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Impacts of land use and cover type on runoff and soil erosion in a marginal area of Portugal

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ABSTRACT

This paper presents the results of soil hydrological and erosional responses to different land use and cover types in a marginal area of Portugal. The six land uses and vegetation covers studied (cereal crop, fallow land, shrub cover, recovering autochthonous vegetation, land afforested with *Pinus pinaster* and pastureland) are representative of situations commonly found throughout central and northern Portugal and also in other Mediterranean systems. The specific goals were to evaluate and compare the hydrological and erosional response of soils representing different land uses and vegetation types, to establish the influence of climatic variability and soil surface characteristics, and to assess the efficiency of alternative land uses proposed by the Common Agrarian Policy in terms of hydrogeomorphic behaviour.

The results show significant hydrogeomorphic responses among land uses/covers, indicating arable land and coniferous afforestation as the most serious in terms of runoff and soil erosion. With these types of land use, the soil transported by runoff peaks during autumn/winter coincided with the highest and most erosive rainfall in the experiment area. Conversely, shrub cover and recovering oak, resulting from land abandonment and plant succession, and pastureland, as consequence of conversion to arable land, showed the greatest rainfall infiltration capacity and the lowest rate of soil erosion. According to the results, vegetation dynamics emerges as a key factor in quantifying and interpreting the hydrological and erosional response of the land use/covers monitored. Soil erosion can subsequently be controlled by changing land use and increasing the ground cover, which was revealed as one of the basic approaches to controlling soil erosion in all types of land use.

Introduction

Land use and soil cover are considered the most important factors affecting the intensity and frequency of overland flow and surface wash erosion (García-Ruiz, 2010; Kosmas et al., 1997; Mitchell, 1990). Many authors have demonstrated that in a wide range of environments both runoff and sediment loss decrease exponentially as the percentage of vegetation cover increases (Elwell & Stocking, 1976; Francis & Thornes, 1990; Lee & Skogerboe, 1985). In the Mediterranean region there is a great deal of evidence to show that unreasonable land use and soil cover accelerates water erosion processes (Dunjó, Pardini, & Gispert, 2004) and consequently land degradation.

According to the CORINE programme, Spain and Portugal are the Mediterranean countries in the European Union facing the greatest risk of erosion (Desir & Marín, 2007). In Portugal, areas at high risk of erosion cover almost one third of the country (Grimm, Jones, & Montanarella, 2002). The main causes of soil erosion are inappropriate agricultural practices, deforestation, overgrazing, land abandonment, forest fires and construction activities (Grimm et al., 2002; Yassoglou et al., 1998). Amongst these factors, agricultural land uses generate the highest erosion yield (Cheng, 2002; Pardini, Gispert, & Dunjó, 2003; Collins, Walling, Sichingabula, & Leeks, 2001; García-Ruiz, 2010; Hill & Peart, 1999; Nunes, Coelho, Almeida, & Figueiredo, 2010; Wang, Li, Yang, & Tian, 2003).

In Portugal, as well as in many other Mediterranean countries, the main type of land use was rainfed cereal crops until the middle of the twentieth century. After the introduction of modern agriculture, the opening up of the international markets and the lowering of crop prices, market-oriented cultivation of cereals became unprofitable in most marginal areas in Portugal. In addition, socio-economic and political changes in Portugal in the 1970s led to higher agricultural wages and migration from the countryside (Pinto-Correia & Mascarenhas, 1999). Thus, abandoned farmlands became evident, very often in marginal, mountainous or semi-mountainous areas and areas that were difficult to access, in

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which traditional or semi-traditional agriculture was practised until recent decades, involving low input and intensive human labour. Abandonment implied the extensive decline of arable land and resulted in very important transformations to the landscape, characterised by the spread of natural vegetation, including both shrub land and forest.

In 1992, measures accompanying the reform of the Common Agricultural Policy (CAP) were adopted to benefit the environment, early retirement and forestry. These measures aimed to support the envisaged processes of change, and to mitigate some of the effects deemed to be disadvantageous to farmers (Van-Camp et al., 2004). European Economic Commission (EEC) Regulation 1765/92 (EEC, 1992) led to a substantial increase in set-aside land in the European cereal-growing regions (Crabb, Dauven, Firbank, Winter, & Parham, 1998; Van Rompaey, Govers, Van Hecke, & Jacobs, 2001). Agricultural land afforestation (Regulation 2080/92), which established an aid programme for the afforestation of former agricultural lands, also aimed to enhance long-term forest resources and combat soil erosion and desertification by promoting forestry as an alternative form of land use. However, the overall effectiveness of afforestation in reducing soil erosion remains uncertain, due to the poor development of the forest cover in some areas leading to significant areas with sparse tree cover, and the erosional impact of forest harvesting, which usually involves clearcutting (Porto, Walling, & Callegari, 2009). In fact, little data is available. The extent to which these measures are applied in areas under medium/high risk of soil erosion needs to be assessed (Van-Camp et al., 2004).

Additionally, the EU's Common Agricultural Policy recognises the natural handicaps of such areas and their association with depopulation and land abandonment through its structural support for 'Less-Favoured Areas' (Regulation 950/97). Around eighty per cent of the Portuguese Utilised Agricultural Area (UAA) falls within the definition of Less Favoured Areas (LFAs), and a substantial amount of this is classified as mountain area. Much of this mountain zone is designated Objective 1.

According to Caraveli (2000), the implementation of CAP measures in Mediterranean countries has reinforced *intensification* processes in productive practices in the more fertile areas of the lowlands and *extensification* (i.e. abandonment or marginalisation and the collapse of traditional farming systems) in the LFAs, which has been going on for decades. Land use changes characteristic of extensification include fewer cultivated fields, more shrub patches, larger areas of natural pastures, and abandonment of some patches, followed by the development of stratified bush communities. The CAP agreement requires Member States to maintain a permanent pasture area, which should prevent the wide-scale ploughing up of land for arable cultivation and potential problems with soil degradation often associated with arable farming in some areas (Van-Camp et al., 2004). Nevertheless, the influence of grazing on vegetation development and soil erosion processes is rarely quantified in literature on the subject (Ries, 2009).

The specific objectives of the current research were: (i) to evaluate and compare the hydrological and erosional response of soils under different land uses and vegetation types in central inland Portugal and (ii) to assess the efficiency of alternative land uses proposed by the CAP for soil erosion control. The six land uses and vegetation types studied (cereal crop, fallow land or short-term abandonment, shrub land, recovering autochthonous vegetation, arable land afforested with *Pinus pinaster* and arable land transformed into pastureland) are representative of situations commonly found throughout central and northern Portugal, and also in other Mediterranean systems. The main aim was to obtain consistent conclusions for ecosystem management in marginal areas of Portugal. This information on the hydrogeomorphic response could be useful in the future as a guide for regional soil conservation planning.

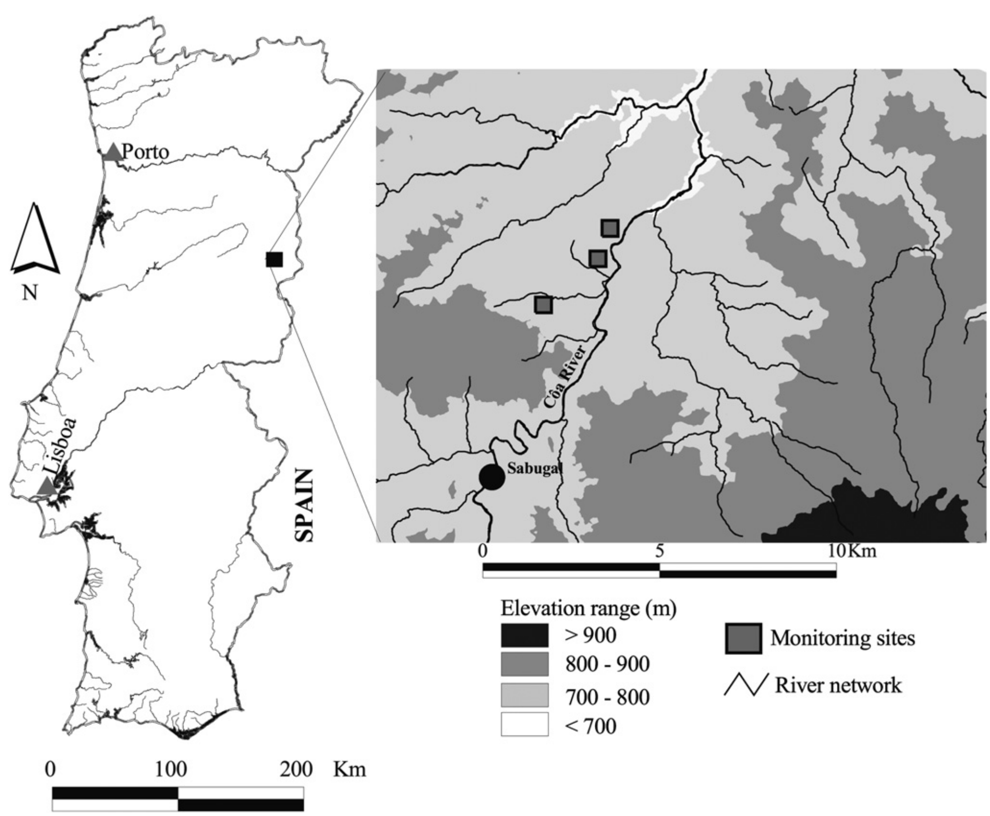

Fig. 1. Study area and sites monitored.

Material and methods

Study area

The study was carried out in the high Côa river catchment, in a peripheral area of Portugal close to the Spanish border (Fig. 1). The substratum comprises mainly granites with poor, shallow soils, classified as distric cambisols (FAO-UNESCO, 1974, 59 p.), and an undulating relief with elevation ranges from 700 to 900 m a.s.l.

The area has a sub-humid Mediterranean climate, characterised by wet, cool winters (5.8 °C average temperature) and hot, dry summers (25.8 °C average temperature). The mean annual precipitation of 800 mm has a high inter-annual variable distribution and seasonal concentration (Fig. 2). The wettest periods of the year are concentrated in the autumn and winter months, between October and February, and the driest in summer, between June and September. The amount of rainfall differed greatly over the two years studied, with about 500 mm falling in 2005 and 1200 mm in 2006, i.e., 300 mm below and 400 mm above the average for the period 1960–2003 (Fig. 2). Despite this variability, they both reflected the seasonal pattern typical of the Mediterranean region, with rainfall concentrated in the autumn and winter months. The highest figures were recorded in October/November and the lowest between June/August.

Background

Agricultural activities dominated land use in marginal areas of Portugal for many decades. In the 1960s, approximately over half the utilized agricultural area was divided between non-irrigated cereals (the dry system) and unseeded fallow rotations. Cereal crops were sown from October to mid November to make use of autumn precipitation for germination. Spring was the main growing season and mature cereals were harvested in June to early July before the onset of the hot, dry months. Cereal fields were rotated with unseeded fallow in order to regenerate soil moisture and nitrogen levels for the following year's cereal rotation.

Agricultural activities have become less important since the mid-20th century, when a rural exodus took place, mainly because of poor conditions for agriculture (a Mediterranean climate, undulating relief, and poor, shallow soils), uncompetitive farm structures (with small, scattered plots), the peripheral location of the area, the lack of alternative employment sectors and the extensive presence of elderly farm owners. Furthermore, the socio-economic and political changes in Portugal in the 1970s that led to higher agricultural wages and migration from the countryside, made it difficult to maintain traditional management and manual shrub clearing, which was essentially based on low labour costs.

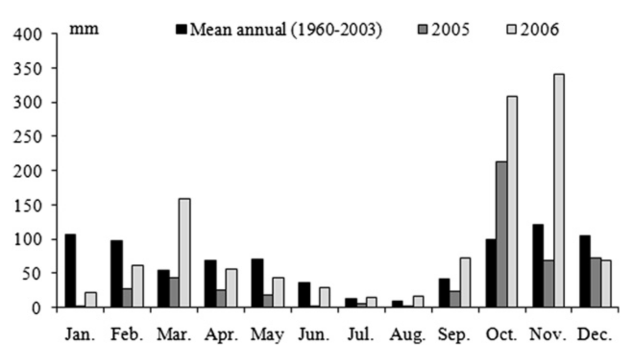

Fig. 2. Mean annual precipitation (1960–2003) and monthly distribution in 2005 and 2006.

According to SROA (Service of Agrarian Recognition and Management, 1970) statistics, in the middle of the last century cereal cultivation occupied about 55% of the total area of the Guarda district. Five decades later, the same crop only represented 10% of the total surface (CORINE Land Cover, 2000), meaning that approximately 80% of the cereal crop area had been abandoned.

Complete farm abandonment has resulted in enhanced natural secondary succession and the spread of scrub and woodland (Lasanta, Arnáez, Errea, Ortigosa, & Ruiz-Flaño, 2010). In the first stage of land abandonment, after 4–5 years, the dominant vegetation belongs mainly to the Gramineae family and forms a sparse herbaceous cover. Perennial shrubs, mainly dominated by *Cytisus multiflorus* and *Lavandula sampaioana*, follow after 15–20 years of farmland abandonment. Some small areas are covered by recovering oak, indicating a very lengthy abandonment of circa 30–40 years. *Quercus pyrenaica* willd. woodland typifies the potential vegetation in the study area. The unmanaged growth of large quantities of vegetal fuel has led to a dramatic increase in forest fires and burnt areas (Carvalho, Coelho, Ferreira, & Charlton, 2002), and therefore difficulty in regenerating *Quercus*.

The 1992 MacSharry reforms to the European Union Common Agricultural Policy have reinforced the falling rates of cereal production. The reforms included a set-aside program requiring farmers to take certain percentages of their arable land out of production. With the opening up of international markets and the lowering of crop prices, the market-oriented cultivation of cereals became unprofitable in most of Portugal. Farmers receive more in the form of direct payments per hectare under the set-aside regime in comparison with arable crop production. Consequently, they put greater percentages of their farms into set-aside. As an example, in the Guarda district early retirement has affected about 10 000 farmers and an area between 60 000 ha and 90 000 ha, since 1996. This represents about 40% of the total number of farmers and 30%–45% of the utilised agricultural area.

In contrast, pastureland has increased by over 25%, in the last two decades (INE, 2000). In fact, recent EU agri-environmental measures support the maintenance of natural pastures or the extensive cultivation of fodder crops (without deep ploughing and the use of fertilisers) and the livestock unit subsidy supports maintenance of livestock (Borges et al., 1997). The current CAP measures for Portugal also promote forest development measures (EU Regulation 2080) by supporting new plantations and shrub clearance.

Methodologies

The experimental design compared six different land uses associated with traditional land use, land abandonment and subsequent plant recovery, and alternative land uses proposed by the CAP for marginal areas (extensification of land use and conversion of arable land to forest).

The selected land uses/covers are as follows:

Cereal crops (traditional land use)

The cereals, mainly rye culture, are planted from October to mid November to make use of autumn precipitation for germination. Spring is the main growing season and mature cereals are harvested from June to early July before the onset of the hot, dry months. In March/April the 20–30 cm of top soil is turned over and remains without vegetation until sowing. This process is called laying fallow.

Fallow land (traditional land use or short-term abandonment)

In dry cereal systems with Mediterranean marginal soils, fallow land is a traditional part of the cereal rotation system. During fallow cycles, land remains unseeded for 2, 3 or more years to enhance soil fertility and soil moisture availability for subsequent crops. No chemical fertilisers or manures are used, and the plant residue is kept in the fields. Fallow lands are usually used as grazing land in traditional land use agropastoral herding practices in the territory.

Shrub land (long-term abandonment)

When arable land is abandoned, a process of plant colonisation begins. This is a complex process in which different variables interact: ecological conditions (both physical and biotic factors), human activity (the agricultural history of the fields as well subsequent management, namely grazing, fire, clearing, etc.) and time. Before shrubby species, mainly *Cytisus* spp., proliferate, abandoned fields in central inland Portugal are invaded by herbaceous plants during the first years of abandonment. It can take more than 15–20 years for shrub land with a high percentage of ground cover to develop. Due to the accumulation of biomass in abandoned fields after recolonisation, there has been an increase in forest fires.

Recovering oak (very long-term abandonment)

The Pyrenean oak (*Quercus pyrenaica* willd.) is the autochthonous species in this area. Human activities over the centuries have led to considerable deterioration of the native arboreal vegetation characteristic of the region. The restoration of native vegetation is a very long process, disturbed by the regular occurrence of forest fires.

Afforested land (conversion of arable land to forest)

The main aim of Afforestation Regulation 2080/92 (Community Aid Scheme for Forestry Measures in Agriculture) was to reduce agricultural surpluses, but the EU also hoped that it would 'enhance forest resources'; 'provide greater ecological balance in countryside management'; and 'combat the greenhouse effect". The CAP measures for afforestation of marginal fields promote the use of a wide range of native species; however the main species selected in the area studied was *Pinus pinaster*. In Portugal, soil preparation before planting, often carried out by public works companies, involves the use of heavy machinery and deep ploughing techniques.

Pastureland (conversion of arable land into pasture and extensification of land use)

Recent EU agri-environmental measures support the maintenance of natural pastures or extensive cultivation of fodder crops (without deep ploughing and the use of fertilisers) and the livestock unit subsidy supports the maintenance of livestock. The study area was used for grazing cattle and the unit head per hectare was lower than 1. This value has been classified as light to moderate grazing (Rauzi & Smith, 1973; Van Haveren, 1983).

In this study area, it was decided that the six selected plots, with an average area of 50 m^2, would have a similar parent material (granite rocks), soils (distric cambisols), aspect (east), elevation (735–750 m a.s.l.), climate and specific slope gradient (around 10%), so that the results would be comparable.

In the six plots, overland flow and erosion yields were measured using small, permanently established bounded runoff plots (8×2 m) draining into a modified *Gerlach* trough (Shakesby, Coelho, Ferreira, & Walsh, 2002; Coelho, Ferreira, Boulet, & Keizer, 2004). The results for the first three months of the study were rejected to avoid the effects of changes resulting from the construction of the plots. During the 2-year monitoring period (2005–2006), runoff from the plots was collected after every rainfall event and sediment losses were collected every month. Runoff water samples and sediments were also collected, with the aim of determining < 0.5 mm fraction. Fraction > 0.5 mm was collected each month from the *Gerlach* boxes. The rainfall data used for the study period was obtained by using a tipping-bucket rainfall gauge (Pronamic Professional Rain Gauge) linked to an Onset Hobo Event Logger calibrated to tip once every 0.2 mm of rainfall. The average intensity [I_e = (total rainfall/total time) (mm h^{-1})] and maximum intensity at 60 min (I_{60}), 30 min (I_{30}) and 10 min (I_{10}) were calculated for each rainfall event. Runoff coefficients for each rainfall event were calculated as the ratio of runoff to rainfall. Maximum intensity at 60 min (I_{60}), 30 min (I_{30}) and 10 min (I_{10}) were also determined for each month.

Indices based on the monthly data average, such as the Fournier Index and its modification by Arnoldus (1980) (MFI), are often used to quantify the nature of rainfall variability and its effects on the distribution of soil erosion (De Luís, González-Hidalgo, & Longares, 2009). Basically, the Modified Fournier Index (MFI) was calculated on a monthly basis over the 2 recorded years, according to the following equation:

$$\mathrm{MFI} = \sum_{i=1}^{12} \frac{P_i^2}{P_t}$$

with p_i being the monthly precipitation at month i, and P_t the annual precipitation.

To assess the influence of land use/cover and certain soil characteristics usually considered important in hydrological and erosional processes (such texture, bulk density, soil resistance to penetration and organic matter), soil samples from the top layer at 0–10 cm were collected from three points. The analytical characteristics of the soil samples were determined in the following manner. A Coulter LS Particle Size Analyser was used for grain size analysis for the fraction < 2 mm. Dry bulk density was measured by the use of a cylindrical core of known volume. Soil resistance was assessed using a pocket penetrometer. Organic matter content was determined by the Tinsley method (1950). In each 16 m^2 plot, the total cover (green vegetation and litter) was visually estimated for the different seasons in the two year period 2005–2006; the first at the peak of the growing season (March/April) and the second at the end of the hot, dry season (August/September) when the herbaceous vegetation was completely dry.

To understand the factors influencing runoff generation, the detachment of sediments from the plot and their removal to the outlet, explorative data analysis, correlation analysis and stepwise multiple regressions were performed using the SPSS 17.0 statistical package. One-way analysis of variance (ANOVA) and the Waller–Duncan multiple comparison procedure were performed on each soil property layer and for runoff and soil erosion to test whether the changes in land use and cover were statistically significant (p-value < 0.05). The *Spearman-Rho* correlation coefficient was selected to estimate the correlation between the quantitative characteristics of the soil surface and runoff and sediment production. This rank-correlation method is considered robust against outliers and non-normal distribution of data. Stepwise multiple regression is essentially a search procedure with a prime focus on identifying the independent variable that actually possesses a strong relationship with the dependent variable(s). In fact, this analytical tool involves adding one variable at a time to the regression equation and this form of adding variables in turn to the equation is based on their partial correlation with the dependent variable(s) (Jimoh, 2008).

Results

Soil characteristics and plant cover dynamics

The physical properties of soils and organic matter content for the different types of land use and vegetal covers are summarised in Table 1. There were no significant differences in particle size distribution for the top 10 cm layer among the land cover types. A sandy loam texture was found in all the soils studied, in line with

Table 1
Physical and chemical properties of soils (mean and ±standard deviation) in different land use types/covers.

	Cereal crop	Fallow land	Shrub land	Recovering oak	Afforested land	Pasture land	Anova
Texture (%)							
Sand	74.18 ± 4.17	76.70 ± 1.95	71.96 ± 5.32	69.17 ± 4.18	71.11 ± 3.34	72,04 ± 3,34	ns
Silt	20.99 ± 3.14	19.01 ± 1.47	22.50 ± 4,88	25.35 ± 4.22	24.02 ± 33.15	22.77 ± 4.39	ns
Clay	4.92 ± 1.09	4.30 ± 0.65	5.48 ± 1.56	5.48 ± 1.56	4.88 ± 0.49	5.19 ± 1.43	ns
Soil bulk density (g cm^{-3})							
	85 ± 0.13[a]	1.23 ± 0.11[c]	1.04 ± 0.16[b]	0.91 ± 0.16[ab]	0.81 ± 0.06[a]	1.22 ± 0.07[c]	**
Soil resistance to penetration (g cm^{-2})							
	0.77 ± 0.30[a]	2.86 ± 1.11[b]	2.22 ± 1.24[b]	1.88 ± 0.99[b]	0.60 ± 0.22[a]	3.98 ± 0.59[c]	**
Organic matter (%)							
	0.55 ± 0.27[a]	0.53 ± 0.31[a]	1.38 ± 0.71[b]	1.46 ± 0.23[b]	0.84 ± 0.22[a]	0.73 ± 0.26[a]	**

ns: not significant; **p-value < 0.001; Means within a column followed by different letters differ at the 0.05 probability level according to Waller–Duncan test.

the same parent material on which they lie. In this layer, the soils revealed a very high percentage of sand fractions, over 70% of the total, and a low silt and clay fraction. In general, a sandy, coarse-textured soil drains easily and quickly after rain but has a lower moisture-retention capacity and a lower nutrient-retention capacity. Unlike texture, there was a significant difference in bulk density (g cm^{-3}) among land covers (p-value < 0.001). The lowest values were recorded for the cereal crop and arable land afforested with *Pinus pinaster*, as a consequence of ploughing up the top layer for cereal cultivation, tree planting and the removal of ground cover to avoid forest fires.

Conversely, the highest values for bulk density, which correspond to the lowest porosity percentages, were registered in grazing plots and fallow land or short-term abandoned land. Soil bulk density is a more direct measure of soil compaction (Roberson, 1996, 30 p.) and perhaps the greatest impact of grazing consists of changes to the soil structure due to compaction (Roberson, 1996; Wood, 2001, 11 p.). In fact, the intense and continual pressure from moving livestock easily compacts soils, particularly when they are wet and more susceptible to compaction (Brady, 1984; Warren, Blackburn, & Taylor, 1986). Firestone (1995), for example, observed a 13% increase in the bulk density of grazed soils under oaks in California. Orr (1960) measured an increase of up to 20% in bulk density in the top 4 inches of grazed South Dakota steam bottom soil when compared with exclosures. Compaction is a strong direct effect of force which leads to the indirect effect of reduced infiltration and the resulting force of increased overland flow, which in turn leads to increased erosion (Trimble & Mendel, 1995). Extension of the abandonment stage and the expansion of scrub and wood communities tend to reduce soil bulk density.

Soil resistance to penetration follows a similar pattern to bulk density; the lowest values were registered for the cereal crop and land afforested with *Pinus pinaster* and the highest values for pastureland and short-term abandonment.

Organic matter content is considered the single most important indicator of soil quality and an indicator of the sustainability of ecogeomorphic systems (Imeson, 1995; Sparling, 1991). According to Pardini, Dunjó, Barrena, and Gispert (2000), a limit value of 1.7% of soil organic matter content is considered an indicator of the pre-desertification stage. The soil organic matter content for different land uses/cover types in the area studied was, on average, lower than the limit value proposed by Pardini et al. (2000), especially in soils dedicated to crop production and fallow land, which had averages of around 0.5%. Despite the low organic matter values obtained for afforested and grazed land, there were still no significant differences between these four land uses. Soil erodibility in all land use types was expected to be high because of the sandy soil texture and low organic matter content. Vegetation restoration after abandonment, involving the development of shrub and tree cover, seems to enhance the organic matter within the upper layer of the soil. These changes in soil surface conditions are related to the greater contribution to organic matter provided by the leaves and roots of both the annual and perennial species of these types of land cover.

In fact results for plant cover (Table 2) demonstrate that the highest surface cover was recorded in shrub land and wood plots, with figures exceeding 90%. In contrast, the afforested land revealed average annual values of less than 15% vegetation cover, followed by the dry cereal plot, with an annual mean of 36% of the surface covered by plants. Soils under cereal cultivation registered the greatest variability during the year, with values ranging from 2% to 75% of the total surface. This variability is due to the rapid development of cereal as soon as growth starts. Fallow land or short-term abandoned land and pastureland registered values of 25%–50% after the dry, hot season, and 50%–95% after the wet, cold season, respectively. The lowest plant cover observed at the end of summer is referred to as plant litter or vegetation residue, which falls from plants and covers the soil surface (mulch).

The percentage of plant cover is clearly related to seasonal changes in vegetation: the observed fields were covered by, on average, 66%–75% of vegetation at the end of winter/early spring and 43%–51% at the end of summer. This variability is mainly explained by the maximum and minimum observed herbaceous cover, which reached a peak in early spring and declined during the hot, dry summer season. Moreover, the average values for plant cover in 2005 were lower than those for 2006 as a consequence of differences in the amount of rainfall, which was twice as high in the second year monitored.

Rainfall characteristics

During the 2-year monitoring period (2005–2006) the total rainfall was 504 and 1190 mm for the first and second year, respectively. These values were very different from the average rainfall (823 ± 200.6 mm), calculated for the previous 43 years using data from the main meteorological station in the study area (Nunes, 2007). Despite these differences in the amount of precipitation, its seasonality was typically Mediterranean. During the period studied, more than 80% of the total rainfall fell in autumn and winter, while the spring rainfall was around 10%. In monthly terms, 42% of the total rainfall was concentrated in October in 2005 and 54.5% in October and November in 2006 (Fig. 2). Therefore, the

Table 2
Total plant cover (%) per season for the different land use types/cover monitored.

	Cereal crop	Fallow land	Shrub land	Recov. oak	Afforest. land	Pasture land	Mean
March, 2005	60	45	98	100	10	80	66
Sept., 2005	2	25	80	95	5	50	43
March, 2006	75	50	100	100	30	95	75
Sept., 2006	5	40	95	98	10	60	51
Mean	36	40	92	98	14	71	58

monthly rainfall erosivity throughout the monitoring period, based on the Modified Fournier Index (MFI), increased considerably during these months (Fig. 3), suggesting that the available energy for erosion and transport was highly concentrated in this season.

During the two years of the experiment, a total of 42 rainfall events that generated overland flow were recorded; 14 rainfall events were registered in 2005 and 28 rainfall events in 2006, with amounts ranging from 8.2 mm to 80 mm. The maximum intensity at 60 min (*I*60) during the monitoring period ranged from 2.0 to 28 mm h^{-1}, whilst the maximum intensity at 30 min and 10 min was 20 mm and 11.2 mm, respectively. In some events, these rain rates could be slightly underestimated because tipping-bucket rain gauge are known to underestimate rainfall at high intensities, as a consequence of the rainwater amount that is lost during the tipping movement of the bucket (Molini, Lanza, & La Barbera, 2005).

Runoff and soil loss

Table 3 summarizes the results for the relationship between rainfall and runoff (water running off the plot as a percentage of the total volume of rainwater) and soil loss per land use type/cover during the course of the experiment.

The runoff and sediment yield measured in the cereal crop plot and young tree plantation showed the highest average values and significant statistical differences when multiple comparisons between such uses and the dominant autochthonous vegetation and pastureland were established (Waller–Duncan post hoc method, p-value < 0.000). Recovering oak, shrub land and pastureland registered the lowest coefficient of runoff and soil erosion losses, and the differences between them were not significant.

For different land uses/covers, the statistical results showed the following, for runoff and erosion rates, respectively:

- Recovering oak < Shrub land < Pastureland < Fallow land < Cereal crop < Afforested land;
- Shrub land < Recovering oak < Pastureland < Fallow land < Afforested land < Cereal crop.

The results obtained suggest that the erosion of arable land and afforestation were most serious among the six land uses/covers studied, which agrees with previous reports (Collins et al., 2001; Evans, 2002; García-Ruiz, Ruiz-Flaño, & Lasanta, 1996; Roxo, 1994; Pardini, Dunjó, Gispert, Barrena, & Vigna, 2002; Shakesby, Boakes, Coelho, Gonçalves, & Walsh, 1996, 2002; Ternan, Elmes, Tanago, Williams, & Blanco, 1997; Wang et al., 2003). In fact, the soil loss for the cereal crop, with an average value of close to 630 g m^{-2} $year^{-1}$ (corresponding to 6.3 ton. ha^{-1} $year^{-1}$), was more than 20 times higher than that of fallow land or short-term abandoned land, with a mean value of 20 g m^{-2} $year^{-1}$. Even the small amount of suspended sediments transported from the afforested land was very high in comparison with the cereal crop, at about 426.2 g m^{-2} $year^{-1}$ (or 4.3 ton. ha^{-1} $year^{-1}$). The soil loss from the pasture plot was very low (close to that of recovering oak and shrub land), approximately 5 hundred times less than that of the cereal crop.

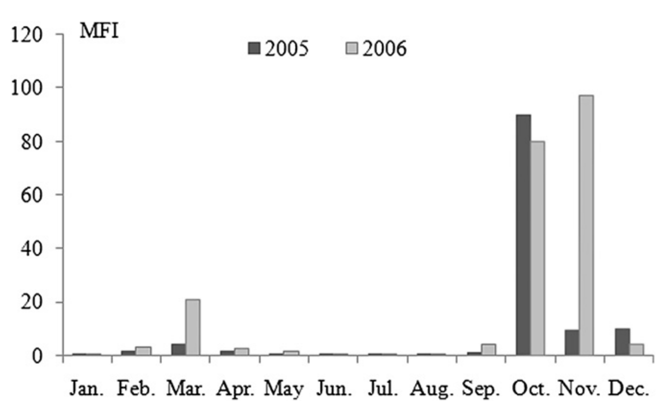

Fig. 3. Monthly variability in Modified Fournier Index in 2005 and 2006.

Significantly larger amounts of runoff and soil loss were recorded during the second year in comparison with the first, due to the amount of rainfall and erosivity; the figure for overland flow was three times higher (with a total of 105 mm for 2005 and 344 mm for 2006) and twice as high for sediment yield (with a total of 726 g m^{-2} for 2005 and 1427 g m^{-2} for 2006).

Fig. 4 presents the results for the monthly rainfall effect on total runoff and soil loss during the experiment. The soil transported by runoff in the cereal and afforested plots peaked during October 2005 and September/October/November 2006, coinciding with the highest amount of rainfall and rainfall energy and erosivity in the experimental area. For cereal crops, this period corresponds to the sowing time and consequently the top layer is highly erodible and easily removed by rainfall. Ploughing completely destroys the vegetation and litter cover, breaks up the soil structure and reduces the number of obstacles to overland flow, leading to a more efficient transport of sediments. This hydrological response is also affected by the lack of macroporosities, meaning that only a little water infiltrates into the soil matrix. The soils also offered weak resistance to penetration (Nunes et al., 2010).

Soil operations for forestation procedures that involve the use of heavy machinery and deep ploughing techniques have a direct and influential effect on soil losses, essentially increasing them. Even in the first years of tree development, especially when it is necessary to control vegetation cover to prevent forest fires and competition from other species, the soil surface remains unprotected for extended periods of the year, thus accelerating water and sediment flows.

The abandonment of cultivated land positively influences runoff and sediment yield, despite the high overland rate obtained for short-term abandonment or fallow land. Conversely, the erosion rates showed a significant decrease, suggesting the importance of non-ploughing management as tool for soil protection.

Previous results also showed that land abandonment and subsequent plant recovery or the conversion of arable land into grassland results in important hydrogeomorphic changes. A generalised delay in runoff, an increase in soil infiltration capacity and a reduction in soil erodibility were recorded.

It can be clearly observed from Table 4 and Fig. 4 that the amount of rain had a directly proportional effect on overland flow in the cereal crop, fallow land and afforested land. The Spearman–Rho correlation coefficients are statistically significant (p-value < 0.000), reflecting a close relationship between these variables during the period studied. Conversely, the Spearman correlation coefficients for rainfall events and runoff were not significant for the shrub land, recovering oak and pastureland (p-value > 0.05). These results suggest that soils subject to human intervention involving current or recent ploughing react more efficiently to the amount of precipitation, whilst lengthy or very lengthy abandonment and the conversion of arable land into grassland seem to be very efficient in reducing overland flow, thus favouring infiltration. In the scatter plots showing cumulative runoff offset against cumulative rainfall (Fig. 5) it is possible to observe the different responses and establish the rainfall amounts required to generate runoff in the types of land use and vegetation covers monitored. The smallest precipitation event producing runoff had a rainfall depth of 8.2 mm and generated overland flow in the cereal crop, afforested land and fallow land plots. The

Table 3
Runoff (in mm and % of total rainfall) and soil erosion (g m^{-2}) during the period monitored.

	Cereal crop	Fallow land	Shrub land	Recov. oak	Afforest. land	Pasture land	Sum	Anova
Runoff								
2005 (mm) (% of rainfall)	37.75 (7.50)	23.25 (4.61)	0.06 (0.01)	0.00 (0.00)	43.38 (8.61)	0.13 (0.02)	104.57	
2006 (mm) (% of rainfall)	117.81 (9.90)	70.25 (5.90)	2.03 (0.17)	0.66 (0.05)	146.18 (12.28)	7.31 (0.61)	344.24	
Median (mm) (% of rainfall)	77.7^{bc} (8.70)	46.7^{b} (5.26)	1.05^{a} (0.09)	0.33^{a} (0.02)	94.78^{c} (10.45)	3.72^{a} (0.32)	224.28	**
Soil erosion (g m^{-2})								
2005	412.9	12.0	0.0	0.0	301.1	0.0	726.0	
2006	841.2	29.8	1.2	1.4	551.3	2.4	1427.3	
Median	627.1^{c}	20.8^{b}	0.62^{a}	0.68^{a}	426.2^{c}	1.2^{a}	1076.7	**

**p-value < 0.001; Means within a column followed by different letters differ at the 0.05 probability level according to Waller–Duncan test.

minimum rainfall depth registered for an event causing runoff in the shrub land, pastureland and recovering oak was 11 mm, 18 mm and 30 mm respectively.

The results obtained for sediment yield also indicated that human activity greatly accelerated sediment transport due to rainsplash, and that types of land use that involve intensive human action are the major sources of soil erosion. On the other hand, abandoned cultivated land and subsequent plant recovery, as well as arable land converted into grassland, were less sensitive to the action of water erosion, as the Spearman correlation coefficients

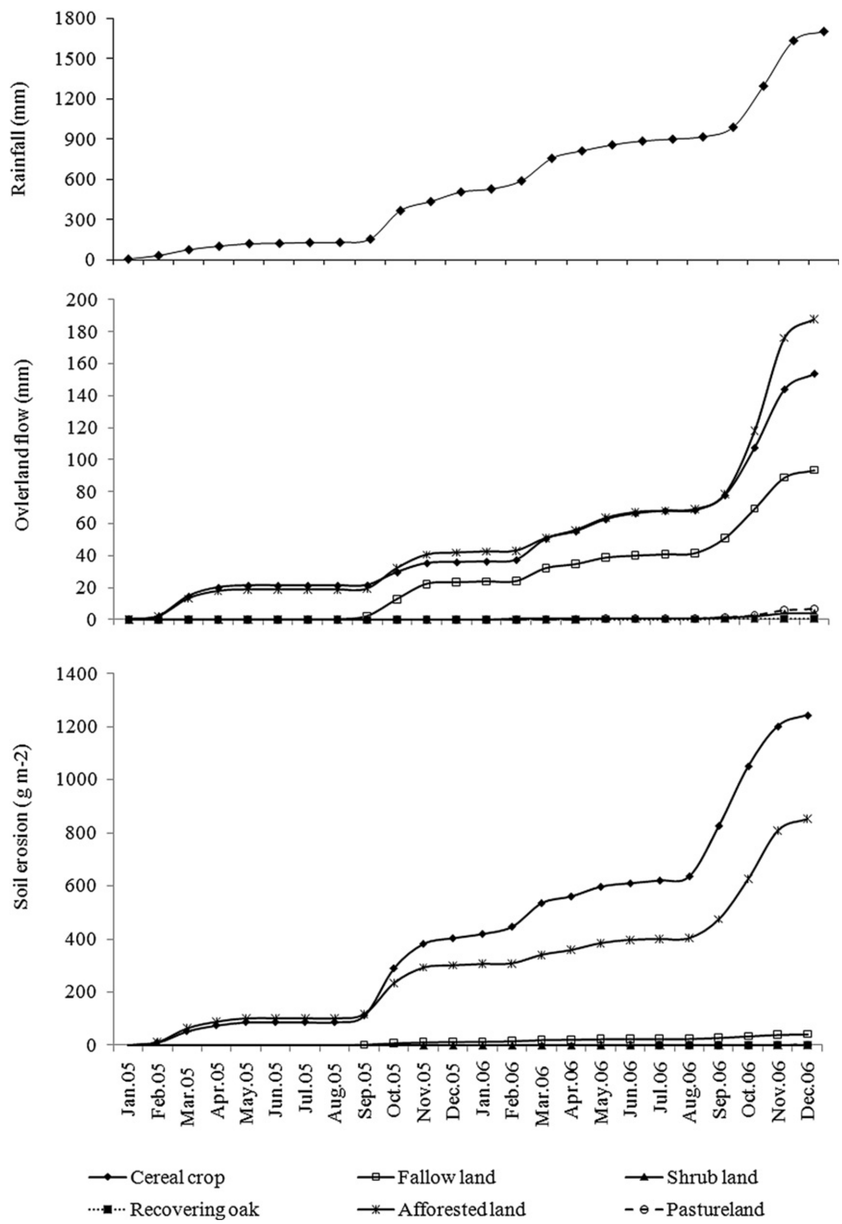

Fig. 4. Cumulative curves of rainfall, overland flow and soil erosion responses in 2005 and 2006.

Table 4
Spearman–Rho correlation coefficients between cumulate rainfall events and runoff and monthly rainfall and soil erosion.

Land use/cover	n	Rainfall event (mm) *vs* runoff (mm)		n	Monthly rainfall (mm) *vs* soil erosion (g m^{-2})	
		Spearman's Rho	*p*-value		Spearman's Rho	*p*-value
Cereal crop	42	0.618	0.000	24	0.904	0.000
Fallow land	36	0.790	0.000	24	0.900	0.000
Shrub land	12	0.580	0.480	24	0.483	0.017
Recovering oak	6	0.662	0.152	24	0.425	0.038
Afforested land	42	0.662	0.000	24	0.842	0.000
Pastureland	15	0.353	0.197	24	0.552	0.005

between monthly rainfall and sediment yield were less significant (p-value < 0.05).

The runoff estimated from stepwise multiple regression models, including rainfall events (Re), average intensity per event (I_e), and maximum intensity at 60 min (I_{60}), 30 min (I_{30}) and 10 min (I_{10}) showed that rainfall was the most important factor affecting the runoff amount, explaining between 64% and 72% of the variance observed for the cereal crop, fallow land and afforested land, and between 43% and 57% of the variance for recovering oak, pastureland and shrub land (Table 5). The multiple regression equation for the cereal crop and fallow land also included maximum intensity at 30 min (I_{30}) and 10 min (I_{10}), increasing this variance by 14% and 10% respectively. The heaviest rainfall events during the period observed appeared to account for this increase, as they involved the strongest rainfall energy and aggressivity (erosivity).

A multiple regression equation was also formulated for monthly soil loss, monthly rainfall (Mr) and maximum intensity at 60 min (I_{60}), 30 min (I_{30}) and 10 min (I_{10}) (Table 6). The results show that the accumulated soil loss for the cereal crop, fallow land and afforested land depending primarily on monthly precipitation explained variations of 70%–87%. The accumulated soil loss recorded from shrub land, recovering oak and pastureland was mainly explained by maximum intensity at 60 min (I_{60}) and 10 min (I_{10}).

Discussion

As pointed out by Imeson (1990), the main characteristics affecting the vulnerability of the Mediterranean area to erosion are intense rainfall after a very dry summer and pronounced short- and long-term fluctuations in rainfall quantity. In fact, the high annual and inter-annual differences in rainfall quantity and intensity are reflected in the typical seasonal pattern for the Mediterranean region, where rainfall is concentrated in the autumn and winter months. Thus, the figures for the monthly erosivity index (MFI) (Arnoldus, 1980) increased considerably during these seasons, due to high erosive rainfall (López Bermúdez & Romero, 1993; Ramos & Porta, 1993; Salles, Poesen, & Sempere-Torres, 2002). The 2-year monitoring period showed a similar trend in the study area, in terms of the heaviest concentration of rainfall and rainfall erosivity. In general, all the recorded runoff events were consistently related to rainfall amount, whilst the soil losses depended fundamentally on the amount and intensity of rainfall. However, correction procedures for rain intensity data sets, in order to minimise the bias introduced by systematic mechanical errors of tipping-bucket rain, are needed in order to improve the relationship between the variables analysed.

Recent research into climate change in Portugal (the SIAM Project) indicates that there has been no clear trend for annual precipitation figures during the 20th century, although a significant reduction in precipitation in late winter and early spring was detected between the 1960s and 1990s (Miranda et al., 2006). The climate change scenarios for the 21st century, including 3 greenhouse gas emission scenarios used by many global and two regional climate models, are much more homogeneous, with almost all models predicting a reduction in annual rainfall in mainland Portugal within the range of 20–40% of the current value, as a result of a decline in the duration of the wet season. Predictions for temperature changes agree on an overall increase in the annual mean, with a much more pronounced maximum summer temperature particularly affecting inland areas of Portugal. This climatic trend will extend the long, dry, hot summers in the Mediterranean region and lead to more frequent and intense extreme weather events, which could increase the rates of erosion and the risk of desertification that is threatening substantial areas of Portugal (Nearing et al., 2005; Nunes & Seixas, 2003).

In attempting to interpret the influence of plot characteristics on runoff generation and sediment production, certain differentiated features can be observed (Table 7): there is a positive correlation between overland flow and sediment yield (r: 0.886; p-value < 0.05) and a significant negative relationship between vegetation cover, overland land flow (r: -0.943; p-value < 0.01) and total sediment production (r: -0.886; p-value < 0.05). There are no more statistically significant correlations between the soil characteristics of the plot (texture, bulk density, resistance to penetration and organic matter) and the output of the experiment. Thus, the vegetation dynamic emerges as a key factor in quantifying and interpreting the hydrological and erosional response of the land use/covers monitored. As can be seen in Fig. 6, increasing vegetation cover leads to an exponential decrease in runoff, but only when this exceeds a threshold value of over 40%. Correspondingly, similar behaviour can be observed with regard to the relationship between sediment loss and vegetation cover.

The results obtained agree with those observed by different authors in varied environments, who consider that runoff and sediment yield decrease with an increase in soil cover with vegetation (Bochet, Rubio, & Poesen, 1998; De Ploey, 1989; Durán Zuazo, Francia Martínez, Rodríguez Pleguezuelo, Martínez Raya, & Carcéles Rodríguez, 2006; Elwell & Stocking, 1976; Francis & Thornes, 1990; Roxo, 1994). However, wide variations in the percentage of plant cover were presented as critical between studies.

Studies carried out in natural Mediterranean environments have shown that when vegetation cover drops below 30% soil erosion and runoff increase dramatically (Francis & Thornes, 1990; Gimeno-García, Andreu, & Rubio, 2007). Thornes (1988) suggests that a value of 40% vegetation cover is considered critical, below which accelerated erosion dominates on sloping land. If the vegetation cover covers an area of more than 40%, it will act as a resilience or protective factor for the land. Molinillo, Lasanta, and García Ruiz (1997) observed an increase in runoff and soil erosion in up to 60% shrub cover and only above this value a reduction in runoff and erosion processes. Sauer and Ries (2008) consider that only plant cover exceeding 60% can significantly reduce soil erosion in semi-arid environments.

Land use and the type of management applied to each site explain, to a large extent, the variability in annual plant cover and, therefore, the occurrence of overland flow and soil erosion processes (De Luna, Laguna, & Giráldez, 2000; Francia Martínez, Duran, & Martínez Raya, 2006; Gómez, Romero, Giráldez, & Fereres, 2004). In Portugal, as well as in the Mediterranean region, the risk of erosion is high in areas dedicated to cereal production, as autumn ploughing leaves the soil unprotected when rainfall can be heaviest and most aggressive. The estimated erosion rates during this period when the soil is unprotected may be 100–1000 times higher than in fields with permanent vegetation cover. In addition, the gradual depletion of nutrients, which reduces organic matter and soil fertility and creates a high level of soil degradation, are further reasons for abandoning agricultural

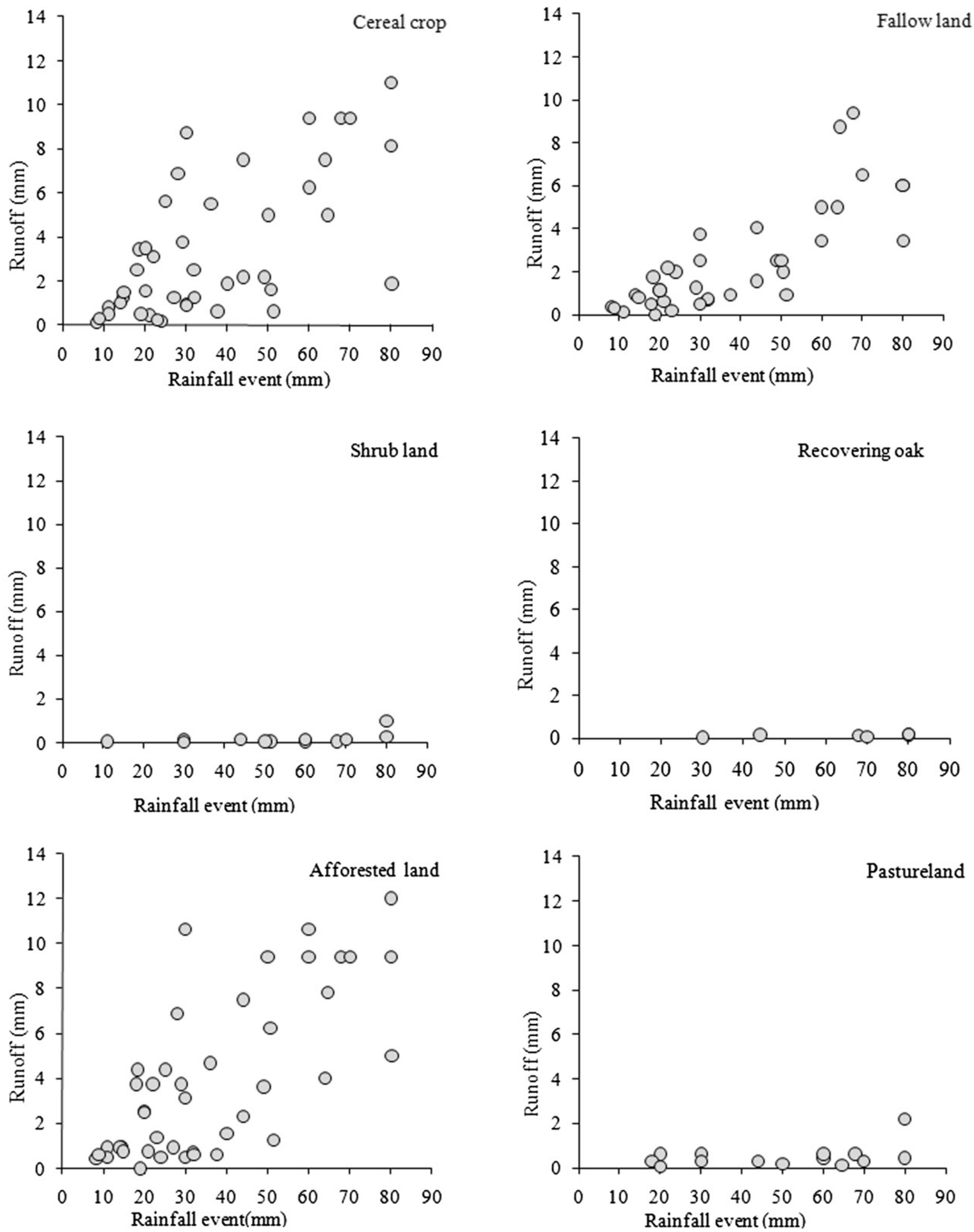

Fig. 5. Scatter plot showing the relationship between rainfall events and runoff.

plots in the changing cultivation process (Paniagua, Kammerbauer, Avedillo, & Andrews, 1999). The traditional method of planting trees with deep ploughing and bare soil has resulted in high erosion rates during the rainfall period, as observed in other agro-ecosystems in Mediterranean Europe (Shakesby et al., 2002; Ternan et al., 1997; Van-Camp et al., 2004).

However, in large parts of marginal areas of the country farmland abandonment has enhanced plant colonisation, replacing historically highly erosive cereal fields with dense shrub and woodland communities. There has been a consequent reduction in overland flow and soil erosion. This hydrological and erosional behaviour, together with the soil properties, is closely interrelated

Table 5
Multiple regressions, correlation and degree of significance for runoff.

Land use/cover	Model	R	Explained Variance(%)	Std. Error of the Estimate	Multiple Regression equation
Cereal Crop	1a	0.802	64.3	2.4008	$RF = -0.877 + 0.114Re$
	2b	0.887	78.7	1.8809	$RF = -1.816\ \ 0.071\ Re + 0.423\ I_{30}$
Fallow land	1a	0.827	68.4	1.5260	$RF = -0.577 + 0.078\ Re$
	2c	0.885	78.4	1.2823	$RF = -1.249 + 0.056\ Re + 0.429I_{10}$
Shrub land	1a	0.756	57.2	0.1121	$RF = -0.124 + 0.005\ Re$
Recovering oak	1a	0.655	42.8	0.0346	$RF = -0.026 + 0.001\ Re$
Afforested land	1a	0.848	72.0	3.0576	$RF = -2.227 + 0.173\ Re$
Pastureland	1a	0.697	48.6	0.2905	$RF = -0.192 + 0.010\ Re$

Dependent variable: RF-Runoff (mm) Models: a- Predictors in the model: (Constant), Re: Rainfall event; b- Predictors in the model: (Constant), Re: Rainfall event, I_{30}: maximum intensity at 30 min; c- Predictors in the model: (Constant), Re: Rainfall event, I_{10}: maximum intensity at 10 min.

Table 6
Multiple regressions, correlation and degree of significance for soil erosion.

Land use/cover	Model	R	Explained Variance(%)	Std. Error of the Estimate	Multiple Regression equation
Cereal Crop	1a	0.837	70.1	41.0053	$SE = 9.703 + 0.635Mr$
	2b	0.894	79.9	34.6351	$SE = 8.590 + 0.443Mr + 9.108I_{10}$
Fallow land	1a	0.900	81.1	0.9310	$SE = 0.800 + 0.0186Mr$
Shrub land	1c	0.829	68.7	0.0824	$SE = -0.06621 + 0.0147I_{60}$
Recovering oak	1c	0.855	73.0	0.1003	$SE = -0.105 + 0.01988I_{60}$
	1d	0.930	86.6	0.0728	$SE = -0.07565 + 0.03414I_{60} - 0.0417I_{10}$
Afforested land	1a	0.934	87.2	19.4970	$SE = -2.708 + 0.515Mr$
Pastureland	1e	0.791	62.6	0.2905	$SE = -0.150 + 0.07254I_{10}$

Dependent variable: SE-Soil erosion (in g m^{-2}) Models: a- Predictors in the model: (Constant), Mr: Monthly rainfall; b- Predictors in the model: (Constant), Mr: Monthly rainfall, I_{10}: maximum intensity at 10 min; c- Predictors in the model: (Constant), I_{60}: maximum intensity at 60 min; d- Predictors in the model: (Constant), I_{60}: maximum intensity at 60 min, I_{10}: maximum intensity at 10 min; e- Predictors in the model: (Constant), I_{10}: maximum intensity at 10 min.

and well understood in terms of the dynamics of plant and litter cycling. Vegetation and litter reduces direct raindrop impact on the soil, prevents the formation of mechanical crusts, enhances infiltration capacity and reduces soil erodibility (Nunes et al., 2010). In these soils, long-term spatially structured vegetation patterns play an important role in addition to cover, by increasing the stability and resilience of the system (Boer & Puigdefábregas, 2005; Cammeraat & Imeson, 1999).

Although abandoned land in humid and sub-humid regions self-regulates the development of natural vegetation (grass, weed, bushes, and later woodland) and normally does not need support except in the first years of abandonment, the cessation of traditional management practices, the creation of large homogeneous patches of vegetation and the accumulation of fuel due to fire exclusion policies are cited as some of the major causes of changes to the forest fire regime in Mediterranean Europe (Moreno, 1996). In fact, Portugal's burnt area has increased chiefly during the last three decades. This rising trend, although including some periods of lower burnt area, distinguishes Portugal from the other southern Member States with the highest burnt areas, particularly in the central and northern regions. According to Van-Camp et al. (2004) it is a common mistake to think that the current impact of soil erosion is most extreme in the driest regions. The greatest pressures from fire occur in areas that produce the most biomass and are under the greatest pressure from agriculture and grazing.

Converting arable land into pasture can be positive, negative, or without impact depending on management practices. Direct measurements of overland flow and soil loss rates from the pasture plot were very low during the period monitored. Less than 1% of the total rainfall and an average of 1.2 g m^{-2} $year^{-1}$ were recorded for soil erosion; these values were comparable to those of the shrub land and oak forest. Several studies have evaluated how different grazing intensities affect both plant cover and water infiltration into the soil. These studies are consistent in showing that as grazing intensity is increased and soil cover is depleted, water infiltration declines and soil erosion increases (Rauzi & Smith, 1973). In fact, the direct impact of cattle hooves reshapes the land. Compaction is, perhaps, the strongest direct impact of force which leads to indirect consequences in terms of overland flow and soil erosion.

Despite these negative effects, the conversion of arable land into extensive grassland had a strong, positive effect on surface runoff and erosion in the area monitored. A permanent plant cover of over 50%, in the form of vegetation or ground litter, provides a cushion between raindrops and the soil, preventing the "splash effect" or dislodging of soil particles by raindrops (Molinar, Galt, & Holechek, 2001). Research findings indicate a threshold at which removing

Table 7
Spearman–Rho correlation coefficient among variables.

	Runoff (mm)	Soil erosion (g m^{-2})	Sand (%)	Silt (%)	Clay (%)	Bulk density (g cm^{-3})	Resist. to penet (g cm^{-2})	Organic matter (%)	Plant cover (%)
Runoff	1								
Soil erosion	0.886*	1							
Sand	ns	ns	1						
Silt	ns	ns	−1.000**	1					
Clay	ns	ns	ns	ns	1				
Bulk density	ns	ns	ns	ns	ns	1			
Resit. to penet.	ns	ns	ns	ns	ns	0.943**	1		
Organic matter	ns	ns	−0.829*	0.829*	ns	ns	ns	1	
Plant cover	−0.943**	−0.886*	ns	ns	ns	ns	ns	ns	1

ns: not significant; ** p-value < 0.01; * p-value < 0.05.

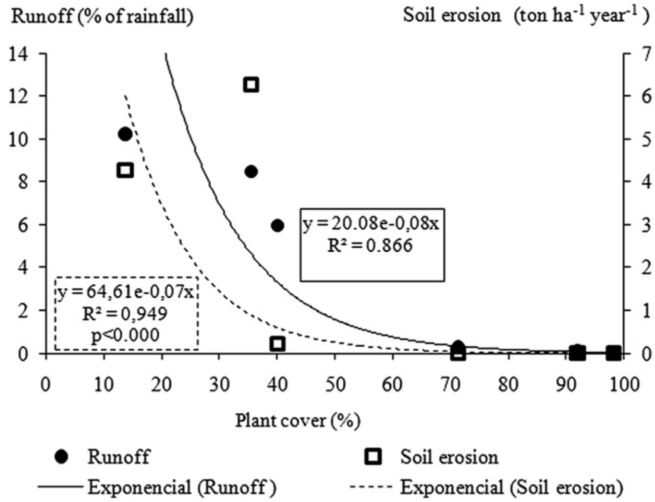

Fig. 6. Relationship between runoff and soil erosion and average percentage of plant cover.

the plant cover and volume have little effect on infiltration rates and soil protection. This threshold is generally about 50% of the current year's growth, which corresponds to the old adage of "take half and leave half" for sustainability (Wood, 2001, 11 p.).

Conclusion and recommendations for soil management

In Portugal, as well as in the Mediterranean countries, important land use and cover changes have occurred in the last century. The abandoning of traditional subsistence systems based on cereal cultivation, probably the most important change, has taken place mainly in the more disadvantaged areas where farming systems in general and livestock farms in particular are often operating close to the margins of sustainability. This was originally a consequence of the difficulties associated with adopting modern farming systems. Later, it was the result of the demographic exodus from these rural areas, and more recently it has been reinforced by the implementation of CAP measures. In several areas, cereal crop soils were neglected and a natural vegetation succession occurred, increasing plant recovery and establishing shrub and woodland areas. In other areas, the adoption of measures aimed at reducing intensive agricultural methods involved afforestation schemes and conversion to grazing land.

There are important differences in the hydrological and erosional functioning of the different land uses/cover types monitored. Scrub and woodland are considered better for soil and water conservation, producing less surface runoff and therefore less soil erosion. The results obtained also show a positive trend in organic matter content, highlighting the importance of vegetation in these very shallow soils with a low clay content in increasing structural stability and avoiding soil loss. The major threat to these ecosystems is associated with controlling the frequency of forest fires.

Conversely, cereal cultivation and tree planting accelerate runoff and soil erosion, which is attributed to soil tillage which loosens the soil and reduces anti-erodibility. Erosion and land degradation became a problem in Portugal when arable farming expanded into marginal areas over the decades. The poor water and soil protection provided by young pine is attributed to the poor ground coverage under the trees.

In fact, the amount of bare soil on a site is generally a good indicator of the soil's vulnerability to erosion and degradation. Good soil coverage is an essential element in soil conservation programmes. Vegetation protects the soil from eroding in various ways. Rainfall interception by the plant has two main consequences, the most important being that it reduces the erosive power of impacting raindrops. It also reduces the volume of water reaching the soil surface. Subsequently, soil erosion can be controlled by changing land use and increasing ground coverage, which was shown to be one of the basic approaches to controlling soil erosion in all land use types.

On the basis of the experiment results, pastureland should be encouraged, particularly for the degraded soils that are used to produce cereals in order to minimise the amount of soil loss by erosion, thus avoiding slumping and promoting stability. Accommodating pasture management with a weighted number of grazing animals per area unit and extending pasture rotation times could reduce soil erosion processes effectively and ongoing land degradation could be prevented according to the 'Directive of the European Parliament and of the Council Establishing a Framework for the Protection of Soil' (Commission of the European Communities, 2006). Additionally, is important to emphasise that extensive grazing is the main focus of landscape management in marginal areas of the Mediterranean region with very low population densities, only small resident communities, little mechanised agriculture and poor communications (Lasanta et al., 2010).

In addition to better pasture management, another possible consideration may be management of native shrub land and recovering oak. Land afforestation should be supported by a set of measures to minimise the impact of site preparation techniques, forest management and fire prevention on soils.

However, in the study area, as well as in the majority of Portuguese rural areas, key problems remain and are complex to solve. They include: a) How to prevent the process of rural depopulation that took place in the middle of the last century and continues nowadays? b) How to provide an appropriate income to attract young farmers to depopulated areas where the majority of the population are elderly? c) How to improve farm structures that consist of small scattered plots? d) How to develop management systems that favour soil conservation and combat land degradation but maintain economic viability? e) How to adjust Mediterranean agriculture to climate change scenarios for the 21st century?.

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