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Hydrology and Earth System Sciences
Discussions

The impact of road and railway embankments on runoff and soil erosion in eastern Spain

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Abstract

Road and railway infrastructure increased in the Mediterranean region during the last three decades. This included the building of embankments, which are assumed to be a large source of sediments and runoff. However, little is known about soil erosion rates, the factors that control them, and the processes that contribute to detachment, transport and deposition of sediments from road and railway embankments. The objective of this study was therefore to assess the impacts of road and railway embankments as a source of sediment and water, and compare them to other land use types (citrus plantations and shrublands) representative of the Cànyoles watershed to evaluate the importance of road embankments as a source of water and sediment under high magnitude low frequency rainfall events. Sixty rainfall experiments (1 m^2 plots; 60 min duration; 78 $mm\,h^{-1}$ rainfall intensity) were carried out on these land use types: 20 on two railway embankments (10 + 10), 20 on two road embankments (10 + 10), and 10 on citrus and 10 on shrubland. Road and railway embankments were characterized by bare soils with low organic matter and high bulk density. Erosion processes were more active in road, railway and citrus plots, and null in the shrublands. The non-sustainable soil erosion rates of 3 $Mg\,ha^{-1}\,y^{-1}$ measured on the road embankments were due to the efficient runoff connectivity plus low infiltration rates within the plot as the runoff took less than one minute to reach the runoff outlet. Road and railway embankments are both an active source of sediments and runoff, and soil erosion control strategies must be applied. The citrus plantations also act as a source of water and sediments (1.5 $Mg\,ha^{-1}\,y^{-1}$), while shrublands are sediment sinks, as no overland flow was observed due to the high infiltration rates.

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1 Introduction

Mediterranean landscapes are heavily influenced by humans. These cultural ecosystems are characterized by a relatively high population density, a long history of human settlement and an intense exchange of goods and people. This was possible due to a dense road network, originally designed during the Roman Empire, expanding over the last two millennia, and being widespread during the 20th century. These roads resulted in an increase of on-site soil erosion during construction because of the exposure of bare soil materials. The embankments increased the water and sediment delivery off site due to the connectivity along the road embankments and adjacent areas (Cerdà et al., 2007; Martínez-Zavala et al., 2008). Roads serve as additional drainage lines in the landscape and generate large runoff volume due to soil sealing and enhanced overland flow connectivity (Safari et al., 2016), which is a main topic in semiarid lands (Cerdà et al., 2010; Parsons et al., 2015).

Soil erosion processes are very active in Mediterranean type ecosystems as a consequence of the intense rainfall, steep slopes, reduced vegetation cover, low soil organic matter and erodible parent materials (Merino-Martin et al., 2012; Angulo-Martinez and Begueria, 2012; Parras-Alcantara et al., 2013; Bisantino et al., 2015; Nadal-Romero et al., 2015). However, most of the intense soil erosion is due to human activities, which are millennia old (Lozano-Parra et al., 2014; Costa et al., 2015; Ibáñez et al., 2015; Laudicina et al., 2015) due to non-sustainable land use practices in agricultural land and recurrent forest fires in the rangelands. Land degradation is a consequence of forest fires (Keesstra et al., 2014a; Guénon et al., 2013), intense ploughing (Lopez-Vicente et al., 2008; García-Orenes et al., 2009), use of herbicides (Cerdà et al., 2009), land abandonment (Cerdà, 1997; Tarolli et al., 2014), but also due to the construction of road and railway infrastructures as we will demonstrate here.

Roads create new landscape elements (Cheng et al., 2015) and change soil properties, landforms and geomorphological processes (Brevik and Fenton, 2012; Tømmervik et al., 2012; Jiménez et al., 2013; Lee et al., 2013; Cao et al., 2015). The size of modern roads and railway networks has increased drastically in the Mediterranean area. This infrastructure created embankments and cut slopes, and little is known about the erosional response of these areas to rainfall and the disturbance they induce in their ecosystems, both on and off site. There is also little information about the soil erosion in the road and railway surface, although the high porosity of the railway material and the asphalt cover in the roads results in no soil erosion on those parts. However, the soil losses and water losses of the embankments should be high due to the bare soils and steep slopes (Cerdà, 2005).

Despite the increase in infrastructure, and the recognition of roads (mainly the embankments) as an important source of sediments and runoff, few studies have focused on erosional process on road and railway embankments in comparison to other research topics (Diseker and Richardson, 1961; Diseker and Sheridan, 1971; Croke, 2005; Foltz et al., 2009). There are examples around the world of the increase of soil erosion rates on roads and railways (Jordán and Martínez-Zavala, 2008; Martínez-Zavala et al., 2008; Cerdà et al., 2009; Jordán et al., 2009; Xu et al., 2009; Dong et al., 2012; Seutloali and Beckedahl, 2015), but the research on embankments is still poor.

Due to the high economic and environmental impact of soil losses from road embankments (Xu et al., 2006), some rehabilitation and restoration programs (e.g compost/mulch) have been carried out (De Oña et al., 2009; Bakr et al., 2012), but they still need to be developed and we need to know the rates of embankment soil erosion under different climates to plan future rehabilitation and restoration programs. Moreover, we need exact quantifications of the soil erosion along embankments to design rehabilitation and restoration programs. In addition, it is necessary to compare those measurements with ones done in other land uses of the region to understand the changes in the soil erosion processes induced by the embankments.

In Mediterranean type-ecosystems, where rainfall erosivity is high and the climate is dry, road embankments are covered by sparse vegetation (Bochet et al., 2009, 2010), are or even bare (Cerdà, 2007). In the Mediterranean, insufficient studies have been carried out about soil and water losses along roads, despite the fact that it is widely

accepted that they contribute high yields of sediments and water (Navarro and San Martín, 2000; Cerdà, 2007; Jordán and Martínez-Zavala, 2008; Jordán et al., 2009; Martínez Zavala et al., 2008; Safari et al., 2016).

This paper reports on a study of the impact of road and railway embankments on soil and water losses delivery by means of rainfall simulation experiments which are compared to measurements carried out on nearby shrublands and citrus plantations, which are the most common land uses in Eastern Spain.

2 Material and methods

2.1 Study site, soil analysis and field experiments

Six study sites were selected in the Canyoles river watershed in Eastern Spain (Fig. 1): two railway embankments, two road embankments; one site with shrubs and one citrus plantation. Embankments occupy < 1 % of the catchment area, while shrubland and citrus, cover 49 and 7 %, respectively. The shrub and citrus sites served as reference sites in order to understand the impact of the road and railway embankments on soil and water losses in the region. Rock fragments on the soil surface, bare soil and vegetation cover were determined at 100 points using a grid of 10 cm × 10 cm on the 1 m^2 plots. Soil analyses included soil organic matter content (Walkley and Black, 1934), soil moisture was analysed gravimetrically (Gardner, 1986) and bulk density according to Blake and Hartge (1986). Rainfall simulations followed the methodology of Cerdà (1998). We applied a simulated rainfall, since this allows comparison of the impact of a determined rainfall intensity and duration in soils under different land uses and management to understand the impact of land use changes on soil erosion under high magnitude – low frequency rainfall events of the same intensity and duration applied to plots of the same size.

Rainfall simulations were carried out over ten paired plots (1 m^2) and the surrounding 2 m^2 as the buffer area per plot. In total, 60 experiments were conducted (60 min duration; 78 $\mathrm{mm\,h^{-1}}$ intensity) for plots on 2 railways embankments ($n = 10 + 10$), 2 road embankments ($n = 10 + 10$), 1 chemically managed citrus plantation ($n = 10$) and 1 shrubland ($n = 10$) in August of 2011. This rainfall intensity has a 15-year return period for storms in the study area (Cerdà, 1996). A three-nozzle (Hardi-1553-12) rainfall simulator with constant rainfall intensity and 2 m fall height was used. The rainfall simulator device consists of a metallic structure with telescopic metal legs. The structure was covered with a plastic sheet to protect the experiments against wind. Deionized water was used to avoid the influence of water chemical composition on the soil response (Agassi et al., 1994). Experimental plots were framed by galvanized iron sheets, installed in April 2011. They were equipped with a collector and a drainpipe (outlet) to collect overland flow and entrained sediment. The rainfall reached a Christiansen coefficient of 85.7 % under laboratory conditions. Mean drop size was 2.68 mm, with a mean drop velocity of 3.78 $\mathrm{m\,s^{-1}}$ and a mean kinetic energy of 9.34 $\mathrm{J\,m^{-2}\,mm^{-1}}$ (Cerdà, 2015), similar to the rainfall properties measured in the region for intense rainfall event (Cerdà, 1997). This device used in this study was slightly higher than for the original apparatus used in Cerdà (1996) and successfully used in García-Orenes et al. (2012), Iserloh et al. (2012, 2013) and León et al. (2013).

For determination of the runoff rate, runoff was collected at 1 min intervals (60 measurements in total). Runoff samples collected every 5 min in 1.5 L bottles (a total of 12 per experiment). Samples were oven-dried until constant weight (24 h, 105 °C) and sediment yield was quantified by weighing. Sediment concentration in runoff ($\mathrm{g\,L^{-1}}$) was calculated using sediment yield and runoff volumes. Time to ponding was measured with a chronometer by the same person from the onset of the rainfall initiation until the development of ponds on 40 % of the total plot surface. This was considered as an indicator of the soil wettability. Time to runoff was determined when the surface runoff began to develop on the plot surface (c.f. Cerdà and Doerr, 2007). Time to runoff at the outlet was measured when the discharge reached the plot outlet. The differences between time to runoff and time to ponding and between time to runoff at the outlet and time to runoff initiation were used to help in estimating the connectivity of the flows

within the plot. The runoff coefficient was calculated from the total runoff (Q) and total rainfall (P) (runoff-rainfall, $Q/P \cdot 100$). The steady-state infiltration rates were calculated by means of the Horton equation (Cerdà, 1996). The erosion rate and sediment yield were calculated by means of the sediment concentration and the runoff discharge (see Cerdà, 1998).

2.2 Statistical analysis

Data normality and hetereosceoadity were analysed using the Shapiro–Wilk's and Levene's test, respectively. Data were considered normally distributed and homogeneous at $p > 0.05$. Rock fragments and bare soil cover were normally distributed and meet the homogeneity of the variances requirements. The remaining variables did not follow normality and homogeneity even after logarithmic, Box–Cox and Square Root transformations. Thus, rock fragment and bare soil data comparisons were carried out using the parametric One-Way ANOVA test. When the ANOVA null hypothesis was rejected, the Tukey HSD post-hoc test was used to find differences between groups. For the other variables, data comparisons were carried out using the non-parametric Kruskal–Wallis test (KW). If significant differences were identified, the multiple comparisons post-hoc test was applied. Differences were considered significant at a $p < 0.05$. A multiple regression analysis was carried out with log-transformed data using general regression models to predict time to ponding, time to runoff, time to runoff at the outlet, steady-state infiltration rate, runoff coefficient and total runoff, sediment concentration in runoff and sediment yield and soil erosion, using vegetation cover, rock fragment cover, bare soil cover, soil moisture, soil organic matter content, bulk density and slope angle as co-variates. All these variables were tested in the model and multicollinearity was assessed. Evidence of collinearity is observed when the co-variates have a correlation higher than 0.8-0.9, a variance inflation factor (VIF) > 10 and a tolerance > 0.1 (Loprinzi et al., 2013). In our work, organic matter and bulk density had a correlation above 0.9, a VIF of 15.38 and 15.00 and a tolerance of 0.065 and 0.066, respectively. Bulk density was discarded from the models and the organic matter VIF was reduced and the tolerance increased to 8.99 and 0.12, respectively. The Pareto chart of t values of regressions was used to determine the importance of effects. Regressions were considered statistically significant at $p < 0.05$. Validation of the regression models was carried out by assessing the residuals normal distribution, with the Shapiro–Wilk test. Residuals normality was considered at a $p > 0.05$. Principal component analysis using varimax rotation based on the correlation matrix (using log-transformed data) was applied in order to identify the relations among variables and the association of the variables according to land use. Statistical analyses were carried out using Statistica v.10.0 (StatSoft, 2010).

3 Results

3.1 Vegetation, rock fragments and bare soil

Significant differences were observed among vegetation cover in the studied plots (KW = 27.00, $p < 0.001$). Vegetation cover in the shrubland plots (56.5 ± 22.1 %) was significantly higher than in citrus, railway and road embankments plots (Table 1). Differences in rock fragment cover among areas were also significant ($F = 772.72$, $p < 0.001$). On average, rock fragment cover was significantly higher on road (46.7±7.9 and 45.3 ± 10.1 %, on average) and railway embankments (47.6 ± 14.4 and 46.5 ± 10.8 %), than in citrus (17.3 ± 4.4 %) and shrubland plots (21.8 ± 12.3 %), where the rock fragments were present but did not fully cover the soil surface. Significant differences were also observed among plots for bare soil ($F = 1300.97$, $p < 0.001$). The bare soil cover was significantly higher in citrus (77.7 ± 4.72 %) than in railway (47.9 ± 14.3 and 49.5 ± 10.95 %), road embankments (49.2 ± 9.0 and 50.5 ± 10.9 %) and shrubland plots (21.7 ± 11.3 %) (Table 1).

3.2 Soil moisture, organic matter, bulk density and slope angle

Soil moisture was significantly different among the studied areas (KW = 33.41, $p < 0.001$). Soil water content was higher in citrus orchards (8.1 ± 1.2 %), which was due to irrigation and high clay content, than in shrubland, road and railway plots, where moisture content ranged between 4.1 ± 0.5 and 6.2 ± 1.4 % (Table 2). Significant differences were also identified in soil organic matter contents from the different study plots (KW = 33.41, $p < 0.001$). Soil organic matter content was significantly higher in shrubland (6.09 ± 2.14 %) than in citrus and railway and road embankment plots, where it ranged between 0.79 ± 0.13 and 1.48 ± 0.14 % (Table 2). Soil bulk density varied significantly among the studied areas (KW = 41.00, $p < 0.001$). Bulk density in railway and road embankments plots (range of 1.40 ± 0.09 to 146 ± 0.10 $\mathrm{g\,cm^{-3}}$) was higher than in citrus (1.19 ± 0.05 $\mathrm{g\,cm^{-3}}$) and shrubland areas (0.82 ± 0.11 $\mathrm{g\,cm^{-3}}$). Significant differences were identified among slope angles (KW = 42.04, $p < 0.001$). Slope angles were significantly higher in railway and road embankments (range of 32.60 ± 1.84 to 33.60 ± 1.84 %) than in shrubland (7.90 ± 0.99 %) and citrus (3.90 ± 1.10 %) plots (Table 2).

3.3 Runoff generation, from ponding to runoff at the outlet

Significant differences were observed in the time to ponding among the studied plots (KW = 35.82, $p < 0.001$). Time to ponding was high and variable in shrubland (791.00 ± 606 s) (Table 3). The same pattern was identified in the time to runoff. Significant differences were identified among plots (KW = 41.76, $p < 0.001$). Time to runoff at the outlet was significantly different among the studied areas (KW = 41.61, $p < 0.001$). It was also significantly higher in shrubland (3600 ± 0) in comparison to citrus (266.30 ± 46), road (421.40 ± 99 and 367.10 ± 45) and railway plots (428.50 ± 74 and 391.30 ± 24). In the shrubland plots, time to runoff at the outlet was not determined because the high infiltration rates prevented allow runoff generation. The variability was high in railway 1 and citrus and low in shrubland (Table 3). Significant differences were identified in the lag time between to runoff and ponding among plots (KW = 22.05, $p < 0.001$). The time that the ponds last until the runoff was initiated was significantly higher in the shrublands (791.00 ± 606) than in the remaining plots. The time to runoff at the outlet was not measured in the schrublands, since it was not observed during the experimental period (one hour). The time that the runoff took to reach the outlet was also significantly different among studied areas (KW = 28.46, $p < 0.001$) (Table 3).

3.4 Steady-state infiltration rate, runoff and sediment yield

Significantly differences were identified in steady-state infiltration rates among the plots (KW = 37.62, $p < 0.001$). Infiltration rates were significantly higher in shurbland than in railways, road embankments and citrus plots. Citrus plots had the lowest infiltration rates. Runoff coefficients and total runoff were significantly different among the studied plots (KW = 41.43, $p < 0.001$). Citrus plots showed a significantly higher runoff coefficient and total runoff than road and railway plots, meanwhile the shrubland plots did not generate runoff (Table 4). Significant differences were also identified in sediment concentration among plots (KW = 41.31, $p < 0.001$). Sediment concentration was significantly higher in road and railways study areas than in citrus and shrubland. The variability was high in citrus (Table 4). Significant differences were identified in sediment yield and soil erosion (KW = 41.49, $p < 0.001$). As in sediment concentration, the values observed in sediment yield were significantly higher in roads and railway plots than in citrus or shrubland plots. Soil erosion was significantly different among the studied sites, with no erosion in the shrublands, high erosion in the citrus plantation, and extremely high erosion in the road and railway embankments (Table 4).

3.5 Multiple regressions

The multiple regressions carried out were significant in all the cases. The covariates used explained time to runoff at the outlet, steady-state infiltration rate, runoff coefficient and total runoff, sediment concentration and sediment yield and soil erosion very

well, with a percentage of explanation of 94, 90, 93, 95 and 91 %, respectively. The lowest capability for explanation was observed in time to ponding (59 %) (Table 5). The variables that significantly explained time to ponding were soil organic matter, rock fragments, vegetation cover, and slope angle (Fig. 2a). Time to runoff was mainly dependent on soil organic matter, rock fragments and slope angle (Fig. 2b). Time to runoff at the outlet was explained mainly by soil organic matter, vegetation cover and rock fragment (Fig. 2c). Soil organic matter, slope angle, vegetation cover and rock fragment cover explained significantly the behaviour of time to runoff at the outlet (Fig. 2d). The runoff coefficient and total runoff were significantly explained by soil organic matter, rock fragments, vegetation cover and slope angle (Fig. 2e). Sediment concentration was mainly dependent on soil organic matter, slope angle and rock fragment. Finally, sediment yield and soil erosion were explained by soil organic matter, rock fragment and vegetation cover (Fig. 2e and f). Overall, soil organic matter is the variable with the greatest influence on the dependent variables. On the other hand, soil moisture did not explain significantly any of the models. In all cases, the models residuals followed the normal distribution (Fig. 2), according to the Shapiro wilk test ($p > 0.05$) (Table 5).

3.6 Multivariate analysis

The first two factors identified by the principal component analysis explained a total of 86.87 % of the total variation. We identified 4 different groups. Group 1 was composed by runoff and time to runoff coefficient, bare soil, time to runoff at the outlet, lag time between runoff at the outlet and time to runoff, sediment yield or soil erosion ($\mathrm{g\,m^{-3}}$ or $\mathrm{Mg\,ha^{-1}}$, yield and erosion are correlated and either of the two could be used), bulk density and sediment concentration.

Group 2 included rock fragment and slope angle, while group 3 was composed by the lag between time to ponding and time to runoff, time to runoff, time to ponding, steady-state infiltration rate, vegetation cover and organic matter. Finally, the fourth group included only soil moisture (Fig. 3a). Figure 3b shows that the soil properties, water and sediment losses are very different among study sites. The results showed that the variables of group 1 were positively correlated with the variables of group 2 and negatively correlated with the variables of the groups 3 and 4. The variables of the group 3 had a positive correlation with the variable of the group 4 and negative with the ones of the group 2. The variables of groups 1 and 2 are associated with road and railway embankments plots and citrus, where high values were identified. The variables grouped in the group 3 had high values in the shrubland plots. Finally the variable of the group 4 had high values in the citrus plots.

4 Discussion

The results showed that vegetation cover, soil moisture and soil organic matter were lower in road and railway embankments than in citrus and shrubland plots. However, rock fragments, bulk density, and bare soil were high in the road and railway plots. Previous studies in Mediterranean environments observed that soils with reduced vegetation cover, soil moisture and soil organic matter are more vulnerable to erosion (Cerdá, 1997a, b, 1998; Castrignano et al., 2008; Blavet et al., 2009; Mohammad and Adam, 2010; Gabarrón-Galeote et al., 2013). Bare soils and soils with high bulk density are more susceptible to erosion because the infiltration capacity is reduced and therefore more overland flow is generated that can erode the soil (Seeger and Ries, 2008; Lee et al., 2013). This paper confirms those findings and highlights that organic matter is the variable with the highest influence on soil and water losses in the studied areas and that road embankments are very active sources of soil and water, due to the reduced land cover (< 1 %) in relation to citrus (7 %) and shrubland (49 %). This study looks into the factors that control these soil losses with the aim of understanding the system dynamics better and potentially providing direction to mitigate this unsustainable situation.

4.1 The influence of rock fragments

Previous research found that rock fragments decrease soil erosion at the microplot scale and lowered runoff as they protect the soil from raindrop impact (Poesen et al., 1994; Martinez-Murillo et al., 2013). Our study found that the road embankments contain mainly rock fragments, but they still had the highest soil losses, higher than the bare soil of the citrus plantations. The high slope angle also contributed to these erosion rates. Other authors such as Cerdà (2001), Martínez-Zavala and Jordán (2008) and Zavala et al. (2010) observed a positive correlation between rock fragments and runoff initiation and total runoff. Usually, rock fragment cover has a negative correlation with time to ponding, time to runoff, with runoff coefficient, sediment concentration and erosion rate. The results of Cerdà (2001), Martínez-Zavala and Jordán (2008) and Zavala et al. (2010) also showed that rock fragments were negatively correlated with bulk density and organic matter. This is contrary to the findings in this study on road embankments, where a positive correlation was observed between rock fragments and runoff coefficient, sediment concentration and erosion rate. Those studies were carried out in non-disturbed and vegetated soils, where rock fragments cover was lower than in the road and railway plots. Moreover, the road and railway embankments were constructed with very poorly sorted material and it is very likely that rock fragments were embedded in the soil profile (Fig. 4). According to Poesen and Lavee (1994) rock fragments embedded into the soil profile can inhibit water infiltration and facilitate soil erosion. The influence of rock fragments on infiltration depends on their position, size and cover (Poesen and Lavee, 1994). This will need further research, since we measured the rock fragment cover, but not the position they occupied in the soil profile, although observations suggested that most of them were embedded in the soil matrix and crust. The material used for road and railway construction is very poorly sorted and highly disturbed due to the transport and redistribution by heavy machinery. Under natural soil conditions the rock fragments create a diverse ecosystem with macropores, biota and soils rich in organic matter, but in the road embankments the rock fragments act as an inert body within the soil matrix due to the soil disturbance. In this situation, rock fragments may not favour the development of macropores and preferential flows underneath them such as exists in the natural soils of the shrublands, and then the rock fragments may act as a crust, reducing the infiltration rates and increasing runoff.

4.2 Runoff timing and volume

Time to ponding is an important parameter in experiments like the ones performed in this study as it shows the initiation of runoff generation is related to soil erosion and infiltration rates (Assouline et al., 2007; León et al., 2013). Time to ponding gives information about the saturation of the soil surface and the infiltration capacity of the soil (Cerdà, 1996).

In our experiments no runoff was observed in the shrubland plots because of the macropores, high organic matter content, and low bulk density of the soils, which contributes to high infiltration rates (Cerdà, 1997). Shrubland covered soils have very stable aggregates (Cerdà, 2000; Bruun et al., 2015; Chaudhuri et al., 2015), and low erosion rates similar to those seen in forest due to an increase in infiltration rates (Keesstra, 2009b). In the shrubland plots studied at the Cànyoles river watershed the conditions resulted in such a delayed ponding and runoff initiation that we measured no runoff in any of the experiments after a full hour of simulated rainfall at 78 $\mathrm{mm\,h^{-1}}$. However, the citrus plantations and road embankments had a quick ponding time, fast runoff and a high total runoff volume. This confirms the importance of vegetation as a protective shelter for the soil, but also as a source of changes in soil properties leading to improvement in soil organic matter, soil biota, soil porosity, and the subsequent reduction of runoff at plot scale, as observed in this study. Previous works observed similar results at pedon, slope and watershed scales (Cerdà and García-Fayos, 1997; Bochet et al., 2006; Keesstra et al., 2009b; Reichert et al., 2015).

The key factor to explain the different hydrological behaviour in the shrublands as compared to the road and railway embankments is the soil organic horizon, as organic matter changes soil water behaviour (Parras-Alcántara et al., 2013; Hueso-González

et al., 2014; Ola et al., 2015). Organic matter and associated biota favour the formation of macropores and stable aggregates. These soil structural features contribute to reducing runoff as the water can easily infiltrate via macropores (Martínez-Zavala and Jordán-López, 2009). In addition a higher water storage capacity is associated with soils rich in organic content, such as the ones generated by the shrub litter and the decomposition of organic matter (Kröpfl et al., 2013; Palacio et al., 2015). The combination of higher organic matter, soil biodiversity and water storage improves the overall soil quality (Brevik, 2009; Campos et al., 2014; Fterich et al., 2014; de Araújo et al., 2015).

Vegetation cover and soil organic matter also increase soil aggregation, facilitate water infiltration, and delay time to ponding (Franzluebbers et al., 2002). Therefore, it is important to have vegetation cover. However, on the embankments vegetation development was in general very poor (Fig. 4) due to the lack of policies to promote vegetation rehabilitation. In addition the colonization of the embankments by vegetation is very slow. The key reason for this is the removal of seeds by overland flow (García-Fayos et al., 2010; Bochet et al., 2015). If overland flow can be reduced and vegetation cover can be improved, these changes in vegetation cover and organic matter in the embankments' soils will trigger an improvement in the soil quality that will reduce soil and water losses.

These insights can be useful for future restoration programs. Recent research in similar environmental conditions on soils affected by abandonment, embankments or intense chemical agriculture have demonstrated that the focus should be on vegetative recovery (García Orenes et al., 2012; Lee et al., 2013; Cerdà et al., 2015; Keesstra et al., 2015). Efforts in active planting after embankments construction should be carried out, in order to avoid high runoff rates.

4.3 Connectivity

The research conducted in the Cànyoles river watershed showed that the road embankments are an efficient source of water and sediment under intense thunderstorms as observed in previous studies in the same region (Cerdà, 2007), and in other regions of the world (see review by Navarro-Hevia et al., 2015). We found that within the plots runoff connectivity is very high, as demonstrated by the short time between ponding and runoff initiation and between the time to runoff and discharge at the runoff outlet. The runoff reached the runoff outlet in less than 1 min in the embankments plots. Although, connectivity within the plots is high, we can say little about the connectivity of the runoff generated from the plots to the river system, as it depends on landscape units that the flow of water and sediment may encounter on its way downstream. This must be evaluated and monitored for each catchment area specifically. However, because the runoff and sediment is generated close to roads the embankments have drainage systems that evacuate the runoff and sediments to nearby fluvial systems efficiently, and this water and sediment will be quickly transported into the drainage system compared to other erodible areas such as orchards that generally cover larger areas, increasing the chance that sediment can be redeposited or water to infiltrate within the field. This is a research topic that must be studied in order to understand the fate of the sediments and water. The first step to create a good sediment budget for any area is to start at the sources of the sediment.

Many works studied the contribution of the roads, and trails to the generation of runoff and sediments in several parts of the world (Younkin, 1973; Humphreys, 1982; Arnáez et al., 2004; Sidle et al., 2004; Coa et al., 2013, Blong and Arnáez et al., 2004). However, the greatest part of the research was focused in the impact of forest roads (Burroughs and King, 1989; Ziegler et al., 2001; Gruszowski et al., 2003; Ziegler et al., 2007; Negishi et al., 2008; Foltz et al., 2009), meanwhile, little attention has been paid to road and railway embankments, which according to the results of this work highly vulnerability to soil erosion and can be a significant source of runoff and sediments.

4.4 Implications for restoration

Road and railway embankments are a strong disturbance in the Mediterranean landscape. The data presented here confirm that soil losses can reach $3\,\mathrm{Mg\,h^{-1}}$ on road

embankments; meanwhile a nearby area with shrublands did not generate any runoff or sediment. Roads and railways are expensive and big investments for any society and should be protected and conserved to prevent environmental damages. This research into soil erosion and water losses will give us some insight in how to manage and avoid the degradation of this infrastructure and highlights the need to establish road embankment restoration programs. Those strategies must use local materials to reduce soil losses and reach a sustainable state from the environmental and economical point of view. This study shows that vegetation cover is the key factor to reduce soil and water losses, which has also been shown at different scales in previous studies: watershed (Keesstra et al., 2014b), slope (Novara et al., 2011) and pedon (Mekonnen et al., 2015). The restoration and rehabilitation of the road embankments can promote soil development (Jiménez et al., 2013) and soil and water conservation and for this, new strategies should be implemented. In Mediterranean type ecosystems the most successful strategy would be to apply mulch or allow the vegetation cover to recover (Giménez-Morera et al., 2010; Novara et al., 2011, 2013; Cerdà et al., 2015).

5 Conclusions

Road and railway embankments are characterized by low vegetation cover and organic matter and high bulk density, which result in low infiltration rates and very erodible soils. These conditions explain the vulnerability of the embankments to soil erosion, but we also found that orchards are vulnerable to soil erosion, although the soil losses were two times higher in road and railway embankments ($3\,\mathrm{Mg\,ha^{-1}\,h^{-1}}$) than in citrus plots ($1.5\,\mathrm{Mg\,ha^{-1}\,h^{-1}}$). The shrubland plots showed no soil and water losses during our experiments, which is due to the deep soils and the dense vegetation cover, which results in a high infiltration capacity. Within the citrus and road embankments plots, we found an efficient connectivity of the flow as the ponds were transformed into runoff in less than 4 min and the runoff reached the outlet in less than one minute. This showed that embankments form an important source of runoff and sediment in the landscape, which can potentially cause off-site problems with flooding and sediment accumulation. This study highlights the need to reduce the impacts of road embankments on soil erosion, especially in areas with sparse vegetation and intense rainfalls, such as the Mediterranean region. Future research should find strategies to reduce soil losses to improve the sustainability of the road and railway embankments.

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Table 1. Mean, standard deviation (SD) and coefficient of variation (CV) of vegetation cover, rock fragments and bare soil in the railway and road embankments, citrus plantation and shrublands (1) in the Cànyoles river watershed. Different letters represent significant differences at $p < 0.05$. $N = 60$.

	Railway1	Railway2	Road1	Road2	Citrus	Shrubland
Vegetation Cover (%)						
Mean	4.50b	4.00b	4.10b	4.20b	5.00b	56.50a
SD	1.58	1.83	1.79	1.48	1.41	22.05
CV	0.35	0.46	0.44	0.35	0.28	0.39
Rock Fragments (%)						
Mean	47.60a	46.50a	46.70a	45.30a	17.30b	21.80b
SD	14.35	10.78	7.92	10.11	4.37	12.25
CV	0.30	0.23	0.17	0.22	0.25	0.56
Bare Soil (%)						
Mean	47.90b	49.50b	49.20b	50.50b	77.70a	21.70c
SD	14.32	10.95	9.04	10.89	4.72	11.33
CV	0.30	0.22	0.18	0.22	0.06	0.52

Table 2. Mean, standard deviation (SD) and coefficient of variation (CV) of the soil moisture, soil organic matter, bulk density (0–2 cm depth) and slope angle in the railway and road embankments, citrus plantation and shrubland in the Cànyoles river watershed. Different letters represent significant differences at $p < 0.05$. $N = 60$.

	Railway1	Railway2	Road1	Road2	Citrus	Shrubland
Soil Moisture (%)						
Mean	4.07c	4.29bc	4.43bc	4.27bc	8.10a	6.24b
SD	0.48	0.79	0.91	0.65	1.22	1.38
CV	0.12	0.18	0.21	0.15	0.15	0.22
Soil Organic Matter (%)						
Mean	0.79c	0.80c	0.86c	0.93c	1.48b	6.09a
SD	0.13	0.15	0.10	0.07	0.14	2.14
CV	0.17	0.19	0.12	0.07	0.10	0.35
Bulk Density ($g\,cm^{-3}$)						
Mean	1.46a	1.43a	1.40a	1.45a	1.19b	0.82b
SD	0.10	0.07	0.09	0.07	0.05	0.11
CV	0.07	0.05	0.06	0.05	0.04	0.13
Slope angle (%)						
Mean	33.60a	32.90a	33.00a	32.60a	3.90c	7.90b
SD	1.84	2.02	1.41	1.84	1.10	0.99
CV	5.47	6.15	4.29	5.64	28.22	12.59

Table 3. Mean, standard deviation (SD) and coefficient of variation (CV) of time to ponding, time to runoff, time to runoff ate the outlet, the differences between time to runoff and time to ponding, and time to runoff at the outlet and time to runoff in the railway (2) and road embankments (2), citrus plantation (1) and shrubland (1) in the Cànyoles river watershed. Different letters represent significant differences at $p < 0.05$. $N = 60$. Data in seconds.

	Railway1	Railway2	Road1	Road2	Citrus	Shrubland
Time to ponding						
Mean	158.70b	135.80b	147.90b	131.10b	101.70c	791.00a
SD	27.80	28.00	20.93	23.24	34.49	606.59
CV	0.18	0.21	0.14	0.18	0.34	0.77
Time to runoff						
Mean	375.90b	347.30b	367.00b	326.90bc	215.40c	1377.50a
SD	75.01	32.21	100.05	47.08	20.10	845.14
CV	0.20	0.09	0.27	0.14	0.09	0.61
Time to runoff outlet						
Mean	428.50b	391.30bc	421.40b	367.10bc	266.30c	3600a
SD	74.37	24.96	99.23	45.18	46.20	0
CV	0.17	0.06	0.24	0.12	0.17	0
Time to runoff – Time to ponding						
Mean	217.20b	211.50b	219.10b	195.80b	113.70b	791.00a
SD	82.82	53.28	82.69	53.43	44.64	606.59
CV	0.38	0.25	0.38	0.27	0.39	0.77
Time to runoff outlet – Time to runoff						
Mean	52.60a	44.00a	54.40a	40.20a	50.90a	0b
SD	19.36	22.25	16.72	14.58	38.98	0
CV	0.37	0.51	0.31	0.36	0.77	0

Table 4. Mean, standard deviation (SD) and coefficient of variation (CV) of steady-state infiltration rate, runoff, sediment concentration, total runoff, sediment yield, and soil erosion in the railway (2) and road embankments (2), citrus plantation (1) and shrublands (1) in the Cànyoles river watershed. Different letters represent significant differences at $p < 0.05$. $N = 60$.

	Railway1	Railway2	Road1	Road2	Citrus	Shrubland
Steady state infiltration rate (mm h^{-1})						
Mean	7.06b	6.65b	6.93b	6.27b	4.12c	78.00a
SD	1.47	1.53	1.45	1.92	0.90	0
CV	0.21	0.23	0.21	0.26	0.22	0
Runoff coefficient (%)						
Mean	57.47b	56.63b	53.72b	56.81b	71.50a	0.00c
SD	2.32	5.11	4.37	5.77	6.63	0.00
CV	0.04	0.09	0.08	0.10	0.09	0.00
Total runoff (l)						
Mean	44.83b	44.17b	41.90b	44.31b	55.77a	0.00c
SD	1.81	3.98	3.41	4.50	5.17	0.00
CV	0.04	0.09	0.08	0.10	0.09	0.00
Sediment concentration (g L^{-1})						
Mean	14.11a	13.71a	13.97a	13.91a	5.25b	0.00c
SD	1.77	1.41	2.79	2.83	1.24	0.00
CV	0.13	0.10	0.20	0.20	0.24	0.00
Sediment yield (g)						
Mean	633.69a	605.13a	585.30a	623.85a	296.23b	0.00c
SD	93.26	76.93	127.02	172.56	88.83	0.00
CV	0.15	0.13	0.22	0.28	0.30	0.00
Soil erosion (g m^{2} h^{-1})						
Mean	316.85a	302.56a	292.65b	311.93a	148.11	0.00c
SD	46.63	38.46	63.51	86.28	44.42	0.00
CV	0.15	0.13	0.22	0.28	0.30	0.00
Soil erosion (Mg ha^{-1} h^{-1})						
Mean	3.17a	3.03a	2.93b	3.12a	1.48c	0.00d
SD	0.47	0.38	0.64	0.86	0.44	0.00
CV	0.15	0.13	0.22	0.28	0.30	0.00

Table 5. Multiple regression models results.

Dependent variable	Multiple R	R^2	R^2 adjusted	F	p	SW p
LogTime to ponding	0.79	0.63	0.59	15.027	*	0.406
LogTime to runoff	0.83	0.70	0.66	20.336	*	0.079
LogTime to runoff outlet	0.97	0.95	0.94	161.16	*	0.591
LogSteady-state infiltration rate	0.95	0.91	0.90	88.59	*	0.475
LogRunoff coefficient and LogTotal Runoff	0.97	0.94	0.93	134.57	*	0.748
LogSediment concentration	0.98	0.95	0.95	172.99	*	0.114
LogSediment yield and LogSoil erosion	0.97	0.95	0.94	160.62	*	0.982

[*] $p < 0.001$. check journal name.
Shapiro wilk (SW) p value of residuals distribution.

Figure 1. Location of the study area in eastern Spain.

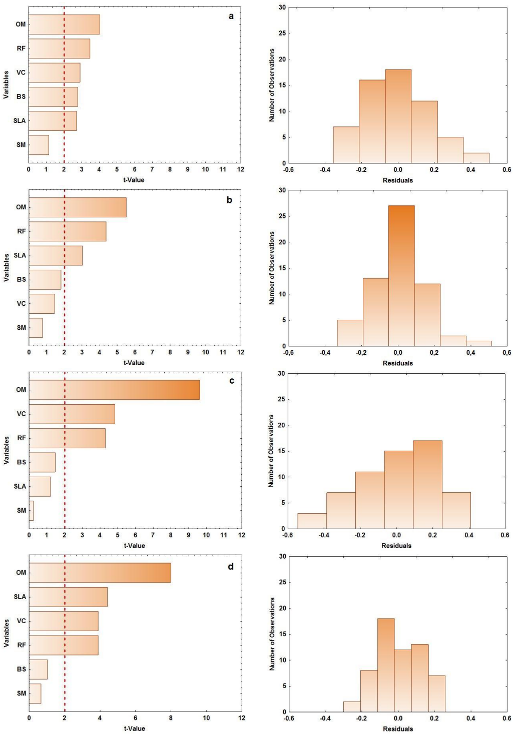

Figure 2.

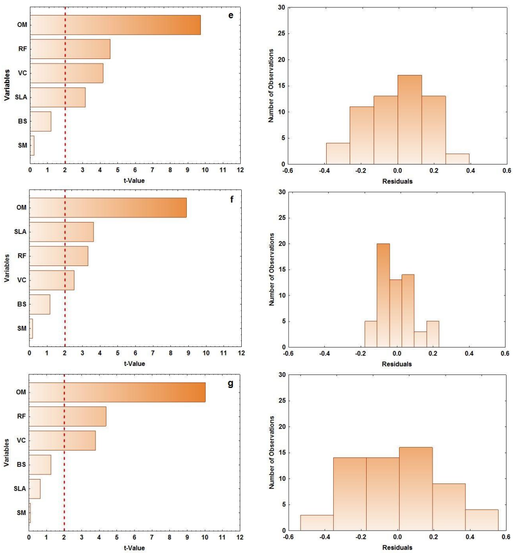

Figure 2. Pareto charts of *t* values (left column) and the respective histograms of the residuals (right column) for the general regression models carried out for **(a)** time to ponding, **(b)** time to runoff, **(c)** time to runoff at the outlet, **(d)** steady-state infiltration capacity. **(e)** Runoff coefficient/total runoff, **(f)** sediment concentration and **(g)** sediment yield/soil erosion. The dotted red line represents the value beyond the predictor variables that explain the dependent one. The independent variables with a pareto *t* value higher than 2.12 significantly explained the dependent variable. Vegetation cover (VC), rock fragments (RF), bare soil (BS), soil moisture (SM), soil organic matter (OM), bulk density (BD) and slope angle (SLA).

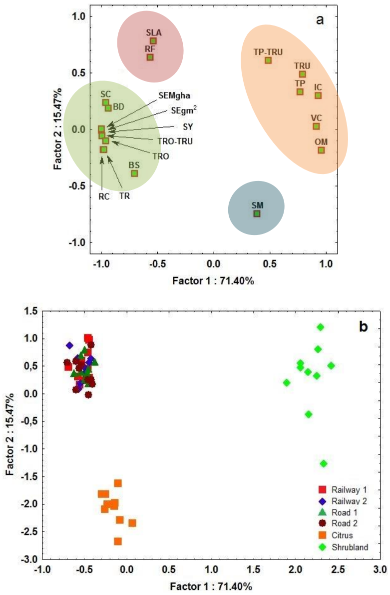

Figure 3. Relation between Factor 1 and factor 2. **(a)** Cases and **(b)** variables. Vegetation cover (VC), rock fragments (RF), bare soil (BS), soil moisture (SM), soil organic matter (OM), bulk density (BD), time to ponding (TP), time to runoff (TRU), time to runoff at the outlet (TRO), time to runoff – time to ponding (TRU-TP), time to runoff at the outlet – time to runoff (TRO-TRU), steady-state infiltration rate (IC) runoff coeficient (RC), total runoff (TR), sediment concentration (SC), sediment yield (SY), soil erosion ($\mathrm{g\,m^2\,h^{-1}}$) (SE$\mathrm{g\,m^2}$), soil erosion ($\mathrm{Mg\,ha^{-1}\,h^{-1}}$) (SEMgha) and slope angle (SLA).

Figure 4. Photographs of the road and railway embankments studied. Note the lack of vegetation cover in both photographs and prominent rill development in the upper photograph.