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Identifying erosive periods by using RUSLE factors in mountain fields of the Central Spanish Pyrenees

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Abstract. The Mediterranean environment is characterized by strong temporal variations in rainfall volume and intensity, soil moisture and vegetation cover along the year. These factors play a key role on soil erosion. The aim of this work is to identify different erosive periods in function of the temporal changes in rainfall and runoff characteristics (erosivity, maximum intensity and number of erosive events), soil properties (soil erodibility in relation to freeze-thaw processes and soil moisture content) and current tillage practices in a set of agricultural fields in a mountainous area of the Central Pyrenees in NE Spain. To this purpose the rainfall and runoff erosivity (R), the soil erodibility (K) and the cover-management (C) factors of the empirical RUSLE soil loss model were used. The R, K and C factors were calculated at monthly scale. The first erosive period extends from July to October and presents the highest values of erosivity (87.8 MJ mm ha^{-1} h^{-1}), maximum rainfall intensity (22.3 mm h^{-1}) and monthly soil erosion (0.25 Mg ha^{-1} month^{-1}) with the minimum values of duration of erosive storms, freeze-thaw cycles, soil moisture content and soil erodibility (0.007 Mg h MJ^{-1} mm^{-1}). This period includes the harvesting and the plowing tillage practices. The second erosive period has a duration of two months, from May to June, and presents the lowest total and monthly soil losses (0.10 Mg ha^{-1} month^{-1}) that correspond to the maximum protection of the soil by the crop-cover (C factor = 0.05) due to the maximum stage of the growing season and intermediate values of rainfall and runoff erosivity, maximum rainfall intensity and soil erodibility. The third erosive period extends from November to April and has the minimum values of rainfall erosivity (17.5 MJ mm ha^{-1} h^{-1}) and maximum rainfall intensity (6.0 mm h^{-1}) with the highest number of freeze-thaw cycles, soil moisture content and soil erodibility (0.021 Mg h MJ^{-1} mm^{-1}) that explain the high value of monthly soil loss (0.24 Mg ha^{-1} month^{-1}). The interactions between the rainfall erosivity, soil erodibility, and cover-management factors explain the similar predicted soil losses for the first and the third erosive periods in spite of the strong temporal differences in the values of the three RUSLE factors. The estimated value of annual soil loss with the RUSLE model (3.34 Mg ha^{-1} yr^{-1}) was lower than the measured value with ^{137}Cs (5.38 Mg ha^{-1} yr^{-1}) due to the low values of precipitation recorded during the studied period. To optimize agricultural practices and to promote sustainable strategies for the preservation of fragile Mediterranean agrosystems it is necessary to delay plowing till October, especially in dryland agriculture regions. Thus, the protective role of the crop residues will extend until September when the greatest rainfall occurs together with the highest runoff erosivity and soil losses.

1 Introduction

Soil erosion in agricultural areas has been studied intensively throughout the last decades and rates have been measured at continuous and event scales. Moreover, temporal variations in soil losses are usually studied at long-term scale due to changes in land use (Navas et al., 2005; Wei et al., 2007) or changing climatic conditions during the past and future predictions (Zhang, 2006). However, it is widely accepted that most soil erosion and sediment yield is triggered by intense rainfall and runoff events (Lecce et al., 2006) and the percentage of precipitation that produces the greatest erosion is very low. In addition, the dominating erosion process depends on rainfall intensity either for low intensity events when splash erosion dominates on the interrill areas or during high intensity events when considerable runoff volumes and rill erosion dominates (Kuhnert et al., 2007). On the other hand, temporal variations in soil erodibility during concentrated flow

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can be mainly explained by variations in soil moisture content (Knapen et al., 2007). Moreover, winter conditions with seasonally frozen soils may have strong effects on aggregate stability, soil structure and erodibility, and consequently in runoff and erosion. Erosion risk maps and soil prediction models that include these factors increase the accuracy of their predictions (Kværnø and Øygardena, 2006).

Most studies attribute the effect of crops in reducing soil erosion to the effects of the above-ground biomass (Gyssels et al., 2006). However, soil redistribution by conventional tillage practices has been recognised as a process of intense landscape transformation. Newly-formed erosional landsurfaces are much more widespread in the local landscape after the harvest. Moreover, in cultivated lands the above ground biomass temporally disappears after the harvest and collection of crop residues and then concentrated flow erosion occurs. Low roughness generated by tillage and bare soil after harvest promotes an increase in soil erosion in agricultural lands (Gómez and Nearing, 2005). Hence, the agricultural practices play a strong control in triggering erosional processes. In addition, seasonal variations in soil erodibility under different tillage practices have been identified by Knapen et al. (2007).

The Mediterranean environment is characterized by a contrasted climate with irregular but frequent and intense rain events, low vegetation cover and poor soil characteristics. Soils of Mediterranean agrosystems are particularly vulnerable to changes in such parameters and erosion rates are very high in some areas (Arnaez et al., 2007). Moreover, climate change is increasing the temperature, changing the temporal and spatial distribution of rainfall along the year (Meehl et al., 2005), and increasing the frequency of extreme events, especially in Mediterranean areas (e.g. Tapiador et al., 2007). An increase of extreme daily rainfall in spite of decrease in total values has been recorded in Spain and other Mediterranean countries (Alpert et al., 2002). Therefore, there is great interest in determining the temporal pattern of soil erosion and sediment delivery at seasonal and monthly scales (e.g. Mathys et al., 2007).

In mountainous areas of northeastern Spain the precipitation regime is characterised by a bi-modal annual distribution, with one main maximum in autumn and a secondary peak in spring. Convective storms are frequent in this area during summer with intense precipitation and high values of maximum intensity (Sánchez et al., 2003) and explain the greatest part of the sediment load exported to reservoirs. Changes in the frequency of extreme floods have been identified in mountain areas of the Iberian Range (Machín et al., 2005) and of extreme dry-spell in the middle Ebro Valley (NE Spain) (Vicente-Serrano and Beguería-Portugués, 2003). Moreover, changes in precipitation at seasonal scale have been identified in Aragón (NE Spain) and Valencia (E Spain) during the second half of the twentieth century (Cuadrat et al., 2007; González-Hidalgo et al., 2001) showing a precipitation decrease in autumn and winter, an increase in summer and no changes in spring. The temporal pattern of weathering processes in badland areas in the north-central Spanish Pyrenees presents also field evidences of seasonal variations (Nadal-Romero et al., 2007). The call for erosion control measures adapted to local farming practices is stressed. Nonetheless, the assessment of monthly and seasonal variations of erosion rates in cultivated fields is still an outstanding question that needs a quick answer due to the strong inter-annual variability of rainfall characteristics in Mediterranean areas.

This work aims to identify different erosive periods in relation to temporal changes in rainfall characteristics (erosivity, maximum intensity and number of erosive events), soil properties (soil erodibility in relation the freeze-thaw processes and soil moisture content) and tillage practices. For this purpose the rainfall and runoff erosivity (R), soil erodibility (K) and cover-management (C) factors of the RUSLE model (Renard et al., 1997) were used. The RUSLE model is widely used in Mediterranean areas (e.g. Ramos and Porta, 1994). The monthly values of the R, K and C factors were calculated in a set of agricultural fields in NE Spain in a mountainous area of the Central Pyrenees. The results of this study could be used for best management practices (BMPs) that are highly recommended within the agrarian policy of the European Union. The information gained will provide data of interest to promote effective measures to avoid soil degradation in the high-productive dryland fields of Mediterranean countries.

2 Material and methods

2.1 Study area

A farmland area of winter barley (52.2 ha) surrounding the Estaña lakes was selected to carry out this study. This area is located in the province of Huesca (NE Spain, Fig. 1a) between the Cinca and the Noguera Ribagorzana rivers, in the southern limit of the External Ranges of the Central Pyrenees, close to the northern boundary of the Ebro basin. The selected fields are underlayed by limestones affected by diapirs largely composed of gypsiferous marls, dolostones, limestones and occasionally salt deposits (Barnolas and Pujalte, 2004). The elevation of the study area ranges from 677 to 729 m a.s.l. (López-Vicente and Navas, 2005) with a mean slope of 10.3% (López-Vicente et al., 2006b). Field evidence of gully erosion has been observed in the steepest fields.

This area has a continental Mediterranean climate with mean annual precipitation of 619, 536 and 446 mm at the weather stations of Benabarre, Camporrélls and Canelles, respectively, for the period 1997–2006 (Fig. 1b). These weather stations located NW, SW and SE of the study area at a distance of around 10 km have an elevation of 740, 628 and 508 m a.s.l., respectively (Fig. 1a). In spite of the short distance between the weather stations the differences

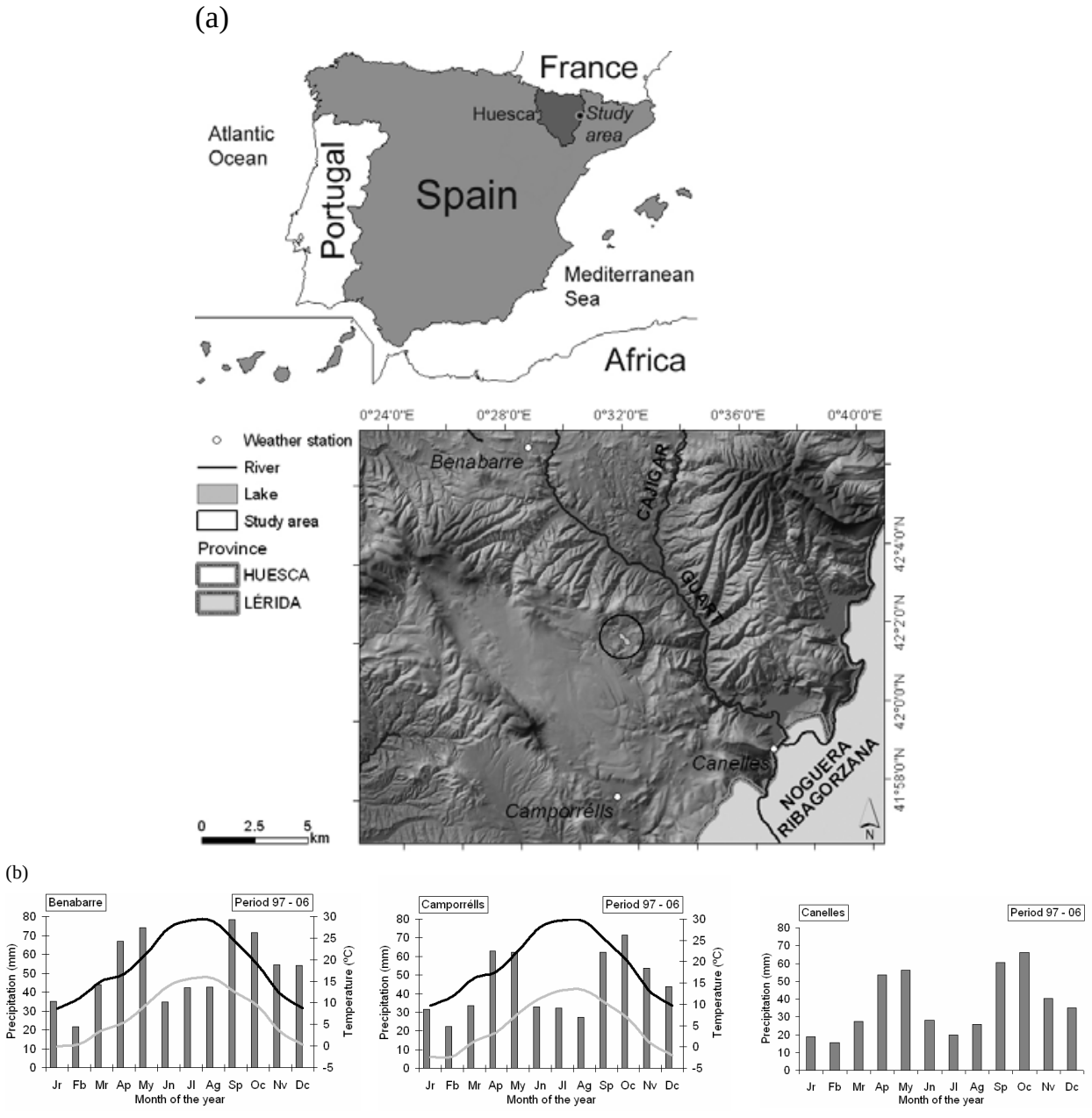

Fig. 1. Geographic situation of the study area in the province of Huesca, Spain. Weather stations of Benabarre, Canelles and Camporrélls over the digital elevation model of the region **(a)**. Monthly values of precipitation and minimum and maximum temperature at the weather stations of Benabarre, Camporrélls and Canelles **(b)**.

in the annual precipitation are explained by their geographical situation, between the semiarid areas of the Ebro valley to the south (Camporrélls and Canelles) and the humid areas of the Pyrenees to the north (Benabarre). Weather, land use and tillage practices in the study area are representative of rainfed agricultural areas in Mediterranean mountainous agrosystems.

2.2 Rainfall and runoff erosivity factor (R)

Soil loss in agricultural fields is associated with the product of the total storm energy (E, MJ ha^{-1}) and the maximum intensity in 30 min (I_{30}, mm h^{-1}). The result of this product is the EI_{30} index or storm erosivity index (MJ mm ha^{-1} h^{-1}) that reflects the combined effect of soil detachment and runoff transport capacity to produce net soil erosion. Renard

et al. (1997) defined the rainfall factor R (MJ mm ha^{-1} h^{-1}) as the sum of the EI_{30} values for the whole year according to the equations:

$$R = \frac{1}{n}\sum_{j=1}^{n}\left[\sum_{k=1}^{m}(E)\,(I_{30})_k\right] \quad (1)$$

$$EI_{30} = (E)\,(I_{30}) = \left(\sum_{K=1}^{m} e_r \Delta V_r\right) I_{30} \quad (2)$$

where j is the number of erosive events for the n number of years; k is the temporal interval; m is the number of temporal intervals established for each storm event; e_r (MJ ha^{-1} mm^{-1}) is the kinetic energy of a storm for the r period; and ΔV_r (mm) is the volume of rainfall registered during the r period. When n=1 the calculated R value is the rainfall erosivity for one specific year. The kinetic energy is assessed in the RUSLE model following the approach of Brown and Foster (1987) such as:

$$e_r = 0.29[1 - 0.72\exp(-0.05 i_r)] \quad (3)$$

$$i_r = \frac{\Delta V_r}{\Delta t_r} \quad (4)$$

where i_r (mm h^{-1}) is the rainfall intensity for the r period; and Δt_r (min) is the duration of the r period.

Soil erosion rates in the rill and interrill areas as well as the rates of sediment yield in the deposition areas are mainly controlled by storm events with medium and high values of intensity and rainfall volume. Hence, the erosivity factor in the RUSLE model is calculated from erosive storm events with values of rainfall volume higher than 12.7 mm or with a value of intensity higher than 6.35 mm in 15 min. The guide of the RUSLE model established a period of six hours with a rainfall volume lower than 1.27 mm to distinguish between two different storm events.

The R-RUSLE factor assesses the effect of the rainfall impact on the soil surface as well as the magnitude of runoff. However, it does not account the water supplies from snow melting neither the water from irrigated areas nor the effect of rainfall impact over frozen soil.

When detailed information about rainfall each 15 or 30 min is not available the EI_{30} index can be estimated from daily and monthly values of precipitation. In this paper the approach of Loureiro and Coutinho (2001) has been used to assess the annual R factor at the three weather stations as well as to determine the spatial variability of R between these weather stations. Loureiro and Coutinho (2001) analyzed at 17 rain-gauges in southern Portugal the relationship between the calculated EI_{30} values and two parameters: the monthly rainfall for days with $\geq$10.0 mm (rain$_{10}$; mm) and the monthly number of days with rainfall $\geq$10.0 mm (days$_{10}$; n) finding a good correlation (r^2=0.84). The regression equation obtained by these authors was:

$$EI_{30\text{month}} = 7.05\text{rain}_{10} - 88.92\text{days}_{10} \quad (5)$$

2.3 Soil erodibility factor (K)

Soil erodibility is a complex property and is thought of as the ease with which the soil is detached by splash during rainfall or by runoff or both. In the RUSLE model the soil erodibility factor (K, Mg h MJ^{-1} mm^{-1}) is the rate of soil loss per rainfall erosion index unit as measured on a unit plot that is 22.1 m long, 1.83 m width and has a 9% slope. The K factor is a lumped parameter that represents an integrated average annual value of the soil profile reaction to the processes of soil detachment and transport by raindrop impact and surface flow, localized deposition due to topography and tillage-induced roughness, and rainwater infiltration into the soil profile (Renard et al., 1997). This factor can be assessed as a function of five soil parameters: percentage of organic matter (OM, %), percentages of modified silt (2–100 μm) and sand (100–2000 μm), and classes of aggregates structure (s) and soil permeability (p). For those cases where the silt fraction does not exceed 70% the following equation is used to calculate the K factor:

$$K = \frac{[2.1\times10^{-4}(12-OM)M^{1.14} + 3.25(s-2) + 2.5(p-3)]}{100} 0.1317 \quad (6)$$

where M is the product of the percentages of modified silt and sand. The RUSLE model established four different soil structure classes (Table 1) and six permeability classes (Table 2) that were taken from the National Soils Handbook No. 430 (USDA, 1983). This handbook defined the permeability classes according to the soil texture, though this parameter can also be assessed by field estimation of the saturated hydraulic conductivity (K_{fs}, mm day^{-1}). The approach of Rawls et al. (1982) is used in the RUSLE model to estimate the different permeability classes (Table 2) according to K_{fs} values.

2.3.1 Soils with rock fragments

Surface rock fragments reduce significantly the splash detachment rates in a manner similar to the crop residues that protect the soil surface from raindrop impact. However, in coarse textured soils surface and subsurface rock fragments affect infiltration and thus runoff by reducing the soil void space and soil hydraulic conductivity and increasing the soil erodibility. Although the percentage of coarse fragments varies along the soil in the same area, rocks appear in the soil profile as a frame, especially in interrill areas, where runoff cannot move them. Moreover, rock fragments larger than 2 mm were excluded when K-factor values were estimated in Eq. (6). To account the effect of rocks in soil erodibility the RUSLE model includes the following approach:

$$K_b/K_{fs} = (1 - R_W) \quad (7)$$

where K_b (mm day^{-1}) is the modified saturated hydraulic conductivity after accounting the effect of rock fragments, and R_W (%) is the weight percentage of coarse fragments.

Table 1. Soil structure classes (s) according to USDA (1983).

Soil structure class	Soil structure USDA (1983)
1	Very fine granular and very fine crumb (<1 mm)
2	Fine granular and fine crumb (1–2 mm)
3	Granular and medium crumb (2–5 mm) and coarse granular (5–10 mm)
4	Very coarse granular and very coarse prismatic, columnar, blocky, platy or massive (>10 mm)

Table 2. Permeability classes (p) according to USDA (1983), Rawls et al. (1982).

Permeability class	Texture USDA (1983)	Saturated hydraulic conductivity (mm h^{-1}) Rawls et al. (1982)
1 (fast and very fast)	Sand	>60.96
2 (moderate fast)	Loamy sand, sandy loam	20.32–60.96
3 (moderate)	Loam, silt loam, silt	5.08–20.32
4 (moderate slow)	Sandy clay loam, clay loam	2.03–5.08
5 (slow)	Silty clay loam, sand clay	1.02–2.03
6 (very show)	Clay, silty clay	<1.02

2.3.2 Seasonal variations in soil erodibility

K values are difficult to estimate mainly because of seasonal variations in soil properties that are primarily related to three factors: soil freezing, antecedent soil-water and soil-surface conditions (soil texture and structure). The greater the number of freeze-thaw cycles, the longer the erosion resistance of a soil is at a minimum. Freeze-thaw cycles reduce bulk density, stability and cohesion of the soil leading the soil to its maximum value of soil erodibility ($K_{\max}$) at the beginning of the free-freezing period. Moreover, high soil-water content can delay infiltration and water movement into the soil profile. Hence, soil during the thawing period is extremely susceptible to erosion caused by splash and runoff. On the other hand, during the free-freezing period soil erodibility decreases exponentially reaching its lowest value ($K_{\min}$) at the end of this period. Although the time span between the maximum and minimum values of soil erodibility varies with location and soil type, a value of 6 months or less appears to be reasonable in most areas and scenarios. López-Vicente et al. (2006a) estimated in 71.2 the mean number of freeze-thaw cycles per year for the study area from minimum and maximum daily values of temperature from the weather stations of Benabarre and Camporrélls.

When the value of the rainfall erosivity factor is lower than 6808 MJ mm ha^{-1} h^{-1} yr^{-1} the maximum and minimum values of soil erodibility, as well as the duration of the period of maximum soil erodibility ($t_{\max}$, day) can be calculated as follows:

$$K_{\max}/K_{\min} = 8.6 - 0.019R \quad (8)$$

$$K_{\max}/K_{\text{nom}} = 3.0 - 0.005R \quad (9)$$

$$t_{\max} = 154 - 0.44R \quad (10)$$

These equations were established according to the U.S. customary units therefore conversion from SI units must be done.

2.4 Cover-management factor (C)

The cover-management factor of the RUSLE reflects the effect of cropping and management practices on erosion rates. The C factor is the most commonly used to compare the relative impacts of management options on conservation policy. This factor allows estimating how the conservation policy will affect the average annual soil loss. The soil loss ratio (SLR) is an estimate of the ratio of soil loss under actual conditions to losses experienced under reference conditions (clean-tilled continuous-fallow). An individual SLR_i (0–1) value is thus calculated for each time period i, as:

$$SLR_i = PLU_i CC_i SR_i SC_i SM_i \quad (11)$$

where the sub-factors for each time period i are the prior land (PLU_i), the canopy cover (CC_i), the surface roughness (SR_i), the surface cover (SC_i), and the antecedent soil moisture (SM_i). The equations for the sub-factors are the following:

$$PLU_i = C_f C_b \exp -[(c_{ur} B_{ur}) + (c_{us} B_{us}/C_f^{C_{uf}})] \quad (12)$$

$$CC_i = 1 - F_c \exp(-0.1H) \quad (13)$$

$$SR_i = \exp[-0.66(R_U - 0.24)] \quad (14)$$

$$SC_i = \exp\left[-bS_p\left(\frac{0.24}{R_U}\right)^{0.08}\right] \quad (15)$$

where C_f is a surface-soil-consolidation factor, C_b represents the relative effectiveness of subsurface residue in consolidation, B_{ur} (lb acre^{-1} in^{-1}) is mass density of live and dead roots found in the upper inch of the soil, B_{us} is mass density of incorporated surface residue in the upper inch of the soil (lb acre^{-1} in^{-1}), c_{uf} represents the impact of soil consolidation on the effectiveness of incorporated residue, and c_{ur} and c_{us} are calibration coefficients indicating the impacts of subsurface residues. F_c (%) is fraction of land surface covered by canopy, H (ft) is distance that raindrops fall after striking the canopy. R_u (in) is surface roughness at initial conditions and just before tillage practices, b is an empirical coefficient that indicates the effectiveness of surface cover in reducing soil erosion and S_p (%) is percentage of land area covered by surface cover.

The prior land use sub-factor expresses the influence on soil erosion of subsurface residual effects from previous crops and the effect of previous tillage practices on soil consolidation. The canopy cover sub-factor expresses the effectiveness of vegetative canopy in reducing the energy of rainfall striking the soil surface. The surface roughness subfactor measures how depressions and barriers trap sediment and water, during a rainfall event, causing rough surfaces to erode at lower rates than do smooth surfaces under similar conditions. The surface cover sub-factor estimates how crop residues, rocks, and other nonerodible material reduce the transport capacity of runoff. Finally, antecedent soil moisture is an inherent component of continuos-tilled fallow plots, and these effects are reflected in the soil erodibility factor. Hence, no adjustment is made for changes in soil moisture to calculate the C factor.

Each SLR_i value is then weighted by the fraction of rainfall and runoff erosivity (EI_{30i}, %) associated with the corresponding time period, and these weighted values are combined into an overall C factor value as:

$$C = \frac{1}{EI_{30t}}\sum_{i=1}^{n} EI_{30i} SLR_i \quad (16)$$

where EI_{30t} (%) is sum of EI_{30i} percentages for the entire time period, n is the total number of time period i. The values of C factor ranges from 0 (total control of the erosion) to 1 (no effectiveness of cover-management practices).

2.5 Data collection

Rainfall values are recorded each 15 min at the weather station of Canelles and at daily time-steep at the weather stations of Benabarre and Camporrélls. Hence, monthly and annual values of EI_{30} and R, respectively, have been calculated at Canelles following Eqs. (1), (2), (3) and (4), whereas annual values of R have been estimated for the three weather stations following Eq. (5) for the period 1997–2006. The database of Canelles was obtained from the Regional Water Authorities (Confederación Hidrográfica del Ebro) and the rainfall record of Benabarre and Camporrélls from the Spanish National Meteorological Institute.

A field survey was carried out and a total of 60 soil samples were collected in the selected agricultural fields to estimate the parameters of the erodibility factor (Fig. 2). Samples were air-dried, grinded, homogenized and quartered, to pass through a 2 mm sieve. The general soil properties analysed were: organic matter (OM), coarse fragments (>2 mm, R_w) and soil texture (<2 mm). Analysis of the clay, silt and sand fractions were performed using laser equipment. Organic matter was determined by the Sanerlandt method (Guitian and Carballas, 1976) using a titrimeter with selective electrode. Machín (unpublished data) made a soil map (FAO, 1998) identifying eight soil types (Fig. 2). López-Vicente et al. (2005) measured the saturated hydraulic conductivity for each soil type obtaining values that range from 9.9 to 2252.5 mm day^{-1} for Haplic Gypsisols and Haplic Leptosols, respectively. Two types of structure of soil aggregate were identified. Very coarse granular and very coarse prismatic structure (class 4) was associated to Luvic Gleysols, Haplic Gypsisols and Gypsic Regosols and granular and medium crumb and coarse granular structure (class 3) was associated to Haplic Calcisols, Haplic Regosols, Lithic Leptosols, Hypercalcic Calcisols and Haplic Leptosols.

The volumetric soil water content (θ_S) in the upper 8 cm of the soil was measured using a Theta Probe soil moisture device. Soil moisture was controlled in 79 points following a regular grid to obtain a representative database of the soil moisture that was measured in February, May, August and December. The Theta Probe equipment was calibrated in laboratory for the different soil types.

The soil loss ratio, *SLR*, was calculated for periods of fifteen days. To estimate the prior land use sub-factor, *PLU*, the data of mass density of live and dead roots and of the incorporated to the surface residue in the upper inch of the soil, and the consolidation of soil surface for barley fields were obtained from the guide of the RUSLE model (Renard et al., 1997). To calculate the canopy cover sub-factor, CC, the values of proportion of land surface covered by canopy, and the distance of raindrops falls after striking the canopy were also obtained from these authors.

The role of rainfall interception by crops on the seasonal variations of soil erosion was analyzed by Castro et al. (2006) in olive orchards in Córdoba (Spain). In this work the rainfall interception of the crop vegetation and residues were added in the assessment of the canopy cover following Morgan (2001). The rainfall interception has a value between 0 and 1 and is defined as the amount of rainfall that remains in the branches and leaves of the canopy and crop residues and returns to the atmosphere by evaporation. In this work, the values of rainfall interception for barley (0.14) and its

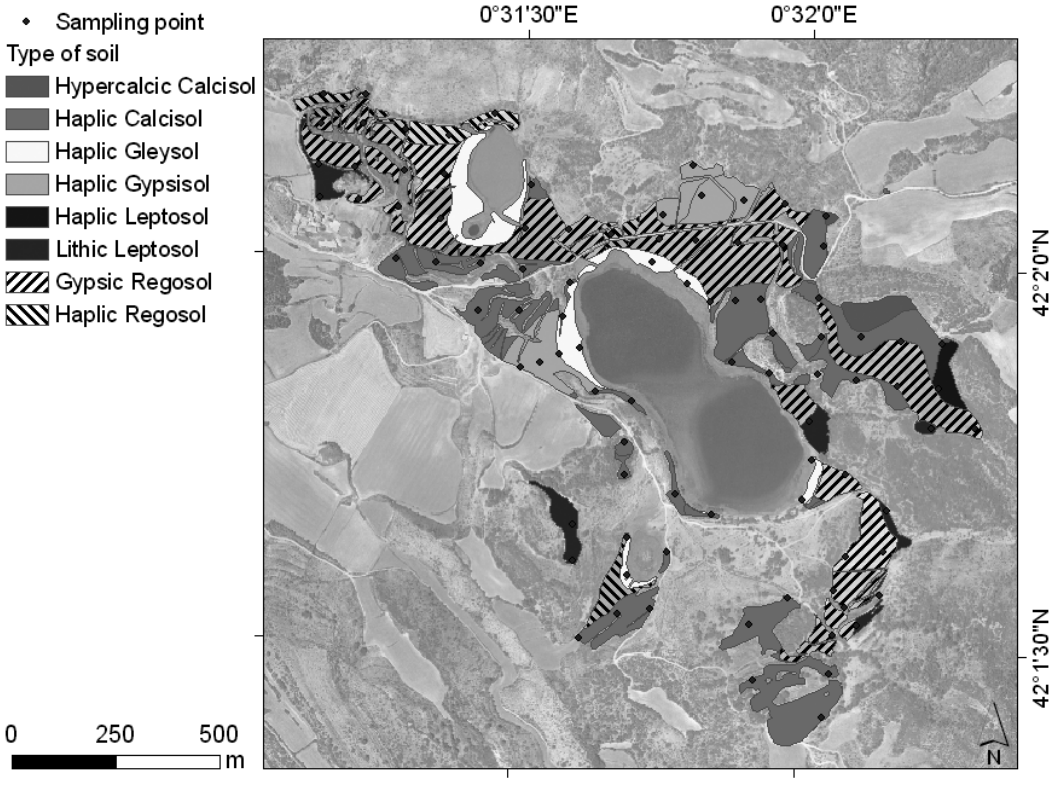

Fig. 2. Map of soil types of the study area (Source: Machín) and sampling points.

residues (0.03) were obtained from Eberbach and Pala (2005) and Cook et al. (2006), respectively.

The values of initial roughness for barley fields just before and after tillage which in the study area is mouldboard plow (Renard et al., 1997) were used to calculate the surface roughness and surface cover sub-factors. The percentage of coarse fragments was also used to assess the sub-factor of surface cover.

3 Results and discussion

From a total of 729 storm events recorded at Canelles for the period 1997–2006, 124 correspond to erosive storm events (17%). The values of rainfall erosivity, EI_{30}, and maximum intensity, I_{30}, ranged between 2 and 1216.3 MJ mm ha^{-1} h^{-1}, and between 1.6 and 69.8 mm h^{-1}, respectively. The calculated mean values of rainfall erosivity and maximum intensity and were 81.3 MJ mm ha^{-1} h^{-1} and 15.2 mm h^{-1}, respectively, showing a strong monthly variability in both parameters. The mean value of I_{30} for the study area is higher than that obtained by Usón and Ramos (2001) in vineyards of Barcelona (NE Spain) with a mean value of 10 mm h^{-1} and a maximum of 103 mm h^{-1} which is quite similar to the obtained in our study area. September had the maximum mean value of I_{30} (26.9 mm h^{-1}), whereas the mean values from December to March ranged between 5.4 and 7.1 mm h^{-1}. This variability was also observed in the EI_{30} values, with a mean of 107.1 MJ mm ha^{-1} h^{-1} for the May–September period which is higher than the mean registered in the November–April period (26.8 MJ mm ha^{-1} h^{-1}). The highest values of rainfall erosivity were associated with the highest values of maximum intensity. The mean value of EI_{30} for the June–August period was 334% higher than that for the January–March period. However, the rainfall was only 19% higher for the June–August period. The Pearson correlation coefficient between the erosivity and precipitation was low (r=0.47) (Fig. 3a) and it was high (r=0.95) between the erosivity and the maximum intensity of rainfall (Fig. 3b).

On the other hand, the erosivity presented a high monthly variability. The mean erosivity is higher than its median value in nine months and higher than its 75th-percentile in May (Fig. 3c). This variability is explained due to the high variability in rainfall erosivity during the April–October period, especially in September. The 10 most erosive storm events happened in September (6 events), October (2 events), August (1 event) and May (1 event), whereas the 10 highest values of maximum intensity were registered in September (7 values), October (1 value), August (1 value) and May (1 value). Moreover, 31% of the identified erosive events happened in September and October.

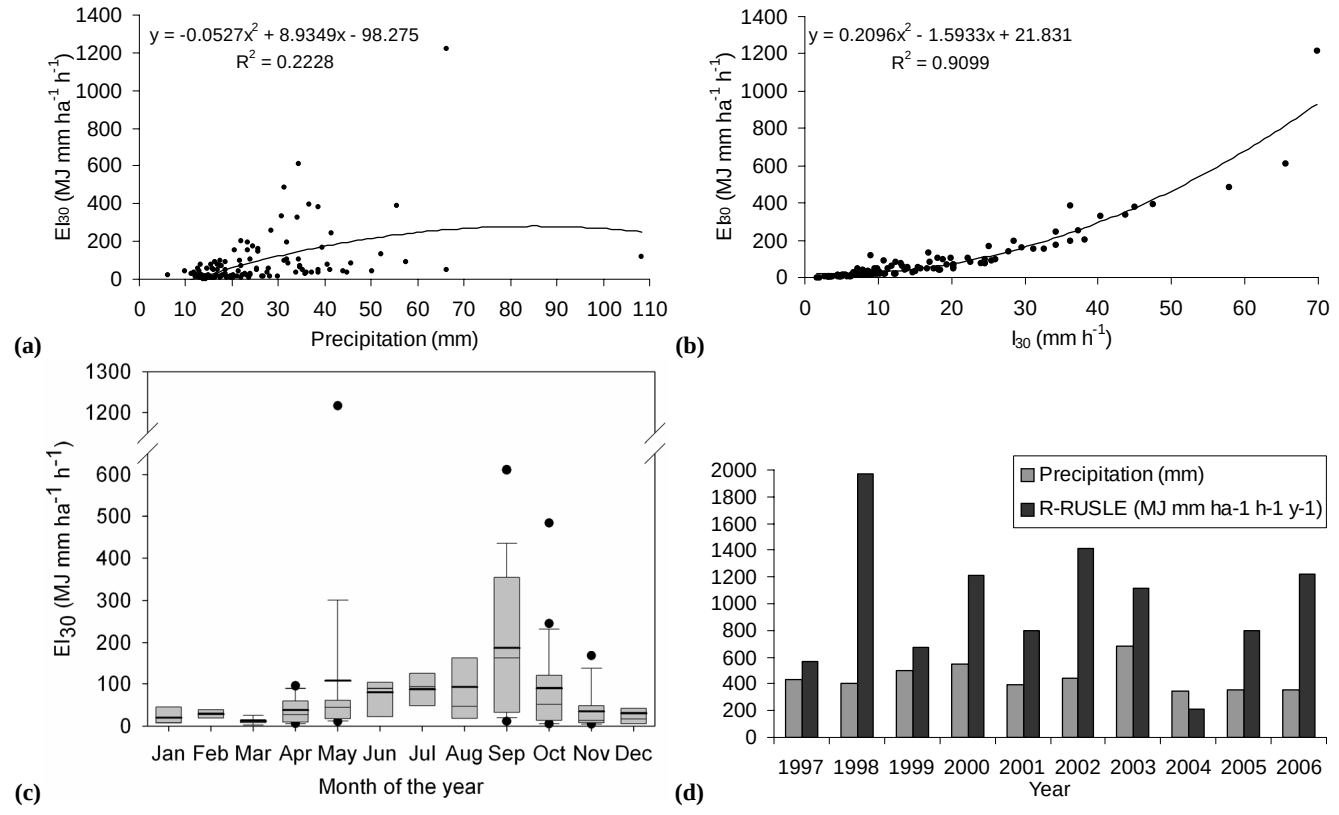

Fig. 3. Correlation between the runoff and rainfall erosivity values with their values of precipitation **(a)** and maximum intensity **(b)**. Monthly values of runoff and rainfall erosivity in a box plot diagram **(c)**. Annual values of precipitation and runoff and rainfall erosivity factor for the period 1997–2006 at the weather station of Canelles **(d)**.

The mean value of R was 1000.3 MJ mm ha^{-1} h^{-1} yr^{-1} at the Canelles weather station with a wide range of variation between 215.0 and 1969.2 MJ mm ha^{-1} h^{-1} yr^{-1} in 2004 and 1998, respectively (Fig. 3d). The R factor was calculated for a dry period (mean annual rainfall 445.53 mm) because 8 years of the period 1997–2006 had a lower value of rainfall than that measured in the weather station of Canelles for the reference period (1961–1990: 519.95 mm). The estimated values of the rainfall and runoff erosivity factor estimated with the approach of Loureiro and Coutinho (2001) were 829.9, 1210.2 and 1078.7 MJ mm ha^{-1} h^{-1} yr^{-1} at the weather stations of Canelles, Benabarre and Camporrélls, respectively. The estimated values of the R factor increase with the values of annual precipitation. In spite of the differences between the annual values of precipitation and rainfall and runoff factor for the different weather stations the temporal pattern of monthly rainfall is the same at the three weather stations. These results agree with values obtained in other Mediterranean areas as central and southern Italy (580–2300 MJ mm h^{-1} ha^{-1} yr^{-1}) (Diodato, 2004) and NE Spain (1049–1200 MJ mm ha^{-1} h^{-1} yr^{-1}) (Ramos and Porta, 1994).

For better characterizing the storm erosivity in the study area, the ten year frequency single storm erosivity (10-yr EI_{30}, in Renard et al., 1997) was calculated following the generalized Pareto distribution that was successfully applied by Vicente-Serrano and Beguería-Portugués (2003) in a study of extreme hydrological events in the middle Ebro valley (NE Spain). The rainfall erosivity of the ten year frequency was 706.1 MJ mm ha^{-1} h^{-1} and the estimated mean volume of precipitation for this rainfall event was 76.3 mm. According to this value there is only one rainfall event with a higher value of rainfall erosivity, that corresponds to the outlier of May (Fig. 3c) and explains the high value of R registered in 1998 (Fig. 3d).

The organic matter in the soil samples ranged between 0.7 and 7.5% with a mean of 2.4%. Almost all of the soil textures were silt-loam and the values of M ranged between 0.3 and 0.9 (Table 3). The mean and maximum percentages of coarse fragments were 21 and 56%, respectively, which are common within Mediterranean areas (Govers et al., 2006). The high stone contents modified the original value of saturated hydraulic conductivity from 557.6 to 433.4 mm day^{-1}. The mean soil erodibility was 0.011 Mg h MJ^{-1} mm^{-1} reaching a maximum value of 0.03 Mg h MJ^{-1} mm^{-1} (Table 3). Values

Table 3. Basic statistics of soil parameters in the samples studied.

	mean	minimum	maximum	SD
Organic matter (%)	2.4	0.7	7.5	1.5
Modified silt (%)	90.4	19.4	100.0	9.5
Modified sand (%)	9.6	0.0	80.6	9.5
Product of the percentages of modified silt and sand	661.3	1.0	2442.8	401.2
Coarse fragments (%)	21.0	0.0	55.7	9.7
Sat. hydraulic conductivity (mm day^{-1})	557.6	9.9	2252.5	505.3
Modified sat. hydraulic conductivity (mm day^{-1})	433.4	8.0	1979.8	396.5
Soil erodibility (Mg h MJ^{-1} mm^{-1})	0.011	0.000	0.030	0.006

of soil erodibility change within each soil type in accordance with the spatial variability of the percentage of coarse fragments, organic matter and clay and silt content. The effect of coarse fragments in the values of the class permeability sub-factor is limited to those areas with high values of coarse fragments obtaining a mean value of soil erodibility that is only 2.5% higher than the value calculated for the K factor without the effect of coarse fragments. The soils with a coarse granular and very coarse prismatic structure and low organic matter contents present higher erodibility than those with a granular and medium crumb structure and high content in organic matter. These results agree with the decrease in soil erodibility calculated by Tejada and Gonzalez (2006) in soils of Sevilla (southern Spain), and suggest the clear role of organic matter on the stability of soil aggregates.

The lowest soil moisture was obtained in August, with a mean content of 10.6%, whereas the means for February, May and December were 13.1, 15.6 and 17.7%, respectively. The highest rates of soil erodibility were obtained in Luvic Gleysols and Haplic Gypsisols due to their low saturated hydraulic conductivity and organic matter and the lowest rates were in Haplic Leptosols and Calcisols. The minimum and maximum values of soil erodibility due to seasonal variations were 0.004 and 0.029 Mg h MJ^{-1} mm^{-1}, respectively. The K_{max}/K_{min} ratio was 7.5. This high value was similar to the ratios of 7.4 and 10 obtained by Hussein et al. (2007) in a semi-arid catchment of northern Iraq where the rainfall and runoff erosivity was 900 MJ mm ha^{-1} h^{-1}. According to Renard et al. (1997), high K_{max}/K_{min} ratios are expected in regions with low mean seasonal or annual R values and less uniformly distributed monthly R values, such as in our study area. The duration of the period of maximum soil erosivity, t_{max}, was 128 days. From this value, the duration of K_{min} and K was estimated in 50 and 187 days, respectively.

The highest mean of soil loss ratio, SLR_i, was in the November–April period (0.23), which is much higher than for the rest of the year (0.12) (Fig. 4). These values are controlled by the schedule of the tillage practices and the phenology of the crops and agree with those obtained by Renschler et al. (1999) in agricultural fields of southern Spain showing strong monthly variations in EI_{30i} and SLR_i.

3.1 Identifying erosive periods

The calculated values for the different parameters of rainfall and runoff erosivity (Fig. 4a), soil erodibility (Fig. 4b) and cover-management (Fig. 4c) were combined to identify the characteristics of the erosive periods in the study area. Due to the cyclical pattern of the climatic phenomena, as well as the tillage practices, the results were ordered from November (start of the sowing) to October (end of the plowing). The first erosive period, EP-I in Fig. 4 and Table 4, has a duration of four months, from July to October, and is characterized by the highest values of rainfall erosivity and maximum rainfall intensity (Table 4). This period accounts 41% of the total erosive events in the year. The typical storm event in EP-I (Fig. 5a) has a mean duration of 712 min (Table 4) and is associated in most cases to the high rainfall produced by convective storms that occur between the end of summer and autumn (Llasat, 2001). On the other hand, EP-I has the lowest value of soil moisture and almost none freeze-thaw cycles. In agreement with these values the lowest soil erodibility rate occurs in this period. The mean value of the cover-management, 0.15 (Table 4), is associated with the harvest that leaves crop residues on the soil surface in July and August as well as with plowing in September and October. The European Common Agricultural Policy (CAP) concerned by the future of farming systems, prohibits the plowing operations before the first of September in row crops (Real Decreto 2352/2004 – BOE, 2004).

The second erosive period, EP-II, has a duration of two months, May and June, and is characterized by the minimum value of the cover-management (Table 4) that corresponds to the maximum protection of the soil by the crop canopy at the end of its growing season. The mean values of rainfall erosivity and maximum intensity are lower than those in EP-I and the typical storm event lasts longer than in EP-I (Fig. 5b). EP-II presents the highest soil moisture and none freeze-thaw cycles. Soil erodibility is slightly higher than in EP-I.

The third identified erosive period, EP-III, is the longest and has a duration of six months from November to April. EP-III has the lowest values of rainfall erosivity and maximum intensity and the duration of a typical rainfall event

Table 4. Mean values of erosivity (EI_{30}), maximum intensity (I_{30}) and duration of a erosive storm event (EE-t) and percentage of erosive events (EE), number of freeze-thaw cycles (F-T), soil moisture content in the upper 8 cm (θ_S), soil erodibility factor (K) and cover-management factor (C, 0–1) for each erosive period (database for the period 1997–2006 at the Canelles weather station and field data measured in 2005 and 2006).

Erosive period	duration	$EI_{30\text{median}}$	$I_{30\text{median}}$	EE-t	EE	F-T	θ_S	K	C	Soil loss	
	month	MJ mm ha^{-1} h^{-1}	mm h^{-1}	min	%	n	%	Mg h MJ^{-1} mm^{-1}		Mg ha^{-1} EP^{-1}	Mg ha^{-1} month^{-1}
EP-I	4	87.8	22.3	712	41.1	0.2	10.6	0.007	0.15	1.00	0.25
EP-II	2	66.3	13.1	864	19.4	0.0	15.6	0.011	0.05	0.19	0.10
EP-III	6	17.5	6.0	1155	39.5	11.7	15.4	0.023	0.23	1.46	0.24

almost doubles that in EP-I (Fig. 5c). The mean soil erodibility is the highest of the three periods (Table 4) and is three times higher than the rate in the first period because almost all the freeze-thaw cycles are concentrated in EP-III in coincidence with the highest soil moisture content. Moreover, the cover-management is at its highest because crops are at the stages of sowing, tillering and at the early stages of the growing season (Table 4).

For a better assessment of the temporal variations in the studied parameters, the total and monthly soil losses were calculated for each erosive period (Table 4) as the product of the rainfall erosivity, soil erodibility, cover-management and topographic factors and without considering corrections by support practices (Renard et al., 1997). The LS topographic factor of slope length and steepness was calculated following the approach of Moore and Burch (Moore and Wilson, 1992) and using the enhanced digital elevation model of the study area (López-Vicente and Navas, 2005). The selected methodology was satisfactory used in Sicily, Italy (Di Stefano et al., 2000) and NE Spain (Martínez-Casasnovas and Sánchez-Bosch, 2000). The lowest rates in total and monthly soil erosion are found in EP-II, whereas EP-I has the highest monthly soil erosion. Nonetheless, EP-III has monthly soil erosion similar to EP-I and the highest total rate of soil erosion due to its longer duration. The mean value of predicted soil loss was 3.34 Mg ha^{-1} yr^{-1} for the selected set of barley fields. This value was then compared with the erosion rates measured by using fallout ^{137}Cs in eight soil samples that are included on an ongoing research in the study area (Navas et al., personal communication, 2007). The calculated value of soil loss with ^{137}Cs corresponds to the average value of soil erosion during the last four decades. The mean value of measured soil loss was 5.38 Mg ha^{-1} yr^{-1}. The estimated rate of soil erosion was lower than the measured rate and can be explained by the low values of precipitation recorded at the Canelles weather station during the period 1997–2006. However, both values of estimated and measured soil loss are similar to those calculated by other authors under similar climatic conditions for cultivated areas (Navas et al., 2005; Renschler et al., 1999; Ramos and Porta, 1994).

The seasonal trends observed in the study area with higher rates at the end of autumn and in summer were also found in badlands of the south-eastern Pyrenees (Regüés and Gallart, 2004), in north-central Pyrenees (Nadal-Romero et al., 2007), in cultivated fields of Navarra in north Spain (De Santisteban et al., 2006) and in southern French Alps (Mathys et al., 2007). Concerning the role played by frost, Bullock et al. (1988) found that frost only has an effect on moist soils in which the water content exceeds 0.2 g g^{-1}. Hence, the calculated soil erodibility for winter months will be overestimated under drier and warmer winter conditions.

Soil erodibility is one of the most important factors to estimate soil losses. Hence, a more accurate assessment of this property than the made with the RUSLE model will be necessary to account for the chemical and mineralogical composition of the soil such as Tejada and Gonzalez (2006) made in wheat fields of Spain.

Approaches which promote early canopy development may reduce the amount of erosive rainfall by increasing rainfall interception by the crop canopy. Litter cover plays an important role in runoff and on the reduction of soil loss and is also fundamental for the control of erosion during intense rainfall (Bochet et al., 2006). Thus, from the results of our study we propose to start plowing in October instead of September. This plowing delay will extend the rainfall interception and surface protection by crop residues as well as will reduce the total number of days of bare soil in the year. Another effective measure that could be adopted is to increase the thickness of the crop residues where it may be possible to increase the rainfall interception (Cook et al., 2006) and thus reduce the amount of water that reaches the soil surface. This practice does not require elaborate tillage operations and will increase the percentage of organic matter in the soil reducing the soil erodibility. Finally, planting cover crops (rye or ryegrass) could be a solution to minimize soil erosion and runoff in the period between the harvest and plowing. These strategies agree with those proposed by Martínez-Casasnovas and Sánchez-Bosch (2000) for the prevention of land degradation in agricultural fields under Mediterranean conditions.

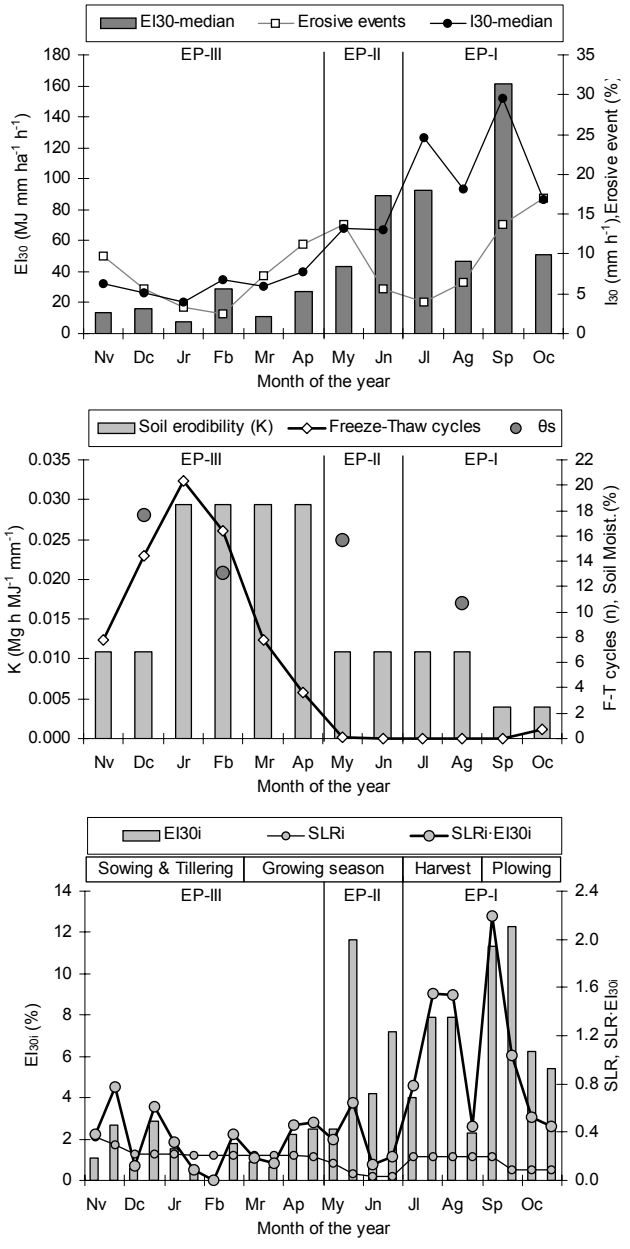

Fig. 4. Monthly median values of erosivity (EI_{30}), maximum intensity (I_{30}) and percentage of the erosive storm events **(a)**. Soil erodibility (K), number of freeze-thaw cycles (F-T) and percentage of soil moisture content (θ_S) **(b)**. Percentage of rainfall erosivity (EI_{30i}), soil loss ratio (SLR) and product of the percentage of rainfall erosivity and soil loss ratio **(c)**.

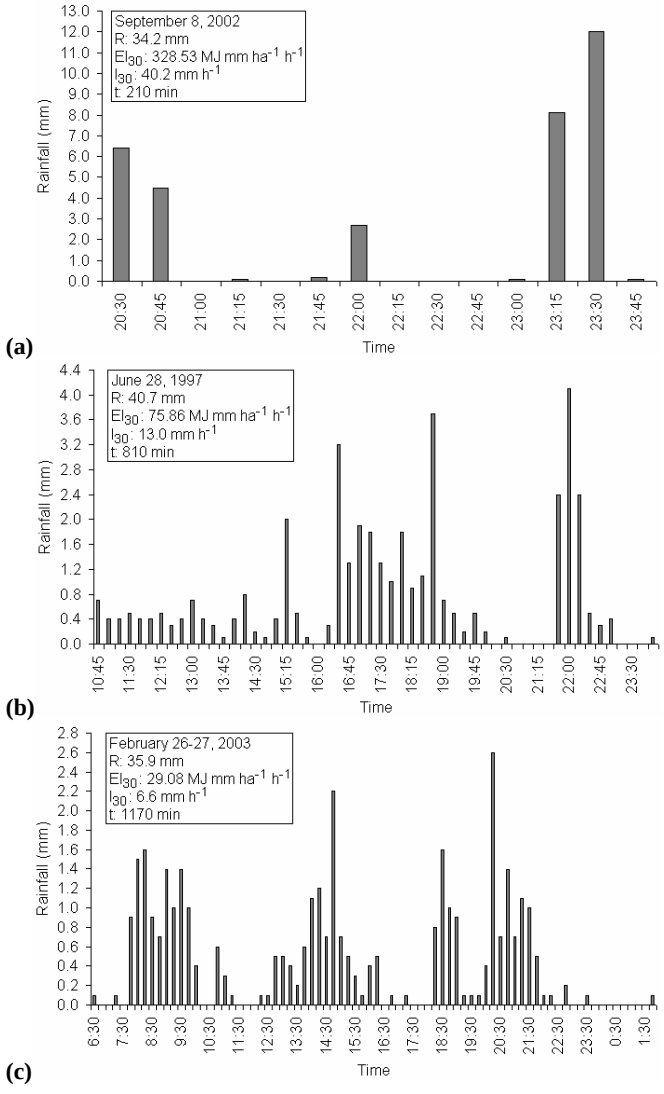

Fig. 5. Hyetograph of the typical erosive storm event for the first **(a)**, second **(b)** and third **(c)** erosive period.

In spite of the clear differences in the climatic parameters for the identified erosive periods, we also consider as Usón and Ramos (2001) that further research may be done including rainfall values registered each 5 or 10 min. This will allow a more accurate assessment of the R factor. Because soil moisture is a key parameter in soil erosion in Mediterranean environments a soil moisture sub-factor will be of interest to account its effect on the formation of surface crust. These proposed improvements will help to assess the effects of the temporal and spatial variations of rainfall that are expected to happen in Mediterranean areas due to climate change.

The patterns of rainfall distribution in this study are representative of Mediterranean environments. Moreover, the described tillage practices are common in dry farmlands. Therefore, the results obtained can be implemented in runoff and erosion models to improve their predictions in Mediterranean agrosystems.

4 Conclusions

The monthly values of rainfall and runoff erosivity, soil erodibility and soil loss ratio have shown a strong temporal variability along the year. The first erosive period identified in this work has a duration of four months, from July to October, and is characterized by the highest values of rainfall erosivity, maximum rainfall intensity and monthly soil erosion and the minimum values of erosive storm duration, freeze-thaw cycles, soil moisture content and soil erodibility. The second erosive period is the shortest with a duration of two months, from May to June, and presents the lowest rates of total and monthly soil losses that correspond to the maximum protection of the soil by the crop-cover. The third erosive period has a duration of six months, from November to April, and presents the minimum values of rainfall erosivity and maximum rainfall intensity. The erosive storm events associated with this period present the longest duration, and the soil erodibility is the highest value of the three erosive periods in accordance with the high number of freeze-thaw cycles and wettest soil. The monthly soil loss is slightly lower than in the first erosive period though the total soil loss is higher. The estimated annual soil loss during the period 1997–2006 is lower than the calculated value with ^{137}Cs though both values are similar to those obtained in other Mediterranean rainfed agroecosystems.

This work has highlighted that the interactions between the rainfall erosivity, soil erodibility, and cover-management can explain similar predicted soil losses found in the first and the third erosive periods in spite of the strong differences in the values of the three factors. The second erosive period, May and June, is the period with the lowest rates of soil erosion in the year. To promote sustainable strategies for the preservation of the fragile Mediterranean agroecosystems and especially in dryland agriculture it is recommended to delay the plowing practices till October. This delay will extend the protection role by the crop residues in September, as this month concentrates the highest rainfall and runoff erosivity and soil losses.

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