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IMPACT OF LITHOLOGY AND SOIL PROPERTIES ON ABANDONED DRYLAND TERRACES DURING THE EARLY STAGES OF SOIL EROSION BY WATER IN SOUTHEAST SPAIN

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ABSTRACT

Soil erosion by water in abandoned dry terraces is one of the most important environmental problems in semi-arid areas, enhancing biological degradation and reducing possible resources that can be obtained. However, little is known about the effects of the types of lithology and soil properties on the early stages of soil erosion. Therefore, the main aim of this research was to assess the effect of different lithologies (marls, limestones and metamorphic –phyllites, schists and greywackes- materials) and soil properties on the early stages of soil erosion by water in abandoned dry terraces, compared with similar terraces still in agricultural use. Soil analyses (texture, aggregate stability and bulk density) and 22 rainfall simulations were carried out under dry conditions. During the experiments, local inclination, vegetation and stone cover, total organic matter and antecedent soil moisture were also quantified.

The results showed that the highest soil loss (41.41 g m^{-2} in cultivated plots and 17.05 g m^{-2} in the abandoned plots) and runoff (3.79 L m^{-2} in the abandoned plot) occurred on marl substrata. Marls also showed the shallowest infiltration front (9 cm) and lowest infiltration rate (4.3 cm min^{-1}). Limestones and, especially, metamorphic areas, showed a lower degree of soil erosion, higher infiltration rates and deeper infiltration fronts.

Key words: soil erosion by water; lithology; soil properties; abandoned dry terraces; rainfall simulations.

1. INTRODUCTION

Land abandonment can be defined as the phenomenon of ceasing agricultural activity in a specific area for an indefinite period, with no imminent intention of returning to that activity or any other profit-oriented activity (Cammeraat *et al.*, 2010; Haddaway *et al.*, 2014; Lasanta *et al.*, 2000; Martínez-Hernández, 2014). The process of abandonment can be considered as a global dynamic associated with: i) the gradual decrease in traditional agricultural practices (García-Ruiz & Lana-Renault, 2011; Kou *et al.*, 2016); and ii) the aggravation of land degradation processes as a result of increased sediment yield through runoff (Macdonald *et al.*, 2000; García-Ruiz *et al.*, 2013; Hatna & Bakker, 2011). The non-planned areas of land abandonment can enhance soil erosion by water (Cammeraat *et al.*, 2010; Haddaway *et al.*, 2014), reduce biodiversity (Cammeraat *et al.*, 2005; Robledano-Aymerich *et al.*, 2014), lead to several changes in river discharges (Cammeraat *et al.*, 2005; Kou *et al.*, 2016; Plieninger *et al.*, 2014) and alter soil quality (Keesstra *et al.*, 2012; Khaledian *et al.*, 2016)).

In most European countries, land abandonment reached its peak after the industrialization that took place during the 19th Century and after the The Second World War (Gellrich & Zimmermann, 2007). According to several authors land abandonment in Mediterranean areas has continued due to EU policies, urbanization, globalization and desertification (Geeson *et al.*, 2002; Lasanta Martínez *et al.*, 2010; López-Vicente *et al.*, 2016; Robledano-Aymerich *et al.*, 2014). By contrast, in eastern European countries, land abandonment and re-vegetation areas are more likely be the consequence of post-socialist economic progress (Moravec & Zemeckis, 2007). The generalization of this phenomenon has led to the publication of many reports in recent decades covering most Mediterranean territories (Cammeraat *et al.*, 2010; Lasanta *et al.*, 2015). In Spain, the areas for which most studies on land abandonment and the corresponding degradation processes have been published are basins and valleys in the Pyrenees, the Iberian System, Central Ebro Valley, and southeast of Spain (García-Ruiz & Lana-Renault, 2011; Bienes *et al.*, 2016; Nadal-Romero *et al.*, 2011a). Southeast Spain, and more specifically, the province of Murcia (*Región de Murcia*), henceforth Murcia, is second in the number of publications related to land abandonment and its hydrological problems (Romero Díaz, 2016). The causes that lead to land abandonment are multiple in Murcia (López Bermúdez, 1995; Kosmas *et al.*, 2002; Alonso Sarría *et al.*, 2016) and include rural abandonment, emigration to urban areas and rural population aging. However, it is not only sociological circumstances that reduce interest in continuing to farm the land. Non-suitable land uses, environmental and factors are also determining factors, including: i) steep slopes (Nadal-Romero *et al.*, 2014; Nord & Esteves, 2010); ii) poor soils and plots in easily eroded areas such as bad lands (Martínez-Murillo *et al.*, 2013; Nadal-Romero *et al.*, 2011b); iii) low water storage capacity and degradation by livestock (Hochschild *et al.*, 2003; Pulido-Fernández *et al.*, 2013); iv) long periods of drought (Nadal-Romero *et al.*, 2015; Ruiz Sinoga *et al.*, 2010); v) soil erosion by water and decreased water supply (Rey Benayas *et al.*, 2007; Cerdà *et al.*, 2009); and, vi) a variety of climatic conditions (Alonso Sarría *et al.*, 2016). However, for other authors it is not clear whether the adequate use of abandoned lands can or cannot totally prevent the possible risks of soil erosion by water (Abaci & Papanicolaou, 2009; Lasanta *et al.*, 2015).

In this area of southern Spain, several studies have been conducted to assess hydrological processes and sediment yield at hillslope and catchment scales. For example, Belmonte-Serrato *et al.* (2013) measured infiltration processes using a minidisc infiltrometer; Romero-Díaz *et al.* (2007) obtained an average sediment yield of about 97.7 t ha^{-1} $year^{-1}$, measuring the visible erosion of piping processes using a GPS method; Lesschen *et al.* (2008) calculated similar values for the *Cárcavo Basin*, estimating soil loss rates for abandoned terraces at about 87 t ha^{-1} year^{-1} by means of a multi-age DEM comparison; Romero-Díaz *et al.* (2016) estimated the high occurrence of gully erosion in abandoned plots on marl substrata and very low levels on metamorphic ones by applying qualitative erosion samplings. In these studies, pedological and lithological factors were found to be closely involved in generating soil erosion features (Cerdá, 1997; Quinton *et al.*, 1997). However, there is a general lack of information at pedon scale concerning the quantification and assessment of the environmental factors that really activate or prevent soil erosion by water (Romero-Díaz *et al.*, 2017).

So, to prevent land degradation processes initiated by natural and human impacts after abandonment (Arnáez *et al.*, 2011; Seeger & Ries, 2008), a successful comparison at pedon scale between cultivated and abandoned areas could provide a database for developing general land management policies and suitable environmental solutions, such as mulching, the use of geo-textiles or re-vegetation (Cerdá *et al.*, 2016; Giménez-Morera *et al.*, 2010; Hueso-González *et al.*, 2016). To this end, small portable rainfall simulators are considered useful tools for assessing early interrelated stages of soil erosion processes by water such as splash, initial rainfall-runoff processes, infiltration, sediment yield, water turbidity or nutrient suspensions (Cerdá, 1999; Iserloh *et al.*, 2013; Rodrigo Comino *et al.*, 2016a; 2016b; Prosdocimi *et al.*, 2016a).

Consequently, the main aim of this paper was to quantify and to assess the effect of lithology (marls, limestones and metamorphic rocks) and soil properties on the early stages of soil erosion by water in abandoned dry agricultural terraces. In this way, the novelty of this research is related to carry out an assessment at pedon scale to complete the information of soil erosion research for larger scales such as hillslope or catchment.

To achieve this goal twenty-two rainfall simulations (11 in abandoned areas and 11 in active agriculture lands) were carried out and the main environmental characteristics (inside the plots), such as local slope, vegetation and stone covers, total organic matter content and antecedent soil moisture content were measured. Moreover, several physical properties of the soils (texture, aggregate stability and bulk density) were analysed in the search for the possible statistical significance of the results obtained. Our hypothesis concerns that it is possible to find one or more environmental drivers that enhance the early stages of soil erosion by water in abandoned dry agricultural terraces.

2. MATERIALS AND METHODS

2.1. Study area

Three study areas were selected for this research, considered as representative places, all situated in the province of Murcia (11313 km^2) in south-eastern Spain (Fig. 1). The province is quite uneven, with numerous mountain chains running in an ENE-WSW direction and often higher than 1000 m.a.s.l., valleys, basins, intra-mountain corridors, plains and high plateaus (Romero Díaz, 2007). From a geological point of view, south-eastern Spain lies within the Baetic System and includes materials from the three subareas usually classified as Prebaetic and Subbaetic System (external areas) and Baetic System (internal areas) (Rodríguez Estrella, 2007). They were formed in the Alpine orogeny and are characterized by faults with ancient activity from the Late Miocene. In Murcia, there are about 120-150 sunny days per year and the annual average temperature is about 18 ºC, with hot summers and mild winters. In general, rainfall is low throughout the region (300-350 mm y^{-1}) and summer is the driest season (Alonso Sarría & López Bermúdez, 1994).

Land abandonment is an important phenomenon throughout the province. The cultivated area decreased by 46% from 1991 to 2011, while the non-cultivated area (some of which can be regarded as abandoned) increased by 33% (Romero Díaz *et al.*, 2012). The percentage of people employed in agriculture is the highest in Spain (13.2% in 2013), much above the Spanish average (4.3%), so that any phenomena related to the interruption of agricultural activity are regarded as being of priority importance.

In the regional cartography of land abandonment (Martínez-Hernández, 2014), 2.2% (24522 ha) was classified as abandoned land (post 1980), which represents 4% of the cultivatable surface. From this abandoned area, three representative sampling areas (and easy to access by car) were selected (Fig. 2), corresponding to the most common lithologies and soil types (IUSS-WRB, 2014) in the province: marls (*Calcaric Regosol*), limestones (*Petric Calcisol*) and metamorphic (phyllites, schists and greywackes) parent materials (*Eutric Leptosol*). These areas show similar topographical characteristics: i) terraces with an altitude of 178-332 m.a.s.l. and local slopes of between 0º and 10º; ii) similar climatic (semiarid) and bioclimatic (thermo-Mediterranean) characteristics; and, iv) similar tillage practices (almond and olive orchards) before abandonment. All the plots were abandoned during the same period (2000-2003) (Table I), so the only significant variable is their lithology and soil properties.

2.2. Soil analysis

Soil samples were collected from the top layer (0-5 cm) in every plot (one composite sample per lithology type and three replicates) to obtain information about the surface, where soil erosion by water occurs. Soil samples were air-dried and sieved (<2 mm) in order to analyse: i) texture, using a laser diffractometer to distinguish the percentage of sands (2 – 0.05 mm), silts (0.05 – 0.002 mm) and clays (<0.002 mm) after eliminating the remains of organic matter and soil aggregates with sodium polyphosphate; ii) the carbon/nitrogen ratio (C/N), using a *varioEL cube* analyser (total C and N) and Van Bemmelen factor, which estimates that 58% of organic matter values (measured by LOI method) correspond to organic carbon (Eyherabide *et al.*, 2014), which is the parameter we use for the ratio; iii) bulk density (BK), using steel cylinders (Coile, 1936); iv) soil pH_{H2O} (ratio 1:5); v) electrical conductivity (EC), measured with a conductivimeter; vi) aggregate stability (AS), measured by the wet-sieving method (Ø 0.5 mm) (Diaz-Zorita *et al.*, 2002; Le Bissonnis, 1996).

Moreover, before every rainfall simulation one composite sample, also from the top 0-5 cm layer, was collected close to the ring plot (a total of 22 composite samples) to analyse antecedent soil moisture by air-drying and organic matter (OM) by weighing loss-on-ignition at 105ºC (24 h) and 430ºC (24 h) in a muffle furnace (Davies, 1974; Rosell *et al.*, 2001).

2.3. Rainfall simulations

Twenty-two rainfall simulations were performed during the first two weeks of July 2016 under dry soil conditions (since two weeks without rain). Experiments were carried out in three paired areas on metamorphic (M), marls (MA) and limestone (L) substrata in abandoned (AB) and cultivated lands (C). A sampling strategy was carried out to cover all the representative areas, paying attention to find similar local slopes, vegetation and stone covers. A new plot on the same substratum was chosen after every rainfall experiment, conducting between three and four simulations using distilled water in each studied area. The portable simulator used (Fig. 3) was a nozzle type rainfall simulator (Cerdá, 1999a; Ries *et al.*, 2009), which was described in detail by Iserloh *et al.* (2012). The test plot was circular in shape, with a diameter of 60 cm and an area of about 0.28 m^2. The plot outlet was v-shaped and placed at the deepest point of the plot at surface level. Before beginning the experiments, roughness was measured by the chain method (Saleh, 1993); rock and vegetation covers were quantified by observation and confirmed with a grid of points on the photography in the laboratory, and local inclination degree using a clinometer. Antecedent soil moisture (air dried) and organic matter contents were also measured.

At the beginning, artificial rain was calibrated for a rainfall intensity of 40 mm h^{-1} in order to obtain the best accuracy for the rainfall simulator used, which is related to drop size distribution and kinetic energy (Iserloh *et al.*, 2012). This enables initial soil erosion processes to be compared between areas, as in Rodrigo Comino *et al.*, (2016a; 2016b). We measured the initial rainfall intensity at the beginning and at the end of each rainfall simulation, and only when the intensity was constant (between 5 and 10% differences) were the experiments considered to have been successful. Each experiment lasted 30 minutes, and total water was collected in plastic bottles from the ring plot at five minute intervals. The bottles were changed at the beginning of every new period. The time elapsing between simulation beginning and runoff generation was recorded as well as the exact times of exchanging the bottles when runoff exceeded the capacity of the bottles during the measuring intervals.

After each experiment, soil profiles were performed across the ring plot to measure the infiltration front at 0-20 cm, 20-40 cm and 40-60 cm (averages of maximum and minimum depth).

In the laboratory, the plastic bottles were weighed and the runoff (L) and sediment (g) was calculated by subtracting the tare weight. The collected runoff water in every bottle was filtered separately with circular fine-mesh filter papers (Munktell©. Prod.-Nr. 3.104.185; less than 2 µm mesh). The filters were dried to constant weight at 105 °C and then weighed to determine suspended sediment load for each 5 minute interval. Finally, the runoff (L m^{-2}), sediment yield (g m^{-2}), sediment concentration (g L^{-1}) and infiltration rates (cm min^{-1}) were obtained according to the size of the plot.

2.4. Statistical analysis

The results of soil erosion by water (sediment yield, runoff and sediment concentration) were represented in a box plot graph to observe the maximum, minimum and median values for all the experiments and time intervals using SigmaPlot 13.0 (Systat Software, Inc). The averages and standard deviation (±) for other parameters were also added. Hydrological parameters such as infiltration front and infiltration were represented in the form of lines and bar graphs, respectively.

Prior, normality tests Saphiro-Wilk and equal variance test were performed. Not all the final results showed a normal distribution in every paired field plot (cultivated and abandoned), and so they were compared using non-parametric and parametric tests: Mann-Whitney Rank Sum Test (two groups of data), one-way ANOVA-analysis (more than two groups) and a pairwise multiple comparison procedure using Dunn's Method, with the statistical software SPSS 22 (IBM, USA). Finally, the Spearman rank coefficient was calculated to observe the statistical significance related with the environmental plot characteristics (slope angle, antecedent soil moisture, organic matter, vegetation and rock cover) and soil properties (texture, pH, bulk density, aggregate stability and C/N). Finally, only the highest linear correlations are shown in the scatter plots, which were obtained by using the local slopes, the vegetation cover and the aggregate stability.

3. RESULTS

3.1. Soil properties and environmental plot characteristics

Soil analysis (Table II) allowed us to compare the pedological differences between abandoned and cultivated plots. After abandonment, soil texture in the marl plots were considerably modified, taking on a more loamy character, while sands became more frequent (28.7%) at the expense of clays (-13%).

In the plots with metamorphic bedrock, however, there were no textural changes and the silty character was maintained (79.8%). In the limestone plots, there was a slight increase in sands (+7.3%) at the expense of silt (-8%).

Bulk density was low in all areas, ranging between 1.1 and 1.4 g cm^{-3}. After abandonment, density remained constant in marls (1.1 g cm^{-3}) but slightly increased in limestone and metamorphic areas (by 0.3 and 0.1 g cm^{-3}).

In an inverse relation with bulk density, the organic matter content decreased in limestones (3.1%) and metamorphic plots (2.8%) and remained stable in marls (2.5%).

The C/N ratios were moderately high and indicated poor quality soils because of a scarce release of nitrogen (ratio of 13.8 to 19.0) or even a really scarce release (33.1 in cultivated limestones). Except for marls plots (no changes), all the rest ones got a lower C/N ratio after abandonment, very evident in limestones plots (-16.7).

The pH$_{H2O}$ values were between 8.1 and 8.6. After abandonment, the limestone and metamorphic plots had a slightly lower pH (-0.1 and 0.2, respectively), while in the marl plots the values increased to reach a more alkaline value (from 8.1 to 8.6).

According to the electrical conductivity values, there were no salinity problems since values remained low (≈4 dS/m). The marl plots were the saltiest (0.3 dS m^{-1}), but after abandonment the EC value decreased (-0.2 dS m^{-1}). The other plots presented lower values (0.1 dS/m) which, after abandonment, slightly increased (0.1 and 0.04 dS m^{-1}).

Finally, aggregate stability was low in marly and limestone areas (about 6%) and slightly higher over the metamorphic substratum (18%). The value increased for the first two after abandonment (15% and 10%, respectively) and decreased in the metamorphic plot (11%).

Environmental plot characteristics showed several differences between each studied area (Table III). The lowest local slopes were registered in the abandoned (M-AB) and cultivated (M-C) metamorphic substratum between 0 and 2º, respectively. The highest local inclination was measured in the limestones, where it ranged between 6.25±6.29º (L-AB) and 10±4.08° (L-C). Average vegetation cover (VC) showed minimum values of close to 0% in the metamorphic lithology, and maximums values of 40% in the cultivated marls (MA-C) and abandoned limestones (L-AB). In the rest of the locations, vegetation cover ranged between 10% (L-C) and 28.8% (MA-AB). Regarding stone cover, high values were observed in the soil on the metamorphic substratum, reaching 88.3±16.1% in both abandoned and cultivated plots. The second highest stone cover was registered in the areas of limestones lithology, ranging from 37.5±35.9% (L-AB) to 65±25.2% (L-C). The greatest roughness values were noted in the abandoned land on sedimentary (marls) and metamorphic lithologies with values of between 105.2% and 106.6%.

Regarding antecedent soil moisture content, the cultivated areas on marls, limestones and metamorphic substratum showed the lowest values (close to 0%). Abandoned marls and limestones registered the highest soil moisture with 5.2±8.9% and 2.2±0.6%, respectively. Finally, OM was higher in every abandoned area than in the corresponding cultivated lands. The highest values were recorded in the limestones (L-AB), reaching 4±0.5%, and the lowest values in the marls (2.5%).

3.2. Soil erosion results: runoff, sediment yield, sediment concentration and infiltration

The results of the 22 experiments using the same portable rainfall simulator are presented in Fig. 4. During the experiments, runoff and sediment yield were recorded after different intervals, except in the case of marls, where it was possible to register them after the first period (Fig. 4a, b and c). The fastest runoff generation was reached in marls (first interval) in both abandoned and active agricultural lands, as well as in the abandoned limestone plots. In the cultivated limestone areas and both metamorphic areas, runoff began at the second interval. In the metamorphic cultivated areas, soil erosion by water was recorded at the second (5-10) and third (10-15 minutes) intervals and reached the highest values at the fifth and the sixth intervals. Similar trends were obtained for the limestone plots: from the third interval, runoff, sediment yield and sediment concentration was higher in the abandoned plot than the cultivated one. By contrast, rainfall simulations performed on the marl substratum (higher values of runoff and sediment yield in the abandoned areas) produced high amounts of runoff and soil loss from the beginning of the experiments, but showing the maximum values in the last two intervals. Statistical analysis was carried out to distinguish hydrological (runoff and infiltration) and erosive (soil loss) dynamics for each land use and lithology (Table IV). One-way ANOVA showed that the differences in the median values of rainfall simulations on abandoned and cultivated lands were higher than would be expected by chance and there were statistically significant differences for runoff and sediment yield.

The total average runoff in cultivated lands ranged between 0.09 L m^{-2} (L-C) and 1.89 L m^{-2} (MA-C), and in abandoned lands between 0.11 L m^{-2} (M-AB) and 3.79 L m^{-2} (MA-AB). The mean sediment yield in cultivated areas was between 0.96 g m^{-2} (L-C) and 41.41 g m^{-2} (MA-C), and in abandoned territories between 0.62 g m^{-2} (M-AB) and

17.05 g m^{-2} (MA-AB). This implies a sediment concentration in cultivated areas of between 11.66 g L^{-1} (M-C) and 15.93 g L^{-1} (MA-C), and in abandoned lands from 3.73 g L^{-1} (M-AB) to 30.96 g L^{-1} (MA-AB). Dunn's Method showed that the highest hydrological similarities (runoff and infiltration) within the abandoned lands corresponded to marls and limestones, and for the cultivated areas to the soils on marls and metamorphic lithologies. With regard to sediment yield, the largest hydrological differences in abandoned land were found between marls and metamorphic areas, while in the cultivated lands, marls and metamorphic lithologies showed the most similar hydrological behaviour. The Whitney Rank Sum Test, which was used to compare cultivated and abandoned areas for each lithological type, revealed that metamorphic and calcareous areas showed clear significant differences between runoff and sediment yield. In the marls, no statistical similarities were found for cultivated and abandoned areas. Finally, differences in the median values between the abandoned and cultivated areas relating to infiltration processes were not high enough, so there was no statistically significant difference.

After carrying out the rainfall simulations, the means of the infiltration fronts (Fig. 5.a) and infiltration rates (Fig. 5b) were also calculated. The deepest mean infiltration front was measured in the cultivated metamorphic area, where it reached 23.7 cm, with a total average of about 18.2±5 cm. The lowest average infiltration front was calculated in the abandoned marls, with values between 9±6.7 cm. Similar low values were found for the abandoned metamorphic lithology (9.44±2.7 cm) and cultivated marls (11.3±6.2 cm). Finally, limestones showed similar infiltration fronts, higher in the abandoned lands than in the cultivated one, 13.7±6.1 cm and 12.9±1.9 cm, respectively.

Infiltration using rainfall intensity (mm h^{-1}) and runoff (L m^{-2} $h\text{-}^{1}$) were calculated in cm/min (Fig. 5b). Theoretically, the obtained values should be contrary to those obtained for runoff. During the experiments, the infiltration showed different trends. The highest infiltration rates were observed in the metamorphic areas (M-AB and M-C) and cultivated limestones (L-C) from the first until the third interval, with similar values that ranged from 5.4 to 5.5 cm min^{-1}. After that, the values decreased to nearer 5 cm min^{-1} in the metamorphic areas. Lands on marls showed the lowest infiltration rates, the total average being lower in the abandoned areas (4.3 cm min^{-1}) than in the cultivated ones (4.9 cm min^{-1}). Both lithologies showed a rapid decrease in these rates from the beginning, become stable in the last two intervals. Finally, abandoned limestones (L-AB) showed high variations during the experiments: high infiltration rates from the beginning until the fourth interval, and increasing again after.

3.3. Key factors related to the hydrological and initial soil erosion processes

Two analyses were carried out to assess statistical significance between the rainfall simulation results and possible key factors related to the hydrological and initial soil erosion processes.

Firstly, the Spearman rank coefficient between environmental plot characteristics and rainfall simulations was calculated. Abandoned and cultivated areas (Table V) showed the highest statistical significance between runoff and sediment yield, ranging from 0.724 ($p<0.05$) to 0.879 ($p<0.01$), respectively. Moreover, in abandoned lands a high statistical significance was found between decreasing runoff and increasing rock fragments (-0.633 at level $p<0.05$). As regard lithology (Table VI), metamorphic areas showed the highest statistical significance between the increase in antecedent soil moisture values and runoff (0.943 at level $p<0.01$), and sediment yield (0.886 at level $p>0.05$). Moreover, two more environmental plot characteristics showed high statistical significance: i) a decrease in slope (-0.878 at $p<0.01$) matched an increase in sediment yield; and, ii) a decrease in total organic matter reflected an increase in infiltration rates. For the marls, no environmental plot characteristic showed relevant statistical significance. Limestones provided a high positive correlation between runoff and sediment yield (0.786 at $p<0.05$), and a negative statistical significance between sediment yield and rock fragments (-0.802 at $p<0.05$), and infiltration and slope (-0.729 at $p<0.05$).

Finally, using scatter plots and linear correlations, other possible key factors (environmental plot characteristics and pedological properties) were also assessed (Fig. 6). Only slope, vegetation cover and aggregate stability showed linear trends with the rainfall simulation results. Slope was the most important key factor for runoff generation in abandoned lands (R^2=0.91) and soils on marls (R^2=0.81), and for sediment yield in metamorphic areas (R^2=0.7). Vegetation cover conditioned the sediment yield (R^2=0.58) and runoff generation in cultivated areas (R^2=0.47), and the sediment yield in calcareous territories (R^2=0.46). The only analysed soil property that showed a high linear trend with increasing sediment yield was aggregate stability arranging R^2=0.91.

4. DISCUSSION

Abandonment is a global phenomenon associated with the gradual cessation of traditional agricultural practices, and is the cause of land degradation as a result of increased soil erosion and slope instability (Cammeraat *et al.*, 2005; García-Ruiz & Lana-Renault, 2011; Ruiz Sinoga & Martinez Murillo, 2009). Many authors have focused on this topic, finding pedological factors (such as roughness or texture) and parent materials to be the parameters most highly related to soil erosion by water (Cerdà, 1997; Seeger, 2007). For our part, we found several differences related to soil loss, runoff (and time to runoff generation) and sediment concentration between the different substratums analysed.

The main similarity registered between the active agricultural and abandoned areas studied was the presence of bare soils under dry conditions (soil moisture close to 0%). Only a partial re-vegetation had taken place in the abandoned lands. During erosive events, such as those simulated in our experiment, soils are therefore totally unprotected, so that the erosion may increase and enhance runoff generation (Cerdà *et al.*, 2009; Kosmas *et al.*, 1997; Ochoa-Cueva *et al.*, 2016). In general, we obtained high statistical differences between runoff and sediment yield both in abandoned and cultivated areas, confirming that they were regulated by a Horton hydrological system (Hueso-González *et al.*, 2014; Imeson & Lavee, 1998; Poesen & Lavee, 1994). Using statistical analysis, key factors related to the hydrological and initial soil erosion processes were also assessed. The key factors that were observed to have a linear correlation with the rainfall simulation results were: i) slope, especially for runoff generation in marls (Gabarrón-Galeote *et al.*, 2012; Nadal-Romero *et al.*, 2014); ii) vegetation cover, especially for sediment yield, due to its role as an obstacle (Seeger *et al.*, 2009; Giménez-Morera *et al.*, 2010; Novara *et al.*, 2013); iii) stoniness (especially in abandoned areas), where runoff was reduced; and iv) soil aggregate stability (Lado *et al.*, 2004; Shi *et al.*, 2010; Xiao *et al.*, 2015).

However, some differences were observed in the hydrological responses in the case of soil losses, runoff and infiltration rates depending on the lithology (marls, limestones and metamorphic substrates) and after abandonment.

As several authors (Boix-Fayos *et al.*, 2001; Keesstra *et al.*, 2016; Martínez-Murillo *et al.*, 2013) have highlighted, previous environmental plot characteristics, such as vegetation and stone cover, slope or roughness, are also among the most important factors that enhance the early stages of soil erosion by water. Under field conditions during the experiments we observed a common pattern: i) a delay before runoff generation; ii) the first particle mobilization corresponded to silts and sands (non-cohesive particles) due to early splash effects (Marzen et al, 2015; Lassu *et al.*, 2015; Xiao at al., 2015); iii) solid aggregates were separated when the soil became saturated; and, iv) finally, an increase in soil loss and runoff in the whole plot, showing mechanisms of hydrological connectivity (Cerdà, 2001). Similar results reflecting connectivity processes (Masselink *et al.*, 2016; Zheng *et al.*, 2014) were obtained by Seeger *et al.* (2009) in northern Spain in abandoned hillslopes and Rodrigo Comino *et al.* (2016a; 2016b) in European vineyards, both using rainfall simulations.

Soil analysis also showed that, after land abandonment, the same losses in some textural classes occurred; for example, silt and sands (fine materials) in all the sampled areas showed particularly pronounced losses in marls and limestones. It is possible that after abandonment, soil texture might change due to selective removal of fine particles or by spatial variation in the textural composition of the marls, which is quite common in marly deposits (Cerdà, 1999b; Regües & Nadal-Romero, 2013).

Several studies conducted in arid environments have highlighted that these cumulative textural variations can result in an increase in bulk density values (Bienes *et al.*, 2016; Soane, 1990; Lesschen *et al.*, 2007), enhancing soil crust formation and compaction (Dai *et al.*, 2015Singer & Shainber, 2004). In our study, we observed that soil degradation processes were enhanced by soil erosion by water in the marl and the limestone plots. Metamorphic areas were the slowest to generate runoff and sediment yield. This hydrological behaviour may be related with the high silt values (89-91%) and rock fragment content (88%). These results coincide with those obtained for cultivated areas in a comparison with abandoned lands in Murcia (Belmonte-Serrato *et* *al*. 2013; Romero-Díaz *et al.*, 2007; 2016; Weseamel *et al.*, 2006) or in the Montes de Málaga in southern Spain using rainfall simulations (Martínez Murillo & Ruiz Sinoga, 2003), where runoff on silty soils started after 10 or 20 minutes, or simply did not occur. Soil surface components, such as rock fragments (non-embedded) and vegetation cover can reduce soil losses, although they will not completely avoid runoff (Cerdà, 2001; Morvan *et al.*, 2014; Prosdocimi *et al.*, 2016a). The irregularities of rocks (schischosity in the metamorphic plots) and plants (roots facilitate weathering and infiltration) can offer higher resistance against the movement of the fine sediments (clays and fine silts), causing hydrological variations at intra-plot scale, as has been demonstrated in French vineyards (Ciampalini *et al.*, 2012; David *et al.*, 2014; Follain *et al.*, 2012). As a result, sediments do not necessarily accumulate at the foot of slopes (Gabarrón-Galeote *et al.*, 2012; Rodrigo Comino *et al.*, 2016c, 2017).

Measured runoff activation was faster in tilled marl areas, where its plastic character generates greater soil sealing and a sub-surface crust (Fister *et al.*, 2012; Ries *et al.*, 2013; Singer & Shainberg, 2004). Conventional tilling contributes highly to aerating soil, but does not prevent runoff and sediment yield (Cerdà *et al.*, 2016). The shorter time to runoff in marls resulted not only in higher total runoff but also in greater sediment yield and water turbidity, particularly in abandoned lands. This hydrological behaviour is well known in Mediterranean marl areas, where erosion has been seen to attain very high values, especially in badlands areas (Martínez-Murillo *et al.*, 2013). There are no badlands in the studied areas, but our results were high considerable (about 30 g/L) and similar to those recorded with runoff experiments in other marl areas (Wirtz *et al.*, 2010).

In metamorphic and limestone areas, erosion processes were lower. Soils let more water infiltrate during the experiments as mentioned by Belmonte Serrato *et al.* (2013) or

Rodrigo Comino *et al.* (2016a, 2016b). In order to decrease soil erosion by water in marls and bring values closer to those of metamorphic plots, it would be an interesting idea to promote a change in soil land use management such as Cerdá *et al.* (2016) adding a straw cover or Hueso-González *et al.* (2016) incorporating a cover of organic amendments to lower runoff rates.

The deepest front belonged to the metamorphic area, where runoff began later and values were lower. In the cultivated plots, the infiltration front was deeper because the soils were tilled and aerated, and the rock fragment content was higher (Ruiz Sinoga & Martínez Murillo, 2009). This dynamic was the same as for the marl area, but not for limestone, where a crust layer was detected (Peter *et al.*, 2014; Ries *et al.*, 2013; Singer & Shainberg, 2004). The least deep infiltration front was located in marl area, coinciding with the highest runoff and fastest activation of runoff (Nadal-Romero & Regüés, 2009).

Moreover, infiltration fronts were also related to infiltration rates, as expected (Ruiz Sinoga & Martínez Murillo, 2009; Rodrigo Comino *et al.*, 2016c). Metamorphic plots showed the highest infiltration rates, which remained constant for a long time before decreasing. In limestone study area, infiltration rates were also high and constant until almost the end. By contrast, in marl area, rates were lower, since runoff in marls was usually higher (Robledano-Aymerich *et al.*, 2014; Belmonte Serrato *et al.*, 2013).

Based on the found results, we recommend that environmental policies in abandoned agricultural areas should be aimed at promoting re-vegetation or to encouraging suitable land use management, which will decrease soil erosion by water. It has been demonstrated that this would lead an increase of biological activity (Ruiz Sinoga & Martínez Murillo, 2009; Plieninger *et al.*, 2014; Bienes *et al.*, 2016), and infiltration, reducing soil erodibility. Several studies on how to prevent soil loss have proposed suitable and environmental-friendly strategies to reduce runoff, which could also apply in these Mediterranean areas. These include the use of a straw cover or residues (Cerdà *et al.*, 2016; Prosdocimi *et al.*, 2016b), grass cover (Novara *et al.*, 2011, 2016; Sastre *et al.*, 2016) or geo-textiles and organic amendments (Giménez-Morera *et al.*, 2010; Hueso-González *et al.*, 2014).

5. CONCLUSIONS

Soil erosion by water was assessed in dry abandoned terraces and active agriculture fields on different lithologies and soils with different properties in south-eastern Spain. Using a small portable rainfall simulator, similarities and differences at pedon scale were noted under dry soil conditions. During the field experiments, a clear hydrological pattern was observed: i) a delay in runoff generation; ii) splash effects dissolving the soil aggregates; and iii) high soil erosion rates.

Hence, the main conclusions reached were: i) in land abandonment, soil erodibility can sometimes be reduced as a result of greater biological activity (vegetation cover and organic matter); ii) runoff begins later in metamorphic plots (with more silt particles and greater stoniness) and is activated earlier in marl study area (especially in cultivated fields), where soil sealing and a sub-superficial crust were observed; iii) soil loss is higher in marls, because water retention is lower than in silt (metamorphic) and calcareous (limestone) soils; and finally, related with these dynamics, iv) the deepest infiltration fronts and the highest infiltration rates occur in the metamorphic plot, and, unlike in marl one, infiltration was always deeper (and higher) in plots still in active agricultural use.

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Figure 6. Lineal correlation between soil loss and runoff with slopes (a) vegetation cover (b) and aggregate stability (c).

Table I. Characteristics of the sampling areas.

	Area 1		***Area 2***		***Area 3***	
Id plot	MA-C	MA-AB	L-C	L-AB	M-C	M-AB
Land management	Cultivated	Abandoned	Cultivated	Abandoned	Cultivated	Abandoned
Lithology	Marls		Limestones		Metamorphic	
Abandonment year	2000		2003		2003	
Altitude (m)	184		332		178	
Slope (º)	5		2		5	
Average prec. (mm)	277.3		240.32		272.72	
Max. daily prec. (mm)	45.8		41.61		36.8	
Average Temp. (ºC)	18.19		17.36		17.5	
Max. Temp. (ºC)	32.13		31.98		31.51	
Min. Temp. (ºC)	1.98		0.86		1.86	

* MA-C: cultivated marls; MA-AB: abandoned marls; L-C: cultivated limestones; L-AB: abandoned limestones; M-C: cultivated metamorphic; M-AB: abandoned metamorphic.

Max. = maximum; Prec. = precipitation; Temp. = temperature.

Table II. Chemical and physical properties of the soils.

	Area 1		***Area 2***		***Area 3***	
Lithology	Marls		Limestones		Metamorphic	
Id plot	MA-C	MA-AB	L-C	L-AB	M-C	M-AB
Land management	Cultivated	Abandoned	Cultivated	Abandoned	Cultivated	Abandoned
BK (g/cm^3)	1.16	1.15	1.10	1.38	1.04	1.11
OM (%)	2.5	2.5	4	3.1	3.6	2.8
C(org) (%)	1.45	1.45	2.32	1.80	2.09	1.62
N (%)	0.12	0.12	0.07	0.11	0.11	0.11
C/N Ratio	13.8	13.8	33.1	16.4	19.0	14.7
pH (1:5)	8.12	8.61	8.53	8.39	8.56	8.39
EC (dS/m)	0.34	0.18	0.12	0.23	0.13	0.17
AS at Ø 0.5mm (%)	6	20.6	5.9	16.4	18.1	6.6
Sand (%)	0	28.7	1.8	9.1	0.03	0.
Silt (%)	82.9	67.2	87.8	79.8	89.9	91.1
Clay (%)	17.1	4.1	10.4	11.1	10.1	8.9

* BK: bulk density; OM: total organic matter; C(org): organic carbon; N: nitrogen; EC: electrical conductivity; AS: aggregate stability.

Table III. Environmental characteristics of the plots.

	Area 1		***Area 2***		***Area 3***	
Lithology	Marls		Limestones		Metamorphic	
ID plot	MA-C	MA-AB	L-C	L-AB	M-C	M-AB
Land management	Cultivated	Abandoned	Cultivated	Abandoned	Cultivated	Abandoned
n	4	4	4	4	3	3
Slope (°)	6.3±6.3	6.3±9.5	10±4.1	6.3±6.29	0±0	2±0
Vegetation cover (%)	40±31.6	28.8±36.6	10±14.1	40±40.8	0±0	0±0
Stone cover (%)	0±0	5±0	65±25.2	37.5±35.9	88.3±16.1	88.3±16.1
Roughness (%)	105.2±2.8	106.6±3.8	105.4±2	103.1±1.4	102.5±0.8	105±4.4
w (%)	0.7±0.1	5.2±8.9	0.6±0.1	2.2±0.6	0.3±0.1	0.1±0.1
OM (%)	2.5±0.8	2.5±1.4	3±1.3	4±0.5	2.8±1.2	3.6±1.6

* n: number of experiments; w: antecedent soil moisture; OM: organic matter.

Table IV. Statistical differences between rainfall simulation results.

Land Management	*Lithology*	*Test*	*Runoff*	*Sediment yield*	*Infiltration*
AB	M; MA; L	ANOVA	0.006	0.001	0.003
C	M; MA; L	ANOVA	0.001	0.001	0.003
AB vs C	M	M-W	0.012	0.002	0.515
AB vs C	MA	M-W	0.469	0.469	0.415
AB vs C	L	M-W	0.03	0.03	0.909

*Grey colour means p<0.05.

** AB: abandoned; C: cultivated; M: metamorphic; MA: marls; L: limestones; M-W: Mann-Whitney Rank Sum Test.

Table V. Spearman rank coefficient between environmental characteristics and rainfall simulation results for each type of plot.

		$L\ m^{-2}$	$g\ m^{-2}$	$g\ L^{-1}$	*Inf.*	*S*	*Veg.*	*Rock*	*R*	*w*	*OM*
AB	$L\ m^{-2}$		0.724*	-0.164	**-0.891****	0.533	0.210	-0.633*	0.156	0.200	0.136
	$g\ m^{-2}$	0.724*		0.392	-0.606*	0.262	0.414	-0.473	-0.129	0.469	0.228
	$g\ L^{-1}$	-0.164	0.392	1	0.255	-0.505	0.444	-0.051	-0.087	0.518	00.000
	Inf.	**-0.891****	-0.606*	0.255		-0.561	0.167	0.461	-0.046	0.127	-0.200
C	$L\ m^{-2}$		**0.879****	0.255	**-0.809**	-0.227	0.134	-0.379	-0.340	-0.091	0.045
	$g\ m^{-2}$	**0.879**		0.610*	-0.592	-0.246	0.014	-0.290	-0.457	-0.387	0.023
	$g\ L^{-1}$	0.255	0.610*	1	-0.164	0.024	0.076	-0.421	-0.116	-0.309	-0.345
	Inf.	**-0.809****	-0.592	-0.164		-0.142	-0.382	0.584	-0.019	-0.227	-0.109

** Correlation is significant at the 0.01 level (2-tailed).

* Correlation is significant at the 0.05 level (2-tailed).

* AB: abandoned; C: cultivated; $L\ m^{-2}$: runoff; $g\ m^{-2}$: sediment yield; $g\ L^{-1}$: sediment concentration; *Inf*: infiltration; *S*: slopes; *Veg*: vegetation cover; *Rock*: rock fragments; *R*: roughness; *w*: antecedent soil moisture; *OM*: organic matter during the experiment.

Table VI. Spearman rank coefficient between environmental characteristics and rainfall simulation results for each type of lithology.

		$L\ m^{-2}$	*$g\ m^{-2}$*	*$g\ L^{-1}$*	*Inf.*	*S*	*Veg.*	*Rock*	*R*	*w*	*OM*
M	*$L\ m^{-2}$*		0.771	0.029	-0.771	-0.488		00.000	-0.441	0.886^{*}	0.714
	$g\ m^{-2}$	0.771	0	0.371	-0.314	-0.878^{*}		-0.239	-0.353	**0.943****	0.257
	$g\ L^{-1}$	0.029	0.371		0.086	-0.293		-0.478	-0.265	0.314	0.200
	Inf.	-0.771	-0.314	0.086		0.098		-0.478	0.265	-0.429	-0.829^{*}
MA	*$L\ m^{-2}$*		0.619	0.095	**-0.929**	0.501	-0.204	0.327	-0.683	-0.119	0.476
	$g\ m^{-2}$	0.619	0	0.714^{*}	-0.619	0.250	0.335	-0.109	-0.659	-0.286	0.524
	$g\ L^{-1}$	0.095	0.714^{*}		-0.119	-0.401	0.168	-0.327	-0.586	-0.595	0.048
	Inf.	**-0.929****	-0.619	-0.119		-0.576	0.192	-0.218	0.659	0.333	-0.667
L	*$L\ m^{-2}$*		0.786^{*}	-0.119	**-0.929**	0.507	-0.184	-0.551	0.275	0.048	-0.214
	$g\ m^{-2}$	0.786^{*}	0	0.238	-0.643	0.173	0.184	-0.802^{*}	-0.156	0.333	00.000
	$g\ L^{-1}$	-0.119	0.238		0.381	-0.346	0.344	-0.168	-0.024	0.214	-0.214
	Inf.	**-0.929****	-0.643	0.381		-0.729^{*}	0.356	0.491	-0.228	0.119	0.238

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).
M: metamorphic; MA: marls; L: limestones; *$L\ m^{-2}$*: runoff; *$g\ m^{-2}$*: sediment yield; *$g\ L^{-1}$*: sediment concentration; *Inf*: infiltration; *S*: slopes; *Veg*: vegetation cover; *Rock*: rock fragments; *R*: roughness; *w*: antecedent soil moisture; *OM*: organic matter during the experiment.

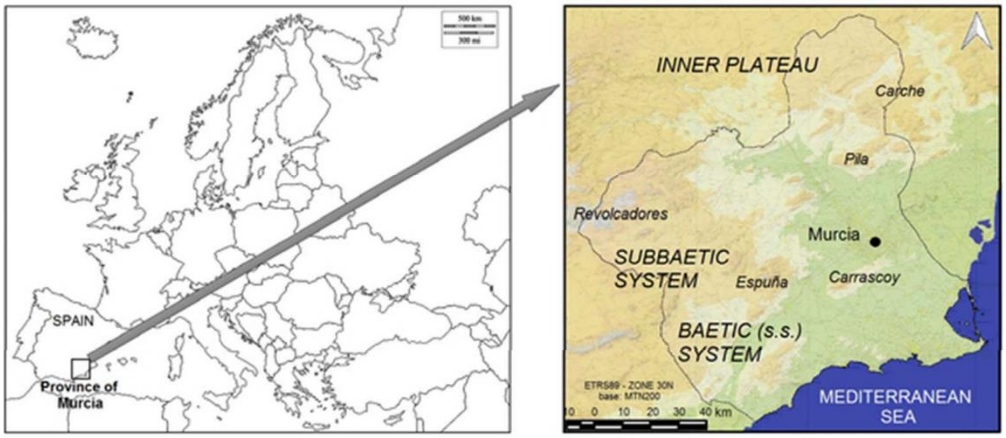

Figure 1. Southeast Spain and province of Murcia.

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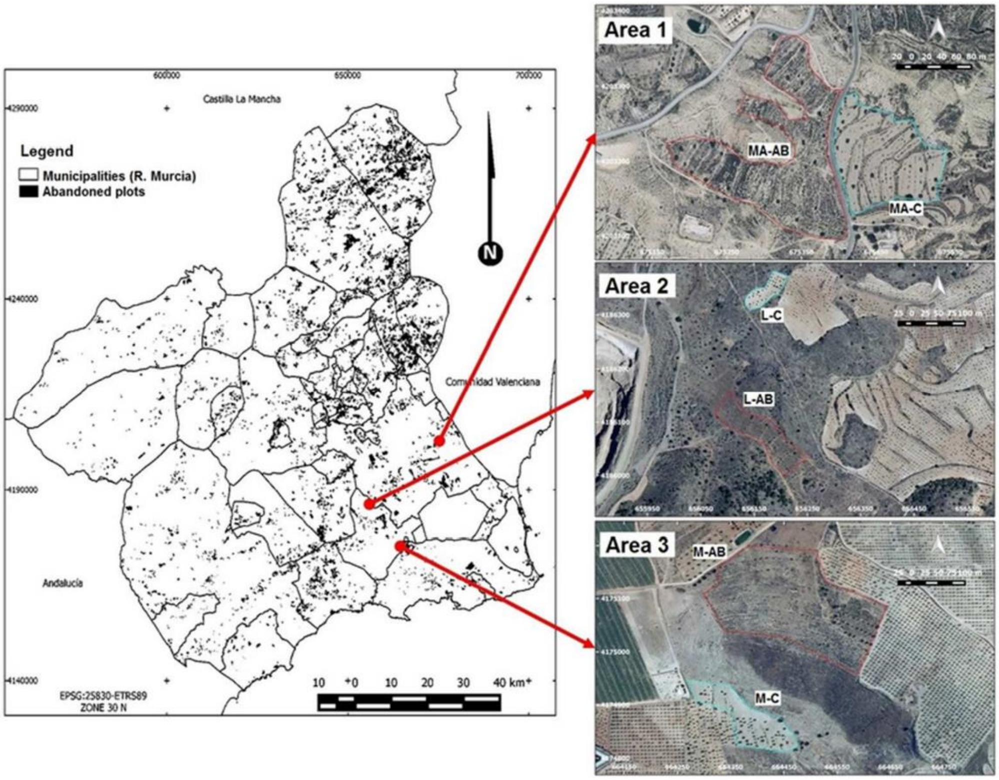

Fig. 2. Sampling areas from land abandonment cartography. *MA-C: cultivated marls; MA-AB: abandoned marls; L-C: cultivated limestones; L-AB: abandoned limestones; M-C: cultivated metamorphic; M-AB: abandoned metamorphic.

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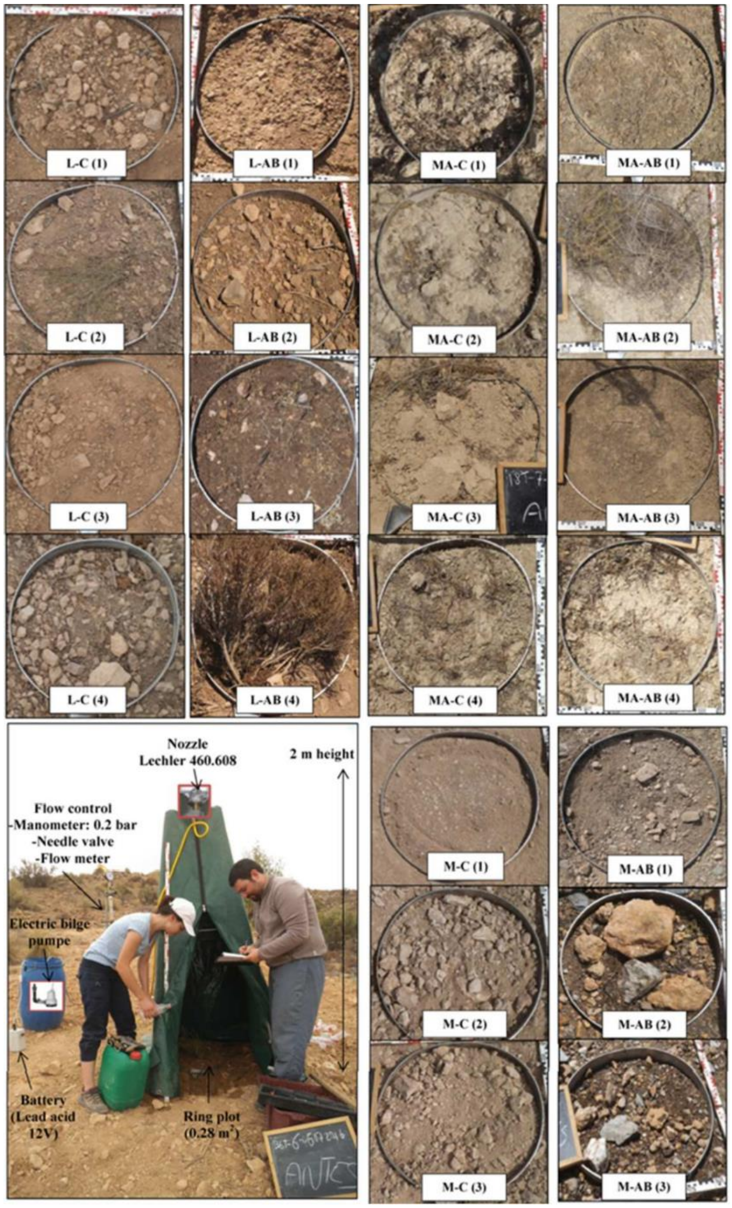

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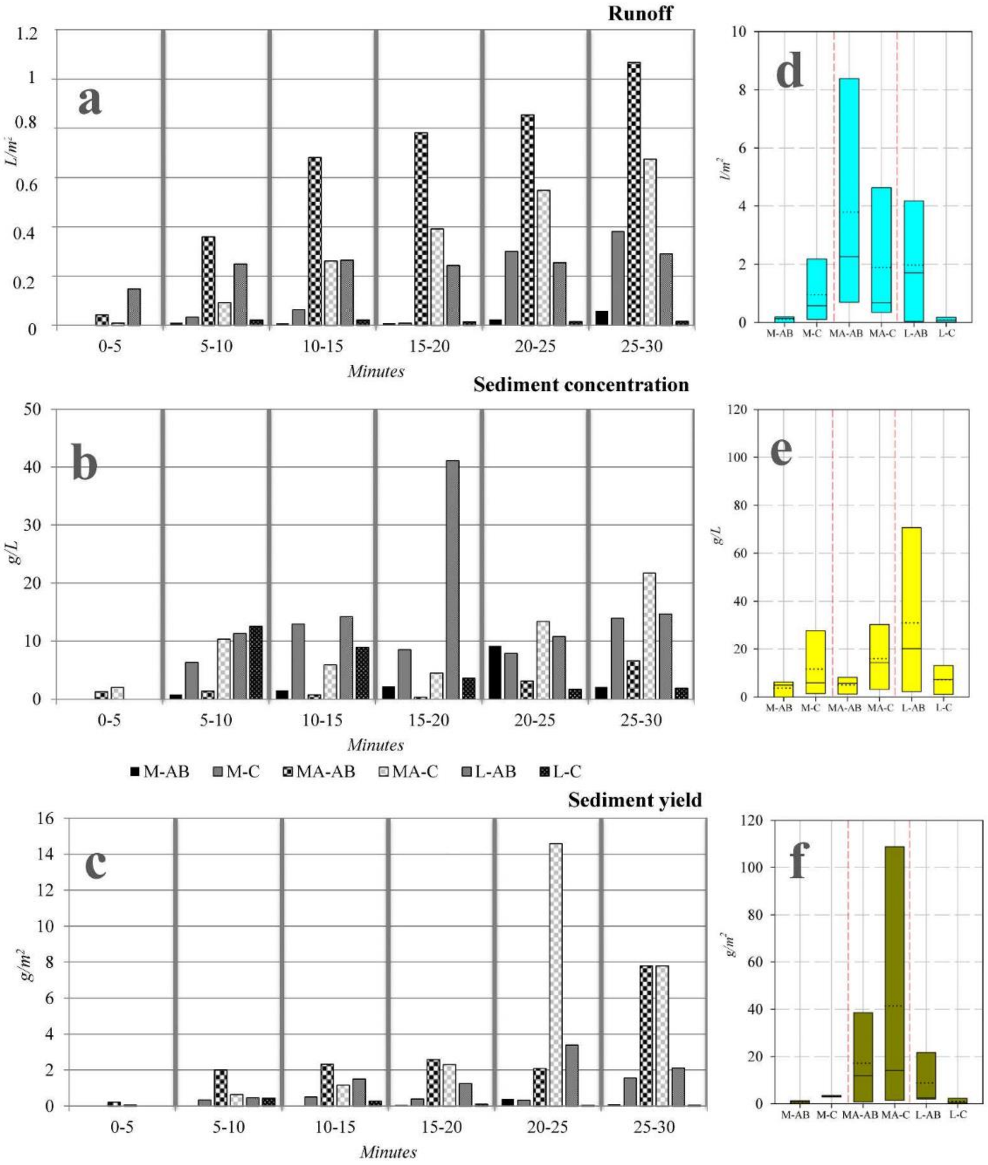

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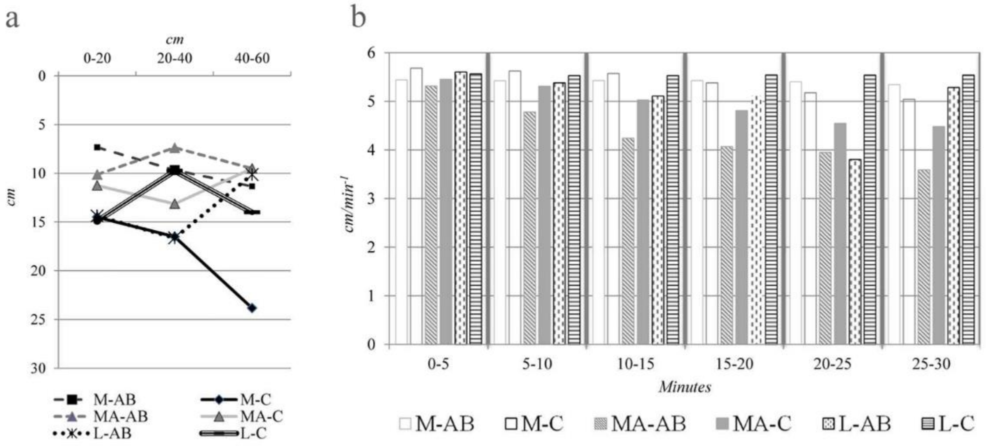

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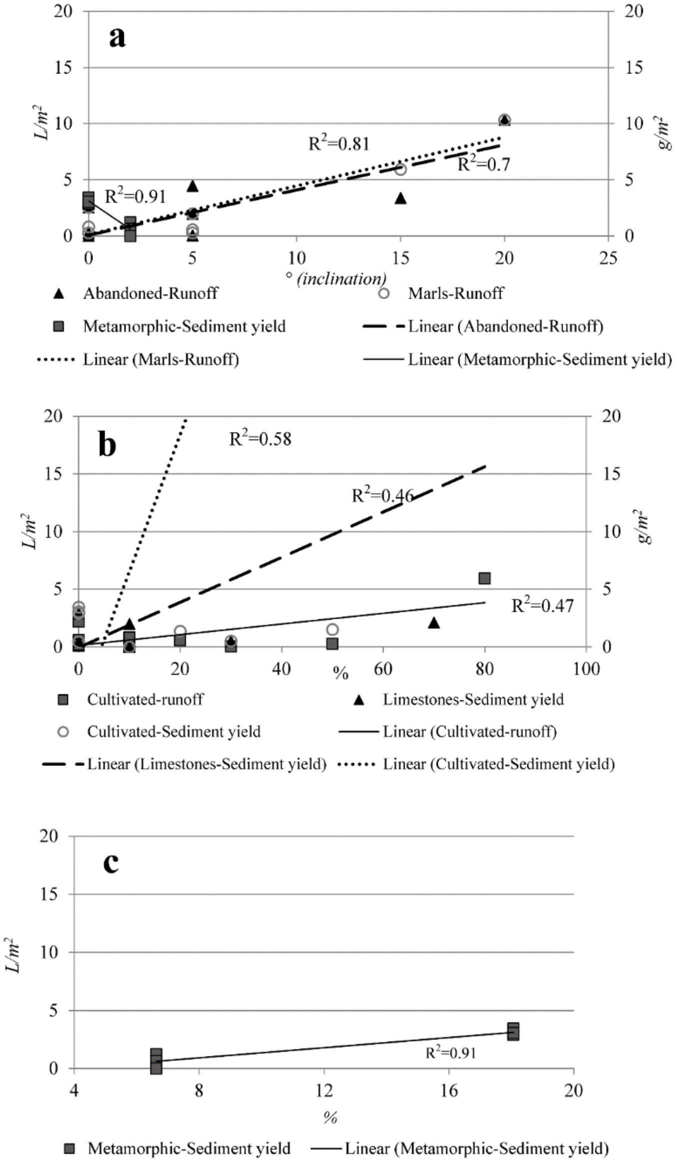

Figure 6. Lineal correlation between soil loss and runoff with slopes (a), vegetation cover (b) and aggregate stability (c).

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