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Ecological and Economic Sustainability in Olive Groves with Different Irrigation Management and Levels of Erosion: A Case Study

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Abstract: In the last 50 years, both the agricultural labour force and irrigated land area have increased almost eightfold in Spain. The main objective of irrigation, in the short term, is to increase agricultural production. However, in the long term, the environmental externalities of irrigation and its direct relationship with soil erosion processes are more uncertain and still poorly studied. In this study, in an olive-growing region of Andalusia, Spain, the variation of several soil parameters related to irrigation and erosion levels was analysed. The results showed that irrigation, while increasing the productive level of the olive groves, entails a progressive alteration of the soil, modifying physical aspects (greater compaction and humidity of the soil together with lower gravel content, porosity and soil weight) and chemical aspects (reduction of the organic matter of the soil and the content of nitrates) that can aggravate the consequences of the erosive processes. In the long term, the productive benefit attributed to irrigation could be unsustainable from an ecological and, consequently, economic point of view. In addition, the lack of sustainability of olive irrigation agroecosystems could be exacerbated by the future restrictive impacts of climate change on water resources in Mediterranean environments. This situation demands spatial planning and alternative management based on soil conservation and rational and efficient forms of irrigation to ensure the sustainability of olive groves and their economic viability.

Keywords: Common Agricultural Policy; deficit irrigation; economic–productive viability; physical–chemical soil characterisation

1. Introduction

Olive grove landscapes form socioecological systems characteristic of Mediterranean environments [1,2]. They are particularly representative in Spain, covering more than 2.5 M ha [3]. In Andalusia, these olive grove landscapes, with an area of 1.5 M ha, form a multifunctional system making an essential contribution of ecosystem services to society, highlighting the production of olives and olive oil. During the last five growing seasons (2012/2013–2016/2017), the region produced an average of 1.19 M t year^{-1} of olive oil [4–6]. In addition, as with many agricultural matrix landscapes with a heterogeneity of habitats and ecotones, olive groves have been shown to serve as reservoirs of biodiversity [7,8].

The enforcement of the Common Agricultural Policy (CAP) in the European Union in 1962 led some traditional farming systems (mountain farming and agroforestry systems) to collapse due to their lack of adaptation to the new regulations (levels and forms of production). These systems were based on the optimisation of the use of natural resources and were adapted to local climatic and geomorphological conditions, but their production levels were relatively low, and they were not competitive with the environmental and sanitary standards established by the CAP or market prices [9]. Faced with this situation, farmers' decisions showed two opposing trends: abandoning their lands in the face of declining economic benefits or intensifying (i.e., increasing or introducing) the use of synthetic agrochemical herbicides, pesticides or fertilisers; generating higher plant density and adopting technological improvements [10]. Both intensification and abandonment of farming systems can have undesirable environmental and socioeconomic consequences. On the one hand, agricultural intensification improves productivity (increasing economic benefits) but is generally accompanied by environmental damage [11], such as soil erosion [12–14] and spatial homogenisation (expansion of monocultures), which affects biodiversity [15]. On the other hand, the abandonment of agricultural activities leads to a total loss of profitability and the degradation of social stability [16], while at the same time causing the accumulation of biomass (scrubbing) fuel by ecological succession (passive restoration), increasing the risk of wildfires [17].

Olive grove agroecosystems have traditionally formed agricultural landscapes [18], as they are adapted to Mediterranean climates where periods of summer drought and water stress are inherent to their dynamics [19]. However, in the last 50 years, the expansion of irrigation to these agroecosystems has increased for merely productive purposes [20,21]. Irrigated olive groves in Andalusia have grown from 5% to about 35% of the total agricultural area [22,23]. Despite the resistance of olive trees to drought, irrigation is important to ensure adequate yields in years with little rainfall in order to reduce the variability of yields from year to year because of the alternate bearing and to increase olive oil production. Despite the high delivery efficiency of some irrigation systems (i.e., drip irrigation), there is high risk of water overuse. This, in turn, could impact the demand for water for human consumption in certain basins associated with large extensions of intensive olive groves and exacerbate soil erosion [24]. Specifically, the average values of soil loss were 19 t ha^{-1} $year^{-1}$ in the 1950s but are highly variable at present, ranging from 23 to 184 t ha^{-1} $year^{-1}$ [25,26]. To reduce erosion and prevent soil degradation or contamination, various conservation techniques, such as vegetation cover or terracing, are applied. However, a soil water balance adapted to the needs of the farming system is also important and could be achieved by increasing water infiltration, avoiding soil compaction and evaporation. In addition, to achieve this balance, it is essential to apply the appropriate irrigation system.

The impacts of the intensification of management highlight the need for policies/strategies designed ad hoc for olive grove agricultural landscapes with the objective of promoting the adequate conservation of the soil, maximising the viability of these agricultural systems and delaying the advance of erosive processes and their consequences [27–29]. Although several factors and management practices other than irrigation can have multiple consequences on the soil environment (i.e., agriculture mechanisation), there are few studies that quantify the consequences of erosion associated with irrigation on the soil and its impact on long-term economic profitability. Considering the restrictions that climate change will impose on the availability of water resources in the near future [30,31], and with the biophysical system serving as the foundation on which any agroecosystem is based [32], it is urgent to study the relationship between erosion, irrigation and profitability in the agricultural landscapes of olive groves. Thus, the objectives of this work, using a case study of an olive-growing region in Andalusia, were (a) to characterise the soils of the studied region considering different erosive levels and olive-growing management systems and (b) to compare, by means of medium- and long-term time projections for different erosive levels, the possible productive and economic consequences for irrigated and rainfed olive groves [33]. The use of time simulation models is a useful and valid tool to explore the uncertainty about the future consequences that may result due to the factors considered in this study (erosion, production and irrigation). Finally, the sustainability of the olive grove landscapes was evaluated based on the soil properties and profitability analysed.

2. Material and Methods

2.1. Study Area

The study area was in the olive-growing region of *Estepa*, in the province of Seville (Andalusia, southern Spain), corresponding to the Protected Designation of Origin (PDO) of the same name (Figure 1).

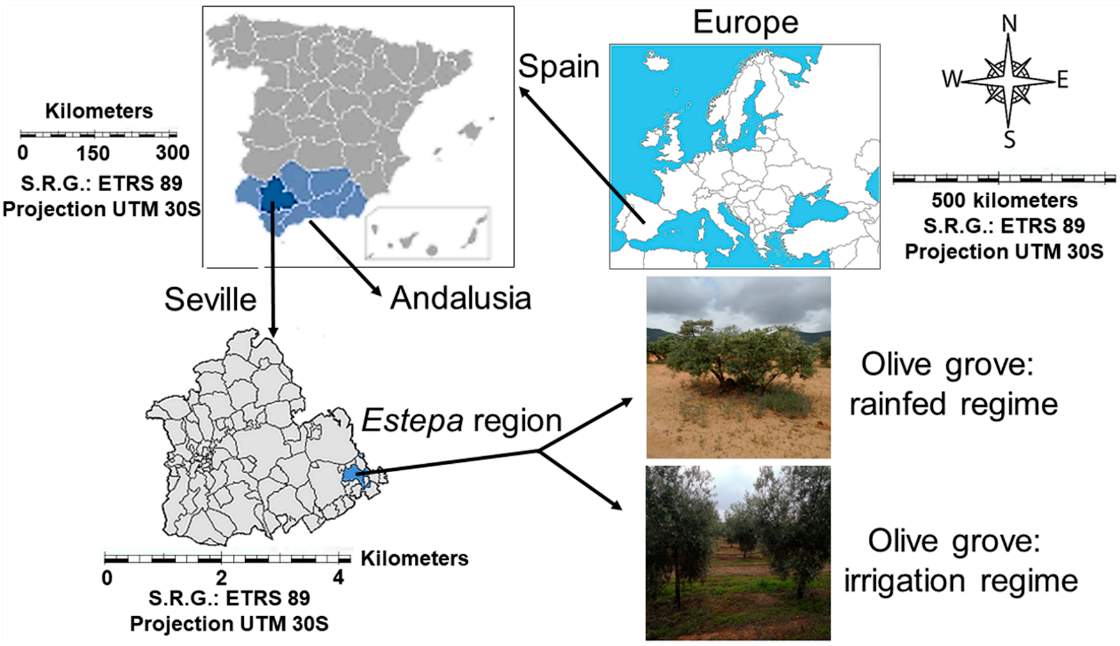

Figure 1. Geographical location of the region of *Estepa* in Andalusia, province of Seville, Spain, Europe. The images correspond to the different integrated olive grove management approaches in the study area. The maps were georeferenced according to the Universal Transverse Mercator (UTM) system, under the geodesic datum ETRS89 (European Terrestrial Reference System 1989), specifically projecting the 30S grid, in which the study area is framed.

This region has 40,000 ha of olive groves along with another 20,000 ha which includes other agricultural land uses and relicts of vegetation [34,35]. The olive groves are located between 200 and 800 masl, under a temperate Mediterranean climate with an average temperature of 17.5 °C and an annual rainfall of 477 mm [36]. The soils of this region have a variable depth, between 30 and 150 cm, with a predominantly limestone substrate of alkaline pH (values between 7.2 and 8.2) [36,37]. Most of the soil texture is silty, with olive groves on *Albariza* soils and calcareous materials [34]. The olive groves of this region are managed, for the most part, in a certified integrated manner, with a plantation density ranging from 100 to 500 trees ha^{-1} and allowing the use of chemically synthesised fertilisers regulated by the Technical Control Agencies (ATC). While most olive groves are cultivated under a rainfed regime (around 90%), deficit-type irrigation (only in times of water stress and with an average endowment of 1500 cm^3) has been implemented in the remaining 10% [18,36,38].

2.2. Experimental Design and Sample Processing

Stratified sampling was performed according to the erosion levels estimated from the Universal Soil Loss Equation (USLE) and the USLE-Revised USLE (RUSLE) Model (1) [39,40]:

$$A = R \times K \times LS \times C \times P \tag{1}$$

where *A* is annual soil losses, *R* is rain erosivity, *K* is soil erodibility, *LS* is the length and grade of the slope of the territory, *C* is the ground cover and *P* is agricultural conservation practices.

For the estimation of the erosion levels, the cadastral cartography of the Andalusia Government [41], the Spanish Land Occupancy Information System [42] and bibliographic information were used [43,44]. Specifically, factors *R* and *LS* of the USLE-RUSLE model were calibrated from specific bibliographic information for the study area [45,46]. Soil erodibility was calibrated experimentally according to criteria from Gisbert Blanquer et al. [47]. Factor C was calibrated for *Estepa* according to criteria from Gómez et al. (2003) [27]. Thereby, factor C varies with the type of management depending on tree density (considered low in integrated management), canopy diameter (taking an average value for the integrated olive grove of 2.5 m radius) and with the extent (width) of ground covers (applying partial coverages in the study area). Finally, factor *P* was considered to be 1 for all erosion situations, as it was assumed that all plots are subject to tillage practices and none are subject to specific mechanical or soil manipulation erosion control practices [45,46], regardless of ground cover as an agronomic measure considered in factor *C*.

In short, Table 1 shows the parameters of the USLE-RUSLE model adapted and calibrated for the *Estepa* region according to criteria from Rodríguez Sousa et al. [2]:

Table 1. Classification of the olive groves of *Estepa* in erosive levels according to the Universal Soil Loss Equation-Revised Universal Soil Loss Equation (USLE-RUSLE) model. The factor *LS* is also expressed as a percentage; *C* and *P* are dimensionless.

Erosive Level	Olive Grove Area in ha (%)	Factors					A (t ha^{-1} y^{-1})
		R (J ha^{-1})	*K* (Mg J^{-1})	*LS*	*C*	*P*	
Null	22,494 (57.00)	109.7	0.82	0.00 (0%)	0.16	1	
Slight	8366 (21.20)	109.7	0.89	0.18 (3%)	0.16	1	2.81
Moderate	3828 (9.70)	109.7	0.56	0.70 (7%)	0.16	1	6.88
Severe	4775 (12.10)	109.7	0.95	2.20 (15%)	0.16	1	36.68

Of the total 3828 ha with moderate erosion, 1755.90 ha have deficit irrigation, while of the total 4775 ha with severe erosion, 2190.34 ha are under deficit irrigation [18]. In general, olive groves are rainfed, especially in Andalusia (almost 80%). The expansion of irrigation in recent decades had a greater incidence, in many cases, in those olive groves in more marginal environmental situations (high slopes and eroded or shallow soils). Consequently, in traditional olive groves in flat areas, such as *Estepa*, rainfed management tended to be maintained, with few exceptions in more restrictive areas. It is therefore uncommon to find olive groves under irrigation in areas with slight or no erosion and, in *Estepa*, these are not present. Thus, considering four levels of erosion in rainfed and two levels of erosion in irrigated olive groves, six treatments were obtained. Considering accessibility and the public character of the lands with olive groves, four plots were randomly sampled within each erosion level and management type (with or without irrigation), obtaining a sample size of n = 24 plots (Figure 2).

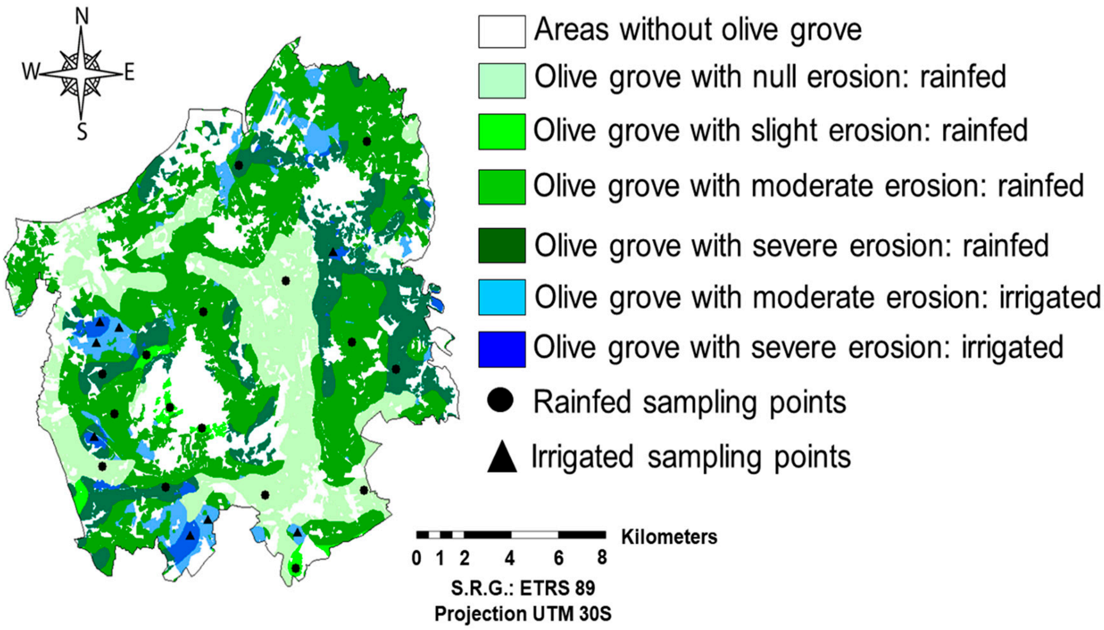

Figure 2. Map of the region of *Estepa*, which shows the olive-growing territory classified according to its erosion and rainfed or deficit irrigation regimes. Sampling points are also shown on olive groves belonging to the different erosive levels (null, slight, moderate and severe).

In each sampled olive grove, a transect of 1 km in length was established in which three soil samples were taken equidistantly using a core of fixed weight and volume (112.40 gr and 141.372 cm^3, respectively). The soil samples used to calculate the physical–chemical parameters studied were dried at 105 °C for 24 h. Table 2 shows the most relevant parameters, their usefulness and the method of obtaining them.

Table 2. Soil physical–chemical parameters analysed, indicating corresponding units, abbreviations, their usefulness as indicators and the procedure followed to calculate them (equations and methodology).

Parameters (units)	Abbreviations	Usefulness	Equations and Methodology
Gravel (%)	G	Soil structural indicators	Sample sieving [48,49]
Sands (%) Silts (%) Clays (%)	Sands Silts Clays	Soil textural indicators. USDA criteria (sands: 2 mm to 50 µm; silts: 50–2 µm; clays: <2 µm)	Bouyoucos densitometer [48,50]
Porosity (%)	Porosity	Total amount of soil pores	$Volume\ sample - Volume\ dry\ soil = Volume\ pores$; $\%\ Porosity = \left(Volume\ pores \times Volume\ sample^{-1}\right) \times 100$ [49]
Moisture (%)	Moisture	Amount of soil pores with water (Porosity − Moisture = Aeration)	$Weight\ sample + Water - Weight\ dry\ soil = Weight\ water$; $\%\ Moisture = \left(\text{Weight water} \times Weight\ sample + Water^{-1}\right) \times 100$ [49]
Soil weight (t ha^{-1})	W	Amount of soil per unit area	$Weight = 100 \times height \times Apparent\ density$ [43]
pH (—)	pH	Indicator of acidity or basicity of soil	Direct estimation [51]
Organic matter (%)	OM	Soil fertility indicator	$OM = 1.724\ [Carbon]$; indirect calculation through the estimation, by colourimetry, of edaphic carbon (%) [52]
Phosphatase (µmol p-nitrophenol gr^{-1} h^{-1})	Phosphatase	Transformation from organic phosphorus to phosphates (primary plant nutrient)	Colourimetry [53,54]
Nitrates (ppm)	Nitrates	Diffuse soil contamination indicator	Colourimetry [55–57]
Texture (—)	Texture	Soil textural classification	Textures triangle [58]

2.3. Productive and Economic Data of the Olive Grove

From the surveys carried out with the farmers and owners of the sampled olive groves (n = 24), production and economic information was obtained referring to the last two years (2017–2018), considering as data the average of these years. Among other information, data about crop yields (olive oil production) linked to plantation density, selling price of the olive oil, economic incomes with or without subsidies received and production costs were collected.

With the average values from these data, long-term projections (150 years) were made on the productive level and the degree of economic profitability per hectare of an olive grove according to its erosive level and management type (rainfed or irrigated). For this purpose, an experimentally calibrated equation [2,26] was used from the samples carried out and bibliographic sources [36,37], assuming a decrease in productivity over time due to the negative effect of Erosion (2):

$$Production_{(t)} = P_i \times \left(c_1 + c_2 \times \ln\left(W_j - Er_j \times t\right) + c_3 \times \left(\ln\left(W_j - Er_j \times t\right)\right)^2\right) \quad (2)$$

where *Production (t)* is the production of each management i at time t (t ha^{-1}); c_1, c_2 and c_3 are specific constants of the study area dependent on annual precipitation and soil type, being 0.7388, −0.3471 and 0.0401, respectively; P_i is the initial production (t = 0) of management i (t ha^{-1}); W_j is the weight of soil corresponding to the erosive level j; Er_j is the erosion rate proper to the erosive level j; and t is the simulation time.

Personal survey data were used to calibrate the productivity model and make temporary projections of the economic and productive profitability of each type of agricultural management. The following assumptions were made, which were considered permanent throughout the simulated period: (a) the olive grove is currently eligible for CAP subsidies under any type of management [23]; (b) the average production from the extraction of 1 L of olive oil from olives varies annually between 18% and 21% [38], with an average production of 19% being taken as general data for the study region [59]; and (c) it was assumed an average production in the integrated olive grove between 1500 and 4000 kg olives ha^{-1}, along with the abandonment of the farming system when production is below that threshold [22]. Production and profitability data (with or without CAP subsidies) accumulated per hectare were also calculated according to their erosive level and management type.

2.4. Statistical Analysis

To verify the differences of the soil parameters at different erosive levels and the management applied (rainfed or irrigation) in the olive groves, the assumptions of normality and homoscedasticity of the samples were tested using the Shapiro–Wilk and Levene's tests, respectively. Firstly, the possible existence of collinearity between the multiple parameters collected was tested using a principal component analysis (PCA), and the most relevant parameters to analyse the relationship between erosion levels and irrigation management were selected (see Table 2). Secondly, the possible existence of interactions between the two factors of the study (i.e., management and erosive levels) was tested to prove the existence of possible significant differences for the dependent variables (i.e., soil parameters) between equivalent erosive levels in the management types analysed (i.e., moderate and severe erosion in rainfed and irrigated olive groves) through the application of an ANOVA. For those variables that did not comply with the requirements of normality or homoscedasticity, a nonparametric Kruskal–Wallis test was employed. In addition, following the same methodology, possible differences between the considered erosion levels for each dependent variable were determined. To determine possible differences between the treatments for each dependent variable, a Tukey post hoc test for normal and homoscedastic variables or a Tamhane test for non-normal variables was carried out. The differences in production and profitability (with or without CAP subsidies) accumulated per hectare according to their erosive level and management type were tested applying a mean differences test. All statistical analyses were carried out with RStudio software [60,61], using the car library and the agricolae, dplyr and PMCMRplus packages [62,63], considering a level of significance of α = 0.05 in all analyses.

3. Results

All soil parameters analysed by PCA showed strong collinearity (determining value < 0.001) and all parameters showed a normal distribution and homoscedastic behaviour, except for the soil gravel content (G) and moisture. The interactions between olive-growing management and erosion were highly significant ($p < 0.001$ ***) for all dependent variables, thus leading to a separate analysis of both factors.

3.1. Soil Characterisation of the Olive Grove

3.1.1. Soil Characteristics and Water Management Regimes Considering Coincident Levels of Erosion

Table 3 shows the main results regarding the descriptive statistics and significant differences for the physical soil parameters analysed in the coincident erosive levels (i.e., moderate and severe) in rainfed and irrigated olive groves in the *Estepa* region.

Significant differences were found in the gravel content and moisture of the soil. Irrigated olive crops presented greater soil moisture (36.79%) than rainfed crops. In turn, decreases of up to 90.81% in the gravel content and 4.85% in the soil pores were observed in the irrigated olive groves, resulting in a more compacted soil. Irrigation did not significantly affect the finest soil particles and, therefore, their overall texture.

Table 3. Mean values (x) and standard deviation (SD) of the physical soil parameters measured in the olive groves sampled for the different water management regimes, also including the estimation of soil texture. *p*-values ($p < 0.05$ *: significant value; $p < 0.01$ **: very significant value; $p < 0.001$ ***: highly significant value). G: gravel; W: soil weight.

Management	Rainfed	Irrigation	*p*-Value
	x ± SD	x ± SD	
G (%)	1.96 ± 1.87	0.18 ± 0.18	0.030 *
Sands (%)	55.85 ± 13.42	61.67 ± 4.12	0.261
Silts (%)	25.74 ± 6.17	22.57 ± 5.71	0.304
Clays (%)	18.40 ± 7.25	15.76 ± 1.60	0.332
Porosity (%)	59.93 ± 3.68	57.02 ± 1.71	0.085
Moisture (%)	23.83 ± 6.54	37.70 ± 4.78	<0.001 ***
W (t ha^{-1})	11,207.14 ± 2133.96	9695.78 ± 1580.05	0.130
Texture	sandy loam	sandy loam	—

Table 4 shows the results for the chemical soil parameters analysed.

Table 4. Mean values (x) and standard deviation (SD) of the soil chemical parameters measured in the olive groves sampled for the different water management regimes. *p*-values ($p < 0.05$ *: significant value; $p < 0.01$ **: very significant value; $p < 0.001$ ***: highly significant value). OM: organic matter.

Management	Rainfed	Irrigation	*p*-Value
	x ± SD	x ± SD	
pH	8.04 ± 0.15	8.00 ± 0.17	0.671
OM (%)	1.96 ± 0.61	1.57 ± 0.55	0.196
Phosphatase (µmol p-nitrophenol gr^{-1} h^{-1})	0.47 ± 0.07	0.46 ± 0.07	0.890
Nitrates (ppm)	4.72 ± 0.30	6.03 ± 0.51	<0.001 ***

Irrigation significantly influenced the concentration of nitrates in soils, increasing their concentration by 21.72%. At the same time, it resulted in a 19.90% decrease in organic matter but did not significantly affect the other chemical parameters considered.

3.1.2. Soil Characteristics and Water Management Regimes Considering All Levels of Erosion

Table 5 shows the soil physical parameters for the different erosive levels in each management type of the olive groves sampled. There were highly significant differences for each dependent variable (i.e., physical parameters) in at least one of the evaluated treatments (i.e., levels of erosion) ($p < 0.001$ *** from the ANOVA and Kruskal–Wallis test). For each level evaluated in each variable, the results of the post hoc analysis through the realisation of a homogeneous subset matrix between the sampled treatments (i.e., null, slight, moderate and severe erosion under rainfed management, and moderate and severe erosion under irrigation) are represented. Two levels present different group classifications only when the results of the post hoc test suggested the existence of significant differences ($p < 0.05$ *).

For the granulometric variables, a decrease in the gravel content of the soil was detected (particles between 2 mm and 6 cm) as the level of erosion increased, with this loss of gravel being more pronounced in irrigated olive groves. In this sense, rainfed plots with severe erosion together with plots with moderate and severe erosion with irrigation formed a single statistical group differentiated from the rest of the plots due to their low gravel content.

The estimated texture, closely linked to the limestone content characteristic of the study area, corresponded to soils of medium-fine texture with good water retention. Thus, the soil of *Estepa* was predominantly loamy, combined mostly with sands or silts, for all erosion levels and the two types of management, with significant differences between all treatments for sand and silt content. However, the irrigated olive groves showed a higher clay content in cases of moderate erosion but not in those of severe erosion.

Regarding the porosity, in the rainfed olive groves, this parameter decreased by about 12% as the level of erosion increased. In the case of irrigated olive groves, this decrease was even more accentuated: 2.33% and 7.39% in olive agroecosystems with moderate and severe erosion, respectively. As expected, soil moisture was significantly higher in irrigated plots (up to 65.53% more in moderate erosion plots and 53.13% in severe erosion plots). Groups with significant differences in porosity and moisture were established according to different levels of erosion (increasing with the degree of erosion), maximising these differences in irrigated olive groves. Ultimately, in rainfed plots, net losses of soil weight of up to 41.04% were reached, increasing this loss with irrigation; 15.13% in olive groves with moderate erosion and 11.17% with severe erosion. The slight, moderate and severe erosion levels in the rainfed management cases together with the level of severe erosion under irrigation did not show significant differences for the weight of the soil per unit area.

Table 6 shows the chemical parameters, indirectly indicating fertility, enzymatic activity and soil contamination, and classification results obtained by means of a Tukey post hoc test. A decrease in pH was observed (almost 8%) as the degree of erosion increased, while in the irrigated olive groves, slightly lower values were observed in the coinciding erosion levels, that is, moderate and severe erosion (0.24% and 0.63%, respectively). These two erosive levels formed a differentiated group with respect to rainfed management. For the parameter organic matter, lower values were detected in olive groves with high erosion (decreases of up to 62.43%). In irrigated cases, a decrease of 18.11% was detected in olive groves with moderate erosion and 23.74% in those with severe erosion, with significant differences observed for all treatments.

Table 5. Mean values (x) and standard deviation (SD) of the physical soil parameters measured in the olive groves sampled for the different levels of erosion and water management regimes, also including the estimation of soil texture. The superindexes, a–f, indicate the classification groups generated in the post hoc tests to establish similar categories. G: gravel; W: soil weight.

Management	**Rainfed**				**Irrigation**	
Erosive Level	**Null (x ± SD)**	**Slight (x ± SD)**	**Moderate (x ± SD)**	**Severe (x ± SD)**	**Moderate (x ± SD)**	**Severe (x ± SD)**
G (%)	11.28 ± 0.42 [a]	7.25 ± 0.04 [b]	3.71 ± 0.06 [c]	0.22 ± 0.01 [d]	0.36 ± 0.02 [d]	0.00 ± 0.00 [d]
Sands (%)	36.18 ± 0.19 [a]	61.51 ± 0.09 [b]	43.29 ± 0.08 [c]	68.41 ± 0.05 [d]	65.52 ± 0.11 [e]	57.82 ± 0.06 [f]
Silts (%)	52.41 ± 0.02 [a]	24.05 ± 0.10 [b]	31.52 ± 0.03 [c]	19.97 ± 0.02 [d]	17.23 ± 0.01 [e]	27.91 ± 0.04 [f]
Clays (%)	11.41 ± 0.17 [a]	14.44 ± 0.01 [b]	25.18 ± 0.09 [c]	11.62 ± 0.07 [a]	17.25 ± 0.12 [d]	14.27 ± 0.02 [b]
Porosity (%)	68.33 ± 0.77 [a]	62.58 ± 0.03 [b]	60.04 ± 0.81 [c]	59.83 ± 0.06 [d]	58.64 ± 0.01 [e]	55.41 ± 0.06 [f]
Moisture (%)	35.10 ± 0.35 [a]	31.03 ± 0.02 [b]	25.30 ± 0.06 [c]	22.38 ± 0.01 [d]	41.12 ± 0.26 [e]	34.27 ± 0.04 [f]
W (t ha^{-1})	15,728.70 ± 541.60 [a]	13,921.60 ± 112.75 [b]	13,140.00 ± 315.71 [b]	9272.80 ± 266.18 [c]	11,151.78 ± 150.46 [d]	8236.80 ± 136.81 [c]
Texture	silty loam	sandy loam	loam	sandy loam	sandy loam	sandy loam

Table 6. Mean values (x) and standard deviation (SD) of the soil chemical parameters measured in the olive groves sampled for the different levels of erosion and water management regimes. The superindexes, a–f, indicate the classification groups generated in the post hoc tests to establish similar categories. OM: organic matter.

Management	**Rainfed**				**Irrigation**	
Erosive Level	**Null (x ± SD)**	**Slight (x ± SD)**	**Moderate (x ± SD)**	**Severe (x ± SD)**	**Moderate (x ± SD)**	**Severe (x ± SD)**
pH	8.55 ± 0.03 [a]	8.27 ± 0.01 [b]	8.18 ± 0.01 [c]	7.90 ± 0.02 [d]	8.16 ± 0.02 [c]	7.85 ± 0.01 [d]
OM (%)	3.70 ± 0.08 [a]	2.90 ± 0.02 [b]	2.54 ± 0.02 [c]	1.39 ± 0.01 [d]	2.08 ± 0.02 [e]	1.06 ± 0.03 [f]
Phosphatase (μmol p-nitrophenol gr^{-1} h^{-1})	0.26 ± 0.01 [a]	0.46 ± 0.02 [b]	0.41 ± 0.01 [b]	0.53 ± 0.02 [c]	0.40 ± 0.01 [b]	0.53 ± 0.01 [c]
Nitrates (ppm)	2.85 ± 0.14 [a]	3.88 ± 0.15 [b]	4.48 ± 0.12 [c]	4.97 ± 0.02 [c]	5.61 ± 0.15 [d]	6.46 ± 0.11 [e]

The enzyme phosphatase, which plays an essential role in the mineralisation of organic *P* and as an indicator of soil enzymatic activity, showed an increase of more than 100% between the lowest and highest levels of erosion. However, irrigation did not influence the presence of this enzyme, which was practically the same for comparable erosive levels. The concentration of nitrates, which are indicators of fertiliser use, increased directly with erosion levels up to almost 75% in rainfed olive groves. On the other hand, irrigation increased nitrate concentration by 25% and almost 30% in moderate and severe erosive levels, respectively.

3.2. Time Projection of Profitability in Rainfed and Irrigated Management

Table 7 shows the production and economic data obtained from surveys of farmers. These data correspond to each of the integrated management types considered: rainfed (n = 16) and deficit irrigation (n = 8). The responses of the farmers indicated that the decision to apply irrigation was related to the objective of increasing crop production, above any other consideration (for example, cost of implantation or related erosion problems).

Table 7. Economic and production data for rainfed and irrigated olive groves. PlantD (plantation density, trees ha^{-1}); production (kg olive ha^{-1}); tree production (kg olive tree^{-1}); selling price (€ kg olive); CAP (environmental subsidy received from the European Union through the Common Agricultural Policy, € ha^{-1} year^{-1}) and costs (operating costs, including machinery, personnel and application of phytosanitary products, € ha^{-1} year^{-1}).

Management	Rainfed			Irrigation		
	Maximum	**Minimum**	**Mean**	**Maximum**	**Minimum**	**Mean**
PlantD	199	100	150.00	499	200	350.00
Production	3499	2000	2749.50	4499	4000	4249.50
Tree production	17.58	20	18.33	9.01	20	12.14
Selling price	0.89	0.70	0.79	0.79	0.60	0.69
CAP	449	350	400.00	549	450	500.00
Costs	1499	1000	1249.50	2499	2000	2249.50

On average, the production of olive groves is considerably higher under irrigation, with an annual production of 4249.50 kg of olives ha^{-1} (807.89 L of oil ha^{-1}), compared with 2749.50 kg of olives ha^{-1} (522.72 L of oil ha^{-1}) produced under rainfed management. In the olive groves with higher production per hectare, the estimated average production per tree is lower than in plots with lower production. This is due to the higher density of plants present in the olive groves of high production per unit area, where the trees are smaller and, therefore, their productive level is lower. In economic terms, the annual benefit (difference between sales revenue and costs) of 1 ha with an irrigated olive grove was 682.65 € ha^{-1}, which increased to 1182.65 € ha^{-1} when considering CAP subsidies. In the rainfed plots, an annual profit of 922.60 € ha^{-1} was observed, increasing to 1322.60 € ha^{-1} when including the CAP subsidies.

Figure 3 shows the time projection of production and benefits per hectare of rainfed and irrigated olive groves, considering their levels of erosion.

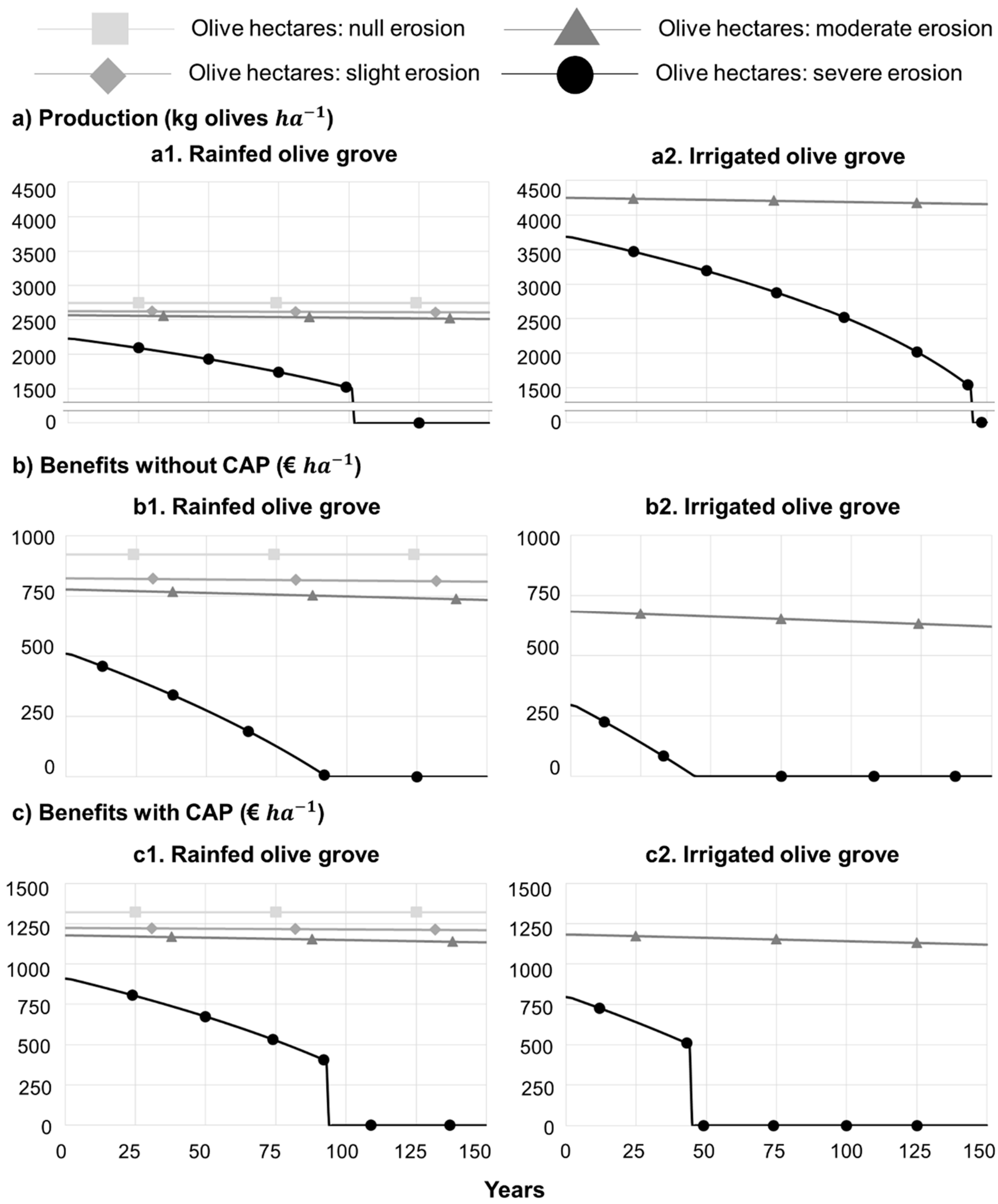

Figure 3. Production per hectare for each erosive level (**a**), in rainfed (**a1**) and irrigated (**a2**) management, and benefits without and with CAP subsidies (**b** and **c**, respectively) for each hectare of each erosive level in rainfed (**b1**,**c1**) and irrigated (**b2**,**c2**) management.

In the olive groves with null, slight and moderate erosion, under rainfed management, the production remained relatively constant (with a small decrease with slight and moderate erosion), between 3000 and 2500 kg of olives ha^{-1} year^{-1} for the period considered (150 years). In the olive groves with moderate erosion, the production of irrigated olive groves was higher than that of unirrigated olive groves (4250 and 2565 kg of olives ha^{-1} year^{-1}, respectively), maintaining a slight decline during the simulation time. The olive groves with severe erosion showed better production in irrigated management compared with unirrigated groves (3700 and 2200 kg of olives ha^{-1} year^{-1}, respectively, in the first year of the period considered). However, in an interval of 100 years for rainfed olive groves and 145 years for irrigated olive groves, those with severe erosion would be abandoned due to a decrease in productivity below 1500 kg of olives ha^{-1} (following the criterion of Gómez-Calero [22]).

In economic terms, with moderate erosion, the profitability of an olive grove, either rainfed or irrigated, was close to 750 € ha^{-1}. In rainfed olive groves, the value was practically constant around this value during the study period, while in the case of irrigation, it fell from a value of 700 to around 600 € ha^{-1} in the last year of the study period. With severe erosion, in the olive groves without irrigation, the estimated profitability was 500 € ha^{-1}, while the irrigated olive groves presented a value of profitability of 250 € ha^{-1}. Profitability would disappear at 100 years under rainfed management and 44 years for irrigated olive groves because the operating costs of the latter would exceed the minimum income from sales considered profitable (3263.28 kg of olive ha^{-1}). With slight or no erosion, rainfed olive groves were profitable throughout the study period, with profits of 760 and 900 € ha^{-1}, respectively. The CAP subsidies received by farmers obviously improve their profits but do not prevent the long-term loss of profitability of severely eroded olive groves, which must be abandoned after 90 and 40 years of simulation for rainfed and irrigated olive groves, respectively.

Table 8 shows the production and economic data per hectare accumulated throughout the simulation time. It was observed that soil erosion levels negatively affect production under both types of management in a highly significant way ($p < 0.001$ ***). In the rainfed olive groves, severe erosion presented production values markedly lower than other levels of erosion. Logically, the decrease in production due to erosion significantly impacted the profitability of olive groves, with this significant relationship increasing in irrigated olive groves despite their increased production due to increased farm costs.

Table 8. Production (kg olive ha^{-1}) and economic profitability (Bnf, € ha^{-1}) of the different types of management and levels of erosion for the simulation period considered (150 years). Without or with CAP (Common Agricultural Policy) refers to receiving or not receiving the environmental subsidies covered by this European policy.

Management	Rainfed				Irrigation	
Erosive levels	**Null**	**Slight**	**Moderate**	**Severe**	**Moderate**	**Severe**
Production	412,000	392,000	381,000	192,000	631,000	406,000
Bnf (without CAP)	138,000	122,000	113,000	25,900	97,700	6780
Bnf (with CAP)	198,000	182,000	173,000	63,100	173,000	28,800

4. Discussion

4.1. Influence of Irrigation on the Soil Characteristics

The irrigation in the studied olive grove showed some soil effects, which were more accentuated in high erosive levels. For example, as in other studies [64,65], a decrease from 21.07% to 9.29% was detected in the soil weight caused by the significant interaction of erosion and irrigation. This soil weight loss associated with the loss of the soil depth (essential fertility aspect) could be mitigated using vegetation cover [66–69], a very uncommon agricultural practice in *Estepa*. According to farmers' responses to the surveys conducted, vegetation cover was present in 54% of the olive groves under a rainfed regime and 33% of the irrigated lands. Another logical and expected effect of irrigation was the increase in soil moisture content. This fact, together with the loss in soil weight, causes greater soil compaction that may hinder root development of plants and increase the speed of circulation of runoff water [70–72]. An increase in fine particles in the soil could be a side effect of textural modification by irrigation in our study. A greater presence of silts and clays associated with crop irrigation was detected by Dong et al. [73] and this increase favoured the retention of water, carbon and organic matter. However, in *Estepa*, the irregular distribution of clays in the different erosive levels could be associated with the type of localised deficit irrigation that would avoid this effect of modifying the texture of the soil [19,36,74–76].

Regarding the chemical parameters of soils, erosive levels with irrigation consolidated differentiated groups with respect to rainfed management, except for pH and phosphatase. Soil pH influences the rate of synthesis, release and stability of phosphatase. Despite significant differences in pH values, the soils remained basic, with values below 7, and irrigation only slightly lowered the pH of the soils. In irrigation management, the organic matter content was lower than in rainfed management and the severe erosive level presented a lower percentage of organic matter for both management types. There could be a reciprocal effect, considering that organic matter can act as an erosion mitigating agent [77,78]; that is, irrigation increases organic matter loss, enhancing the erosion effect, and the low concentration of organic matter enhances the erosive effect of irrigation. The enzymatic activity of the soil was, in general terms, similar in irrigated olive groves compared to rainfed ones, although the increase in moisture could have favoured phosphatase activity and survival of the microbiota and microbial activity [53,79]. This was probably not appreciated in our study because the soils were basic.

Zhou et al. (2019) [80] highlighted that fertilisation is an important factor, especially when using fertilisers with N, which influences crop yield and affects the efficient use of water and nutrients. In *Estepa*, nitrate content, an indicator of N fertilisation, increased directly with erosion levels and its concentration was higher in irrigated olive groves. Numerous studies have shown that irrigation and fertilisation influence nitrate leaching in agricultural ecosystems [81]. According to the results of our study, in agreement with [81], the use of fertilisers should be managed not only considering the amount of fertiliser that is applied but also the irrigation management measures (amount of water, irrigation time and irrigation method). Therefore, irrigation could be as important as fertilisation in leaching water quality, and optimal irrigation combined with optimal fertilisation could reduce the potential environmental risk caused by excessive fertilisation in intensive systems of olive groves. In fact, diffuse pollution is considered one of the main negative environmental externalities of olive groves [1,14]. Regarding erosion, it should be considered that nitrates accumulate mainly in the soil layer of 0–60 cm and, therefore, erosive processes can transport this nutrient along with soil particles over long distances, contaminating other areas farther away [82].

4.2. Influence of Irrigation on the Ecological and Economic Sustainability of the Olive Groves

In Spain, irrigation practices in agriculture make up 19% of the cultivated area and are responsible for 60% of agricultural production and 80% of water consumption [83]. In the socioecological systems of olive groves, rainfed management predominates, with the use of irrigation in these systems being relatively recent [84,85]. Irrigation has been used to achieve greater production and respond to agricultural demand, increasing the benefits for farmers [86]. In addition, irrigation management allows the population to settle in rural areas. In Spain, irrigated agriculture employs almost 8 times the labour per unit area compared with rainfed agriculture [87]. In *Estepa* and, in general, Andalusian olive groves, a type of localised and deficit irrigation predominates to alleviate the limiting consequences of the water deficit on agricultural production without causing serious environmental damage [88,89]. However, despite these advantages of irrigation (in *Estepa*, irrigated olive groves showed an increase in production of up to 55%), the environmental externalities on the soil detected in our study should also be considered. This could condition the ecological sustainability of irrigated olive groves in the long term.

Of concern is the degree of misinformation on the part of farmers regarding regulations that have an impact on the long-term ecological sustainability of olive grove plantations. For example, all the farmers surveyed stated that they were not obliged to use plant covers; however, this agricultural practice is compulsory in integrated management (the overwhelming majority of groves in *Estepa*) according to Royal Decree 1201/2002 [90]. This agricultural practice (soil cover) is even a highly recommended measure in the Andalusian Olive Grove Master Plan [23]. In this sense, it would be relevant to implement and consolidate different scales of active channels of information from the administration to farmers and other involved stakeholders on environmental management practices appropriate to mitigating the erosive processes that condition the sustainability of olive groves over time [28,91].

Clearly, the greater production derived from irrigation is associated with greater economic benefit. However, the results of our study suggest that the medium- and long-term economic sustainability of irrigated olive groves should also be evaluated. According to the surveys carried out, farmers make the decision to irrigate their crops to obtain greater production, assuming, in the short term, a positive linear relationship between the production level and the economic benefits. A more detailed and rigorous evaluation should consider the increase in the costs of olive grove management derived from the maintenance of irrigation (irrigation water pricing and control of water use efficiency) [10] and the lower sale price at source of the olives and olive oil produced under this management [58,59]. The results of the study showed that, despite the higher production of irrigated olive groves, their benefits are similar to those of rainfed olive groves, both in the present and the time projections carried out. In the short term, the decrease in the economic sustainability of irrigated olive groves with severe erosion could be attributed to the need for economic investment in a type of irrigation that increases the efficiency of water resources and avoids aggravating surface erosion by irrigation [21]. In the medium to long term, economic decline could occur due to greater environmental impacts (i.e., diffuse pollution [92] and erosion) that could result from inadequate irrigation (excessive volume of water).

5. Conclusions

The results showed that irrigation in the olive agroecosystems in *Estepa* considerably increases the level of production immediately and in the short term but negatively affects their ecological and economic sustainability due to the degradation of the different soil parameters studied. The generalised irrigation type in the study area is localised and deficient in nature, with less environmental impact than other types of irrigation, such as sprinkler or blanket irrigation (also called flood or surface irrigation). Despite this, the results showed that, when comparing rainfed and irrigated olive groves with equivalent erosive levels, there were significant differences in some soil characteristics. The irrigated olive groves presented lower gravel content and higher soil moisture, decreasing their soil weight. Irrigation also gave rise to a loss of organic matter and a higher content of nitrates. Although irrigation increases production per hectare, this productive bonus may not be directly correlated with the economic benefits for farmers due to a lower selling price on the market for oils from irrigated olive groves and the cost of water. In this context, the promotion of deficit localised irrigation programmes would contribute to increasing water efficiency and saving, especially in situations of water scarcity, which are very common in Mediterranean olive grove areas.

We believe that the results of this study should be considered with some caution since the data analysed correspond to a single period and the absence of irrigation management in olive groves with null and slight erosion. Despite these limitations, the results show that management decisions must be taken in an integrated manner, considering not only economic–productive factors but also ecological aspects. This means that the notable expansion of irrigation in Andalusia should follow more rigorous guidelines considering the trade-offs that can occur with environmental aspects such as soil erosion. In any case, future lines of research should be oriented towards the optimisation of water yield [78,90], with the aim of improving the efficiency of this resource and increasing the general sustainability of olive groves. Exhaustive research should be carried out on the erosion–productivity relationship [2,26]. In addition, considering the restrictions on water resources anticipated in the coming years due to climate change [93–95], measures should be considered to increase rainfed agricultural yields, especially in Mediterranean areas characterised by water stress.

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