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Badlands forest restoration in Central Spain after 50 years under a Mediterranean-continental climate

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ABSTRACT

This study shows the results of a badlands restoration carried out 50 years ago in Central Spain in terms of soil evolution, vegetation and hydrological characteristics. Although gully restoration is frequently employed to recover degraded soils and reduce sediment yield to rivers and reservoirs, analysis of the evolution of this type of action after a long period of time is not so commonplace. Moreover, this study focuses on a unique area under a Mediterranean-continental climate, with granite and sandy soils. Restoration works consisted in the construction of at least 123 check dams and the reforestation of more than 730 ha, with 2700 trees ha^{-1}. Nowadays, the soils have begun to regenerate. Litter thickness and soil humus is 3.7 cm under the pine-forest, while it is null in the degraded soil. Forest soil has a higher resistance to penetration and higher K and P content. However, there are no significant differences in the% OM, in the content of Ca, Mg, Na and N, or in the steady-state infiltration rate, possibly because of the influence of soil texture. These results show that much more time is needed for soil evolution. As a conclusion, however, restoration works did improve forest cover and some physical and chemical soil properties as well as slowing down soil erosion and sediment production. Suitable silviculture and land management of the current pine forest will improve soil conditions and serve to recover the ancient native oak forest that grew before the intense historic degradation.

1. Introduction

Actually there is a need to understand the effects of the land restoration measures (Vallauri et al., 2002; Clarke and Rendell, 2010; Navarro et al., 2014). Forest and agriculture lands need to be monitored to protect water and soil resources when restoration is necessary (Brevik et al., 2014). In this manner, we can know which are the best management practices to apply in degraded areas (Navarro et al., 2014; Mongil et al., 2015a, b; Cerdà et al., 2016; Keesstra et al., 2016; Yazdanpanah et al., 2016). Badlands restoration was frequent around the world during recent centuries, because badlands produce over 80% of the sediment in their basins (Gallart et al., 2002; Poesen et al., 2002; Martínez-Casasnovas et al., 2009; López-Tarazón et al., 2011), although those only occupy a small fraction of their overall surface area (Poesen and Hooke, 1997). Therefore, badlands are usually considered as hotspots for sediment production, even after their restoration (Hooke et al., 2007). However, the results of badlands restorations have not been sufficiently studied in the long term (Vallauri et al., 2002; Navarro et al., 2014). Although several badland restoration projects were studied in Spain (Boix-Fayos et al., 2007; Castillo et al., 2007; Navarro et al., 2014), they do not focus on the influence of restoration on controlling reservoir siltation, despite their economic impact.

Sediment production is a complex process influenced by many factors: lithology (Cerdà, 1997; Valentin et al., 2005); slope (Regüés and Gallart, 2004; Bochet et al., 2009; Torri et al., 2013); slope face (Castaldi and Chiocchini, 2012; Bierbaß et al., 2014); soil properties such as texture, organic matter, structure, moisture and bulk density (Zougmoré et al., 2009; Zhang et al., 2013; Bierbaß et al., 2014); soil crusting (Finlayson et al., 1987; Valentin et al., 2005); weather conditions like aridity, total and extreme precipitation and rainfall intensity (Gallart et al., 2002; Valentin et al., 2005; Zheng et al., 2008); land use transformation such as agriculture, livestock

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grazing, forest crops and the road network (Valentin et al., 2005; Castaldi and Chiocchini, 2012); and the history of the area (Valentin et al., 2005).

Vegetation cover enhances soil infiltration and protects soil against erosion (Valentin et al., 2005; Navarro et al., 2014). Roots assemble and reinforce soil particles, the vegetation canopy intercepts rainfall energy and produces litter that increases soil surface rugosity (Gallart et al., 2002; Valentin et al., 2005; Zheng et al., 2008; Torri et al., 2013; Navarro et al., 2014). Gully reforestation can lower sediment production by over 62% (Gómez et al., 2003; Valentin et al., 2005). Vallauri et al. (2002) showed that soil erosion diminished 50% after land reforestation with *Pinus nigra* in the French Alps. Navarro et al. (2014) also showed the effectiveness of gully restoration, reporting a threefold decrease in sediment concentration in the River Carrión basin (Saldaña, Spain) 80 years after completion of reforestation works and the construction of check dams.

Vegetation also improves the physical, chemical and hydrological properties of soil that ameliorate land stabilization (Bierbaß et al., 2014). One of the reasons is the thicker horizon of litter generated by reforested trees (Navarro et al., 2014), which stabilizes soil structure, the function of the soil microbial community, the nutrients cycle and soil-pH (Zheng et al., 2005). For these reasons, the soil in forest areas is of better quality than in degraded areas (Zheng et al., 2005; Zhang et al., 2013). Nevertheless, soil erodibility in reforested lands decreases only slightly after less than a century compared to degraded soils in the same area (Navarro et al., 2014) or, as shown by Medeiros et al. (2010), it only is 9% lower than in degraded areas.

The evolution of some properties of the soil in reforested lands can be relatively slow, as can be its fertility (Vallauri et al., 2002; Perkins et al., 2012) or earthworm community (Vallauri et al., 1998). Eighty years after gully reforestation, Navarro et al. (2014) did not find any changes in soil resistance penetration, soil-pH, electric conductivity or bulk density. Laudicina et al. (2012) also report that some soil properties had not evolved six decades after reforestation. Other studies have found that vegetation changed soil properties in degraded areas, such as textural fractions, bulk density, porosity, electric conductivity, pH, some nutrient levels, cation exchange capacity, percentage of interchangeable sodium and organic matter (Carter and Ungar, 2002; Zheng et al., 2008; Bierbaß et al., 2014; Navarro et al., 2014).

Normally, soil infiltration rates increase following reforestation (Bruijnzeel, 2004; Zheng et al., 2005; Perkins et al., 2012; Fields-Johnson et al., 2012; Navarro et al., 2014), even though soil hydrophobicity may also rise (Perkins et al., 2012). Water can usually infiltrate quickly and deeper under the forest canopy (Perkins et al., 2012; Bierbaß et al., 2014). Vegetation cover intercepts rainfall, protecting the underlying soil against the impact of raindrops that compact bare soils, while vegetation roots provide a dense network of channels connecting the surface and bottom of the soil (Fields-Johnson et al., 2012).

During the period 1940 to 1960, the Spanish Government implemented a water resources policy mainly based on river regulation and reservoir construction. An important programme focusing on hydrological and forest restoration of numerous degraded watersheds was also launched to protect both the quantity and quality of water in reservoirs during their lifespan. About $1300 \cdot 10^3$ ha were mainly reforested with different pine species to control runoff, erosion and sediment yield in degraded watersheds (Del Palacio, 2013). Most restoration projects were based on torrent correction, badlands restoration and land reforestation (Mintegui et al., 2006).

The aim of this study was to evaluate the evolution of the vegetation cover, soil and erosion processes in a gullied area on granite soils located in Central Spain, under a Mediterranean-continental climate, as a result of a restoration project dating from 1964. The project aimed to decrease the rate of sediment reaching the Santa Teresa reservoir, located downstream of the gullied area. The analysis of this hydrological and forest restoration is very important, as there are very few studies of similar socio-political and environmental scope carried out more than 50 years after completion of the restoration project. The study will show how the new forest and check dams served to control erosion and sediment levels and to improve the soil and landscape, which are important challenges for other degraded regions worldwide.

2. Material and methods

2.1. Study area

The study area is located in the upper basin of the River Corneja, in the municipalities of Tórtoles and Bonilla de la Sierra, in the southwest of the province of Ávila, Spain (UTM ETRS89 30N: 308365, 4492935). It is situated in the Central System Mountains, in the centre of the Iberian Peninsula (Fig. 1).

The study was carried out in 737 ha of gullies and adjacent degraded land, slopes and screes, inside a reforested area of 40 km^2, whose waters flow into the River Corneja (7 km away). This river flows into the River Tormes, a tributary of the River Duero (Fig. 1). The mean annual precipitation is 571 mm, with maximum and minimum rainfall in autumn and summer, respectively. The Fournier Climatic Index (Fournier, 1960) is 41 mm and the Rainfall Erosivity Factor, R (Wischmeier and Smith, 1978), is 860 $MJ \cdot mm \cdot ha^{-1} \cdot h^{-1}$ (ICONA, 1988). The mean annual potential evapotranspiration, calculated by Thornthwaite's method (Thornthwaite, 1948), is 659 mm. The mean annual temperature is 10.6 °C, the mean of the lowest temperatures for the coldest month is −1.7 °C, and the highest temperatures for the warmest month, 28.1 °C. The dry period is 2.4 months long. All these values reveal a Mediterranean-continental climate. The aridity UNEP Index (UNEP, 1997) is 0.89, which corresponds to a humid region (>0.65), even though the annual precipitation is low. However, the Lang Rainfall Index (Lang, 1915) is 53.9, which means it is a semi-arid zone.

Geologic material is mainly igneous, formed by coarse-grained biotitic porphyry monzogranites (IGME, 2008). It shows a weathered, altered appearance comprising boulders and scree. Some hillsides present colluviums with sand and silt mixed with granite stones and blocks. The soils are Orthents and Xerepts (USDA, 2010), with over 70% sand. Soil texture ranges from sandy clay loam to sandy and soil-pH is 6.7.

The terrain is quite rugged, with hills over 1530 ma s l. connected by steep slopes and valleys with creeks and ravines at around 1100 ma s l. The terrain is mainly south facing, though all types of orientations are to be found. A complex network of gullies appears between the aforementioned maximum and minimum altitudes. The length of the gullies varies between 400 and 1500 m and the width is between 10 and 100 m. The gullies and hillslopes are steep, with a mean slope of 60%, even though the slope of the sides of the gullies is nearly 100%. Drainage density varies between 2 and 40 $km\,km^{-2}$.

The native vegetation was most likely holm oak forest (*Quercus ilex* ssp. *ballota* (Desf.) Samp.), with Pyrenean oak (*Quercus pyrenaica* Willd.) at higher altitudes. However, continuous anthropogenic activity generated a very degraded landscape with a sparse shrub cover, formed mainly by *Thymus zygis* Loefl. ex L., *Lavandula stoechas* Lam. and *Cytisus scoparius* (L.) Link. Nowadays, five decades after the start of the hydrological-forest restoration works, a forest mainly composed of *Pinus sylvestris* L. and *Pinus pinaster* Ait. grows on severely degraded land covered by poor steppe vegetation. This vegetation replaced the ancient native forest of holm oak as a con-