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Assessing the Long-Term Impact of Traditional Agriculture and the Mid-Term Impact of Intensification in Face of Local Climatic Changes

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Abstract: In the Mediterranean basin, edaphic salinization, sodification and alkalinization related to anthropic pressures and climatic changes may hinder the ecosystem sustainability. It is pertinent to study the mid and long-term variability of these soil characteristics in face off the macro agricultural system in use (i.e., irrigation or rain-fed). Four irrigated soils from the Caia Irrigation Perimeter (Portugal), Fluvisols, Luvisols, Calcisols and Cambisols were analysed in the mid-term, from 2002 to 2012, for its available Ca^{2+}, Mg^{2+}, K^+ and Na^+ content. Overall, Ca^{2+}, K^+ and Na^+ significantly increased during the period of this study by 25%, 8% and 7%, respectively. Soil organic matter (SOM) and pH for the irrigated soils in the area were already assessed in previous studies with the overall SOM remaining constant ($p \geq 0.05$) and pH increasing ($p < 0.01$) by 5%. We provide the predictive maps for Na^+ and the CROSS predictive & HotSpot evolution map from 2002 to 2012. Rain-fed soils were analysed in the long-term, from 1965 to 2012, for their SOM, pH and non-acid cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) content. While SOM, pH and the exchangeable Ca^{2+}, Mg^{2+} and K^+ significantly increased ($p < 0.01$) by 23%, 8%, 60%, 21% and 193%, respectively, exchangeable Na^+ significantly decreased ($p < 0.01$) by 50%. These results may be related to the local climate changes as, according to the Thornthwaite classification, it went from sub-humid with great water excess (C1B2s2b4) in the climate normal 1951/1980 to sub-humid with moderate water excess (C1B2sb4) in 1981/2010 to semi-arid with little to none water excess (DB2db4) in 1991/2020. The irrigated areas in this Mediterranean region are slowly departing from sustainable goals of soil conservation and better edaphic management and conservation practices, that address the registered climatic changes in the area, could be adopted.

Keywords: soil degradation; anthropic pressure; mediterranean basin; semi-arid; desertification

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1. Introduction

As usually practiced today, agricultural intensification has a double-link effect across the ecosystem, with soils losing their richest layer to the sea through accelerated erosion created by anthropogenic weathering, such as tillage, plowing, harrowing or scarification [1], primary causes responsible for the continuous decline in soil organic matter (SOM) levels and edaphic compaction [2–5]. Also, there is also an increased salinity in soils due the higher amounts of fertilizers in irrigation water [6–8]. Salt accumulation leads, above all, to low agricultural production, soil erosion, decreased permeability and infiltration rate of the soil, low groundwater recharge, compacting, crusting and invariably to low economic returns [9]. The degradation of the Mediterranean basin soils [10,11] is but a particular example of the ecosystem unsustainability with ever growing desertification hotspots due to the global and local climate change and inadequate local practices with the soils becoming more alkaline, saline, and deprived of SOM [1,4,12–14] exposing the importance of adopting a multidimensional approach for agricultural sustainability in the Mediterranean basin, as demonstrated in the studies of Stagnari et al. [15], Pagnani et al. [16] and Farooq et al. [17]. The growing problem of saline and sodic soils already affects a quarter of all agricultural soils degrading the soil structure by means of clay swelling and dispersion and is more present in areas experiencing desertification whether they are arid or semi-arid [18–20]. Alkalinization is another main cause of degradation occurring in the Mediterranean basin soils [8,14,21] that go hand in hand with salinization and sodification in the semi-arid regions [22] and that, according to Laraus [23] may eventually lead to the abandonment of the lands.

Calcium, magnesium, sodium and potassium tend to accumulate in semi-arid and arid regions as the amount of precipitation in the basin is not sufficient to leach the chlorides and sulfates salts even when these soils are under irrigation [24] and, thus, the primary and secondary salinity in the Mediterranean basin seems to be unavoidable with this condition only worsening due to the general thin layers, poorer drainage capacity of these soils and dry climate [1,25]. Where the precipitation, or precipitation plus irrigation water, is less than the potential evapotranspiration (ET0) the cations released, be it by mineral weathering or anthropically added [6], accumulate as there is not enough precipitation to thoroughly leach them away leading to the alkalinization of the soils depending on the equilibrium between the acid (H^+, Al^{3+}) and non-acid cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) in the soil colloids and the equilibrium between H^+ and OH^- in the soil solution, both controlled by the nature of the soil colloids. Because the deflocculating monovalent ions Na^+ and K^+ are not leached from the soils of the dry regions, the type of clays dominating in alkaline soils tend to deflocculate or disperse which furthers the reduced macroporosity, aeration, water percolation and sealing of the soil surface. In our opinion, the edaphic impact of these ions is well described in the 'cation ratio of soil structural stability' (CROSS) equation (Equation (1)) as it considers the different effects of Na^+ and K^+ in deflocculating, and that of Mg^{2+} and Ca^{2+} in flocculating, soil clays that parameterize the structural effects in the soil solution better than the Sodium Adsorption Ratio (SAR) or the Potassium Adsorption Ratio (PAR) as demonstrated by Rengasamy and Marchuk [26] and that is being adopted by the scientific community for the last decade [27–30].

The present study aims to improve the knowledge on how some edaphic parameters evolve in traditional agriculture performed in rain-fed sites and in intensive agriculture via irrigation in a semi-arid region of the Mediterranean basin. Specifically, this study focuses on the variations of (a) the available Ca^{2+}, Mg^{2+}, K^+ and Na^+ in irrigated sites in the mid-term and (b) the non-acid cations in rain-fed sites in the long-term, in the evidence of local climatic changes in real agricultural conditions instead of the more controlled field experiments conducted in small plots as in Di Matteo et al. [31] or González et al. [32] or remote sensing as in Attwa et al. [33], or González-Zamora et al. [34].

$$CROSS = \frac{Na + 0.56K}{\sqrt{\left[\frac{(Ca+0.6Mg)}{2}\right]}} \quad (1)$$

2. Materials and Methods

2.1. Study Area

The study area is positioned in the Alentejo region (NUTS II) between Campo Maior and Elvas in the borderline between Portugal and Spain, at the junction of the rivers Guadiana and Caia, in the Mediterranean basin region with a total area of 14,852 ha. The average annual rainfall is 483 mm, falling from October to March. The geology is heterogeneous and mainly consisting of hyperalkaline and basic rocks. The most important crops in the study area are: *Olea europea* L., *Zea mays* L., *Lycopersicon esculentum* Mill. and *Allium sativum* L. with a preponderance of 35%, 20%, 15% and 15%, respectively. The irrigation water is classified by FAO as C1S1 (i.e., with the lowest levels of salinity and sodicity, water of very good quality) [35]. According to the FAO Soil Resource (WRB) [36] there are 4 Reference Soil Groups (RSG) present, Cambisols, Luvisols, Fluvisols and Calcisols, which are in accordance with what is expected for the Mediterranean ecosystems [25,35,37]. None of the soils were presented to extended irrigation practices since 1965 and, so, soil evolution in rain-fed systems was obtained by comparing the exchange bases Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} from that year to 2012. Since 1969 some of the soils were under irrigation practice with the start of operations of the Caia Irrigation Perimeter and the irrigated soil evolution was obtained comparing Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} from the soil solution for the sample years 2002 and 2012. Laboratory method analysis that quantify the exchange cations applied in the 2002 samples are different from the methods applied in the 1969 and 2012 samples invalidating its comparison but, recurring to the 'Ratio Law' [38] that states that the cations adsorbed in the soil exchange complex (SEC) are in balance with the cations in soil solution at any given time, we analyze the ions in the soil solution and extrapolate these findings to the soil complex. We followed the general methodology presented in Figure 1. Please refer to Nunes [35] and Figures 1 and 2 of Telo da Gama et al. [5] for more details on the study area.

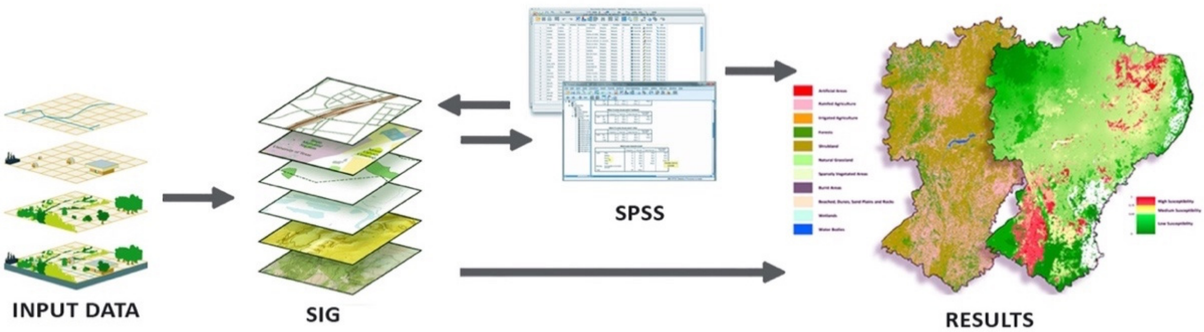


Figure 1. Data treatment–general methodology.

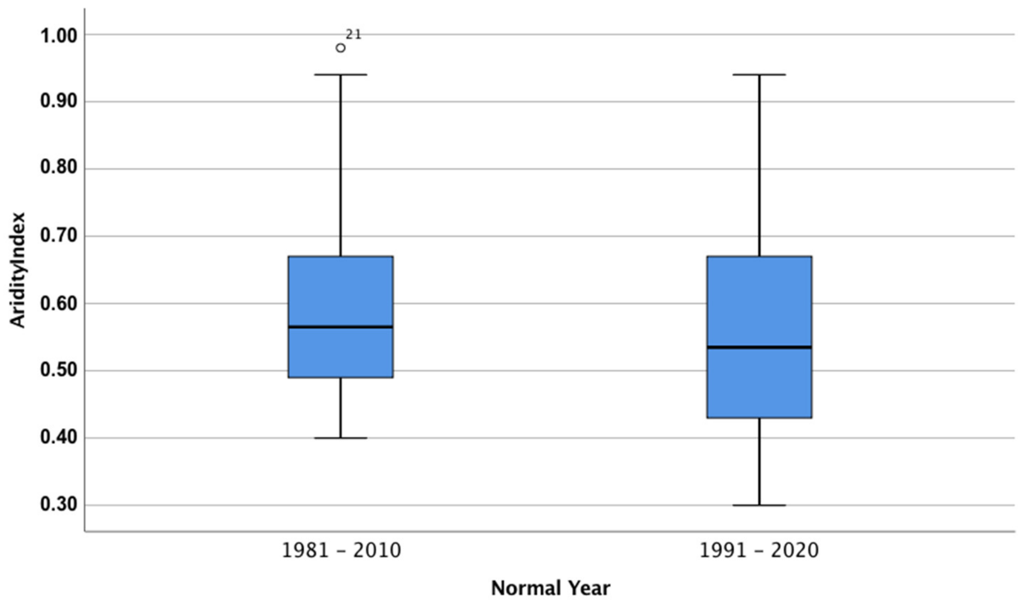


Figure 2. Boxplot chart for the climate normals 1981–2010 and 1991–2020.

2.2. Soil Data

Cardoso in a study performed in the same area in 1965 [39], classified the soils using the dated Portuguese Soil Classification system. We related the samples taken by Cardoso with our study area soils via Geographic Information Systems (GIS) software where the predominant parameter of classification was considered as the key factor to soil classification (e.g., a 'Pag/Pac' was treated as a Pag) were we performed weighted arithmetic means so that the final equations reflect the average weight of each soil. Assuming that the data from 1965 represents the mean values for a specific soil type is a flaw in this study. See Auxiliary data #1.

All samples were correlated, compared and analyzed with physical soil attributes such as land cover percentage, physiographic position, soil useful depth, hydromorphic symptoms, water table distance, stoniness and crop. The tables concerning these results are not shown in this paper (please refer to the Auxiliary data #2) and will be presented in the paper with a parentheses enclosed asterisk "(*)".

Soil data for the 2002 and 2012 samples was obtained according to the methodology presented in Telo da Gama et al. [5], please refer to this paper to obtain a detailed edaphic description of the study area.

2.3. Climatic Data

Three climate normals were considered so that the year of the analyzed sample data were the closest possible to its average (i.e., for the 2012 data we considered the climate normal 1991/2020, for the 2002 the 1981/2010 and for the 1965 the 1951/1980 climate normal was considered). Aridity indexes (i.e., the precipitation-to-evaporation ratio) were obtained dividing the precipitation by the ET0 (Equation (2)).

$$Aridty\ Index = \frac{precipitation}{\mathrm{ET0}} \tag{2}$$

The normal climatic data from:

- 1951/1980 (Table 1) was obtained from the book *O clima de Portugal* [40] that gathered data from the Elvas meteorological station.
- 1981/2010 (Table 2) and 1991/2020 (Table 3) was calculated from monthly data (ranging from 1969 to 2020) gathered in the meteorological station of the study area. The evapotranspiration (ET0) was determined with the unadjusted Hargreaves equation (Equation (3)). The Portuguese Institute of the Sea and the Atmosphere (IPMA) provided the radiation (Ra) values. The homogeneity of the data is guaranteed as logistics in climatic observations remained constant.

$$ET0 = a + b \times \frac{1}{\lambda} \times 0.0023 \times \left(\frac{Tmax + Tmin}{2} + 17.8\right) \times \sqrt{Tmax - Tmin} \times Ra \tag{3}$$

Parameters a (mm d^{-1}) = 0, b = λ = 1; *Ra* (MJ m^{-2} d^{-1}): extra-terrestrial solar radiation; T_{min} (°C): minimum daily air temperature; T_{max} (°C): maximum daily air temperature.

2.4. CROSS

The cation ratio of soil structural stability (CROSS) was determined as presented in the Equation (1) and we assess the evolution of soil dispersion through it as the CROSS reflects the theoretical and empirical observations that the K^+ ion has a dispersion power 0.560 times lower than that of Na^+ and that the Mg^{2+} ion has a flocculation power 0.6 times lower than that of Ca^{2+} as demonstrated by Rengasamy and Marchuk [26].

Table 1. Climate normal 1951/1980 [40].

Month	Aver. Temp (°C)	Max. Temp. (°C)	Min. Temp. (°C)	Prec. (mm)	ET0 (mm)	Aridity Index
January	8.6	13.2	4.0	80.8	16.9	4.78
February	9.6	14.5	4.8	82.0	24.0	3.42
March	11.6	16.9	6.2	80.2	47.2	1.70
April	13.8	19.9	7.7	47.7	56.8	0.84
May	17.5	24.4	10.6	37.6	92.1	0.41
June	21.5	29.0	13.9	25.0	125.0	0.20
July	24.6	33.2	16.0	3.6	140.0	0.03
August	24.3	32.9	15.8	4.4	118.3	0.04
September	21.8	29.2	14.3	27.3	75.0	0.36
October	17.1	23.0	11.2	60.0	36.5	1.64
November	12.0	17.0	6.9	75.1	22.1	3.40
December	8.9	13.5	4.3	77.9	17.1	4.56
year	15.9	22.2	9.6	601.6	771.0	0.78

Table 2. Climate normal 1981/2010 (data registered in the study area meteorological station).

Month	Aver. Temp (°C)	Max. Temp. (°C)	Min. Temp. (°C)	Prec. (mm)	ET0 (mm)	Aridity Index
January	8.8	13.4	4.1	55.9	18.7	2.99
February	10.3	15.2	5.5	47.1	24.5	1.92
March	12.6	18.3	6.9	34.8	50.6	0.69
April	14.3	20.1	8.6	47.7	61.4	0.78
May	17.7	24.1	11.3	37.2	89.1	0.42
June	22.0	29.6	14.4	17.8	123.6	0.14
July	25.3	33.8	16.9	5.8	148.9	0.04
August	25.4	33.9	16.9	4.2	128.9	0.03
September	22.8	29.7	16.0	26.8	79.7	0.34
October	18.0	23.3	12.6	55.5	40.7	1.36
November	13.0	17.9	8.2	73.3	26.7	2.75
December	9.6	13.8	5.5	75.8	14.5	5.23
year	16.7	22.8	10.6	483.7	807.4	0.59

Table 3. Climate normal 1991/2020 (data registered in the study area meteorological station).

Month	Aver. Temp (°C)	Max. Temp. (°C)	Min. Temp. (°C)	Prec. (mm)	ET0 (mm)	Aridity Index
January	9.0	13.7	4.5	49.5	18.5	2.68
February	10.4	15.4	5.4	38.4	24.4	1.57
March	13.3	19.0	7.8	44.1	51.1	0.86
April	15.4	21.2	9.5	45.0	62.6	0.72
May	19.2	25.9	12.5	41.8	94.0	0.44
June	22.6	30.0	15.1	10.1	123.9	0.08
July	26.3	34.7	17.6	2.1	151.0	0.01
August	26.3	34.9	17.7	4.3	130.1	0.03
September	23.3	30.0	16.5	25.0	77.7	0.32
October	18.6	24.0	13.1	68.6	39.9	1.71
November	12.9	17.4	8.5	70.7	24.8	2.85
December	10.0	14.4	5.8	58.0	15.3	3.80
year	17.3	23.4	11.2	457.4	813.2	0.56

2.5. Analytical Methods

The pH (water) for all data samples was determined in a 1:5 (v/v) solution via potentiometric method in an MTROHM 692 pH/Ion Meter [41]. SOM was obtained by the wet oxidation method with potassium dichromate, with a dosing of the excess dichromate by titration with ferrous sulfate following [41–43].

Available Ca^{2+} and Mg^{2+} for the 2012 sample data were extracted with an ammonium acetate solution buffered at pH 7.0 where 10% of lanthanum chloride solution was added and its determinations were obtained by atomic absorption spectrophotometry with flame atomization on a Perkin Elmer Analyzer A300 apparatus [42,44].

Available K^+ and Na^+ for the 2012 sample data were extracted with an ammonium lactate and acetic acid solution buffered at pH 3.65–3.75 [45] and its determinations were obtained by atomic absorption spectrophotometry with flame atomization on a Perkin Elmer Analyzer A300 apparatus.

The exchangeable cations for the 1965 and 2012 soil samples were extracted with an Ammonium acetate solution (1 N NH4OAc) buffered at pH 7.0 [46].

2.6. Statistical Analysis

Statistical analyses were performed using the software package SPSS (v.25) where tests of normality (by Shapiro-Wilk) [47,48], inspection of kurtosis, skewness and standard errors [49–51] and visual inspection of the histograms, normal Q-Q plots and box plots were performed in the climatic, 2002 and 2012 sample data in order to assess if it was normally distributed. Tests for homogeneity of variances (Levene's) [52,53] were also performed in this subset in order to assess its homoscedasticity/heteroscedasticity. In the 2002 and 2012 irrigation sample data we performed, on all normally distributed with homogeneity of variances data, Independent Sample *T*-Tests and we applied the Central Limit Theorem where we have more than 30 samples per subgroup on our non-normally distributed, but with homogeneity of variances, data. Data that showed non-normal distribution and with no homogeneity of variances was directly analyzed by Mean Rank (MR) through the Mann-Whitney *U* Test (*U*) or the Kruskal-Wallis *H* test (*H*). One sample *T*-tests (*T*) were applied to compare rain-fed soil data from the 2012 samples with the means from 1965 and also to compare the means in climatic data from the climate normal of 1951/1980 to the registered data since 1969. All null hypothesis was rejected for a $p < 0.05$. Geographic information system analysis were performed in ArcGIS v 10.5 software package and the predictive maps created with an Ordinary Kriging interpolation which was adjusted for a logarithmic factor equation and, when available, aided by ancillary variables [54–62]. We also performed Getis-Ord Gi HotSpot analysis where the conceptualization of spatial relationships was achieved by inverse distance squared. Non-predictive maps were created with the software package QGIS 2.18.27 'Las Palmas' [63].

3. Results

3.1. Climate

Since the climate normal of 1951/1980 the precipitation has declined approximately 24% and the ET0 has increased 6% in the studied area (Tables 1–3). One sample *T*-tests reveal that the decrease in precipitation and the increase in ET0 were statistically significant between the climate normal 1951/1980 and 1981/2010 ($p < 0.01$) and between the climate normal 1981/2010 and 1991/2020 ($p < 0.01$) but it was not significantly different ($p > 0.05$) when comparing the climate normals 1981/2010 and 1991/2020 (Table 4), probably because of the slow variability of the parameters in such short time span, although a boxplot comparison with a confidence interval of 95% reveals that, indeed, the aridity index average is ever becoming closer to the 0.50 mark (Figure 2), having decreased from an average of 0.78 in 1951/1980 to 0.56 in 1991/2020 (Table 4) with polarized values as high as 0.98 and as low as 0.30.

The annual average rainfall is 465.8 mm, falling mostly from October to March. When compared with the official IPMA climate normal [64] the average monthly temperature of the coolest month continues to be January and that of the hottest month changed from July to August. The most recent climate normal was already presented in Table 3. Even when considering a simple linear projection approach, the aridity index in the study area will, most probably, surpass the 0.50 mark till 2050 (Figure 3).

Table 4. Precipitation, ET0 and aridity index comparisons between climate normals.

Variable	Climate Normal	Mean	*N*	Test	*p*
Precipitation	1951–1980 1981–2010	601.6 483.7	1 30	T(29): −5.337	0.000
	1951–1980 1991–2020	601.6 457.5	1 30	T(29): −6.865	0.000
	1981–2010 1991–2020	483.7 457.5	30 30	T(58): 0.859	0.394
ET0	1951–1980 1981–2010	771.0 817.7	1 30	T(29): 5.728	0.000
	1951–1980 1991–2020	771.0 820.8	1 30	T(29): 5.464	0.000
	1981–2010 1991–2020	817.7 820.8	30 30	T(58): −0.247	0.806
Aridity Index	1951–1980 1981–2010	0.78 0.59	1 30	T(29): −6.617	0.000
	1951–1980 1991–2020	0.78 0.56	1 30	T(29): −7.521	0.000
	1981–2010 1991–2020	0.59 0.56	30 30	IT(58): 0.770	0.445

T: One-sample *T*-test; U: Mann-Whitney *U* test; IT: Two-sample *T*-test; *p*: *p* value.

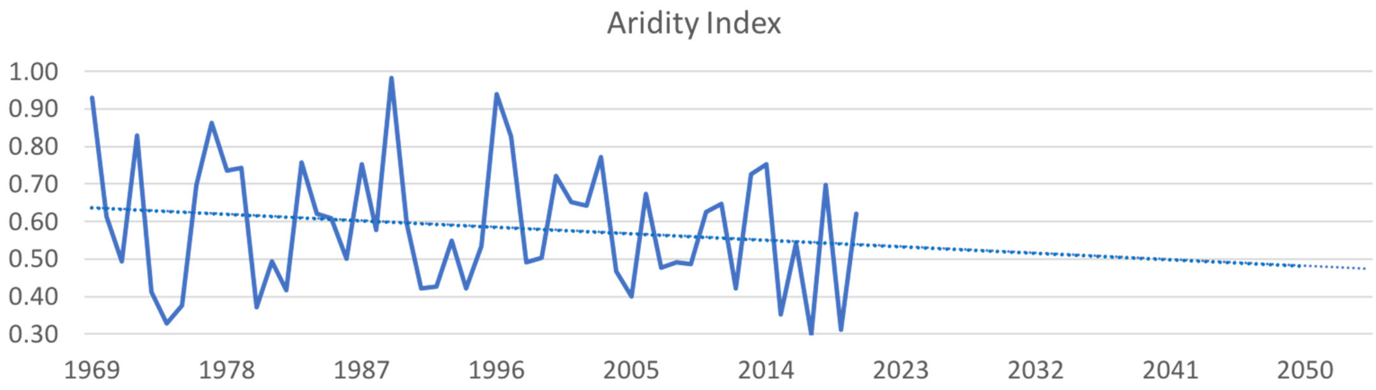


Figure 3. Aridity index in the study area and linear projection for the year 2050.

3.2. Irrigated Soils

An increase of 24.9% (Table 5a; $p < 0.01$) is observed in the levels of available Ca^{2+} from 2002 to 2012. This increase is related to tomato crops where Ca^{2+} increased 75% from 2002 (2348.44 mg kg^{-1}) to 2012 (4119.79 mg kg^{-1}) (*). Although all the studied RSG revealed an increase in available Ca^{2+} (Table 5b) only the Fluvisols showed a significant increase of 28% ($p < 0.01$) in the parameter between sampled years while the Luvisols, Calcisols and Cambisols revealed no statistically significant difference between sampled years ($p > 0.05$). The RSG with the greatest available Ca^{2+} content are the Calcisols with an average, in 2012, of 5717.39 mg kg^{-1}.

The available Mg^{2+} soil content is stable in the mid-term and the parameter didn't revealed any statistically significant difference between sampled years (Table 5a; $p > 0.05$) presenting an average content of 271 mg kg^{-1}. Not even an overall and broad correlation between crop and Mg^{2+} could be found but an RSG specific correlation did revealed that it increased significantly by 18% ($p < 0.05$) in corn grown Luvisols from 2002 to 2012 (N 2002: 78; N 2012: 57; Average 2002: 306 mg kg^{-1}; Average 2012: 361 mg kg^{-1}; Test *T* (133): −2.008, $p = 0.047$) supporting the result shown in the Table 5b for the specific Luvisol RSG that presented a significant increase of 13% ($p < 0.05$). All other RSG revealed no statistically significant differences for this parameter.

Table 5. Mid-term evolution (2002 to 2012) of selected soil parameters in irrigated soils.

	Parameter	Year	RSG	Mean	*N*	Test	*p*
(a)	Ca^{2+} (mg kg^{-1})	2002 2012	Overall	2195 2741	677 784	U: 222,236.000	0.000
	Mg^{2+} (mg kg^{-1})	2002 2012		263 279	677 783	T (1.458): −1.205	0.228
	K^{+} (mg kg^{-1})	2002 2012		204 223	677 784	T(1.459): −2.672	0.008
	Na^{+} (mg kg^{-1})	2002 2012		44.3 47.2	677 765	U: 146,232.000	0.004
(b)	Ca^{2+} (mg kg^{-1})	2002 2012	Fluvisols	1279 1640	394 430	U: 70,675.000	0.000
		2002 2012	Luvisols	3200 3567	160 188	T(346): −1.532	0.126
		2002 2012	Calcisols	5402 5816	85 130	T(213): −1.227	0.221
		2002 2012	Cambisols	1155 1665	36 36	T(70): −1.551	0.125
	Mg^{2+} (mg kg^{-1})	2002 2012	Fluvisols	234 243	394 430	U: 79,545.500	0.130
		2002 2012	Luvisols	315 356	160 187	T(345): −2.110	0.036
		2002 2012	Calcisols	297 271	85 130	T(213): 1.606	0.110
		2002 2012	Cambisols	271 352	36 36	T(70): −1.459	0.149
	K^{+} (mg kg^{-1})	2002 2012	Fluvisols	182 201	394 430	T(822): −1.981	0.048
		2002 2012	Luvisols	230 248	160 188	T(346): −1.713	0.088
		2002 2012	Calcisols	292 266	85 130	T(213): 1.467	0.144
		2002 2012	Cambisols	158 217	36 36	U: 464.000	0.038
	Na^{+} (mg kg^{-1})	2002 2012	Fluvisols	43.6 44.7	394 421	U: 76,685.500	0.063
		2002 2012	Luvisols	45.7 51.3	160 181	T(339): −1.663	0.097
		2002 2012	Calcisols	48.2 49.7	85 129	U: 5206.500	0.533
		2002 2012	Cambisols	36.6 47.3	36 34	T(68): −1.575	0.119

Ca^{2+}: available calcium; Mg^{+}: available magnesium; K^{+}: available potassium; Na^{+}: available sodium; T: Two-sample *T*-test; U: Mann-Whitney *U* test; *p*: *p* value.

There was a significant increase ($p < 0.05$) in available K^{+} in the irrigated areas between sample periods with the parameter increasing 9% from 2002 to 2012 (Table 5a) with a more detailed analysis (Table 5b) revealing that the increase occurred in the irrigated Fluvisols ($p < 0.05$) and Cambisols ($p < 0.05$), presenting these RSG a 10% and 37% increase from

2002 to 2012, respectively, where in the Luvisols and Calcisols subjected to irrigation, the assimilable K^+ content did not offer significant variations ($p > 0.05$) in the mid-term. Also, the available K^+ distribution is the same across the different categories of Physiographic position ($p > 0.05$) but is different across soil texture, with the light textures having less potassium than the medium and heavy ones ($p < 0.05$) (*). As expected, a correlation analyses revealed that the parameter is crop related both in 2002 ($p < 0.01$) and 2012 ($p < 0.01$). For 2002 the Potassium/crop correlation was only significant in the RSG Fluvisols ($p < 0.05$) and in 2012 this correlation was significant in the RSG Fluvisols ($p < 0.05$) and Luvisols ($p < 0.01$) for olive and corn crops (*).

Considering the available Na^+ in the irrigated soils of the study area we registered a significant increase ($p < 0.05$) from 2002 to 2012 of 7% (Table 5a). A more in-depth analysis reveals that this increase isn't related with a particular RSG (Table 5b) as the available Na^+ levels do not undergo statistically significant changes ($p > 0.05$). Therefore, the mid-term increase in available Na^+ in irrigated soils is generalized, and not specific to a particular RSG, and was significantly correlated with soils that present good natural drainage ($p < 0.05$), useful depth > 0.100 m ($p < 0.01$), medium to heavy texture ($p < 0.01$) and crop ($p < 0.01$). The three crops causing the greatest accumulation of available sodium in the studied area are corn (15% increase), cereals (36% increase) and olive (34% increase), all for a $p < 0.05$ (*), with these increases occurring mainly in the Fluvisols and Luvisols RSG. The great CEC of the Luvisols (as presented in Telo da Gama et al. [5]) where corn crop was grown, and the general increase in ET0, provided that the sodium content augmented by 98% during the period of this study in the aforementioned RSG as the error bar (Figure 4) and predictive map analysis (Figure 5) confirm.

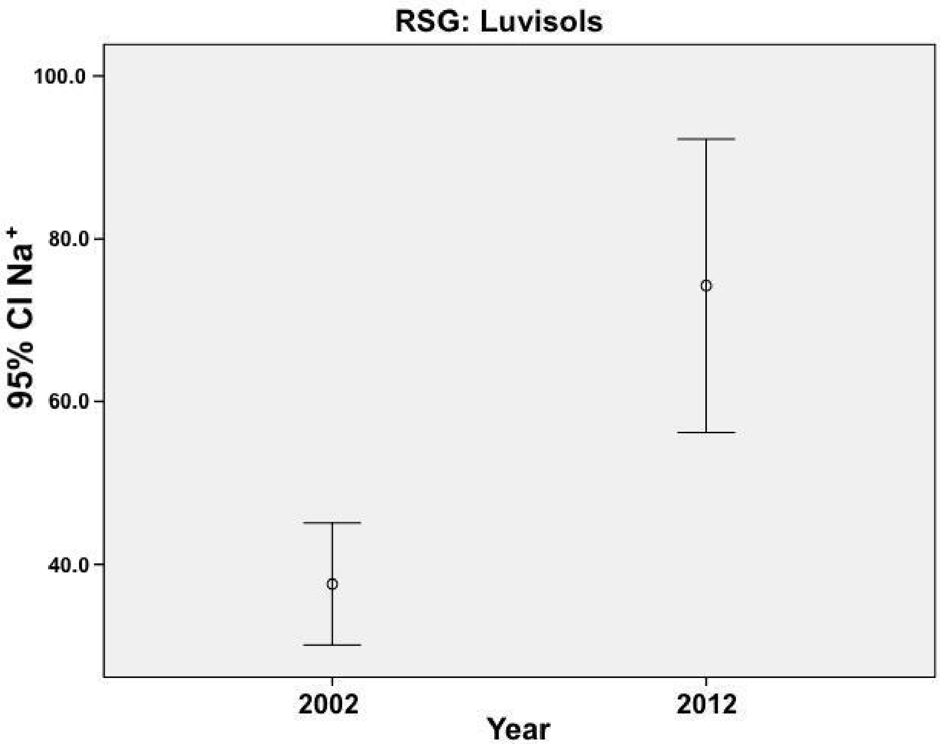
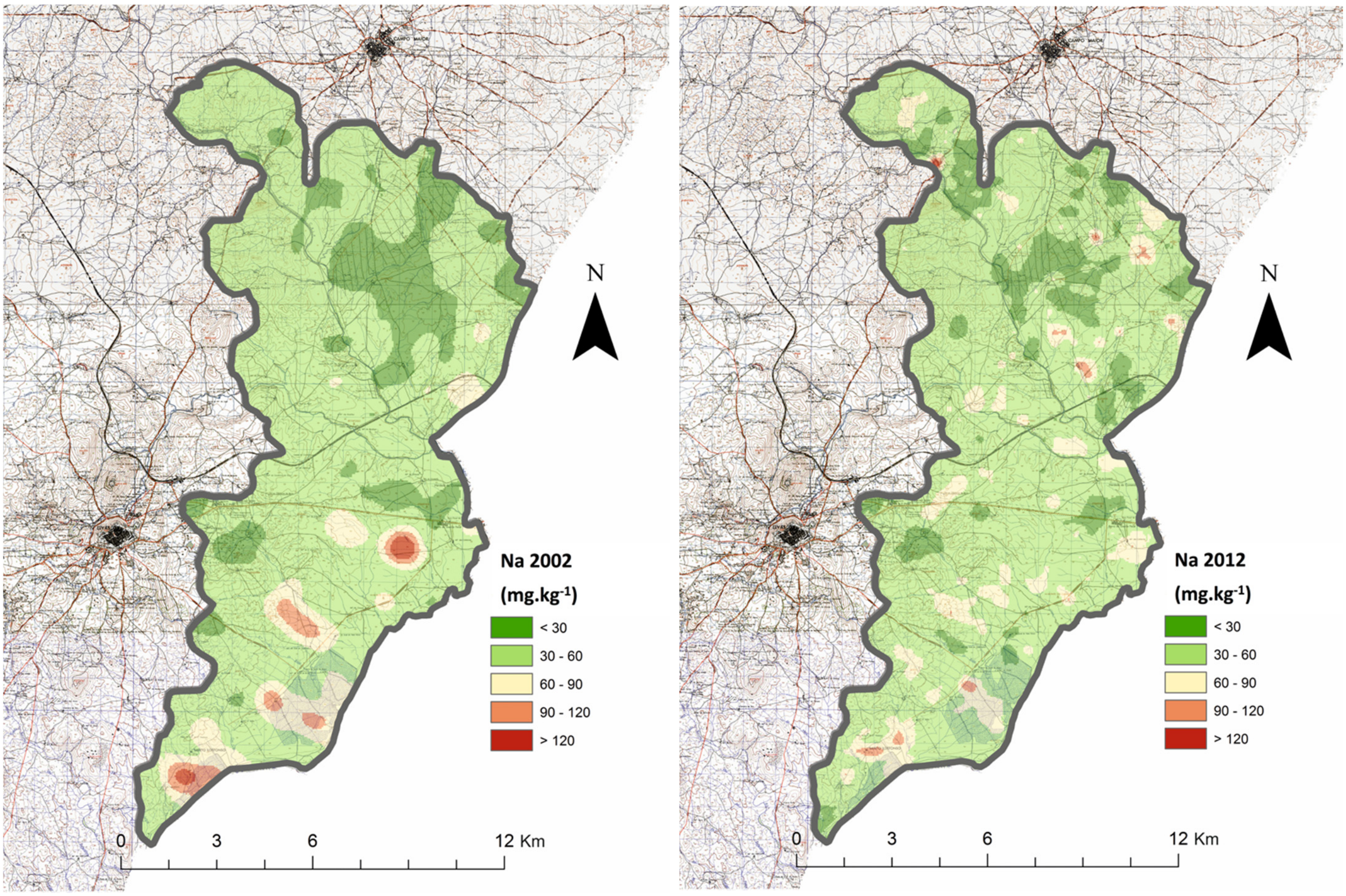


Figure 4. Error bar for Na^+ (mg kg^{-1}) in corn grown irrigated Luvisols.



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

Figure 5. Available Na^+ content (mg kg^{-1}) in the study area for (**a**) 2002 and (**b**) 2012.

3.3. CROSS

The CROSS values of irrigated soils in 2002 and 2012 were significantly higher (35.5% and 12.7%, respectively) than the values of rain-fed soils (Table 6).

Table 6. CROSS evolution when comparing rain-fed and irrigation sites from 2002 to 2012.

Parameter	Year	CS	Mean	*N*	Test	*p*
CROSS (cmol $_{(+)}$ kg^{-1})	2002	Rain-fed	0.215	620	T (1293): 4.440	0.000
		Irrigation	0.291	675		
	2012	Rain-fed	0.165	508	T (1271): 3.150	0.002
		Irrigation	0.186	765		

CROSS: cation ration of soil structural stability; CS: cultural system; T: Two Sample *T*-test; *p*: *p* value.

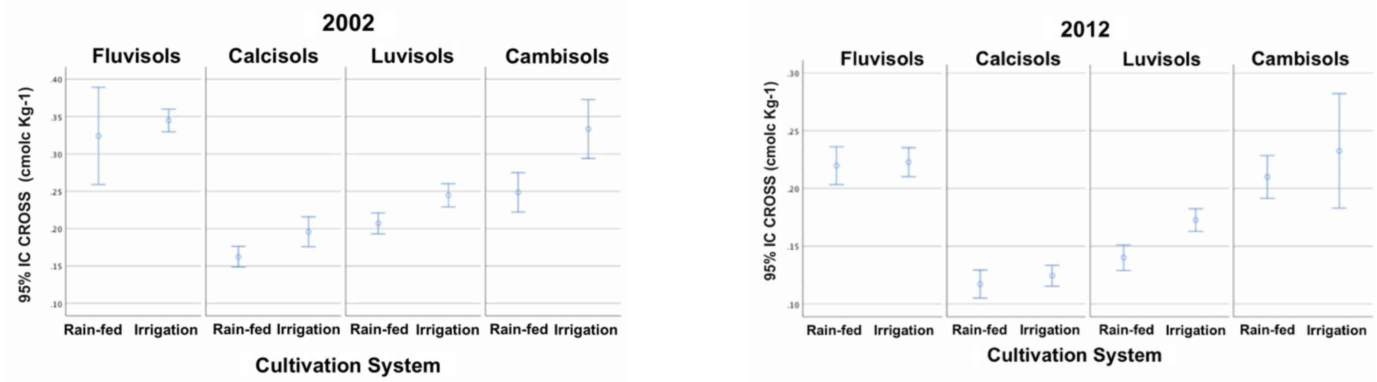
When considering each RSG separately (Table 7, Figure 6), we note that while in 2002 the CROSS increased in Fluvisols, Luvisols, Calcisols and Cambisols (all for a $p < 0.01$) by 25.4%, 20.7%, 20.7% and 35.7%, respectively, in 2012 the CROSS only increased in Luvisols (by 26.1%; $p < 0.01$), remaining constant in the other RSGs ($p > 0.05$).

In areas where Na^+ and K^+ are gaining preponderance over Ca^{2+} and Mg^{2+}, the CROSS is increasing and, in areas where Mg^{2+}, and especially Ca^{2+}, are gaining preponderance over Na^+ and K^+, it is decreasing as shown in the predictive + Hot Spot analysis map (Figure 7) where yellow to red spots depict the areas where the CROSS is augmenting, (i.e., where Na^+ and K^+ ions are gaining preponderance over Ca^{2+} and Mg^{2+} ions) and the greenish to green spots depicts the areas where it is diminishing (i.e., where Mg^{2+} and, above all, Ca^{2+} are gaining preponderance over Na^+ and K^+). Note that the different colors represent varying levels of confidence.

Table 7. CROSS evolution from 2002 to 2012.

Parameter	Year	RSG	CS	Mean	*N*	Test	*p*
CROSS (cmol $_{(+)}$ kg^{-1})	2002	Fluvisols	Rain-fed	0.268	222	U: 31,422.000	0.000
			Irrigation	0.336	394		
		Luvisols	Rain-fed	0.198	194	T (352): 3.569	0.000
			Irrigation	0.239	160		
		Calcisols	Rain-fed	0.155	143	T (226): 2.805	0.005
			Irrigation	0.187	85		
		Cambisols	Rain-fed	0.244	61	T (95): 3.724	0.000
			Irrigation	0.331	36		
	2012	Fluvisols	Rain-fed	0.208	194	T (604): 0.281	0.779
			Irrigation	0.213	412		
		Luvisols	Rain-fed	0.134	152	T (338): 4.349	0.000
			Irrigation	0.169	188		
		Calcisols	Rain-fed	0.110	99	T (227): 0.963	0.336
			Irrigation	0.120	130		
		Cambisols	Rain-fed	0.206	63	U: 1076.000	0.844
			Irrigation	0.219	35		

CROSS: cation ration of soil structural stability; CS: cultural system; U: Mann-Whitney *U* test; T: Two Sample *T*-test; *p*: *p* value.



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

Figure 6. Error bar, by RSG, for CROSS in (**a**) 2002 and (**b**) 2012.

Other comparisons revealed that CROSS variations were correlated to crop, physiographic position, useful depth, texture, ET0 and RSG ($p < 0.01$) (*). The CROSS increases in the Luvisols RSG where crops such as cereals and corn are grown and remained constant where tomato and olive (Figure 8a) are present. In the Fluvisols RSG only the soils where corn crops are grown had a significant increase in CROSS with other crops such as grains and olive maintaining the CROSS averages constant. In the soils where crops like tomato are present, the CROSS mean values have diminished from 2002 to 2012 (Figure 8b).

3.4. Rain-Fed

The average SOM, pH, exchangeable Ca^{2+}, Mg^{2+} and K^+ content have increased by 23%, 8%, 60%, 21% and 193% ($p < 0.01$), respectively, while the exchangeable Na^+ has decreased by 50% ($p < 0.01$) since the parameters were first assessed in 1965 (Table 8).

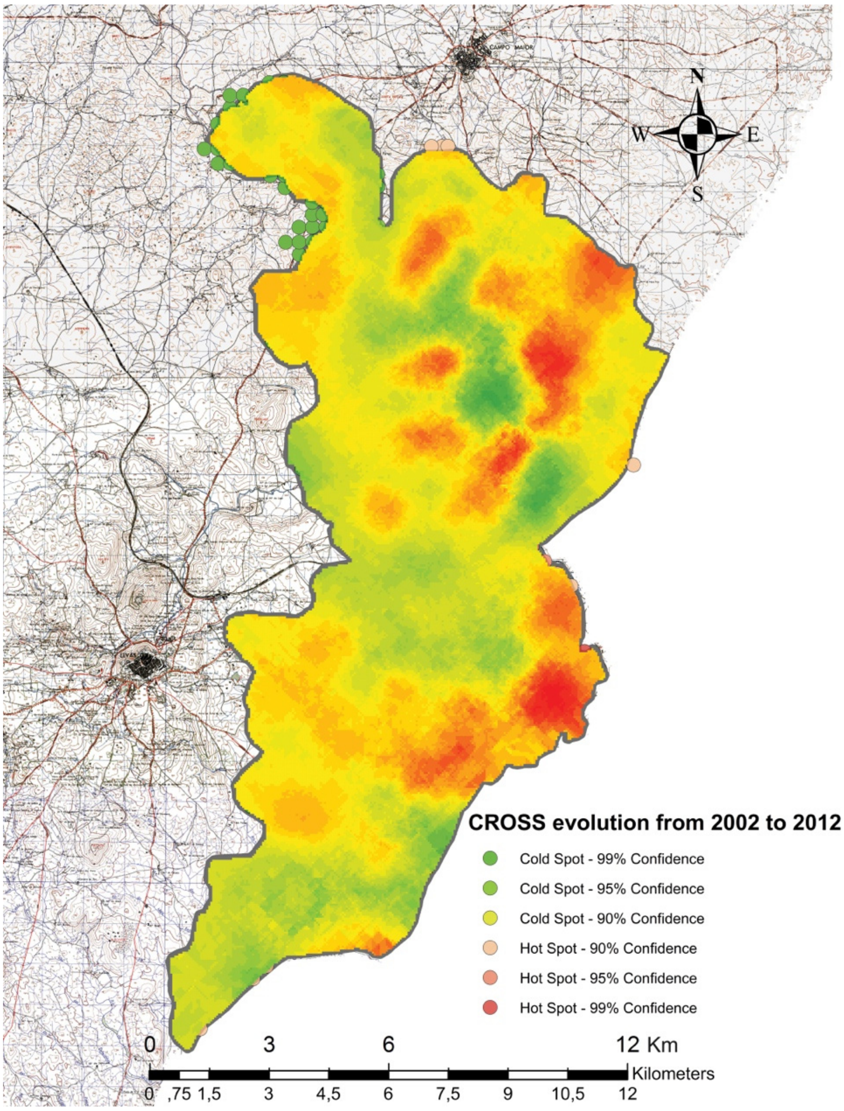
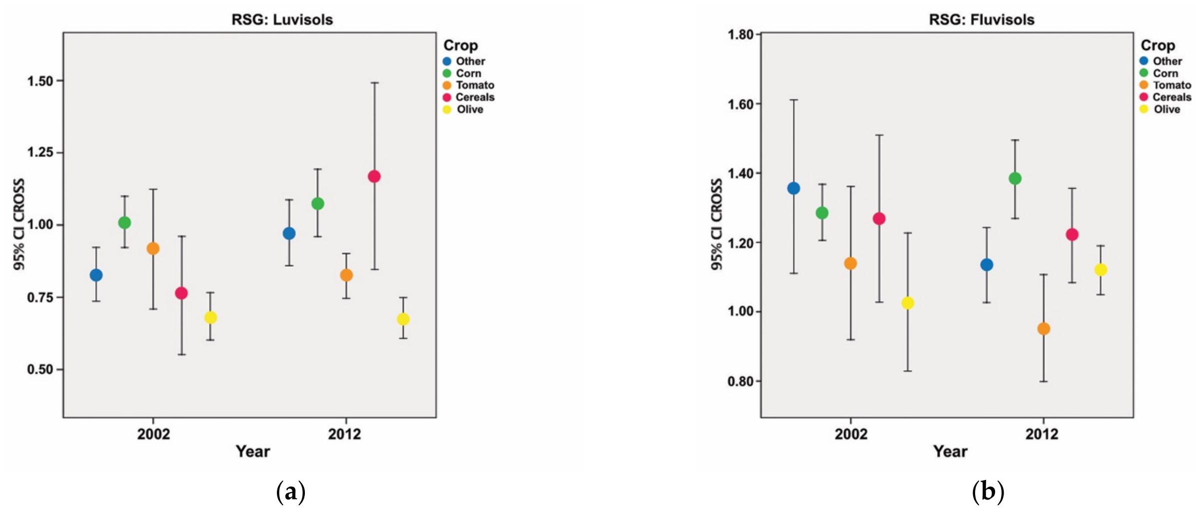


Figure 7. Predictive + Hotspot map of CROSS evolution in the studied area from 2002 to 2012.



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

Figure 8. CROSS mean bars comparison by sample data (2002 and 2012) in (**a**) Luvisols x crop and (**b**) Fluvisols x crop.

Table 8. Long-term evolution (1965 to 2012) of selected soil parameters in rain-fed soils.

Parameter	Year	Mean	*N*	Test	*p*
SOM (%)	1965 2012	1.26 1.55	1 525	T(524): 9.809	0.000
pH	1965 2012	6.43 6.92	1 526	T(525): 10.819	0.000
Ca^{2+} ($cmol_{(+)}$ kg^{-1})	1965 2012	9.66 15.45	1 526	T(525): 10.316	0.000
Mg^{2+} ($cmol_{(+)}$ kg^{-1})	1965 2012	2.25 2.73	1 526	T(525): 5.797	0.000
K^+ ($cmol_{(+)}$ kg^{-1})	1965 2012	0.15 0.44	1 526	T(525): 24.982	0.000
Na^+ ($cmol_{(+)}$ kg^{-1})	1965 2012	0.32 0.16	1 521	T(520): −32.653	0.000

Ca^{2+}: exchangeable calcium; Mg^{2+}: exchangeable magnesium; K^+: exchangeable potassium; Na^+: exchangeable sodium; T: One-sample *T*-test; U: Mann-Whitney *U* test; *p*: *p* value.

4. Discussion

The local climate changes detected between 1951/1980 and the subsequent climate normals is due to the increase in the mean values of the temperature and the decrease in soil moisture that lead to an increase in the ET0, which is accordance with the many studies that analyze the Mediterranean basin climate variability [65–69]. The United Nations Environment Programme [70] only considers a semi-arid climate where the aridity index < 0.50, but the UNCCD [71] states that areas with an aridity index ranging from 0.03 to 0.65 are susceptible to desertification (i.e., drylands). Thornthwaites' climate classification system states that the climate in the study area in 1951/1980 was considered "mesothermal climate (sub-humid) with large excess water in the winter and a summer of (very) low thermal efficiency" (i.e., with the key C1B2s2b4) and that it changed, in 1981/2010, to "mesothermal (sub-humid) with moderate excess of water in the winter and a summer of (very) low thermal efficiency" (i.e., C1B2sb4), and changing again, in 1991/2020, to "mesothermal (semiarid) climate with a winter of little to none excess of water and a summer of very low thermal efficiency" (i.e., DB2db4). Salt-affected soils are commonly distributed in areas where the aridity index is equal or below to 0.75 according to Brady & Weil [38]. With the registered decrease in precipitation and the increase in temperature in the region, arid sites are emerging at merely 100 km in a straight line from the studied area as reported by Verslype et al. [72].

The overall increase in available calcium from 2002 to 2012 can be explained by (a) the excessive use of the element in this cultivation system or (b) edaphic chemical reactions, once that, in the irrigated soils, intensive crops such as *Lycopersicon esculentum* Mill. are produced whose rooting covers a large part of the soil, as shown by Valles et al. [73] and Avilés et al. [74], increasing the edaphic CO_2 concentration which, catalyzed by the irrigation water, solubilizes carbonates (mainly $CaCO_3$) by the reaction of Equation (4), releasing Ca^{2+} in the soil and accumulating (as reported in the results section, a significant increase in Ca^{2+} was detected for this crop). Calcium in the soils of the studied area occurs, above all, in the primary minerals Ca carbonates and is usually present as calcite ($CaCO_3$), dolomite [$CaMg(CO_3)_2$] or even gypsum ($CaSO_4{\cdot}2H_2O$) being the most abundant cation of the SEC [64] playing a critical role in counteracting soil acidification by reducing Aluminum and Hydrogen saturation.

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca(HCO_3)_2 \rightarrow Ca^{2+} + 2HCO_3^- \quad (4)$$

The available calcium increase in the RSG Fluvisols may be related to the cultural intensification practiced in these soils and the cation release according to the aforementioned

Equation (4). However, since this RSG corresponds to the soils of the study area where irrigation has been longer practiced (e.g., 40 years more than Calcisols) [5], the leaching effect should have caused losses of this element. This observed accumulation in Ca^{2+} may occur due to the element being added to the soil. It could also be that the sum of the irrigation water and precipitation were not enough to cause the leaching of this element and, indeed, an increase in the ET0 in the long term was already reported in the results section of this paper, a fact that is also correlated with the study of Brinkman [75]. As for the Calcisols RSG it is no surprise that this RSG presents the greatest concentration of available calcium as is expected for a soil with considering accumulation of secondary carbonates associated with highly calcareous parent materials, which aligns with the studies of Aranda et al. [76] and Wang et al. [77].

Magnesium in the soils of the studied area occur primarily as the Mg carbonate Dolomite ($MgCO_3 \cdot CaCO_3$) and is only second to Calcium as the most abundant cation of the SEC and soil solution of the area as reported by Loures et al. [64] and, like calcium, plays a critical role in counteracting soil acidification by reducing Aluminum and Hydrogen saturation. This cation is usually provided to high valued cash crops sensible to Mg^{2+} deficiency such as tomato, corn, or olive, therefore, the reported increase in the RSG Luvisols may occur due to its possible addition through fertilization, or by the dissolution of dolomite or, also, because the amount of irrigation water plus precipitation, was not enough to leach the element from the soil. Our analysis reveals that the available magnesium content is at the very least being maintained but because of the thick water mantle surrounding it, it is being less tightly adsorbed to soil colloids than calcium and, thus, being more easily leached which causes its non-accumulation in the soils. Also, in the Mediterranean basin, magnesium precipitation as dolomite acts as a contributor for this result, as demonstrated in the study by Días-Hernandez et al. [78].

The overall increase in available potassium in the mid-term for the irrigated soils shows the excessive use of this element in this cultivation system. Potassium is a common input as fertilizer to cash crops as the quantity held in an easily exchangeable condition, at any given time, may be very small as most of the soil K^+ content is present in minerals and nonexchangeable forms being the mineral weathering rates that primarily influence its behavior, as demonstrated in the studies of Sanghamitra et al. [79] and Abd El–Mageed et al. [80] and so the tendency is to its content to increase in irrigated soils as was already proved in the past by Keeley and Quin [81] or Bernal et al. [82]. We believe that the registered increase in the Fluvisols occurs because this RSG is geographically positioned near most of the irrigation points and rivers, that have the longest exposition to irrigation practice and, thus, the increase in available potassium was expected. Overall, soil contents are medium/high in the Fluvisol RSG. We believe that the increase in K^+ in the Cambisols RSG is due to the intensified irrigation practice, since 2002, that these soils underwent, particularly with corn being intensively grown in the RSG as was already discussed in Telo da Gama et al. [5]. The fact that neither the Fluvisols nor Cambisols presented significant differences in the mid-term for the irrigation system could be explained by the already very high concentrations in 2002 in these RSGs because, as stated in the Portuguese manual for crop fertilization [83], most of the crops in soils with an available content of potassium above 200 mg kg^{-1} don't have the need to be fertilized with this nutrient and, most likely, only maintenance amounts of it are being provided to these soils, causing its stability, which is in accordance with most of the studies already mentioned. Also, the heavier textures presented higher potassium amounts which we believe occur because of the greater natural capacity of these textures to retain ions in the SEC and soil solution.

The overall increase in available sodium was expected as the dry, hot climate conditions present in the summer of the Mediterranean basin countries must be counteracted by copious applications of freshwater (e.g., a typical endowment for corn in the basin ranges from 800–900 mm ha^{-1} $year^{-1}$) that, even when of good quality, the applied volume to grow cash crops is so high that sodium accumulates relentlessly, which is in accordance with the vast majority of authors that study soil salinity in the Mediterranean basin. The presented results in Figures 4 and 5 are very interesting as even in soils with good internal drainage and useful depth, the available Na^+ is accumulating. The registered intensification in olive orchards, as demonstrated by Siebert [84], in the Mediterranean basin with increased outputs and also increased inputs in the form of irrigation endowments and fertilization caused the marked accumulation of Sodium in this RSG. As already presented in Telo da Gama et al. [5], there was a 1000% increase in the area this crop occupies since the beginning of this study. Soils with medium texture, good natural drainage and moderately developed are the ones irrigated for the longest period and so this correlation with increased Sodium was expected. It is latent that irrigation increases the levels of available sodium in the soils of the study area. The accumulation of this element would be related to the scarcity of rainfall, which would hinder its loss by leaching, and that is in accordance with the results already presented and the studies by Pilatti and Buyatti [24] and Gonçalves and Martins [85]. These results are also in line with those obtained by Badia [18], Calvo-Polanco et al. [19], Shrivastava and Kumar [20] and Telo da Gama et al. [5], who concluded that the primary and secondary salinity in the soils of the Mediterranean basin seems to be inevitable, since the amount of precipitation is not enough to leach the salts.

The CROSS results point towards a generalized dispersion of soil clay when cultural systems are compared, which is related to the significantly higher concentrations, under irrigation, of exchangeable Na^+, and with the balance of the remaining bases as mentioned by Smith et al. [28]. From the presented results we also conclude that the preponderance with which the CROSS increased is very different when comparing the cultural systems in 2002 and in 2012 as, in 10 years, its preponderance decreased by 64%. This result is related to the increase in the preponderance of exchangeable Ca^{2+} and the decrease in exchangeable Na^+ between the sampled years, which led to a decrease in the dispersant capacity of irrigated soils, which is in line with the study of Markgraf et al. [27] and implying that the dispersion of soil colloids is decreasing in the mid-term. We believe that this occurs due to the marked decrease in leaching and drainage of most of the soils in the study area, the highest ET0 recorded, the dissolution of calcite ($CaCO_3$) and the increase in HCO_3^- in the irrigation water (discussed in Telo da Gama et al. [5]). Therefore, the overall and significant increase in Na^+ and K^+ ions, which facilitate the dispersion of clay particles, is offset by the general and significant increase in Ca^{2+}, which promotes flocculation of said particles as confirmed in the study of Zaker and Emami [30].

As for the rain-fed soils, analysed in the long term, the SOM, pH and exchangeable bases variability are, above all, related to environmental conditions, edaphic parent material and the quality of added residues. The SOM increases, probably, because little to none soil disturbance causes, by edaphic hypoxia, the preservation of microbial and plant compounds, tending to its accumulation (when the microbial oxidation of humus is compensated by enough constant addiction of plant residues) as indicated in the studies of Teixeira et al. [86] and Francaviglia et al. [87]. The increase in pH is related to the greater preponderance in the increase in non-acid cations (Ca^{2+}, Mg^{2+}, K^+ Na^+) than the acidic ones (Al^{3+}, H^+), whose origin would be associated with the irrigation water, fertilizers, liming and bedrock weathering, accumulating said bases as a result of the increasing ET0 (as already discussed, the precipitation water is not enough to cause the cations leaching, which increases the CEC of the soil by the increase in free negative charges present in the clays and humus) [6]. Mineral weathering, fertilization, liming and the irrigation water floods the soil solution and, therefore, the soil exchange complex, with non-acid cations, where Ca^{2+}, Mg^{2+} and K^+ accumulate. The exchangeable Na^+ is decreasing, probably, because this cation is less tightly held than Ca^{2+}, Mg^{2+} and K^+ due to its larger hydrated radius and also because it is not being applied to the soil as fertilizer as discussed in Loures et al. [64] and Telo da Gama et al. [5].

5. Conclusions

As a conclusion of this multi-year study, it is of concern the registered increase in available sodium and calcium (that may imply edaphic salinization, sodification and alkalinization), that the intensification of agricultural soils through the practice of irrigation is showing in the mid-term in the Mediterranean basin. Rain-fed systems are more sustainable in the long term with increasing levels of SOM and decreasing levels of exchangeable Na^+, even though the exchangeable calcium also significantly increases in this cultural system. These are important results as they align with the registered alterations in local climate since 1951/1980, with the ET0 increasing and precipitation decreasing, causing the accumulation of non-acid cations and the decrease in the aridity index, so that it is ever closer to 0.50 where an arid area is officially declared. These results are but one more account of the effect that climatic changes perpetrates in the soils of the basin, increasing its desertification. The extent to which our results are consistent with those of other authors [5,64,76,88–91] that study the Mediterranean Basin edaphic-climatic conditions serve as an important check on the validity of our conclusions.

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