS. The patent heterogeneity of EC values measured in each RSG is due, in our opinion, to the large diversity of agricultural techniques and crops cultivated in the irrigation CS and confirms the aforementioned recent intensification in Cambisols.

This increase in soil salts results from the large volume of water applied to irrigated crops [24,78,79] even when the irrigation water is of very good quality, as is the case of the study area, causing the soil EC to rise. Other reasons are the cultural intensification associated with irrigation, namely the use of inputs such as fertilizers that induce an increase in the ion content of the soil and, hence, of the EC, leading to the secondary salinization of irrigated soils [12,61,78]. Also, as aforementioned, the low leaching capacity of the Mediterranean basin soils and increase in temperature in the region furthers the gap between leached and accumulated salts. It's also worth noting that the registered increase of 2,500 ha of soils under irrigation in the study area, in detriment of the rainfed ones, from 2001/2002 to 2011/2012 (Figure 2) also contribute to the general increase in EC because of the reasons just discussed related to intensification.

### 3.4. Predictive Maps

The SOM content in the soils of the study area range, as expected for the region, from low to very low levels (Table 4). The predictive maps (Figure 4a,b) confirm that the lowest SOM contents are present in the northeast, east, and southeast of the study area which is where the rivers Caia and Guadiana are located and, consequently, most of the irrigation crops (Figures 1b and 2). The highest SOM contents are located at the west where most rainfed areas are located.

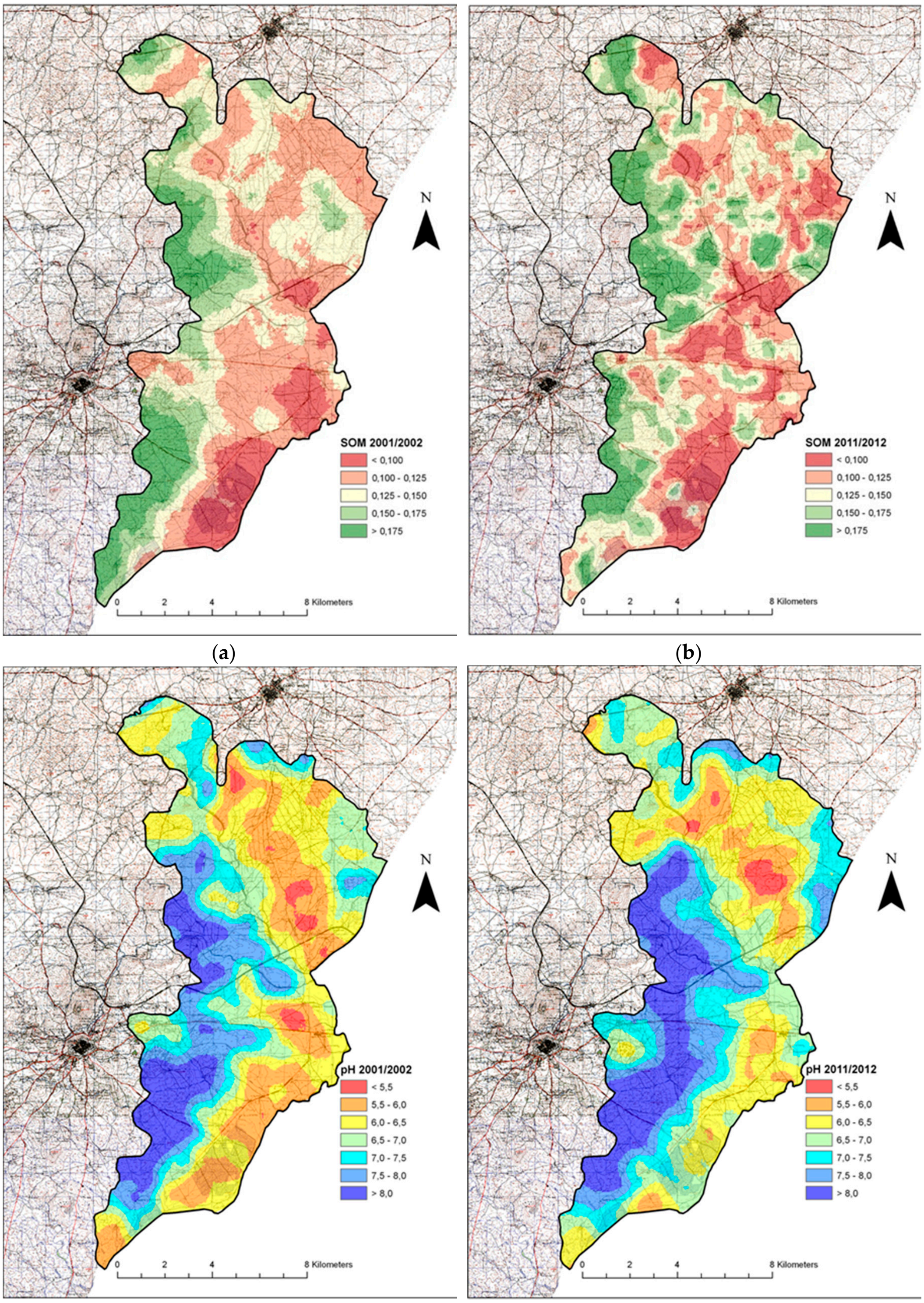
**Table 4.** SOM (%), pH (water) and EC (dS $m^{-1}$) content classes in 2001/2002 and 2011/2012.

| Parameter | Range | 2001/2002 | | 2011/2012 | |
|---|---|---|---|---|---|
| | | Area (ha) | % | Area (ha) | % |
| SOM (g $kg^{-1}$) | <0.100 | 1614.4 | 10.7 | 2499.0 | 16.6 |
| | 0.100–0.125 | 15,371.3 | 35.6 | 4143.8 | 27.6 |
| | 0.125–0.150 | 4002.5 | 26.6 | 3769.7 | 25.1 |
| | 0.150–0.175 | 2229.6 | 14.8 | 2507.4 | 16.7 |
| | >0.175 | 1852.2 | 12.3 | 2106.2 | 14.0 |
| pH (water) | <5.5 | 284.7 | 1.9 | 233.1 | 1.5 |
| | 5.5–6.0 | 2981.4 | 19.8 | 1217.9 | 8.1 |
| | 6.0–6.5 | 3559.1 | 23.6 | 3696.9 | 24.6 |
| | 6.5–7.0 | 2912.8 | 19.4 | 3110.8 | 20.7 |
| | 7.0–7.5 | 1846.5 | 12.3 | 2425.9 | 16.1 |
| | 7.5–8.0 | 1768.7 | 11.8 | 1847.2 | 12.3 |
| | >8.0 | 1682.0 | 11.2 | 2503.4 | 16.7 |
| EC (dS $m^{-1}$) | 0.15 | 13,779.3 | 91.7 | 2721.2 | 18.1 |
| | 0.15–0.30 | 1206.5 | 8.0 | 10,184.1 | 67.8 |
| | 0.30–0.45 | 40.0 | 0.3 | 1959.6 | 13.0 |
| | 0.45–0.60 | 0.0 | 0.0 | 144.2 | 1.0 |
| | >0.60 | 0.0 | 0.0 | 17.3 | 0.1 |

SOM: soil organic matter; pH: hydrogen potential; EC: electrical conductivity.

Regarding the soils $pH_w$, 31.70% for 2001/2002 and 36.80% for 2011/2012 of the soils are near neutrality ($6.5 < pH_w < 7.5$) and there is virtually no presence of very acidic soils ($pH_w < 5.5$) in either. Slightly to alkaline soils ($pH_w > 7.5$) have great representativeness in the study area and have increased their presence by 26.00% and with it the potential to restrain P, Br, Fe, Mn, Zn, Cu and Co availability reducing most crops productivity and also granting readily availability of B, Mo and Se that may accumulate at harmful levels. Soils with $5.5 < pH_w < 6.0$ decreased by 59.10% in the period of this study (Figure 4c,d). We note that it is, above all, in the region at the west that the higher pH values are located and that the lower values are at the north, south, and east of the study area.

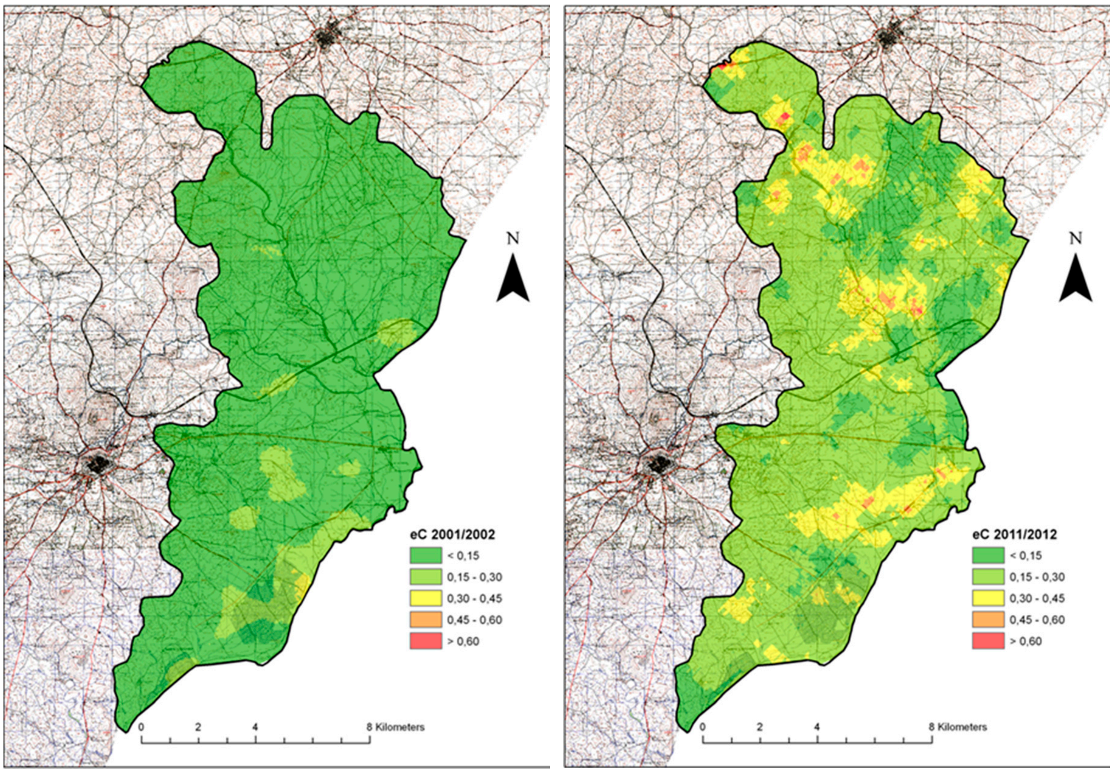
As for EC the majority of soils have a very low conductivity in both sampled universes. In 2001/2002 only 0.30% of the study area (40.0 ha) had an EC > 0.3 dS $m^{-1}$ but in 2011/2012 this rate rose to 14.10% (2,121.1 hectares) representing an increase of 4700.00%. EC is generally increasing (Figure 4e,f) and the highest EC was registered where irrigation has been practiced for longer periods and that the lowest EC are registered where most rainfed areas are located (Figures 1b and 2b). Although the study area EC values are yet far from being considered saline (EC > 4.0 dS $m^{-1}$), and thus not a huge concern at the present time [12,80], it is gaining preponderance which may become a problem in the future if this build-up is not reversed.




(**a**) (**b**)

(**c**) (**d**)

**Figure 4.** *Cont*.




(**e**) (**f**)

**Figure 4.** Predictive maps for SOM (g kg$^{-1}$) in (**a**) 2001/2002, (**b**) 2011/2012, pH (water) in (**c**) 2001/2002, (**d**) 2011/2012 and EC (dS m$^{-1}$) in (**e**) 2001/2002, (**f**) 2011/2012.

## 4. Conclusions

When transitioning from rainfed to irrigation CS, SOM decreased in all soils with the exception of the RSG Cambisols that was able to maintain its SOM content. After Cambisols, the soils with the best buffering capacity to resist SOM loss were the Calcisols, Luvisols and finally Fluvisols that revealed the lowest capacity. Over time all rainfed soils were able to maintain their SOM content and, in the irrigation CS, only the Luvisols showed some depletion. Soil $pH_w$ is increasing in most of this Mediterranean basin area but, as all soils were able to buffer $pH_w$ in the CS transition, the increase isn't related to transition itself. Over time all soils were able to maintain their $pH_w$ in the rainfed CS but in the irrigation CS, the Calcisols and Fluvisols went through some alkalinization with Calcisols presenting a better buffer capacity than Fluvisols but worse overall than Cambisols and Luvisols. Soil EC increased when transitioning from the rainfed to irrigation CS in most of the study area with Calcisols being the only RSG able to maintain salt contents; Fluvisols and Luvisols slightly increased and Cambisols revealed the most increase in EC. Over time, considering the rainfed soils, only Cambisols were able to maintain the EC content with Fluvisols revealing better buffer capacity than Luvisols and Calcisols and in the irrigated CS, all soils increased its EC with Cambisols revealing the worst scenario followed by Luvisols, Fluvisols, and Calcisols, the latter barely incrementing the EC content. These results may be, with the necessary care and adaptations, extrapolated to other regions of the Mediterranean basin or even to other regions with similar edaphic-climatic, and irrigation water, characteristics and can be a tool for improving resource management with the potential to reduce the environmental impact of irrigation.

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