Overland flow generation mechanisms affected by topsoil treatment: Application to soil conservation

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Abstract

Hortonian overland-flow is responsible for significant amounts of soil loss in Mediterranean geomorphological systems. Restoring the native vegetation is the most effective way to control runoff and sediment yield. During the seeding and plant establishment, vegetation cover may be better sustained if soil is amended with an external source. Four amendments were applied in an experimental set of plots: straw mulching (SM); mulch with chipped branches of Aleppo Pine (*Pinus halepensis* L.) (PM); ~~TerraCotten~~ TerraCottem~~hydroabsobent~~ hydroabsorbent polymer~~s~~ (HP); and sewage sludge (RU). Plots were afforested following the same spatial pattern, and amendments were mixed with the soil at the rate 10 Mg ha^{-1}. This research demonstrates the role played by the treatments in overland flow generation mechanism. On one hand, the high macroporosity of SM and PM, together with the fact that soil moisture increased with depth, explains weak overland flow and thus low sediment yield due to saturation conditions. Therefore, regarding overland flow and sediment yield, RU behaves similarly to SM and PM. On the other hand, when HP was applied, overland flow developed quickly with relatively high amounts. This, together with the decrease downward in soil moisture along the soil profile, proved that mechanisms of overland flow are of the Hortonian type.

Keywords: Soil amendments; Overland flow; Erosion; Mediterranean; Soil moisture

1 Introduction

Various factors account for soil hydrology and erosion including soil texture and aggregate stability (Boix-Fayos et al., 1998; Brevik, 2009); gravel content (Van Wesemael et al., 1996); vegetation cover (Cerdá, 1998; Lavee et al., 1998; Calvo et al., 2003); land use and land management which are markedly affected by agricultural use and land abandonment (Lasanta et al., 2000); and particularly soil wettability during rainfall events (Castillo et al., 2003; Shakeby and Doerr, 2006). Soil moisture affects infiltration capacity and the capacity of soils to store new rainfall, as reflected in many physical-based hydrological models (Bronstert, 1994; Bronstert et al., 1998; Seeger et al., 2004). For this reason, the various runoff generating processes (saturation excess overland flow, infiltration excess overland flow, and return flow) are highly regulated by soil moisture (Castillo et al., 2003). In humid areas, overland flow is generated only when and where saturation conditions have been reached (Lavee et al., 1998; Ward and Robinson, 2000). However, Hortonian overland flow can occur when rainfall intensity exceeds the infiltration capacity (Horton, 1933; Ferreira et al., 2000; Calvo et al., 2003, 2005).

Hortonian overland flow is responsible for significant amounts of soil loss in Mediterranean geomorphological systems (Puech and Chabi-Gonnie, 1984; Rao et al., 1998; Beven, 2002; Stomph et al., 2002; Garcia-Ruiz et al., 2013). As a consequence of climatic conditions and human activities, soil is not sufficiently protected by vegetation and is thus subject to loss of organic matter and nutrients (Marqués et al., 2005), which creates a positive feedback process that can lead to desertification (Lavee et al., 1998). Restoration of native vegetation is the most effective way to regenerate soil health, and control runoff and sediment yield production (Inbar et al., 1998; Alegre et al., 2004; Boix-Fayos et al., 2007). The seeding and plant establishment stages are critical (Cerdá, 1998; Adekalu et al., 2007; Smets et al., 2008; Macci et al., 2012), but during these stages the beneficial effects of the vegetation may not be apparent and the soil is highly susceptible to the erosion and depletion of soil quality (Will et al., 2011). Under these conditions, vegetation cover in areas having degraded soils may be better sustained if the soil is amended using an external source of organic matter (Jordán et al., 2010; Chaudhuri et al., 2013; Shazana et al., 2013; Srinivasarao et al., 2013).

Various residue types have been investigated in erosion control studies under Mediterranean climate conditions. The results show that the application of crop mulch, sewage sludge or animal manure positively affects plant cover

(Montgomery, 2007) and improves soil properties (Ferreras et al., 2006; Franco-Otero et al., 2011; González-Ubierna et al., 2012; Hueso-González et al., 2014). Where no vegetation is established, organic amendments can be used to rapidly protect the soil surface against the erosive forces of rain and runoff (Smets et al., 2008; Bark et al., 2012; Gholami et al., 2012). Similarly, other studies have shown that the amendment of soil with polymers including gypsum and polyacrylamide (PAM) prevented seal formation, and reduced overland flow and soil loss (Ben-Hur and Keren, 1997; Flanagan et al., 1997a,b; Yu et al., 2003; Abrol et al., 2013). The studies noted above have also shown that geomorphological processes respond to various soil amendments. However, further studies are needed, given that few comparative studies of amendments have been carried out, particularly in relation to the mechanisms generating overland flow following their addition, simultaneously in time and for afforestation purposes.

In this study we investigated the hydrological effects of five soil treatments in relation to the soil moisture content. The specific objectives of the study were to: 1) analyze the soil moisture profile under various soil management regimes; 2) determine the overland flow mechanisms affected by various topsoil treatments; and 3) determine the sediment yield from amended afforested soil.

2 Study area

The El Pinarillo experimental site is located in the Sierra Tejeda, Almijara and Alhama Natural Park (southern Spain) (Fig. 1). The site is located at 470 m a.s.l., in the upper part of an alluvial fan (calcareous conglomerates) surrounded by mountains with marble as the primary bedrock material, and the climate is dry Mediterranean (mean annual temperature: 18 °C; mean annual rainfall: 589 mm). The study plots were located in an abandoned agriculture field recolonized by shrubs since the 1950s. The current vegetation consists of an open pine forest with typical degraded Mediterranean scrubs and tussocks; the area was affected by a fire that occurred in 1991. The vegetation cover is > 70% and includes *Chamaerops humilis* L., *Cistus albidus* D., *Rosmarinus officinalis* L., *Thymus capitatus* L., *Rhamnus alaternus* L. and annual plants. The soils are classified as lithic and eutric leptosols, according to FAO (2006). They are characterized by a high level of rock fragment cover on the surface (> 50%), 56% total gravel content in the profile, and a sandy-loam texture (sand = 60%, silt = 32%, clay = 8%). The general soil properties and characteristics of the study site are given in Table 1.

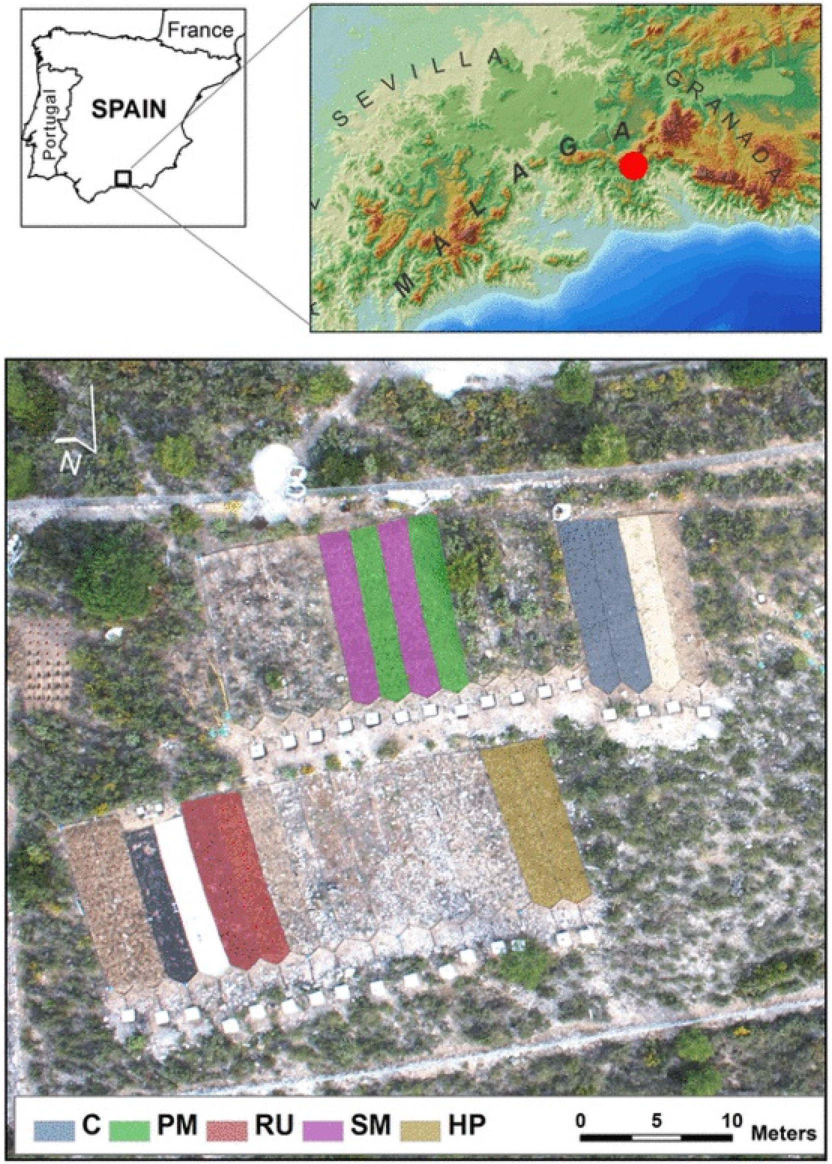

Fig. 1 Location of the experimental site. C: soil afforested, no amendment; PM: mulch with chipped branches of Aleppo Pine (*Pinus halepensis* L.); RU: sewage sludge; SM: straw mulch; HP: TerraCottem hydroabsorbent polymer.

Table 1 Soil properties under natural conditions at the El Pinarillo experimental site. *CEC*: cation exchangeable capacity; *TC*: total carbon; *TN*: total nitrogen; *C/N*: carbon/nitrogen ratio; *EC*: electrical conductivity; *SOC*: soil organic carbon content; *SWC*: soil water content.

Annual rainfall	(mm)	589.0
Climatic regime		Dry-Mediterranean
Main plant species		*Chamaerops humilis*

		Cistus clusii
		Cistus albidus
		Rosmarinus officinalis
		Stipa tenacissima
Soil properties		
Gravel	(%)	56.0
Sand	(%)	60.0
Silt	(%)	32.0
Clay	(%)	8.0
SWC: Field capacity	(%)	25.2
SWC: Wilting point	(%)	6.4
SWC: Available water	(%)	18.8
Aggregate stability	(%)	51.0
CEC	(~~meq~~ meq 100 g~~−~~$^{-1}$)	120.4
TC	(%)	12.5
TN	(%)	0.2
C/*N*		74.0
SOC	(%)	1.9
pH		8.0
EC	(~~µS~~ µS cm~~−~~$^{-1}$)	501.0

3 Methods

3.1 Establishing the experimental plots

Ten closed plots (2 m width × 12 m length; slope gradient: 7.5%; aspect: N170°) were established at the experimental site. The plots are oriented parallel to the line of maximum slope (Fig. 1). The plots were enclosed using steel strips (50 cm width × 1 m length), which were inserted 30 cm into the soil. To ensure plot uniformity, the above-surface vegetation cover in each experimental plot was cut in October 2010, and three doses of a herbicide were applied.

3.2 Amendments

In May 2011, four amendments at rates of 10 Mg ha~~−~~$^{-1}$ were applied as follows: i) two plots were amended with straw mulch (SM); ii) two plots were amended with chipped branches of Aleppo Pine (*Pinus halepensis* L.) mulch (PM); iii) two plots were amended with TerraCottem hydroabsorbent polymer (HP); and iv) two plots were amended with sewage sludge (RU). The amendments were selected according to the inventory of technologies available to combat desertification, suggested by the Ministry of Environment, Rural and Marine of the Spanish Government (PAND, 2008). No amendment was applied to the remaining two plots.

3.3 Afforestation plan

In November 2011, six months following the application of the amendments, the 10 plots were afforested with the same number and spatial pattern of Mediterranean shrubs recommended in the instructions to land managers from the Natural Park authorities of Spain. The plant species used were: *C~~hamaerops~~. humilis* L., *Lavandula stoechas* Lam., *L~~.~~avandula dentatae* L., ~~*L.*~~*Lavandula multifida* L., *R~~hamnus~~. alaternus* L., ~~*R.*~~*Rhamnus oleoides* L., *Pistacea lentiscus* L., *R~~osmarinus~~. officinalis* L. and *T~~hymus~~. capitatus* L. The vegetation in each plot was planted using a grid of 0.5 m. During the afforestation of the plots the soils were tilled to a depth of 25 cm. The two tilled plots that received no amendment were used as controls (C).

3.4 Rainfall, overland flow, soil loss and soil moisture ~~measuremenst~~measurements

In April 2011 a meteorological station (HOBO) was installed in the experimental area. Rainfall was monitored using a tipping-bucket rain gauge (0.2 mm accuracy), which made recordings at 15 min intervals.

At the bottom of each plot, a container of 250 L was installed for collecting overland flow and sediment. The rainfall, overland flow and sediment yield measurements took place from November 2011 to January 2014. Total overland flow for each overland flow event was measured by inserting a ruler into the containers. Overland flow samples (1 L) were collected in the container after each event, for laboratory analysis, to determine sediment concentration. For total sediment yield the sediment concentration was measured at three heights within each container following mixing of the water, and multiplied by the volume of water.

In November 2011, 30 soil humidity probes (HOBO S-SMx-M005) were installed in the experimental area. Specifically, three probes were inserted in the middle of each plot, one at each of three depths (5, 10 and 25 cm) in the soil profile. Soil humidity was monitored and recorded at 10-min intervals.

4 Results

4.1 Overland flow

A total of 56 rainfall events were registered from 22 November 2011 to ~~30~~31 January 2014, but only 25 generated overland flow (Fig. 2). The general overland flow characteristics for the various soil treatments (Table 2) showed that C and HP plots produced a similar average overland flow per event. The average overland flow per event was significantly less for soil amended with SM, PM or RU. There was a similar trend with respect to the maximum overland flow; the highest values were recorded in the HP (127.8 L) and C (116.7 L) plots, associated with rainfall events on 30 September 2012 and 18 November 2012, respectively. Much lower maximum values for overland flow were registered in the SM, PM and RU plots, following an event that took place on 19 January 2013. The same trend was evident in the cumulative totals.

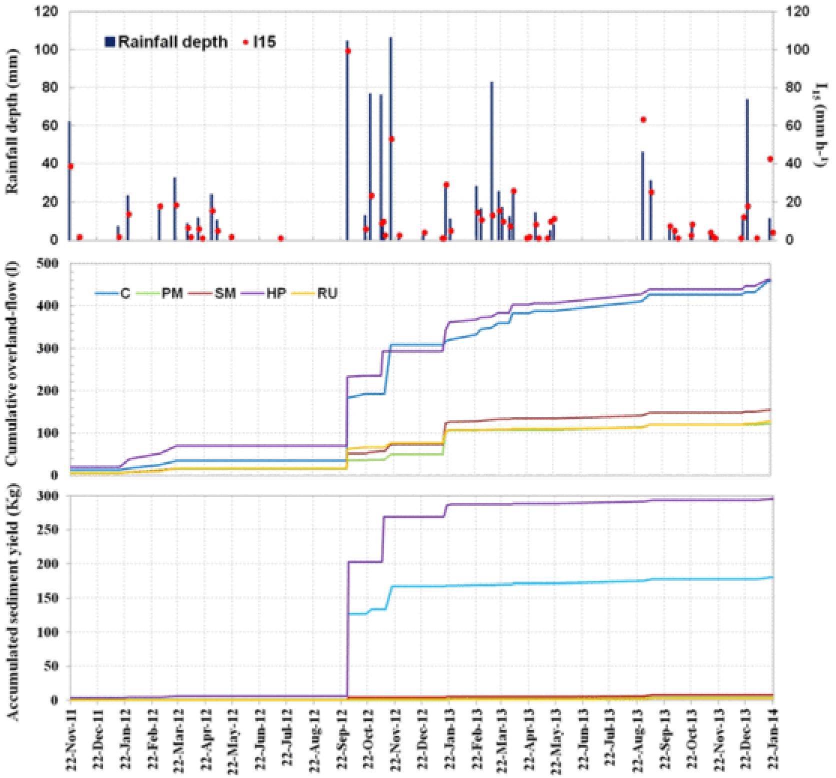

Fig. 2 Rainfall depth (mm), maximum intensity in 15 ~~minutes~~min (I_{15}, ~~mm~~ mm h~~-~~–^{1}), cumulative overland flow (L) and accumulated sediment yield (kg) for the various treatments. C: soil afforested, no amendment; PM: mulch with chipped branches of Aleppo Pine (*Pinus halepensis* L.); SM: straw mulch; HP:

TerraCottem hydroabsorbent polymer; RU: sewage sludge.

Table 2 General overland flow characteristics for the various soil treatments (L). C: soil afforested, no amendment; SM: straw mulch; PM: mulch with chipped branches of Aleppo Pine (*Pinus halepensis* L.); RU: sewage sludge; HP: TerraCottem hydroabsorbent polymer. *N*: number of rainfall events that generated overland flow. *SD*: standard deviation; *Max*: maximum overland flow.

Management	*N*	Average (L)	*SD* (L)	*Max* (L)	Cumulative (L)
C	25	8.0	22.0	116.7	457.3
SM	25	2.7	8.3	50.0	154.6
PM	25	1.3	3.5	56.4	122.7
RU	25	2.2	5.9	28.7	128.1
HP	25	8.1	20.1	127.8	461.8

4.2 Sediment yield

Table 3 shows that there was a strong correlation in the data between the trends for overland flow and sediment yield for the various treatments applied during the study period. The mean sediment yield per event was relatively high in the C and HP plots, while significantly lower values were registered in the SM, PM and RU plots. Very similar trends were found for the maximum sediment yield (Table 3). The overland flow and sediment yield were much higher in the C and HP plots than in the SM, PM and RU plots, but the levels of overland flow in the C and HP plots were similar. The accumulated sediment yield in the HP plots was significantly higher than in the C plots (Fig. 2). It seems that a threshold value of overland-flow generation control exists, which separated the overland flow effects of the SM, PM and RU treatments from those of the C and HP treatments, and therefore determined the sediment yield and continuity.

Table 3 General sediment yield characteristics for the various soil treatments (kg). C: soil afforested, no amendment; SM: straw mulch; PM: mulch with chipped branches of Aleppo Pine (*Pinus halepensis* L.); RU: sewage sludge; HP: TerraCottem hydroabsorbent polymer. *N*: number of rainfall events that generated sediment yield. *SD*: standard deviation; *Max*: maximum overland flow.

Management	*N*	Average (kg)	*SD* (kg)	*Max* (kg)	Accumulated (kg)
C	25	8.6	27.8	125.6	179.8
SM	16	0.4	1.0	4.5	7.6
PM	13	0.2	0.3	1.0	3.3
RU	20	0.2	0.3	1.1	3.1
HP	25	14.8	43.4	187.9	295.0

4.3 Soil moisture

Rainfall events that produced overland flow during the study period were grouped into three classes based on percentile rainfall depth (mm): (i) P_{75} defines events involving a rainfall depth ≥ 61.4 mm; (ii) P_{50} includes those events involving a rainfall depth < 61.4 and ≥ 27.9 mm; and (iii) P_{25} defines the events involving a rainfall depth < 27.9 mm. In each class, two overland-flow events were selected randomly and soil moisture was tested at three depths in the soil profile (5, 10 and 25 cm). Soil moisture values along the soil profile are represented in Fig. 3. Soil moisture at each depth was calculated using the average between first drop and last drop during the rainfall event every 10 ~~minutes~~min.

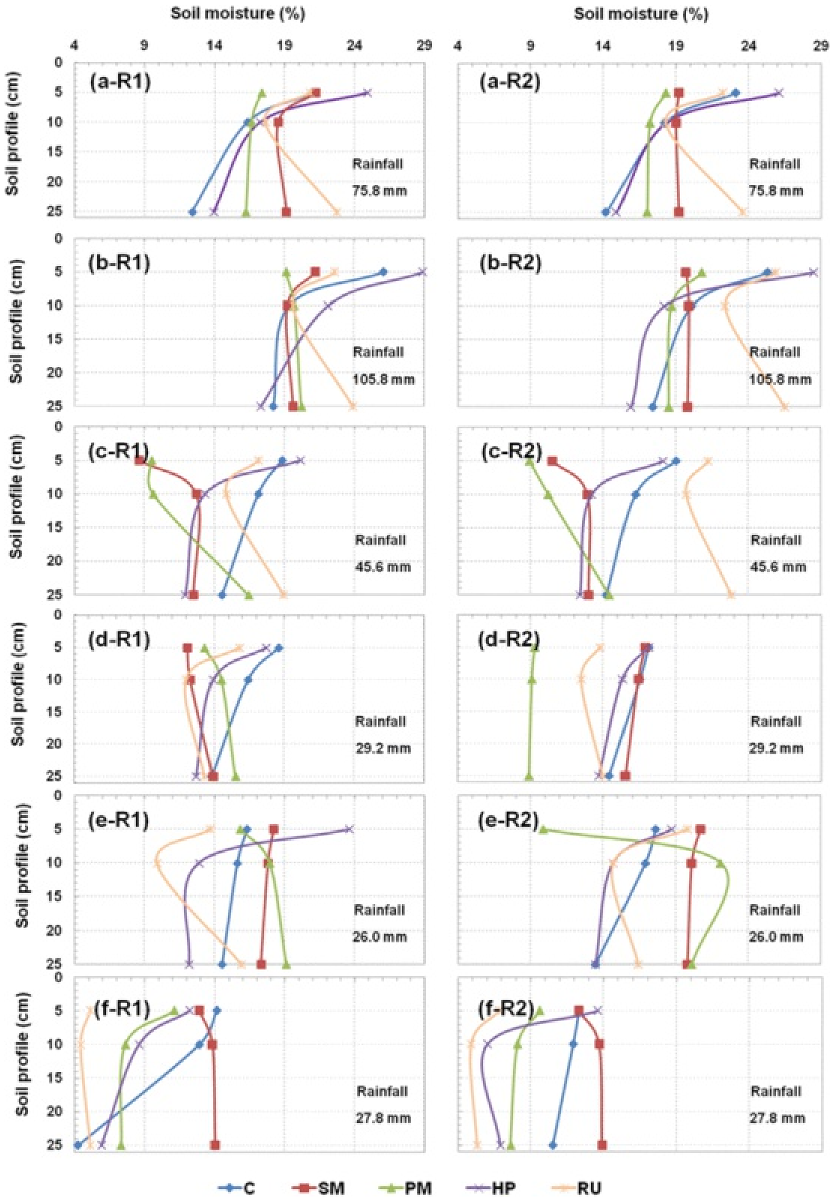

Fig. 3 Soil moisture values in the soil profile. (a) Rainfall event of 7 November 2012 (depth: 75.8 mm; duration: 44.25 h; I_{15}: 8.8 mm h^{-1}). (b) Rainfall event of 18 November 2012 (depth: 105.8 mm; duration: 14.7 h; I_{15}: 52.8 mm h^{-1}). (c) Rainfall event of 29 August 2013 (depth: 45.6 mm; duration: 3.5 h; I_{15}: 63.2 mm h^{-1}). (d) Rainfall event of 19 January 2013 (depth: 29.2 mm; duration: 6.5 h; I_{15}: 42.4 mm h^{-1}). (e) Rainfall event of 5 April 2013 (depth: 26.0 mm; duration: 9.8 h; I_{15}: 25.6 mm h^{-1}). (f) Rainfall event of 23 February 2013 (depth: 27.8 mm; duration: 17.8 h; I_{15}: 14.3 mm h^{-1}). (R1) Replica 1. (R2) Replica 2. C: soil afforested, no amendment; SM: straw mulch; PM: mulch with chipped branches of Aleppo Pine (*Pinus halepensis* L.); RU: sewage sludge; HP: TerraCottem hydroabsorbent polymer.

4.3.1 High rainfall events

The high rainfall depth events chosen for analysis were those of 7 November 2012 (rainfall depth: 75.8 mm; event duration: 44.25 h; I_{15} = highest average maximum intensity for 15 ~~minutes~~min: 8.8 mm h^{-1}) and 18 November 2012 (rainfall depth: 105.8 mm;

event duration: 14.7 h; I_{15}: 52.8 mm h^{-1}). In these two events the greatest soil moisture near the surface (at 5 cm depth) was found in the C and HP plots (Fig. 3a-R1,R2 and b-R1,R2); at 10 cm depth the soil moisture decreased or remained constant in all five treatments. However, at a depth from 10 to 25 cm the trends differed between the C and HP plots and the SM, PM and RU plots. In the C and HP plots the soil moisture continued to decrease, while in the SM, PM and RU plots the soil moisture remained relatively constant or increased, especially in the RU plots.

4.3.2 Medium rainfall events

The medium rainfall depth events chosen were those of 29 August 2013 (rainfall depth: 45.6 mm; duration: 3.5 h; I_{15}: 63.2 mm h^{-1}) and 19 January 2013 (rainfall depth: 29.2 mm; duration: 6.5 h; I_{15}: 42.4 mm h^{-1}). In these two events (Fig. 3c-R1,R2 and d-R1,R2) the change in soil moisture content through the soil profile was less significant than in the high rainfall events. Nevertheless, there was a difference in the trends between the C and HP plots and the SM, PM and RU plots. In the C and HP plots the general trend was for a decrease in soil moisture downward through the soil profile, while in the SM, PM and RU plots the soil moisture remained relatively constant or increased, except for the RU treatment in which the soil moisture decreased from 5 to 10 cm depth.

4.3.3 Low rainfall events

The low rainfall depth events chosen were those of 5 April 2013 (rainfall depth: 26.0 mm; duration: 9.8 h; I_{15}: 25.6 mm h^{-1}) and 23 February 2013 (rainfall depth: 27.8 mm; duration: 17.8 h; I_{15}: 14.30 mm h^{-1}). At soil depths from 5 to 10 cm the soil moisture decreased in the C, HP and RU plots (Fig. 3e-R1,R2 and f-R1,R2). However, at depths from 10 to 25 cm the trend differed between the C and HP plots and the RU plot. In the C and HP plots the soil moisture decreased continuously with depth, but in the RU plot the soil moisture increased. For the event of 5 April 2013, the soil moisture content decreased from 5 to 10 cm depth in the SM plots, but increased in the PM plots (Fig. 3e-R1,R2). However, the trend was different from 10 to 25 cm depth, as the soil moisture content increased or remained relatively constant in both treatments. In the event of 23 February 2013 the soil moisture content increased in the SM plots and decreased in the PM plots (Fig. 3f-R1,R2). Again, the trend was different from 10 to 25 cm depth, as the soil moisture content increased in both treatments relative to the content in the soil from 5 to 10 cm depth.

5 Discussion

According to the results, the hydrological and erosive response in the five treatments showed dissimilarities, despite having similar rainfall exposure and the same original soil properties (Hueso-González et al., 2014). This means that the differences between the treatments play a key role in the soil moisture, overland flow and sediment yield values.

In the C plots (control) the overland flow response to rainfall was very quick and sharp after rainfall started. This, in turn, affected the erosion processes so that the sediment yield behavior had the same trend. At the same time regarding the soil moisture profile, in all the six rainfall events analyzed, the highest soil moisture values were at the top soil, upper 5 cm, while the soil below it (10 and 25 cm) was relatively dry (Fig. 3). In other words, ~~highs~~ high amounts of overland flow were generated when the soil was relatively dry, except for the top soil. In addition the most rapid and sharp response appeared during events with high rainfall intensities that usually occur toward the end of the summer (Ruiz-Sinoga and Romero-Diaz, 2010). These facts mean that overland flow was generated due to rainfall excess (Horton's model) and not due to soil saturation (Lavee et al., 1998; Ward and Robinson., 2000; Beven, 2002; Calvo et al., 2003; Cammeraat., 2004; Latron et al., 2007). The practical conclusion is that in afforested areas with non-amended soil, relatively high values of overland flow and sediment yield are expected.

Regarding the other plots, many studies have demonstrated the effectiveness of using amendments to reduce overland flow and soil erosion in cultivated lands (Edwards et al., 2000; Ojeda et al., 2003; Tejada and González, 2003, 2006; Yu et al., 2003; Marques et al., 2005; Montgomery, 2007; Mulumba and Lal, 2008; Jordán et al, 2010; Gonzalez-Ubierna et al., 2012; Abrol et al., 2013; Robichaud et al., 2013). However, these studies do not explain this conclusion by means of overland flow generation mechanism and/or the soil moisture profile. Our results show variability in the hydrological and erosion response of soils that were amended with mulch, polymer and sewage sludge. Surprisingly, plots amended with SM (straw mulching), PM (mulch with chipped branches of Aleppo Pine) and RU (sewage sludge) were characterized by overland flow and sediment yield responses that were, compared to the control, opposite to those observed in the HP (polymer) plots (Fig. 2). While in SM, PM and RU the overland flow was much lower than the control (C), in HP it was similar to that of C. The sediment yield in SM, PM and RU was very low, while in HP it was higher than C and with similar trends. With respect to water redistribution in the soil profile (Fig. 3), two generalized responses were apparent: i) plots amended with SM, PM or RU showed a more or less uniform distribution of soil water content in the soil profile, in several cases with higher levels of soil moisture with increasing depth; and ii) a non-uniform redistribution of water was evident in plots amended with HP, where the water content decreased with depth, which is similar to what occurred in the control plots.

The plots amended with mulch (SM and PM) showed similar soil moisture all along their profiles. In some cases, higher soil moisture was found at 25 cm depth, even during the relatively short rain events (Fig. 3). Conversely, the moisture in the control plots (C) decreased with depth. This means that the infiltration and percolation rates were relatively high in SM and PM. This is explained by the characteristics of the mulch and the application method. The SM and PM amendments were applied at 10 Mg ha^{-1} over the entire plot, and the top 25 cm of soil was tilled. This caused the formation of macro-pores and cracks in the soil profile which can be easily seen (Fig. 4). The high infiltration rate enabled overland flow to be generated only in cases when the soil was saturated or almost saturated. This model of saturation overland flow is typical of humid and subhumid environments where soils are well-structured and covered by dense vegetation (Lavee et al., 1998; Ward and Robinson, 2000). From the land management point of view the PM and SM amendments were highly effective in reducing overland flow compared with the control plots, and thus the most effective in reducing soil erosion.

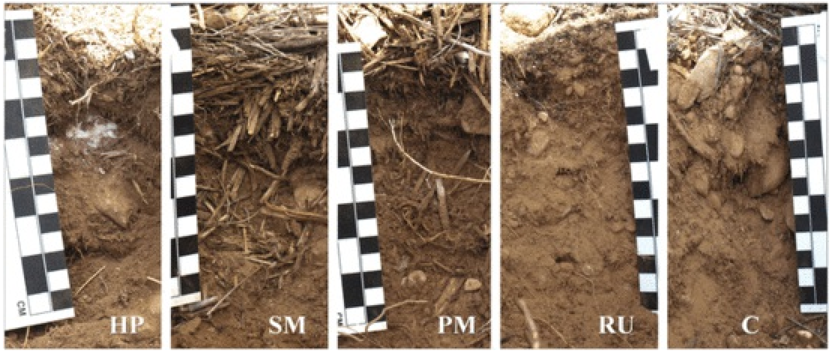

Fig. 4 Soil profiles for the five treatments applied at the experimental site. HP: TerraCottem hydroabsorbent polymer; SM: straw mulch; PM: mulch with chipped branches of Aleppo Pine (*Pinus halepensis* L.); RU: sewage sludge; C: soil afforested, no amendment. In each image the checkered square is 1 cm on each side.

Results similar to those obtained for the SM and PM treatments were found for the RU treatment (Figs. 2 and 3), which involved a similar amendment rate and tillage depth. The mean soil moisture content was greater at 25 cm depth than at 5 cm, while the lowest soil moisture values were found at 10 cm depth in the six events analyzed. These results are explained by the type of vegetation cover that grew in the RU plots. RU treatment encouraged the development of the herbaceous plant *Carlina hispanica* Lam., which entirely covered the plots. The root system of this plant is rhizomatous, with overwintering buds situated between 1 and 10 cm depth in the soil profile, observed during the field surveys (Fig. 5). The thick root system is likely to be highly absorbent and responsible for the lower soil water content at 10 cm depth (Wahrmund et al., 2010).

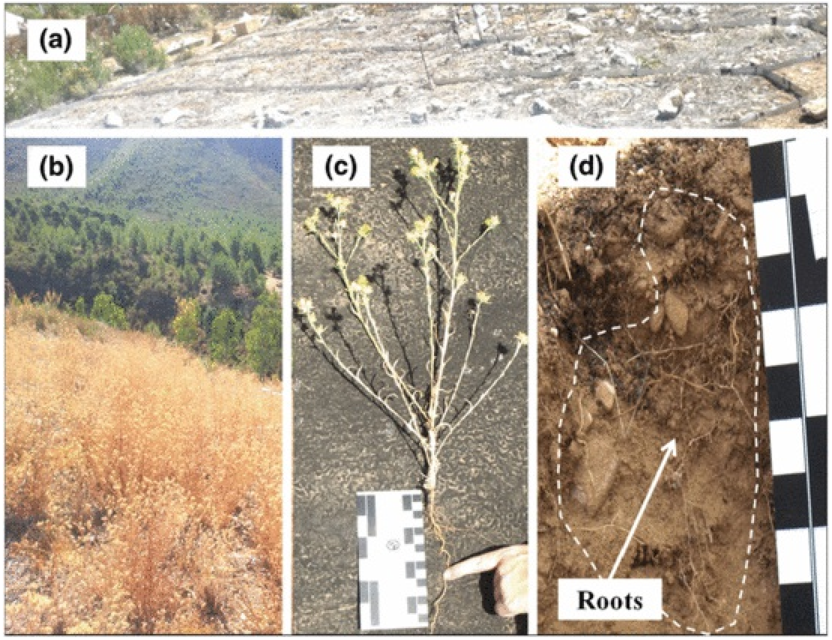

Fig. 5 Plots afforested and amended with sewage sludge. (a) Plots at the beginning of the experiment following the removal of vegetation in October 2010; (b) plots covered by *Carlina hispanica* Lam. in September 2012; (c) *C~~arlina~~. hispanica* Lam.; (d) soil profile in sewage sludge-treated soil, in May 2013. In each image the checkered square is 1 cm on each side.

With respect to the generation of overland flow and sediment yield from the RU plots, our results are consistent with those reported for cultivated lands (Guerrero et al., 2001; Galdos et al., 2004). The RU treatment reduced the total runoff by 72.0% and the total sediment yield by 97.8% relative to the control (C). However, the reduction of overland flow and erosion with sewage sludge amendment was a function of increased vegetation growth and also of the mixing of the soil. Ruiz-

Sinoga et al. (2009) reported that annual plants and dead plants connected to the soil act as sink areas where infiltration is the dominant process. During erosive rain events the plant cover was sufficiently developed in the RU plots to contribute to soil protection as shown by Sort and Alcañiz (1999) and Albaladejo et al. (2000). In addition, no evidence of sediment transport and rill formation was observed within the RU plots. The protective effect of vegetation cover, the direct effect of sewage sludge and the effect of tillage on overland flow and sediment yield production need to be investigated. ~~Evaluating the protective effect of vegetation cover, the direct effect of sewage sludge and the effect of tillage on overland flow and sediment yield production needs to be investigated.~~ Similar results were reported by Ojeda et al. (2003), who showed that when soil was treated with sewage sludge (10 Mg ha^{-1}), vegetation cover was the main factor controlling runoff. The practical conclusion is that RU was effective in reducing overland flow and sediment yield following afforestation. However, unlike the SM, PM, HP and C plots, the RU treatment encouraged the development of herbaceous cover over the plots.

Regarding the HP treatment, the TerraCottem polymers played a different role in the hydrological and erosion response to rainfall. The highest values were found in HP (127.8 and 58.4 L) produced by the rainfall events of 30 September 2012 and 18 November 2012, respectively. In general, the soil in the HP plots was wettable, enhancing the water infiltration process, and the maximum soil moisture content occurred at 5 cm depth. Conversely, among the six events investigated, the HP plot soil profiles showed the most dramatic reduction in soil moisture from 5 to 25 cm depth (Fig. 3), and these plots were associated with more overland flow and sediment yield than the other plots, including the control plots. It is noteworthy that the plants in the HP plots were planted according to the same spatial pattern as used in the other plots, and the polymers were introduced into the soil in holes of 5–10 cm depth. These polymers increased in volume during the rainfall event, and formed a solid to gel-like state that had a binding-sealing effect in the top 5–10 cm depth (Fig. 6). Thus, following a rainfall event, a greater volume of water could be held in the soil. However, once the polymer became saturated it appeared to act as a barrier, and water infiltration was dramatically reduced. Fig. 6 shows that the saturated polymer acted as an impermeable layer and enhanced the generation of overland flow. From the soil management point of view, polymer treatment is not recommended to decrease soil loss.

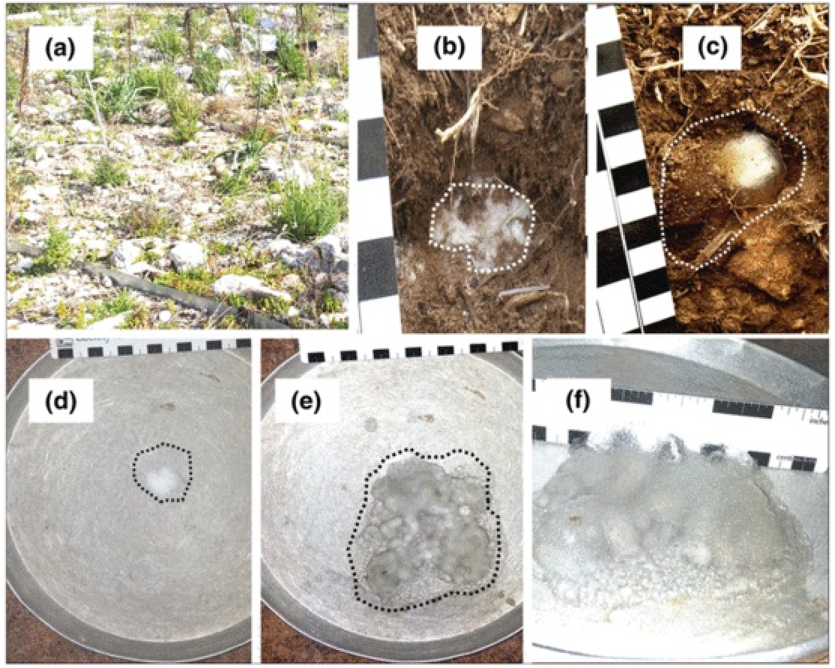

Fig. 6 Plots afforested and amended with TerraCottem hydroabsorbent polymer. (a) Plot amended with polymer and afforested in December 2013; (b) dry polymer in the soil profile in September 2013; (c) polymer hydrated in the soil profile in September 2013; (d) 5 g of polymer prior to the addition of 25 mm of water; time = 0 s; (e) 5 g of polymer prior to the addition of 25 mm of water; time = 10 s; (e) 5 g of polymer prior to the addition of 25 mm of water; time = 45 s. In each image the checkered square is 1 cm on each side.

6 Conclusion

The present study has demonstrated the effects of various treatments on the generation of overland flow, and hence the sediment yield. In the C (control) and HP (polymer) plots, relatively large amounts of overland flow rapidly developed. This cannot be explained by saturation conditions, as the soil moisture content was highest near the surface and decreased with depth in the profile. This, together with the relatively low macro-porosity, proved that the mechanism of overland flow generation was of the Hortonian type.

On the other hand, in the SM and PM plots (straw mulching and mulch with chipped branches of Aleppo Pine), the high level of macro-porosity, together with the increase in soil moisture content with depth, explained the small quantities of overland flow and sediment yield. In the rare case that overland flow developed in these plots, it was minor in amount, and yielded little sediment because of saturation conditions. The processes in the RU plots (sewage sludge) were more complicated; from 10 cm depth the soil moisture content always increased with further depth, usually rapidly. Thus, water infiltrated continuously and there was no rainfall excess. Therefore, in terms of overland flow and sediment yield, the RU plots behaved in a similar way to the SM and PM plots. The fact that the soil moisture content was low at depths of 10 cm is because of the uptake of water at these depths by the roots of *C~~arlina~~. hispanica* Lam.

From a land management standpoint, the SM, PM and RU treatments were the most effective in reducing overland flow and sediment yield following afforestation. In addition, the soil profile became more wettable, which provided more water to support plant survival. However, when afforestation was combined with RU treatment, the vegetation cover resulting from the amendment treatment was the main factor controlling the hydrological processes. Application of the HP treatment caused a decrease in soil moisture content with depth in the soil profile, and overland flow and sediment yield were maximum in this treatment.

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