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Predicting soil erosion after land use changes for irrigating agriculture in a large reservoir of southern Portugal

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Abstract

The construction of the Alqueva reservoir in a semi-arid Mediterranean landscape brought new opportunities for irrigated farming. Land use changes and climate change may alter the risk of soil erosion that was not predicted in the initial development plans and decrease the lifetime of the investment. A comprehensive methodology that integrates the Revised Universal Soil Loss Equation (RUSLE) and geographic information system was adopted to study the effect on soil erosion of different land-uses of the Alqueva reservoir region. Analysing the soil erosion of each land-use it was obtained the following land use erosion vulnerability: Olive orchard>Vineyard>Montado>Alfalfa. The strong erosion variances that were observed in the study area show the importance of locating the 'hot spots' of soil erosion. Simulated scenarios for the entire area can be used as a basis for site-specific soil conservation plans, to promote sustainable land management practices and to facilitate localized erosion control practices and environmentally friendly farming.

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Keywords: Land-use, soil erosion, seasonal variations, RUSLE.

1. Introduction

Soil erosion by water is one of the most severe and dynamic environmental and economic threats around the world, particularly in regions with seasonal climate and a long past of anthropogenic pressure (Garcia-Ruiz et al., 2013). The intensification of this problem is being frequently associated with land-use changes (Kosmas et al., 1997; Bakker et al., 2008; Leh et al., 2013). Soil erosion decreases the productivity of natural and agricultural ecosystem, since the increase of runoff causes the loss of soil depth, reducing the water and nutrients storage capacity, and thus crop yields (Pimentel, 2006; Li et al., 2009; Hancock et al., 2015). Moreover there is off-site negative impacts associated with the increase of runoff that can transport sediments into rivers and reservoirs, causing their pollution and reducing their lifetime (Boardman et al., 2003; Pandey et al., 2007; Ludwig et al., 2009).

The rate of Mediterranean land-use changes in the last century has evidently increased, as a consequence of combination of environmental, economic and social factors (Bakker et al., 2008; Garcia-Ruiz et al. 2013). The

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linking between different land-uses and soil erosion has attracted the interest of a wide variety of researchers (Kosmas et al., 1997; Cerdan et al., 2010; Blavet et al., 2009; Cerdà et al., 2009; Nunes et al., 2011) who has demonstrated that different vegetation cover and/or agriculture procedures, have different impacts on soil properties and overland flow). Erskine et al. (2002) has demonstrated that land use is the dominant factor determining sediment yields in reservoirs and usually the highest values are associated to the cultivated lands (García-Ruiz and Lana-Renault, 2011).

Over the past few decades, numerous advances have been made to assess soil erosion, to overcome the costs and unfeasibility of monitoring in situ. So, there has been substantial investigation into soil loss models that vary according complexity, processes accounted and the information required (Merrit et al., 2003; Bhattarai and Dutta 2008; Volk et al. 2010). The empirical Universal Soil Loss Equation (USLE) is one of the most widely used models for estimating annual soil loss, (Wischemeier and Smith 1978) from agricultural watersheds and its modifications include the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997). Although some disadvantage reported (Volk et al., 2010), RUSLE is easy and valuable to use, because of the structure simplicity, low input data requests and the availability of parameter values. These models have been shown to be useful in combination with Geographic Information System (GIS) techniques and remote sensing because it allows to investigate the spatial distribution of soil erosion processes with reasonable expenses and accuracy (Terranova et al., 2009; Prasannakumar et al., 2011).

The construction of reservoirs in semi-arid landscapes bring new opportunities for irrigated farming. Land use changes may increase the vulnerability to soil erosion. The intensification of irrigated farming has been occurring simultaneously with the abandonment of the typical agroforestry system, increasing the need to promote sustainable practices. The main objective was to study the effect of typical and new land-uses vulnerability on soil erosion, accounting for seasonal variations on rainfall and vegetation cover during the year.

2. Study area

2.1. The Alqueva dam region

The Alqueva reservoir is located on the Guadiana river in the south of Portugal (8º30' W, 38º30' N) (Fig. 1).

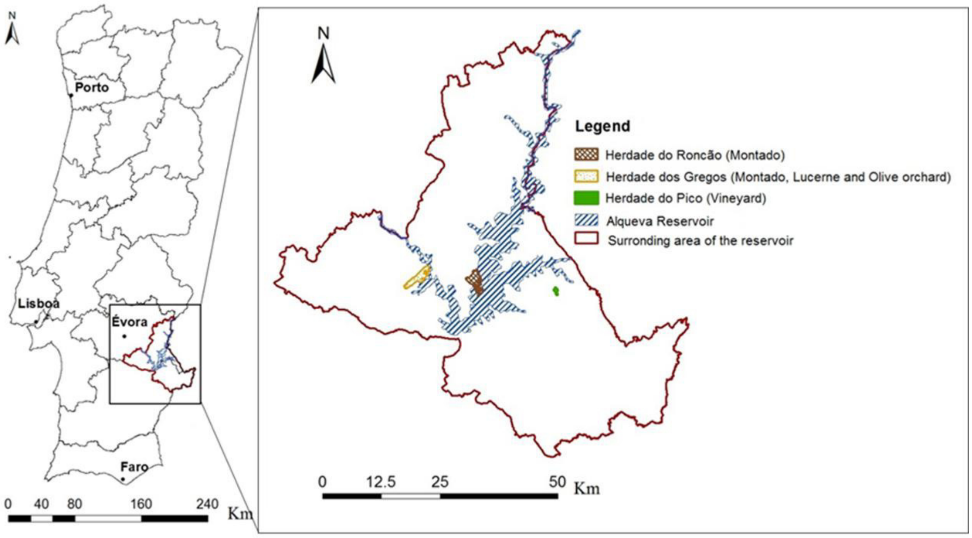

Fig.1 - Location of the Alqueva reservoir and the experimental study areas.

The reservoir covers an area of 250 km^2 (from which 35 km^2 are in Spain) and the total capacity is 4150 hm^3. The lake total shoreline is approximately 1100 km, it extends for 83 km and is considered one of the biggest in Europe (Lindim et al., 2011). The Alueva project was constructed during 1998-2002 (Fig. 2a), and the main objective was to create a strategic water reserve for population consumption, for agriculture irrigation (about 110000 ha), for energy production, as well as for landscape enhancement where several tourist projects can be built. Alqueva dam has direct influence in the regions surrounding it (namely 18 counties).

This region of Alentejo, Southern Portugal, is characterized by a complex landscape structure. A traditional landscape is named “Montado”, an agroforestry system in which agricultural and forest activities complement each other comprising an open formation of oak species combined with a rotation of crops/pastures. There was an intensification of agriculture (cereal production) in combination with extensive livestock breeding in the beginning of the 20th century, which lead for numerous environmental impacts and namely increased soil erosion. Though, especially since Portugal joined the European Community in 1986, the abandonment of agricultural activities in Alentejo increased, and the “montado” system is in transition towards a silvo-pastoral or even purely forestry system (Pinto-Correia e Mascarenhas, 1999). Today, with Alqueva reservoir, the intensification of some farming systems occurs simultaneously with the reduction and ultimate abandonment of others.

The climate is Mediterranean, with hot and dry summers and mild winters. The annual mean for temperature ranges from 24 to 28 °C in hot months (July/August), and from 8 to 11 °C in cold months (December/January). The annual mean of precipitation ranges between 450 and 550 mm, however the region is affected by intense dry periods without precipitation, since almost 80% of the precipitation occurs from October to April.

2.2. Experimental study areas

In order to study the effect of land-use on soil erosion we identified three areas (called in Portuguese “herdades”) namely: “Herdade do Roncão”, “Herdade dos Gregos” and “Herdade do Pico”. Four different land-uses were identified and selected to study namely: montado grassland, vineyard, alfalfa cultivation, and olive orchard (Fig. 2).

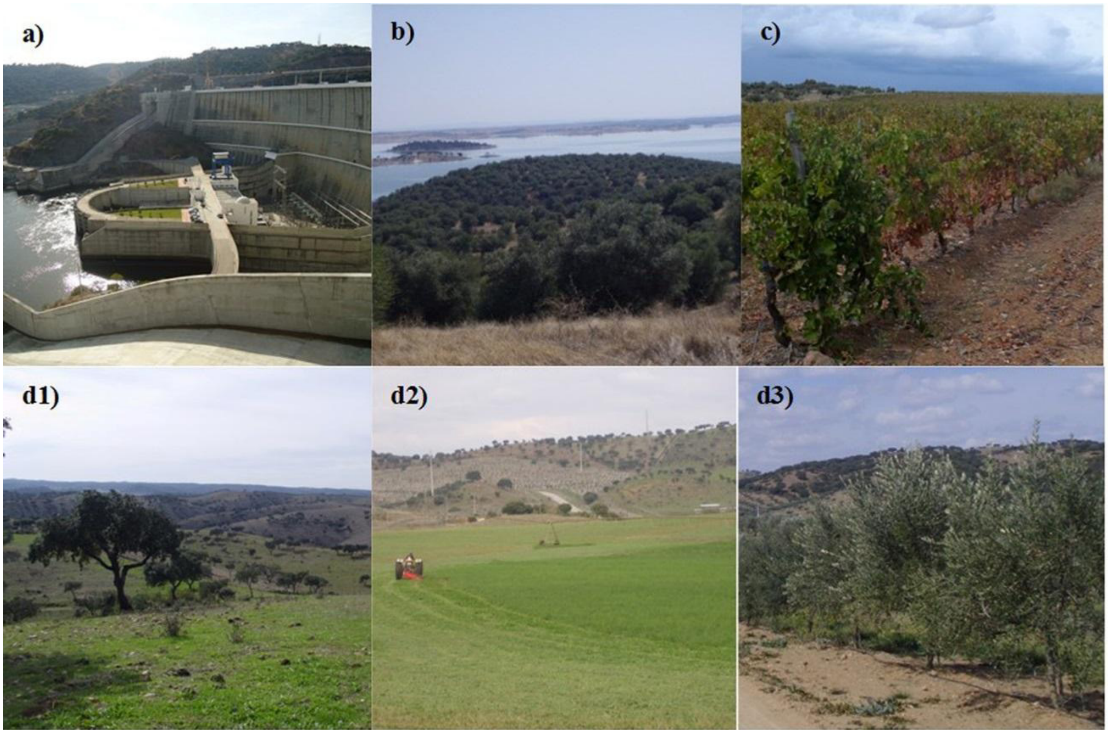

Fig. 2 - Alqueva dam project and land-uses (experimental sites): a) Alqueva dam; b) Montado in the “Herdade do Roncão”; c) Vineyard in the “Herdade do Pico”; d1) Montado system, d2) Alfalfa cultivation and d3) Olive orchard in the “Herdade dos Gregos”.

The “Herdade do Roncão” (739 ha) consist of agro-silvo-pastoral land-use:

- A typical “Montado” characterized by a silvo-pastoral system with low density holm oaks (Fig. 2b), and some olive trees in part of the area where farming was abandoned about 6 years before the study period.

The “Herdade do Pico” (30 ha) consists also of a one land-use:

- A vineyard with drip irrigation, plough between lines and fertilization (Fig. 2c).

The “Herdade dos Gregos” (900 ha) comprises three different land-uses studied:

- A Montado (Fig. 2d1) similarly characterized by a silvo-pastoral system with low density holm oaks and which suffered a fire 3 years before the study period;
- An intensive cultivation of Alfalfa (also called lucerne: *Medicago sativa*) with center pivot sprinkler irrigation, tillage and fertilization (Fig. 2d2);
- An olive orchard with drip irrigation system, frequent ploughing between lines and fertilization (Fig. 2d3).

3. Methodology

This study integrated the use of RUSLE equation, GIS, remote sensing and geostatistics to predict soil erosion and respective factors. RUSLE, is defined as:

$$A=R\ K\ L\ S\ C\ P \quad (1)$$

where A= potential annual erosion (t ha^{-1} year^{-1}), R= rainfall and runoff erosivity factor, K= soil erodibility factor, LS= slope length and gradient factor, C= vegetation cover factor and P= support practice factor (Renard et al., 1997). To study seasonal soil erosion, the erodibility (K) and topographic (LS) factor were aggregate as “static” over the year, and rainfall erosivity (R) and vegetation cover (C) factors were analysed per season. The nex sections describe the RUSLE data collecting and processing for each factor. The spatial data was easily treated with ArcGIS software.

3.1. Soil erodibility factor (K)

Soil erodibility factor (K) represents the susceptibility of a soil to erode and the amount and rate of runoff, as measured under continuously cultivated fallow plot 22.1 m long with a slope of 9% (Renard et al., 1997). It is a quantitative value experimentally determined using an algebraic approximation (Wischmeier and Smith, 1978):

$$K = [2.1 \times 10– 4(12–OM) \times M1.14 + 3.25(S – 2) + 2.5(P – 3)]/100 \quad (2)$$

where OM is organic matter, s is soil structure, and p is permeability class. M is the product of the primary particle size fractions (% MSilt) × (%MSilt + %MSand), where %MSilt is percent modified silt (0.002-0.1 mm), and % MSand is percent modified sand (0.1-2 mm). Modified silt is the amount of silt particles and very fine sand, considered the most susceptible particles to erosion, because can be easily removed by the raindrop splash and runoff water.

A minimum of 25 soil samples with 20 cm depth were collected in each area. The sample localizations, in field, were kept using a Global Positioning System (GPS). Soil permeability and soil structure were estimated in the field. In the laboratory, the particle-size distribution, soil organic matter (OM) and soil total nitrogen (N) were investigated.

The data were subjected to statistical analysis using SPSS 17.0 software, namely the mean, standard deviation (SD), minimum and maximum, coefficient of variation (CV) and skewness of each parameter. To evaluate significant differences between means for each land-use we used multiple ANOVA (Duncan multiple range test). A continuous surface representing the spatial variation of this factor was prepared in ArcGIS 10 software using geostatistic tool.

3.2. Slope length and steepness factor (LS)

Slope Length (L) and slope steepness (S) factors show the influence of topography on soil erosion erosion (Wischemier and Smith, 1978). Direct measurements of slope and slope length were initially proposed to evaluate these factors (Renard et al., 1997). However this method is only suitable for small plots and parcels, because intensive field measurements are obviously not feasible on a regional scale. In watershed scale, the use of a Digital Elevation Model (DEM) in GIS, for data input is a better approach (Nekhay et al., 2009). Therefore, in the present study, a DEM from the region was used in ArcGIS software to estimate this factor. The combined LS factor (without units) was computed using ArcGIS spatial analyst extension, following the equation (3) (Moore and Wilson, 1992):

$$LS = (\text{flow accumulation} \times \text{cell size}/22.13)^p \, (\sin \alpha/0.0896)^q \quad (3)$$

where p and q are empirical exponents (p = 0.4 and q = 1.3) (Moore and Wilson, 1992), flow accumulation signifies the accumulated upslope contributing area for a given cell, cell size is the size of DEM grid cell and α is the slope degree value.

3.3. *Rainfall erosivity (R)*

The rainfall-runoff erosivity (R) represents the erosive potential of raindrops impact and of runoff generated by erosive storms. According to Renard et al. (1997), the rainfall-runoff factor is determined through the sum of erosive storm values EI30 occurring during a mean year, which result for the product of total storm kinetic energy (E) times the maximum 30 minute intensity (I30), where E is in MJ/ha and I30 is in mm/h. The monthly erosive storm empirical index EI30 was computed for 25 meteorological stations in the surrounding area of the Alqueva using the regression equation (Goovaerts, 1999):

$$EI30month = 6{,}56 \times rain10 - 75{,}09 \times days10 \quad (4)$$

where rain10 is the monthly rainfall for days with rainfall higher than 10 mm and days10 the monthly number of days where rainfall exceeds 10 mm. Daily precipitation data during 30 years (1980-2010) were used. Rainfall erosivity maps per season, for the region, were created using geostatistics. The R means for each land-use were estimated.

3.4. *Cover management factor (C)*

The C factor reflects the effect of vegetation on erosion rate (Renard et al., 1997), considering that it reduces the erosive impact of rainfall and slow down overland flow. C factor values diverge from 0 (well-protected soil) to 1 (bare soil) and there is a strict relation with land use types. Remote-sensing has been one of the most widely used methods for mapping the C factor (Van der Knijff et al., 1999; Prasannakumar et al., 2011), because vegetation cover can be estimated using vegetation indices derived from satellite images such as Normalized Difference Vegetation Index (NDVI). NDVI is an indicator of vegetation growth and ranges from -1 to 1. This method gives different prospective on soil erosion studies because allows the estimation of intra-annual changes in vegetation through images for different periods (Ouyang et al., 2010). NDVI was computed utilizing band 3 (red) and band 4 (near-infrared) as follows:

$$NDVI = (NIR - RED)/(NIR + RED) \quad (5)$$

Landsat TM images were processed to obtain NDVI of different seasons. To estimate the C factor, the most common procedure using NDVI involves the use of regression equation model derived from the correlation analysis between the C factor values measured in the field and a satellite-derived NDVI (Van der Knijff et al., 1999):

$$C = e\ (-\alpha(NDVI/(\beta - NDVI)) \quad (6)$$

where α and β are unit less values that determine the shape of the curve relating NDVI and C factor. Van der Knijff et al. (1999) found that this approach gave better results than assuming a linear relationship, and the values of 2 and 1 were selected for the parameters α and β, respectively. The C factor maps were produced in ArcGIS software.

3.5. *Conservation practice factor (P)*

The support practices factor (P) reflects the effects of specific practices that can be used to reduce the amount and rate of erosion, such as contouring, strip-cropping, terracing, and subsurface drainage. These practices affect erosion by modifying the flow pattern, grade, or direction of surface runoff and by reducing the amount and rate of runoff (Renard et al., 1997). In this study, P factor was assigned the value of 1 (no support practice factor) for all land-uses, because the support practices in these areas are not relevant or not existent.

4. Results and Discussion

The effect of each land-use on soil erosion was studied for each factor considered by the RUSLE model.

4.1. Soil erodibility (K)

Soil erodibility was considered time invariant. The mean values of some soil properties and estimated soil erodibility for each land-use are presented in Table 1, as well as Duncan test results. Duncan's test showed significant differences between land-uses for all properties analysed. Means with different letters in the same property are significantly different between land-uses at $p \leq 0.05$. It reveals that land-uses have highly significant effect on soil properties and in turn on soil erodibility. Despite some differences in particle size distribution, the soils were classified as sandy loam. Though, it was clear that the content of organic matter (OM) and nitrogen (N) decreased with the intensification of land-use (alfalfa cultivation, olive orchard and vineyard) and the differences were statistically significant. The low values of OM and N in the intensive land-uses can be explained with the frequent soil ploughing and irrigation system. According to Tesfahunegn et al. (2011), soil tillage mixes the subsoil with topsoil, thus there is more OM decomposition and water erosion easily remove the nutrients from the surface layer. As a result, soil erodibility increased with the intensification of the land use, with lowest values for Montado grassland (0.021 t ha h ha^{-1} MJ^{-1} mm^{-1}) and highest for alfalfa (0.039 t ha h ha^{-1} MJ^{-1} mm^{-1}). Other studies had similar results, showing that the removal of permanent vegetation, the loss of OM and the reduction of aggregation, caused by intensive cultivation, contribute to decrease of soil erodibility (Evrendilek et al., 2004).

Table 1 – Soil properties and soil erodibility (K) means.

	H. Roncão	H. Gregos			H. Pico
	Montado	Montado	Alfalfa	Olive Orch.	Vineyard
Sand (%)	62.71b	53.16a	52.93a	65.81b	56.5a
Silt (%)	22.01a	29.55b	33.79c	24.37a	21.8a
Clay (%)	15.27b	17.29c	13.29b	9.83a	21.6d
OM (%)	4.63c	5.22c	2.08b	2.10b	0.77a
N (%)	-	0.19c	0.11b	0.10b	0.07a
K factor (t ha h ha-1 MJ-1 mm-1)	0.023a	0.021a	0.039c	0.038c	0.029b

Means with different letters in the same property are significantly different between land-uses at **p** ≤ 0.05 (Duncan's test).

4.2. Topography (LS)

The LS factor maps for each area are presented in Figure 3. The highest mean LS factor values occur for Montado areas (1.28 and 1.86 for "Herdade do Roncão" and "Herdade dos Gregos" respectively) and for vineyard (mean of 1.21), and are mainly associated to great slopes. Through the prediction LS factor maps it was easy to identify sensitive areas for some land-uses, because it has been demonstrated that increases in this factor can produce higher overland flow velocities and correspondingly higher erosion (Van Remortel, 2004).

4.3. Soil erosivity (R)

Rainfall erosivity values were estimated for 25 stations and using geostatistic techniques we obtained a regional erosivity map for each season. The mean values of soil erosivity were estimated for each experimental area and are shown in Table 2. The values vary lightly between areas despite close locations, and these variances were taken into account when predicting soil erosion. Looking at values for each season we noticed that rainfall erosivity was characterized by a strong seasonality and the highest rainfall erosivity values were related with the first autumn rain events and the lowest values occur in summer. In percentages, about 47-50% of annual rainfall erosivity occurs in autumn, 20-24% in winter, 17-19% in spring and only 9-10% in summer. Those trends were comparable to the results found in other Mediterranean studies (Van der Knijff et al., 1999, Diodato, 2004).

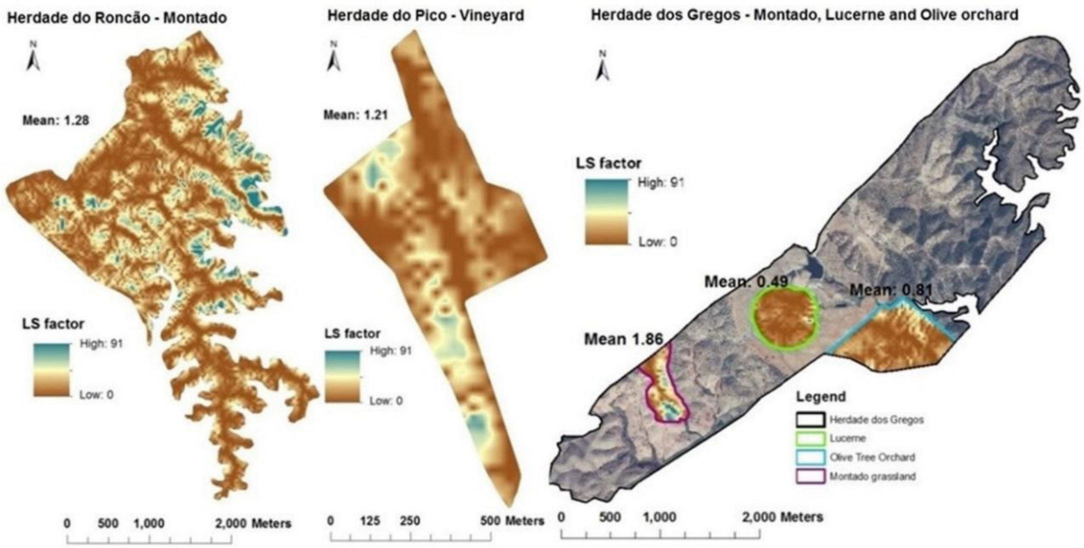

Figure 3 – LS factor for each study area.

Table 2 – Mean values of rainfall erosivity for the experimental study areas, according to each season.

	H. Roncão	H. Gregos	H. Pico
Autumn	423.8	445.7	404.1
Winter	193.4	212.2	170.0
Spring	146.4	152.6	158.7
Summer	79.7	79.9	81.2
Total	875.6	892.0	851.7

4.4. Vegetation Cover (C)

The NDVI and vegetation cover C factor values for each season are shown on Table 3. The NDVI and the C factor are negatively correlated. Higher NDVI values means greater vegetation cover which implies lower soil erosion. So, for the land uses of Montados and olive orchard the vegetation cover is strongly seasonal dependent, being the highest vegetation cover during the winter (C factor <0.2) and the lowest in summer and autumn (C factor >0.69).

Table 3 – Mean values of NDVI and C factor for each land-use.

		H. Roncão	H. Gregos			H. Pico
		Montado	Montado	Alfalfa	Olive Orc.	Vineyard
Autumn	NDVI	0.110	0.127	0.673	0.156	0.152
	C factor	0.789	0.747	0.035	0.690	0.697
Winter	NDVI	0.455	0.494	0.581	0.513	0.193
	C factor	0.193	0.141	0.065	0.125	0.620
Spring	NDVI	0.222	0.241	0.226	0.169	0.224
	C factor	0.567	0.531	0.558	0.665	0.562
Summer	NDVI	0.102	0.107	0.138	0.110	0.138
	C factor	0.797	0.790	0.724	0.780	0.726

On the other hand in alfalfa cultivation and in vineyard the C factor was more reliant on farming practices. For alfalfa land-use the highest vegetation cover (NDVI) occurs during winter but especially in autumn. Alfalfa had the highest NDVI values in autumn and vineyard in summer and spring due to the irrigation. The vineyard had the lowest vegetation cover during all seasons, including winter (C factor >0.6), explained by the frequent soil ploughing in order to remove weeds between lines.

4.5. Soil erosion

All factors were integrated in ArcGIS spatial analyst to quantify soil erosion rates for each season and annually. Table 4 show the erosion values of the different land-uses and the estimated annual means. For all land-uses except alfalfa, the soil erosion was estimated to be higher during autumn season (higher than 8 t/ha). Autumn contributed with more than 50% of annual soil erosion. In this period the soil erosivity reaches a peak due to the high intensity rainstorms typical for Mediterranean regions and due to the very low vegetation cover that did not recover yet after the dry season.

Table 3 - Soil erosion mean values for each land-use and each season (potential annual erosion (t ha^{-1}).

	H. Roncão	H. Gregos			H. Pico
	Montado	Montado	Alfalfa	Olive Orc.	Vineyard
Autumn	9.730	12.770	0.447	9.438	8.823
Winter	1.031	1.175	0.303	0.826	3.440
Spring	2.438	2.736	1.615	3.068	2.778
Summer	1.820	2.267	1.117	1.908	1.851
Annual	15.036	19.108	3.502	15.232	16.892

The RUSLE factors were then integrated using map algebra in ArcGIS and then were generated seasonal and annual prediction maps of soil erosion that are shown in Figure 4. Analysing those maps allows the identification of sensitive areas (hot spots of potential soil erosion). It is evident the topographic influence on soil erosion rates. Throughout the prediction maps it can be seen easily the seasonal variations. Despite the higher soil erodibility (K) measured for alfalfa land use, the annual soil erosion was the lowest of the studied land uses, which was resulting from the low slopes that is installed (LS factor) and high vegetation cover (C factor) during the season with extraordinary rainfall erosivity. On the other hand, the Montado in the “Herdade dos Gregos” present the maximum soil erosion vulnerability despite the lower soil erodibility (K factor). This was a consequence of the greater slopes (LS) that are usual for montado systems and also due to the recent wildfire that affected the natural vegetation cover and did not recover yet. The topography (LS) and the rainfall erosivity (R) are characteristics of local not influenced by land-uses, considering mainly factors that differ with land-use area vegetation cover (C) and the soil erodibility (K). Therefore, a lastly analysis was done to compare the effect of land use, ignoring R and LS factores. Considering only the KC ratio we obtained the following erosion susceptibility: Olive orchard>Vineyard>Montado>Alfalfa. Similar results were obtained by different authors, which observed higher soil erosion rates in orchards and vineyards comparatively to woodlands, scrubland or fire affected land (Cerdá *et al.*, 2009; Kosmas *et al.*, 1997).

5. Conclusions

The observed soil erosion variability reflects the importance of studying different scenarios of land-use, climate change and seasonal variations of vegetation. It was found important differences in hydrological functioning and erosional response of soils under different land uses and vegetation types. Sustainable irrigated farming could a key issue to ensure the vegetation cover mainly during the periods with intensive rainfalls and in the most sensitive areas. The irrigated alfalfa cultivation proves to protect soil during high rainfall erosivity periods, although it is important to understand soil degradation caused by intensive cultivation, tillage and fertilization. In the olive orchard and vineyards it should be promoted the soil conservation technique called “strip cropping” instead of frequent weed removal. The abandonment of montado systems leaded to poorly managed forest areas and constrains the sustainability of the system, increasing forest fires risk and vulnerability to soil erosion.

The soil erosion prediction maps under different scenarios and the contribution of each factor can be used as a solid base to create a Decision Support System (DSS), which will promote sustainable management of different land-uses in the region, based on spatial variability of soil characteristics and topography, and on seasonal variations of rainfall and vegetation cover. Site specific soil conservation practices and mitigation measures will allow soil erosion reduction and consequently prolong the lifetime of the investment.

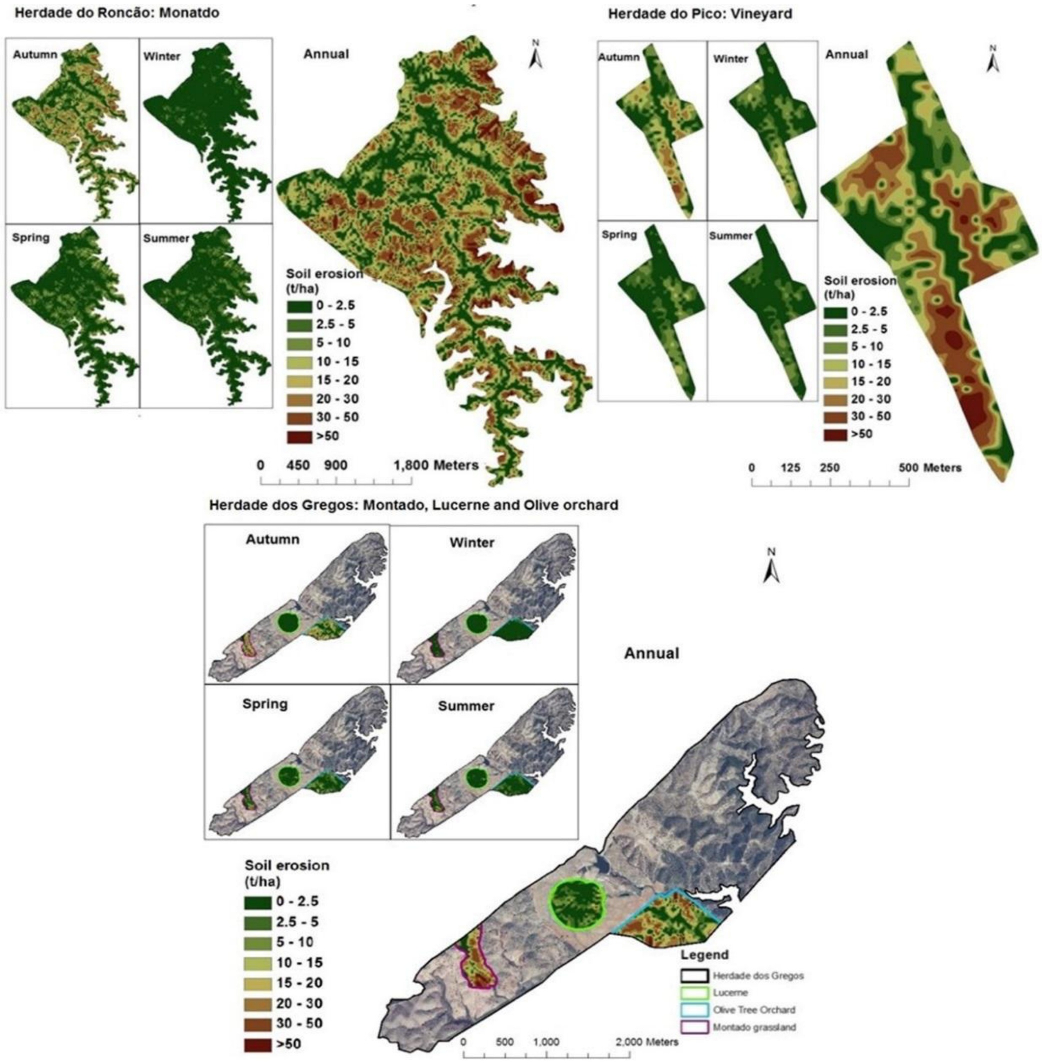

Figure 4 – Prediction maps of soil erosion for each land-use, accounting seasonal variations.

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