Cuadernos de Investigación Geográfica *Geographical Research Letters*	2023	Nº 49	pp. xx-xx	EISSN 1697-9540

http://doi.org/10.18172/cig.5506

CIRCULATION WEATHER TYPES AS A KEY FACTOR ON RUNOFF INITIATION AND SEDIMENT DETACHMENT IN MEDITERRANEAN SHRUBLANDS

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ABSTRACT. In this research, the circulation weather types (CWTs) associated with individual surface pressure data at different atmospheric heights were used to correlate and quantify soil erosion events collecting soil loss (g m^{-2}), runoff (l m^{-2}) and sediment concentration (g L^{-1}) using field plots and sediment collectors. Representative Mediterranean shrubland, located at Sierra de Enguera (Eastern Spain), was used as a case study where 213 rainfall episodes and related soil loss events were recorded for the 2010-2014 period. Average annual precipitation of 544 mm was registered, summarizing a total of 2,720.1 mm for the five years of the research period. A total of 34.4% of the registered precipitation events ranged from 10 to 29.9 mm, 23.5% from 30 to 49.9 mm, and 15.9% from 50 to 99.9 mm. The dynamic low-pressure with fronts (DLp+f) CWT was found to generate the highest precipitation amount reaching 60.6% of the total precipitation (105 of the 213 events). Over a third (35%) of the precipitation events occurred during Eastern CWT, which accounted for 48% of the total precipitation with average values of 17.6 mm per event. From the total runoff, 65.6% was related to the combined Eastern and cold drops (CD) CWT. The DLp+f CWT was found to produce 48.9% of sediment mobilization, of which 73.5% of this amount was generated by Eastern CWT. The highest sediment concentration event was found for the southern CWT under thermal low-pressure (TLp) reaching 51.65 g L^{-1}, followed by A (anticyclones) with the Eastern CWT (42.23 g L^{-1}). As a whole, the southern is the CWT generating the highest average sediment concentration (28.66 g L^{-1}), followed by Easter CWT. Our findings suggest that CWTs contribute to foreseeing the periods with the highest soil losses and may help to prevent them. We discuss the need to analyse the changes in soil erosion rates due to CWT to better characterize the soil erosion process and assess the soil erosion rates, improve the current soil erosion models and investigate how climate change is changing the role CWT plays in runoff initiation and sediment delivery.

Please, cite this article as: Rodrigo-Comino, J., Senciales-González, J.M., Pérez Albarracín, A., Bandala, E.R., Escrivà Saneugenio, F., Keesstra, S.D., Cerdà, A. 2023. Circulation weather types as a key factor on runoff initiation and sediment detachment in Mediterranean shrublands. *Cuadernos de Investigación Geográfica* 49. http://doi.org/10.18172/cig.5506

Tipos de tiempo como factor clave en el inicio de la escorrentía y el arranque de sedimentos en matorrales mediterráneos

RESUMEN. En esta investigación, los tipos de tiempo (CWT, por sus siglas en inglés) asociados con datos de presión de superficie individuales a diferentes alturas atmosféricas se utilizaron para correlacionar y cuantificar los eventos de erosión del suelo que corresponden a la pérdida de suelo (g m^{-2}), la escorrentía (l m^{-2}) y la concentración de sedimentos (g L^{-1}) utilizando parcelas de erosión y colectores. Se utilizó como estudio de caso una zona de matorral mediterráneo representativo, ubicado en la Sierra de Enguera (este de España), donde se registraron 213 eventos de precipitación y eventos relacionados de pérdida de suelo durante el período 2010-2014. Se registró una precipitación media anual promedio de 544 mm, sumando un total de 2.720,1 mm para los cinco años de investigación. El 34,4% de los eventos de precipitación registrados varió de 10 a 29,9 mm, el 23,5% de 30 a 49,9 mm y el 15,9% de 50 a 99,9 mm. Se encontró que la baja presión dinámica con frentes (DLp+f) generó la mayor cantidad de precipitación alcanzando el 60,6% de la precipitación total (105 de los 213 eventos). Más de un tercio (35%) de los eventos de precipitación ocurrieron durante el CWT del Este, lo que representó el 48% de la precipitación total con valores promedio de 17,6 mm por evento. Del total de la escorrentía, el 65,6% estuvo relacionado con el CWT combinado de gotas frías y tiempos del este (CD). Se encontró que el DLp+f producía el 48,9% de la movilización de sedimentos, de los cuales el 73,5% de esta cantidad fue generada por el CWT del Este. El evento de mayor concentración de sedimentos se encontró para el tipo de tiempo del Sur con baja presión térmica (TLp) alcanzando 51,65 g L^{-1}, seguido por A (anticiclones) del Este (42,23 g L^{-1}). En su conjunto, el sur es el CWT que genera la mayor concentración promedio de sedimentos (28,66 g L^{-1}), seguido del Este. Nuestros hallazgos sugieren que los CWT contribuyen a prever los períodos con mayores pérdidas de suelo y pueden ayudar a prevenirlos. Discutimos la necesidad de analizar los cambios en las tasas de erosión del suelo debido a cada tipo de tiempo para caracterizar mejor el proceso de erosión del suelo y evaluar las tasas de erosión del suelo, mejorar los modelos actuales e investigar cómo el cambio climático está cambiando el papel que juega los CWT en el inicio de la escorrentía y en la entrega de sedimentos.

Keywords: Precipitation, Soil erosion, Land management, Human-affected ecosystems, Regional issues.

Palabras clave: Precipitación, Erosión del suelo, Gestión de tierras, Ecosistemas afectados por el hombre, Temas regionales.

Received: 21 July 2022

Accepted: 6 February 2023

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1. Introduction

Understanding soils as an indispensable Earth resource is necessary to know how ecosystem services work and which human activities can take place in a specific land (Jónsson and Davíðsdóttir, 2016; Keesstra *et al.,* 2018a; Norman, 2020). For millennia, humans have used the soil to establish settlements and to obtain minerals or food (Altinbilek, 2004; Neville 2007). However, prolonged exploitation has generated serious issues affecting the quality and, subsequently, soil fertility (Rodrigo-Comino *et al.,* 2021). For decades, scientists have reported that soil is being affected by numerous land degradation processes such as soil compaction (Al-Dousari *et al.,* 2019; Drewry *et al.,* 2008), sealing (Larsen *et al.,* 2009; Munafò *et al.,* 2013), arson fires (Fernandez-Anez *et al.,* 2021) or contamination (Radziemska *et al.,* 2019; Rodríguez-Seijo *et al.,* 2018). Among them, anthropogenic soil erosion is one of the land degradation processes threatening humankind's sustainability (Bork *et al.,* 2003; Brown, 1981; Panagos *et al.*, 2020) because it causes nutrient loss in agricultural fields, damages lowlands, increases desertification risk inducing biodiversity and generate productivity losses (An *et al.,* 2019; Di *et al.,* 2019; Xie *et al.,* 2019).

The Mediterranean belt is one of the most affected areas by soil losses due to the intensification of urbanization (Egidi *et al.,* 2021), agriculture (Mohammed *et al.,* 2020; Raclot *et al.,* 2009; Vanwalleghem *et al.,* 2011) or grazing (Kairis *et al.,* 2015; Minea *et al.,* 2019). Prospects regarding climate change trends are claiming that soil erosion is becoming more intense in the most vulnerable lands (Borrelli *et al.*, 2020; Nearing *et al.,* 2004), with the consequent higher risks of desertification (Martínez-Valderrama *et al.,* 2016) and deterioration of rural economy (Ashby, 1985; Bayu, 2020; Sobral *et al.,* 2015).

Soil erosion is a complex process involving numerously interrelated and inherent factors such as rock and vegetation cover, antecedent soil moisture, roughness, slope, soil management or soil properties (Auzet *et al.,* 2002; Sun *et al.,* 2013). It also depends on the weather conditions before and during erosive events and, for this reason, generating knowledge about weather conditions will allow the scientific community to foresee the negative consequences of soil erosion and develop efficient control measures (Rodrigo-Comino *et al.,* 2019). To achieve this goal, defining the different circulation weather types (CWTs) and the rainfall events that may produce runoff and soil loss is a significant need. The CWTs have been extensively used for different purposes and classifications (Brazel and Nickling, 1986; Hess and Brezowsky, 2010; Lamb, 1972; Schroeder *et al.,* 1964) but are mainly restricted to specific areas and focused on weather forecasting and historical climate research (Ramos *et al.,* 2015). Recent improvements, during the last two decades, in remote sensing techniques, satellite information and climate datasets have made it possible to conduct more accurate studies considering larger scales and longer periods (Cortesi *et al.,* 2014; Fernandez-Raga *et al.,* 2017; Kidson, 2000; Trigo and DaCamara, 2000).

The relationship between weather types and soil erosion was originally used to assess landslides close to river or mountain catchments (Nadal-Romero *et al.,* 2014; Pattison and Lane, 2012). These works suggested that it is possible to find a correlation using a large number of precipitation events. Other studies (Nadal-Romero *et al.,* 2015; Peña-Angulo *et al.,* 2020, 2019) analysed large datasets from the Mediterranean belt to correlate weather types and soil erosion rates (Peña-Angulo e*t al.,* 2021). However, little information is available about the way that CWTs affect runoff generation at the pedon scale, and most of the research is carried out in agricultural or forestry landscapes. This paper assesses the sediment delivery and runoff yield which will give a wider view of the soil erosion process and the climatic factors involved when vegetation cover changes.

To our best knowledge, assessments at hillslope and pedon scales considering CWTs and soil erosion are scarce. Recently, our research group (Rodrigo-Comino *et al.,* 2020a, 2019) carried out studies on CWTs in vineyards in Southern and Eastern Spain, comparing active and abandoned vine plots, and conventional soil management systems. Both studies found key steps for designing soil erosion control measures to mitigate the negative impact of extreme rainfall and runoff considering atmospheric conditions. However, the need for new approaches to detect the amount of rainfall needed to activate soil losses and prevent erosive events remain, and this is relevant for shrublands and forest as most of the previous research comes from agricultural land. The main goal of this study is to assess the relationship between CWTs and soil erosion at the pedon scale. To achieve this goal, a representative hillslope located in the Mediterranean belt was selected as a case study to, specifically, i) analyse CWTs associated with individual surface pressure data at different atmospheric heights; ii) detect CWTs and individual surface pressure data generating soil losses; and iii) estimate how shrublands are affected by soil losses.

2. Materials and methods

2.1. Study area

A typical Mediterranean *maquia* ecosystem representing a large area of the Mediterranean climatic region was selected as a study case. The shrublands are widespread due to the degradation of the original forest covers and they are diverse in plant composition but with similar characteristics: lower biomass than forest land and adapted to forest fires due to sprouting and seedling strategies. The experimental soil erosion station of Sierra de Enguera is located in the Eastern Iberian Peninsula (60 Km from the coast) at an altitude of 758 m above sea level (Fig. 1). The climate is typically Mediterranean (Csa according to Köppen and Geiger (1930) and Kottek *et al.* (2006) with a mean annual temperature of 12.7ºC, mean annual rainfall of 540 mm, and characterized by a long drought period (from June to September). Intense rainfall events usually bring daily rainfall amounts higher than 100 mm. Soils are classified as Inceptisols (Soil Survey Staff, 2014) and show rock outcrops and a cover of rock fragments. The vegetation is composed of a mixture of Mediterranean *maquia* species (*Ulex parviflorus* Pourr., *Pistacia lentiscus* L., *Erica multiflora* L., *Juniperus oxycedrus* Sibth. & Sm., *Quercus coccifera* L. and *Rosmarinus officinalis* L.). The experimental station was constructed in January 2010, and runoff information collection started in October 2010 and lasted 5 years (from October 2010 to September 2014). The data from January to October 2010 were not considered due to the disturbances created by the plot installation.

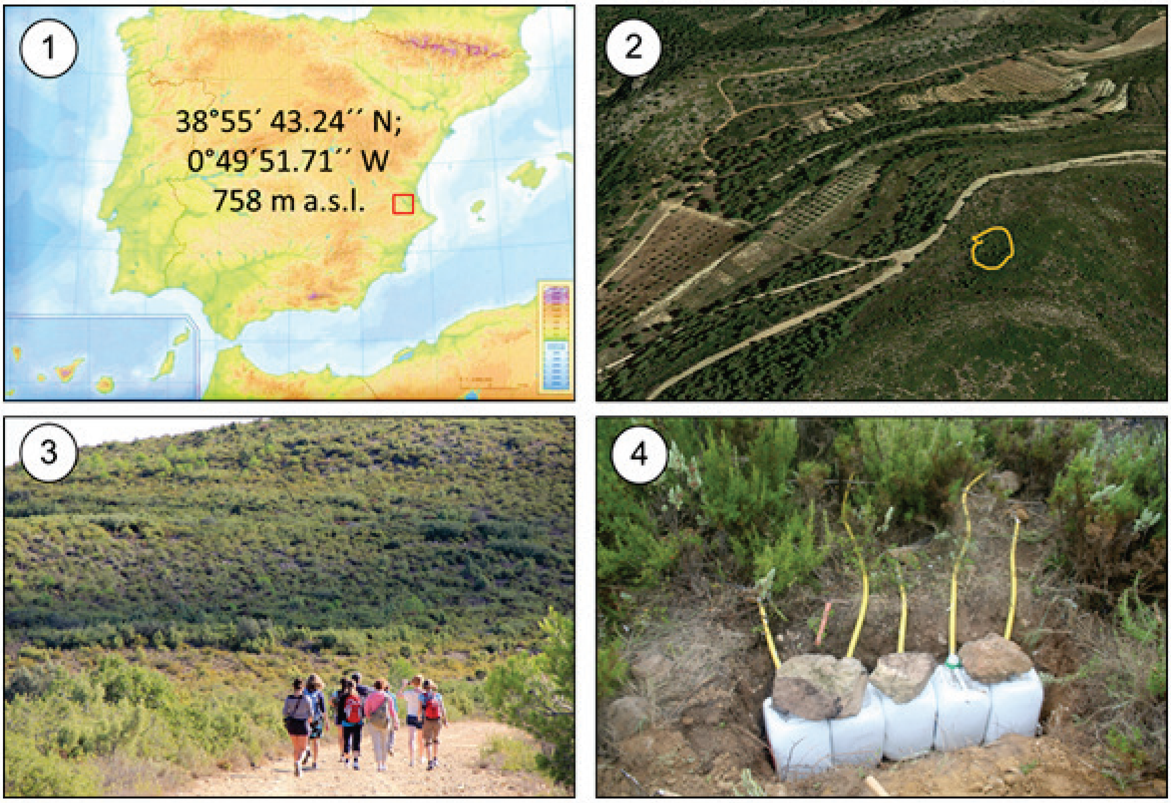

Figure 1. Localisation of the study area (1 and 2), landscape (3) and plots (4).

2.2. Assessment of CWTs

A total of 213 rainfall events were selected from the continuous rainfall records of the nearby meteorological station. A rainfall event is considered to have a minimum total rainfall value of 1 mm and is separated by a minimum of 6 continuous dry hours (Rodrigo-Comino *et al.,* 2020a. All singleday (24 hours) events were counted. For multi-day events, only those retaining the same CWT, wind surface direction, or recorded no erosion, were counted.

In each event, individual surface pressure data (500 hPa) and dominant surface wind (intensity and direction) were recorded on the study experimental station. This study is aimed to identify and classify CWTs using synoptic maps. This assessment requires the use of a variety of downscaling procedures that attempt to relate circulation-scale variability (large scale) to precipitation variability at local scales (Jones *et al.,* 2013). To achieve this goal, we used the following meteorological sources: i) Wetter Zentrale (https://www.wetterzentrale.de); ii) Leeds University website (http://homepages.see.leeds.ac.uk); and, iii) the Spanish Agency of Meteorology (AEMET; http://www.aemet.es/es/portada).

Using the meteorological sources described before, the CWTs were catalogued and related to precipitation volumes and numbers of events, as well as their soil erosion results. The CWTs identified correspond to the following individual surface pressure data exhaustively described (Nadal-Romero *et al.,* 2015; Rodrigo-Comino *et al.,* 2020a): i) Dynamic low-pressure without fronts (DLp); ii) Thermal low-pressure (TLp); iii) Dynamic low-pressure with fronts (DLp+f); iv) Cold Drop (CD); v) Anticyclones with fronts (HP+f); vi) Anticyclones/Weak pressure (A). In another study, Rodrigo-Comino *et al.* (2020a) observed that other conditions that exhibited height inversion, related to coastal areas or arid and semi-arid lands close to the Iberian Peninsula. These conditions were excluded from this analysis because that classification was not adequate for soil erosion assessment. This assessment was based on how, and to what extent, the situation at 500 hPa affects the volume and the number of events that have an impact on soil erosion. The events have been classified according to the duration since this is how the runoff and soil loss values have been recorded.

2.3. Sampling plot strategy and soil erosion assessment

Sixteen circular plots (from 0.33 to 0.45 m^2, average 0.38 m^2) were constructed with drainage connected to a 30 L container through a 40 mm diameter pipeline in the same slope, but under four different canopy cover (4 x 4 plots): *Quercus coccifera* L., *Pistacia lentiscus* L., *Ulex parviflorus* Pourr. and *Rosmarinus officinalis* L., to collect information about the detachment of sediments and runoff initiation. The runoff discharge and sediment concentration were collected, and plots borders, drainage, collectors, pipes and deposits were repaired after each rainfall event. Information on 150 erosive events was collected. Soil erosion rates and runoff coefficients were calculated for each rainfall event. Rainfall data was supplied by the Spanish Agency of Meteorology (AEMET) meteorological station located 5 Km from the study site. Sixty-four (four per plot) soil samples at 0-2 cm depth were collected to determine calcium carbonate content, grain size, organic matter, and bulk density. Soil organic matter was determined by the Walkley-Black method (Walkley and Black, 1934). Bulk density was measured using the ring method (Al-Shammary *et al.,* 2018) and calcium carbonate with the potassium dichromate method. The grain size was determined with the pipette method (Deshpande and Telang, 1950).

3. Results

3.1. Soil characterization

In Figure 2, the characterization of the soil properties obtained after sampling the study area is presented. Vegetation cover averaged 95% (maximum 98% and minimum 89%). Litter cover amounted to 31.1% (maximum 48 and minimum 19%). Rock fragment cover percentage was 19.8% (maximum 32% and minimum 13%) and gravel 6% (maximum 9.5% and minimum 2.7%). Organic matter in the samples was 6.12%, bulk density 1.01 gr cm^{-3} and calcium carbonate 59.1%. Soil texture was identified as clay loam.

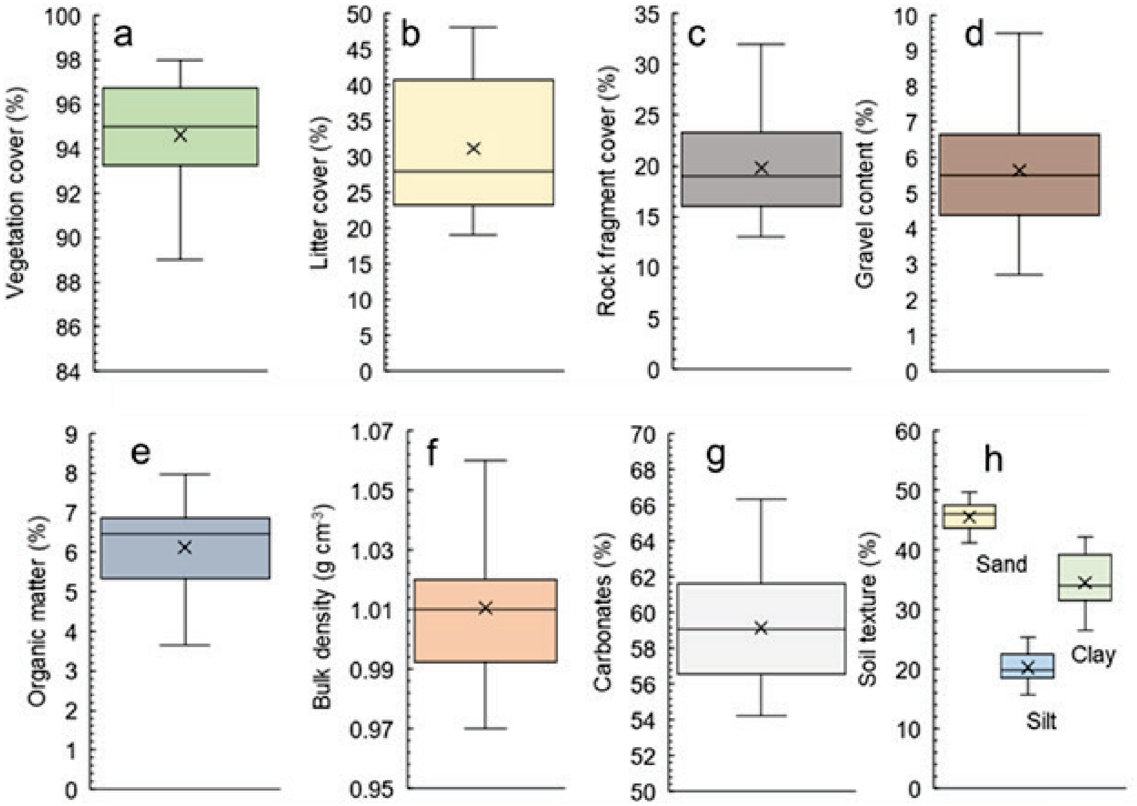

Figure 2. Soil properties and environmental characteristics within the studied plots.

3.2. Characterization of precipitation events (2010-2014)

A total of 213 precipitation events were identified during the studied period (Fig. 3). The mean annual precipitation was 544 mm (October to September). The yearly precipitation distribution was 554.2 mm in 2010; 590.4 mm in 2011; 593.7 mm in 2012; 560 mm in 2013; and 422.4 mm in 2014. The total accumulated rainfall was 2,720.1 mm. The three highest rainfall events recorded reached 176.8 (15/11/2012), 145.5 (23/11/2011) and 100.5 mm (25/04/2013).

Figure 4 shows the classification of each precipitation event in the base of the different individual surface pressure data described in Methods. The information was used to obtain the percentage of each rainfall related to the soil erosion events (top part) and the number of events considering each surface pressure data (bottom part). The 34.4% of the total events ranged from 10 to 29.9 mm, 23.5% from 30 to 49.9 mm and 15.9% from 50 to 99.9 mm. The highest precipitation amount was generated by DLp+f reaching 60.6% along 105 events, one of them higher than 100 mm and four in the 50-99.9 mm range. However, the highest number of events (85) generated precipitation values ranging from 1 to 4.9 mm (39.9%). A total of 55 events (25.8%) were recorded with precipitation values in the 10 to 29.9 mm interval, and 48 events (22.5%) ranged from 5 to 9.9 mm. The occurrence of HP+f (34 events) and CD (21 events) accumulated 13.0 and 11.6% of the total precipitations, respectively. It is worth highlighting that CD was able observed during one precipitation event within the 50-99.9 mm value range. In contrast, the mildest precipitation events (only one within the 29.9-50 mm range, and the rest lower) occurred with DLp (5.5%), A (4.8%) and TLp (4.4%), registering 18, 22, and 13 of the total set of events, respectively.

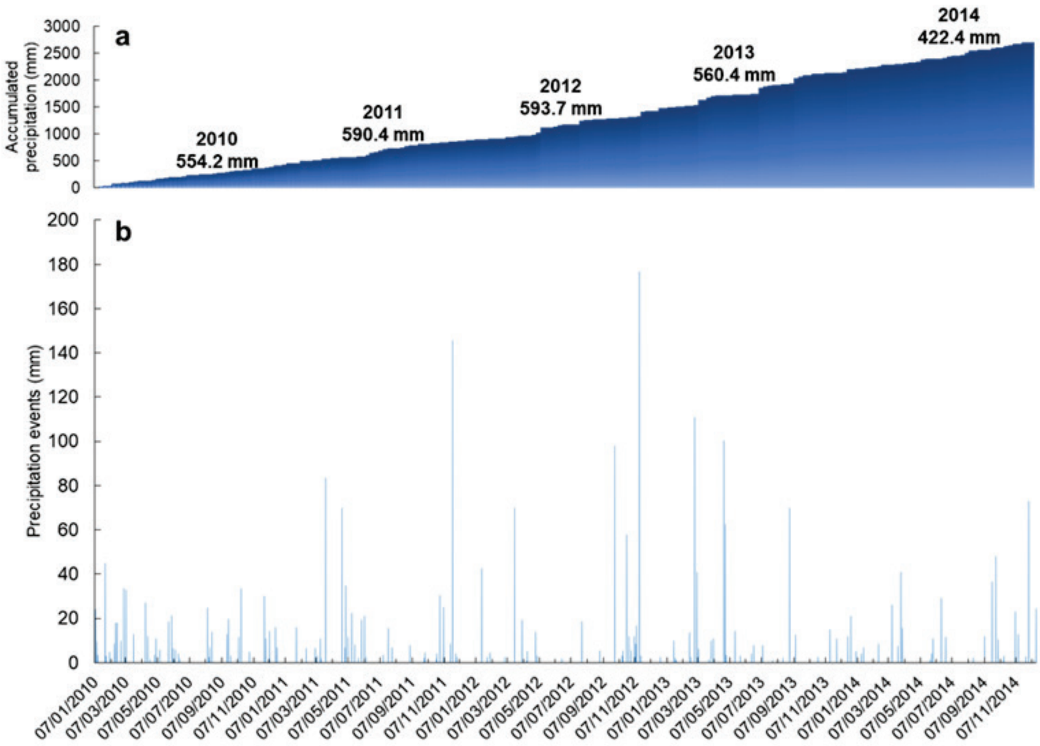

Figure 3. Temporal distribution and accumulated precipitation events during the studied period

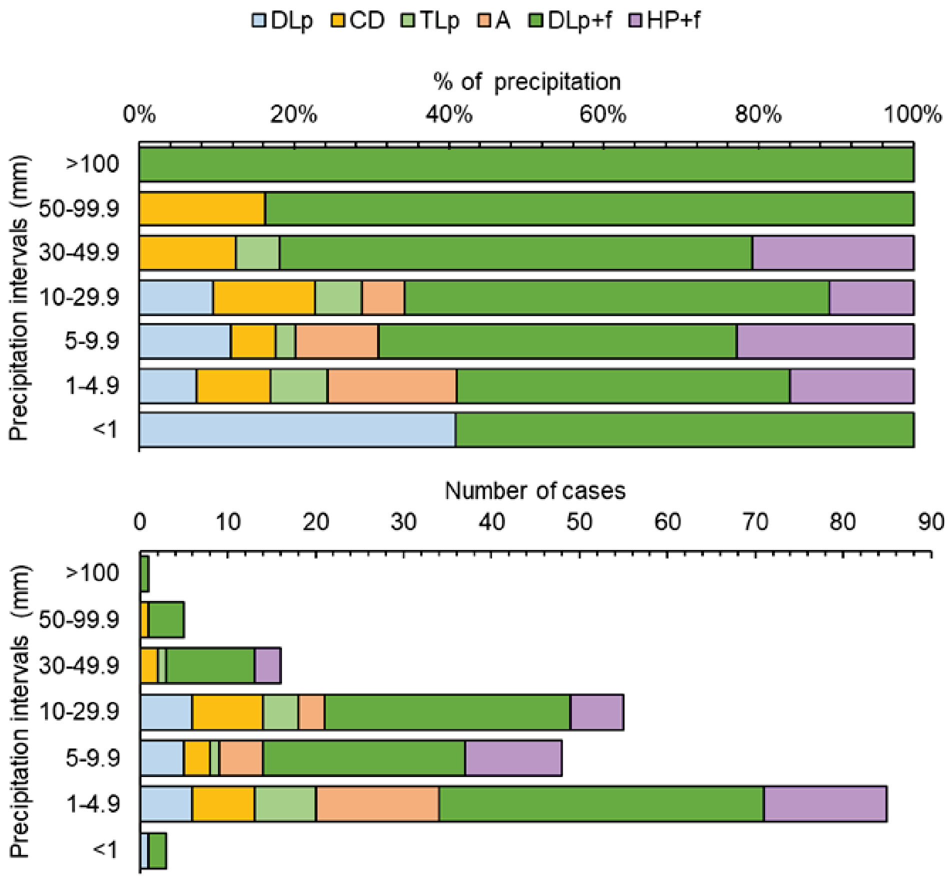

Figure 4. Classification of precipitation events per intervals considering each individual surface pressure data. i) Dynamic low-pressure without fronts (DLp); ii) Thermal low-pressure (TLp); iii) Dynamic low-pressure with fronts (DLp + f); iv) Cold Drop (CD); v) Anticyclones with fronts (HP + f); vi) Anticyclones/Weak pressure weather systems (A).

In Table 1 and Figure 5, the number of events distribution (%) and total precipitation of the events registered for the different CWTs are summarized. It was found that 35% of the precipitation events occurred during Eastern CWT, summarizing 48% of the total precipitation with an average precipitation value of 17.6 mm per event. Western and North CWT registered 17% and 13% of the events, respectively, but also the lowest precipitation amount (245.8 mm and 244.3 mm, respectively), and averages (6.6 and 8.8 mm, respectively). Southern CWT recorded 16% of total precipitation along 34 events averaging 11.9 mm. Finally, mixed atmospheric conditions accounted for 19% of the total precipitation, averaging 13 mm per event along 40 events.

Table 1. Number of events (n), total precipitation (mm), average total rainfall and standard deviation (S.D.) of the events recorded for the different weather types

Weather types	Total precipitation	N° of cases	Average	S.D.
N	94.2	9	10.5	14.4
N-NE	0	0	0	0
NE	673.6	28	24.1	30.9
E-NE	111	3	37	45.9
E	494.5	41	12.1	13.5
E-SE	26.5	2	13.3	0.4
SE	265.8	21	12.7	11.6
S-SE	0	0	0	0
S	138.6	13	10.7	9.6
S-SW	0	0	0	0
SW	71.2	9	7.9	6.1
W-SW	7.9	2	4.0	2.2
W	131.7	24	5.5	3.0
W-NW	35	2	17.5	7.8
NW	145.7	18	8.1	11.6
N-NW	5.4	1	5.4	0
Mixed	520	40	13.0	15.8

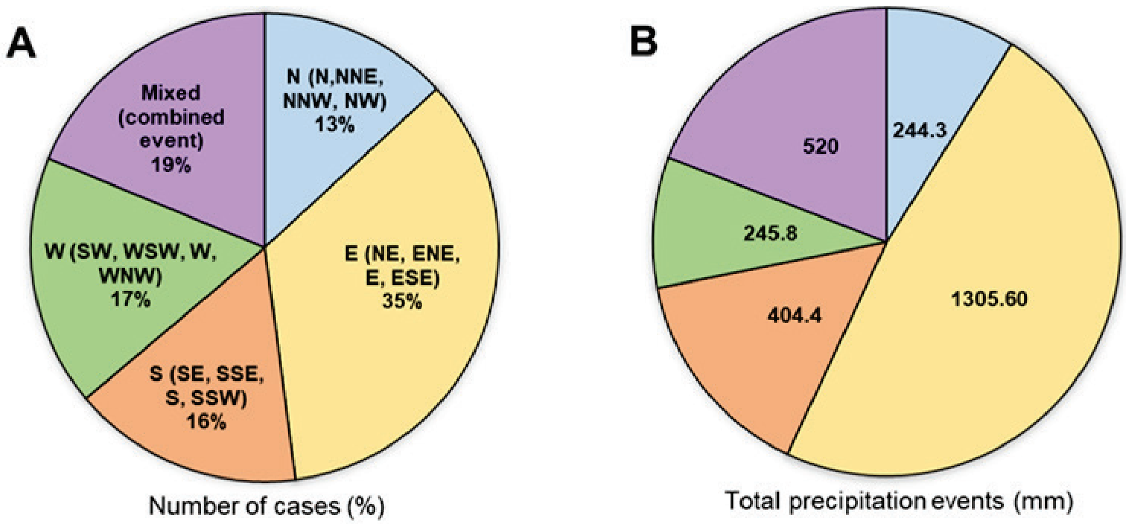

Figure 5. Distribution of the number of events (%) and total precipitation (mm) of the events registered for the different weather types.

3.3. Runoff generation depending on the weather types

Out of the 150 rainfall events, only 40 (less than one-third) registered runoff, suggesting that, in general, the longer the event lasts, the greater the volume per rainy day. In Table 2, runoff generation and total discharges are summarized for all the events recorded. It is worth highlighting that the most repeated rainfall events lasted one day (104 times). Similarly, the longer the event lasts, the higher the average runoff coefficient recorded, which implies a progressive saturation of the soil and runoff generation. Considering rainy days (Table 3), 37 of the 213 rainfall events registered runoff. Considering the specific CWT, Eastern CWT recorded most of the events and the highest percentage of runoff (50%), accounting for almost half of the events where runoff was recorded (37 out of 78).

Table 2. Number of runoff events used to assess runoff and soil loss generation, and sediment concentration classified per duration days

Duration (days)	Nº events	Total days	Total volume (mm)	mm/day	Runoff (l)	Runoff (mm)	Average runoff coefficient	Soil loss (g m^2)	Sediment concentration (g l^{-1})
1	104	104	1154.4	11.1	23.4	63.3	2.0	1063.0	16.8
2	33	66	752.9	11.4	25.9	72.4	3.4	1987.6	27.5
3	11	33	567	17.2	29.8	81.1	5.3	2884.5	35.6
4	0	0	0	0	0	0	0	0	0
5	2	10	246.8	24.7	17.2	45.9	7.0	904.7	19.7
Total	150	213	2721.1					6839.2	

Table 3. Weather types and, runoff and soil loss characterization. i) weather type (WT); ii) number of cases (n); iii) precipitation (P); iv) Runoff estimated in liters (R); and v) average runoff coefficient (Av. Rc %)

WT	n	P(mm)	Av	R(l)	R (mm)	Av. Rc (%)	Cases with R	Events with R	Rc (%)	% of cases with R	SL (g)	SC (g l^{-1})
N	28	245.3	8.8	4.3	11.9	4.9	10	7	4.8	35.7	246.2	20.7
E	74	1305.6	17.6	70.7	198.1	20.2	37	19	15.2	50.0	5563.1	29.0
S	34	404.4	11.9	6.7	18.5	4.9	12	5	4.6	35.3	43.6	2.7
W	37	245.8	6.6	1.2	3.3	0.8	5	2	1.3	13.5	16.0	4.8
Mixed	40	520.0	13	10.9	31.3	3.7	14	7	6.0	35.0	971.0	31.1
Total	213	2721.1					78	40			6839.8	17.67

Considering the 40 events showing runoff (Table 4), 262.74 mm of precipitation was recorded (9.7% of the total precipitation), from which 54.8% correspond to DLp+f. CD summarized 25.3% of the total runoff volume while HP+f represented 11.8% of the runoff volume. The highest volume of runoff corresponds to weather types from the Eastern (78.5%). The remaining types of weather conditions account for 5.1% of the total events, and volumes are always below 5% of the total with a predominance of association with Eastern winds. However, there is an exception with the TLp, where the greater volume of runoff occurs with Southern weather types.

Table 4. Assessment of atmospheric conditions, rainfall events, runoff generation and weather types. i) Dynamic low-pressure without fronts (DLp); ii) Thermal low-pressure (TLp); iii) Dynamic low-pressure with fronts (DLp + f); iv) Cold Drop (CD); v) Anticyclones with fronts (HP + f); vi) Anticyclones/Weak pressure weather systems (A); vii) atmospheric situation (AS); viii) average (Av).

AS	$l \cdot m^{-2}$	N	E	S	W	Mixed	Total	%
DLp	Total	0.15	1.78	0	0.15	0.38	2.46	0.9
	Av.	0.15	1.78	0	0.15	0.38	0.49	
CD	Total	0	66.47	0	0	0	66.47	25.3
	Av.	0	5.57	0	0	0	1.11	
TLp	Total	0	0.09	7.87	0	0.09	8.05	3.1
	Av.	0	0.09	3.93	0	0.09	0.82	
Al	Total	0	10.67	0.22	0	0	10.89	4.1
	Av.	0	3.56	0.22	0	0	0.76	
DLp+f	Total	11.72	94.40	8.89	3.16	25.69	143.87	54.8
	Av.	1.11	6.01	1.26	0.79	3.09	2.45	
HP+f	Total	0	24.35	1.55	0	5.11	31.01	11.8
	Av.	0	6.09	0.78	0	1.70	1.85	
Total		11.87	197.76	18.53	3.31	31.27	262.74	100
%		4.5	75.3	7.1	1.3	11.9	100.0	

3.4. Soil erosion rates depending on the weather types

The Eastern CWT was found to generate the highest volume of sediment discharge, both in total amount ($g\ m^{-2}$) and concentration ($g\ L^{-1}$), with 95.4% of the total mass.

Considering the 40 events that recorded runoff (Table 5), a total of 6.8 kg was collected, which implies 19,845.11 $g\ m^{-2}$ (considering 0.34 m^2 plots). It was found that DLp+f generated 48.9% of the mobilized sediments, and of this amount, 73.5% was generated by Eastern CWTs. CD registered 25.4% of the soil loss, all related to Eastern CWTs and HP+f, which represent 12.9% of the mobilized soil loss. The remaining CWTs supposed to be lower than 7% soil losses, all of them associated with Eastern CWT, except TLp, where most of all the mobilized mass was generated by Southern CWT.

Table 5. *Assessment of atmospheric conditions, rainfall events, soil loss and weather types. i) Dynamic low-pressure without fronts (DLp); ii) Thermal low-pressure (TLp); iii) Dynamic low-pressure with fronts (DLp + f); iv) Cold Drop (CD); v) Anticyclones with fronts (HP + f); vi) Anticyclones/Weak pressure weather systems (A); vii) atmospheric situation (AS); viii) average (Av)*

AS	$g\ m^{-2}$	N	E	S	W	Mixed	Total	%
DLp	Total	2.68	42.42	0	2.68	12.80	60.57	0.3
	Av.	2.68	42.42	0	2.68	12.80	12.11	
CD	Total	0	5036.68	0	0	0	5036.68	25.4
	Av.	0	419.72	0	0	0	83.94	
TLp	Total	0	0.87	1179.07	0	0.87	1180.82	6
	Av.	0	0.87	589.54	0	0.87	118.26	
A	Total	0	1306.85	2.23	0	0	1309.09	6.6
	Av.	0	435.62	2.23	0	0	87.57	
DLp+f	Total	460.48	7133.22	320.26	125.86	1662.16	9701.99	48.9
	Av.	51.16	475.55	45.75	31.47	207.77	162.34	
HP+f	Total	0	2372.45	39.77	0	143.76	2555.98	12.9
	Av.	0	593.11	19.88	0	47.92	132.18	
Total		463.16	15892.49	1541.33	128.54	1819.58	19845.11	100
%		2.3	80.1	7.8	0.7	9.2	100.0	

Sediment concentration differed from total soil losses and runoff results (Table 6). DLp+f showed high sediment loads per unit volume (17.61 g l^{-1}), but not the highest values. TLp-Southern CWTs recorded the highest sediment concentration (51.65 g l^{-1}) followed by A-Eastern CWTs (42.23 g l^{-1}), and HP+f-Eastern WTs (33.58 g l^{-1}), suggesting that, as a whole, the Southern CWT generated the highest sediment concentration, followed by the Eastern CWT. The Western CWT of Atlantic Ocean origin generated the lowest sediment concentration.

Table 6. Assessment of atmospheric conditions, rainfall events, sediment concentration (g l^{-1}) and weather types. i) Dynamic low-pressure without fronts (DLp); ii) Thermal low-pressure (TLp); iii) Dynamic low-pressure with fronts (DLp + f); iv) Cold Drop (CD); v) Anticyclones with fronts (HP + f); vi) Anticyclones/Weak pressure weather systems (A); vii) atmospheric situation (AS); viii) average (Av)

AS	N	E	S	W	Mixed	Av
DLp	6.21	8.23	0.00	6.21	11.59	6.45
CD	0.00	26.11	0.00	0.00	0.00	5.22
TLp	0.00	3.32	51.65	0.00	3.32	11.66
A	0.00	42.23	3.43	0.00	0.00	9.13
DLp+f	13.54	26.04	12.42	13.73	22.30	17.61
HP+f	0.00	33.58	8.84	0.00	9.70	10.42

4. Discussion

4.1. Soil erosion as a worldwide concern and the need for weather types research

Previous investigations conducted from the pedon scale (de Lima *et al.,* 2003; Telak *et al.,* 2021) to the regional or continent ones (Carretier *et al.,* 2018; Panagos *et al.,* 2015) concluded that soil erosion is a big concern for humankind due to the possible irreparable consequences on food security, biodiversity and natural resources. However, less attention is paid to responsible atmospheric factors at different heights (Fernández-González *et al.,* 2012; Jones *et al.,* 2013) than the methods used and the final consequences in form of soil and water losses. The main goal of this research was to understand how soils react after each precipitation event because of different barometric situations and diverse CWTs. Nowadays, this topic is poorly studied at the hillslope scale due to the elevated amount of data needed to establish a statistically considerable trend (Peña-Angulo *et al.,* 2021; Rodrigo-Comino *et al.,* 2019). The specific number has not been delimited and it is a key point to be stated in coming investigations. However, this difficult task will also depend on climate variations. Also, this research will be affected by the season monitored corresponding to the most representative years within the climatic trend of each region. In this study, a total of 213 precipitation events (rainfall and snow) were collected over 5 years. We can state that, despite the three extreme rainfall events higher than 100 mm, the precipitation was in line with the usual trend of Eastern Spain (Piñol *et al.,* 1998). In 2014, the rainfall amount was less than 500 mm, which also agrees with the occurrence of dry periods of the Mediterranean belt in the last decades studied by other scholars with clear ecological implications (Dong *et al.,* 2019; Guillot *et al.,* 2019; Vautard *et al.,* 2007; Vicente-Serrano *et al.,* 2004). Our research is a good example of the variability of the weather types that induce soil erosion, but also that few weather types are responsible for the high erosion rates in a location. To update the world knowledge on soil erosion and to plan future restoration and rehabilitation plans new studies on the weather types are necessary.

4.2. Weather type research. A need for standardization of the methods

We classified the total collected precipitation per interval. This allowed us to determine the most representative precipitation events and ranges and the least usual ones. Precipitations less than 50 mm were the most common reaching 57.9% in total volume. Only 16% was higher than that, which originated from cold drops and DLp+f. Considering the CWTs, the Eastern WTs generated heavier precipitation events, coming from the Mediterranean Sea. This agrees with previous studies highlighting the connection between heavy rainfall events and the Eastern WT (Littmann, 2000; Senciales-González and Ruiz-Sinoga, 2020), and also, the difficult predictability (Alpert *et al.,* 2004; Hochman *et al.,* 2019). Also, several local publications informed about the rapid development of these extreme precipitation events when cold and warm air streams keep in contact with rapid interchanges (Benhamrouche and Martín Vide, 2011; Clar, 2017; Nuñez Mora, 2007). Eastern WTs and both cold drops and DLp+f were also responsible for the maximum runoff and erosion collected in the study area. These results coincide with other investigations made at the regional scale after comparing multiple plots and several years of monitoring (Nadal-Romero *et al.,* 2015; Peña-Angulo *et al.,* 2020, 2019). Also, in agricultural fields such as vineyards, the same WTs were able to generate the highest soil erosion rates and water losses. At larger scales, these high soil and water losses could even generate catastrophic events such as the ones of July 2021 in China and Western Europe. It is very common as other authors demonstrated in the past regarding urban flash floods, gully generation or landslides close to rivers without vegetation cover (Camarasa Belmonte and Segura Beltrán, 2001; Camarasa-Belmonte, 2016; Portugués-Mollá *et al.,* 2016). This is not only observed along the European Mediterranean belt, for example, the study conducted by Gilabert and Llasat (2018), highlighted that Eastern WTs under Mediterranean conditions may also generate extreme flood events, for example, in California (USA).

Once the scientific community accept that weather-type research should be developed at a world scale, we could better understand the soil erosion phenomenon. There is a key issue to be solved: the standardization of the methods. Right now, the three main concerns are to establish a range of rainfall intensity to be consistent from one study to the other. Upon different studies, we found that the ranges varied due to the different climates and, then, because of different rainfall intensities. This makes it difficult to compare results from one region to another, from one author to the other. It must be developed a rank for the rainfall intensities will be used by all the authors to allow us to make comparisons among study sites. Another key issue to improve the knowledge of weather types and soil erosion is to determine the main weather type during the measurements of the soil losses. We suggest here that the weather type should be considered multiple (different weather types in one rainfall event) when this will occur, but one should be the predominant weather type when the rainfall event will be characterized. The multiple weather types of rainfall events are a discussion topic for the future. And finally, another key methodological concern is to determine the period of rainfall (and soil erosion) event. We suggest that the rainfall events must be separated at least by 6 hours of dry weather and the rainfall events should be separated once this dry period takes place.

4.3. Weather types and soil conservation

From an applied and scientific perspective, it is necessary to consider potential environmental solutions to be applied in areas affected by extreme rainfall events concentrated in a few events- They are difficult to be predicted such as the catastrophic floods in China and Germany shown along with July 2021 and recurrent rainfall events that cause economic damages and casualties. Those rainfall events are found on different continents and in climatic conditions. Furl *et al.* (2018) found the Blanco River flood in South Texas an extreme event and Angillieri *et al.* (2017) in El Rodeo village, Northwestern Pampean Ranges in Argentina. Those extreme events are found in different climates, including the aridest ones such as the Atacama Desert where Izquierdo *et al.* (2021) researched catastrophic flood events with a mudflow. Or in temperate ones (Smith *et al.,* 1996). All those examples of extreme runoff and soil loss showed that research on the weather types is necessary to understand past events, manage the present ones and foresee the future ones to better manage them.

One of the solutions to the high erosion rates and corresponding flooding is the key relevance that vegetation cover plays on soil conservation, water infiltration capacity and retention (Collins, 2004;

Martínez-Casasnovas *et al.,* 2009; Mohammed *et al.,* 2020). In abandoned areas or human-affected ecosystems such as our study area, the conservation of a healthy vegetation cover is definitive to achieve sustainable soil erosion rates. Our research has shown that the shrubland is a highly protective vegetation cover, and this can be a solution for urban areas with a high level of impermeabilization and agricultural land also affected by high erosion rates (Novara *et al.,* 2019).

High soil erosion rates were found in this research during the eastern and cold drop atmospheric conditions, and this informs us that the soils should be covered with plants or mulches during the Autumn period when the highest soil losses take place. Previous research demonstrated that there are solutions to the millennia-old mismanagement of Mediterranean ecosystem types. Rodrigo-Comino *et al.* (2020b) used the cover of *Vicia sativa* Roth. to reduce the soil losses in vineyards. Cerdà *et al.* (2021a) applied weeds as cover crops in olive groves with success. Novara *et al.* (2019) cover crops in olive and vineyards and Cerdà *et al.* (2021b) in *Prunus persica* found that tillage or herbicides are the cause of the main soil degradation that use cause a reduction in the soil organic matter, aggregate stability and soil water retention capacity. This is why the use of control measures such as the ones applied in organic farming is recommended to restore soils in Mediterranean ecosystems (Baiamonte *et al.,* 2019).

Finding the causes of the soil losses will allow us to better find the right management. Determining the weather types and when they occur such as we did in this research will contribute to planning better restoration strategies. This is a worldwide benefit. High erosion rates are found in other regions of the Planet. Then, it is needed to apply sustainable management in many areas of the world due to the natural conditions (climate, sloping terrain, loss of forest or excessive tillage) and they must be designed upon the environmental conditions. This means that each region should develop weather types and soil erosion relationship studies to plan the most successful management for soil and water conservation. Madarász *et al.* (2021) found that conservation tillage is definitive to control the soil losses in Central Europe, and Klik and Rosner (2020) reviewed the long-term conservation experience in Austria and their impact on soil erosion. Rutebuka *et al.* (2021) demonstrated also the importance of terracing to reduce soil erosion rates. Chen *et al.* (2019) on the effect of vegetation coverage on soil erosion in a small watershed in China, and Kassawmar *et al.* (2018) and Negese *et al.* (2021) in Ethiopia. The two decades of research by Prasuhn (2020) demonstrate the impact of the conservation programs on soil losses in Switzerland. All this research will be highly beneficial from using a weather-type research approach that will inform when and which magnitude of soil erosion they are facing.

Understanding the influence of weather types on soil erosion is a key approach also to understanding the dynamics of soil erosion processes. The connectivity concept informs about how the sediment and water are transported and then connected from one scale to another (i.e. from pedon to watershed scale) and this is related to the intensity of the rainfall, and then to the weather type. The research of Keesstra *et al.* (2018b) showed that the connectivity of the sediments in a watershed or slope is highly dependent on the rainfall event characteristics. The weather types research approach should bring information about when and how long the soil erosion events take place. Zhao *et al.* (2020) assessed the sediment connectivity of a catchment in the Loess Plateau in China and confirmed the impact of afforestation and check dams reducing the connectivity, but also found that the rainfall volume and rainfall intensity are relevant. Weather types research will inform about the periods where the connectivity is higher. López-Vicente *et al.* (2021) also found that the sediment connectivity is determined by factors such as soil erosion barriers in a small basin recently affected by a forest fire; however, in both study sites the rainfall was considered the key factor, and then weather types contribute to better understand the soil erosion processes. The connectivity issue is highly related to conservation strategies that use to reduce soil losses due to the reduction in connectivity. This is found in agricultural land (Ares *et al.* 2020) but also in rangelands (Johnson *et al.* 2021). Climatic conditions always play a key role in connectivity, which can be assessed properly via the weather types research we developed here. We can now confirm that some weather types induce higher connectivity such as the East winds and some others such as the Western ones reduce the connectivity of the sediment and water under shrubland ecosystems.

The large dataset of weather types can help to improve the soil erosion models or complete other ones such as the recent improvements in soil biodiversity (Orgiazzi and Panagos, 2018), shallow water (Hajigholizadeh *et al.,* 2018), or the phosphorus in the sediments (Krasa *et al.,* 2019). Soil erosion modelling has been also reviewed for post-fire conditions by Lopes *et al.* (2021) and we found that the weather types contribute to a better understanding of the soil erosion processes and this should be incorporated into the models.

Even more relevant is that the large dataset of weather types must help to improve the soil erosion models. The information the weather types bring should also be used for the development of future soil erosion models that will take into account climate change. The climate change scenarios offer to the scientific research community information about the change in temperature and rainfall, but it will be also a change in the weather types and then soil erosion. Those research fields -weather types, soil erosion models and climate change- are new challenges that this paper shows as opportunities for future research directions and projects.

5. Conclusions

Circular Weather types (CWT) associated with individual surface pressure data at different atmospheric heights were analysed for 213 rainfall events (2010-2014) and soil and water losses were measured for the period to establish which kind of precipitation event related to each CWT can activate soil and water losses. Considering average annual precipitation of 544.0 mm and a total of 2720.1 mm during the study period, we concluded that a total of 34.4, 23.5 and 15.9% of the collected events ranged from 10 to 29.9 mm, 30 to 49.9 mm and 50 to 99.9 mm, respectively. The highest precipitation amount was generated by DLp+f (dynamic low-pressure with fronts) reaching 60.6% of the total precipitation, and 35% of the precipitation events occurring during eastern CWT (48% of the total precipitation). Most of the total runoff was collected during the Eastern CWT and cold drops (CD) summarizing 25.3% of the total runoff volume. Almost half of the mobilized sediments correspond again to DLp+f and 73.5% of this amount was generated from Eastern WTs too. Southern WTs under TLp (Thermal low-pressure) amounted to the highest sediment concentration reaching and the Southern WT the highest sediment concentration, followed by the Eastern ones.

Acknowledgements

Artemi Cerdà thanks the Co-operative Research program from the OECD (Biological Resource Management for Sustainable Agricultural Systems) for its support with the 2016 CRP fellowship (OCDE TAD/CRP JA00088807), POSTFIRE Project (CGL2013-47862-C2-1 and 2-R) and POSTFIRE_CARE Project (CGL2016-75178-C2-2-R) sponsored by the Spanish Ministry of Economy and Competitiveness and AEI/FEDER, UE. This paper was written as a result of the collaboration that was initiated due to COST ActionES1306: Connecting European Connectivity research and COST CA18135 FIRElinks: Fire in the Earth System. Science and Society. We wish to thank the Department of Geography secretariat team (Nieves Gómez, Nieves Dominguez and Susana Tomás) for their support over three decades to our research at the Soil Erosion and Degradation Research team (SEDER), with special thanks to the scientific researchers that as visitors from other research teams contributed to the SEDER research. The collaboration of the Geography and Environmental Sciences students was fruitful and enjoyable. Finally, we would like to thank the program "Visiting Scholars" of the Plan Propio de Investigación y Transferencia by the University of Granada (Granted to Jesús Rodrigo-Comino and Saskia Keesstra).

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