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Are biodiversity indices of spontaneous grass covers in olive orchards good indicators of soil degradation?

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Abstract

Spontaneous grass covers are an inexpensive soil erosion control measure in olive orchards. Olive farmers allow grass to grow on sloping terrain to comply with the basic environmental standards derived from the Common Agricultural Policy (CAP). However, to date there are very few studies assessing the environmental quality and extent of such covers. In this study, we described and compared the biodiversity indicators associated to herbaceous vegetation in two contrasting olive orchards in order to evaluate its relevance and quality. In addition, biodiversity patterns and their relationships with environmental factors such as soil type and properties, precipitation, topography and soil management were analyzed.

Different grass cover biodiversity indices were evaluated in two olive orchard catchments under conventional tillage and no tillage with grass cover, during 3 hydrological years (2011–2013). Seasonal samples of vegetal material and pictures in a permanent grid (4 samples ha^{-1}) were taken to characterize the temporal variations of the number of species, frequency, diversity and transformed Shannon's and Pielou's indices.

Sorensen's index obtained in the two olive orchard catchments showed notable differences in composition, probably linked with the different site conditions. The catchment with the best site conditions (deeper soil and higher precipitation), with average annual soil losses over $10\,t\,ha^{-1}$ and a more intense management, presented the highest biodiversity indices. In absolute terms, the diversity indices were reasonably high in both catchments, despite the fact that agricultural activity usually severely limits the landscape and the variety of species. Finally, a significantly higher content of organic matter in the first 10 cm of soil was found in the catchment with the worst site conditions, average annual soil losses of $2\,t\,ha^{-1}$ and the least intense management. Therefore, the biodiversity indicators associated to weeds were not found to be suitable for describing the soil degradation in the study catchments.

1 Introduction

Soil biodiversity represents the variability among living organisms. Although it is usually related with micro-organisms such as bacteria, fungi, protozoa and nematodes and meso- and macro-fauna (acari, springtails, earthworms, termites, etc.), it also includes plant roots in view of their interactions and symbiosis with other soil components. Soil organisms are responsible for nutrient cycling, regulating the dynamics of soil organic matter, soil carbon sequestration and greenhouse gas emission, and for modifying the physical structure and hydrological regimes of the soil, among other processes. These processes are not only essential to the functioning of natural ecosystems, but they also play a key role in the sustainable management of agricultural systems (FAO, 2014). Biodiversity conservation involves nature's resources to provide the goods and services needed by society.

Biodiversity loss is one of the main environmental risks assuming the planet. The new 2020 Biodiversity Strategy (European Commission, 2011; 2011/2307 INI) aims to improve the contribution of fisheries and agricultural and forestry sectors to biodiversity. The six targets covered by the EU strategy for 2020 are: (1) implementation of the EU nature regulations; (2) to increase the protection and restoration of ecosystems as well as the services they provide, and a better use of green infrastructures; (3) more sustainable managements in agriculture and forestry; (4) to make progress EU fish stocks and sustainable fisheries; (5) the control of Invasive Alien Species; and (6) a greater EU contribution to reduce global biodiversity loss. Agriculture and forestry mean almost 72 % of the land in the EU and play a key role in Europe's biodiversity. On the other hand, the current reform of the Common Agricultural Policy (CAP), and the new Multi-annual Financial Framework for 2014–2020, imply significant opportunities to improve synergies not only in soil biodiversity but also with respect to other degradation processes such as soil loss (European Commission, 2014a).

In this context, one key drawback for the proper implementation of protection policies is the lack of a well-defined quantitative measure or indicator of biodiversity (Spangen-

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berg, 2007; Moonen and Barberi, 2008). The distinction between the use of biotic indicators and biodiversity indicators to determine the state of the environmental aspects of different systems is not usually clear. Measuring the diversity of process-related indicators may be a good way of measuring how well agro-ecosystems react against environmental changes (Moonen and Barberi, 2008). The bio-indicators of soil quality are commonly associated to the biological activity of their microorganisms; however, weed biodiversity may be a simpler way to measure the risk of soil degradation, given that richer and more complex ecological niches produce more efficient cover and soil protection, as well as habitat and food opportunities for other elements of the trophic chain, such as birds or reptiles.

The study of weeds and their interactions have been traditionally associated with the improvement in crop yield (e.g. Graziani et al., 2012; Kamoshita et al., 2014; Mimee at al., 2014) or habitat and species conservation (e.g. Albrecht, 2003; Hyvönen and Huusela-Veistola, 2008; Aavik and Liira, 2009) in agronomical and ecological terms, respectively. However, their importance as indicators of soil loss and degradation has scarcely been explored.

An area of over 2.5 Mha is dedicated to growing olives in Spain (MAGRAMA, 2013), which represents about 41 % of the world olive production. Olive harvesting and its associated agri-food industries are especially important in rural areas from a socio-economical viewpoint. Over 60 % of the area dedicated to olives is located in Andalusia, the Southern most region of the country. A high risk of soil degradation has been described by different authors such as Goméz-Limón et al. (2009) and Gómez et al. (2014) as the result of the interaction of climatological and topographical factors and/or inappropriate soil management. Olive trees have traditionally been cropped under rainfed conditions and on sloping areas where other crops have difficulty growing; they usually provide very low yields or require large investments in order to exploit them properly. The characteristics of the Mediterranean type of climate, where long dry periods alternate with intense rainfall events, in conjunction with soil management systems that pursue bare soils to minimize water competition entail a high susceptibility to severe water erosion of the soil. Therefore, the use of cover crops has been promoted for soil protection, given their proven effectiveness in controlling water erosion (Gómez et al., 2004, 2009a, b; Márquez-García et al., 2013; Taguas et al., 2013, among others). In fact, growing in between the olive tree rows is currently a compulsory requirement if the mean slope of the plot is over 10 %, according to cross-compliance rules (European Commision, 2014b).

The ideal cover crop should be able to provide a high surface coverage in a short time, on often very poor soils. In addition, it should tolerate compaction by machinery traffic and different herbivore species. It should also justify its economic investment by spontaneously regenerating without the need to seed annually. In Mediterranean areas, such as Andalusia, the annual and intra-annual variability of the precipitation and temperature determine the rate of development during the most erosive periods. This entails large differences in the efficiency of the use of cover crops in commercial olive orchards, which are highly dependent on the annual environmental conditions (Gómez and Giráldez, 2009). Different types of vegetative covers can be considered, ranging from spontaneous grass covers to sown mono- or multi-specific covers. Mono-specific covers behave more homogeneously, despite their higher sensitivity to adverse weather conditions than spontaneous covers with a greater variability including more wild species (Soler et al., 2004). Spontaneous covers are usually irregular and develop slowly, which may result in greater competition for water and nutrients during the most critical periods of the olive growing cycle. However, due to its zero cost, it is a common alternative in low production olive farms (e.g. Taguas et al., 2013). Furthermore, additional advantages of spontaneous covers in terms of biodiversity, carbon sequestration and landscape improvement, etc., make it worth our while to study their potential contribution.

The starting hypothesis of this study was that wider ecological niches mean lower risks of soil degradation in terms of organic matter decline and soil losses. In addition, we postulate that the interactions of soil and weed management explain better

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the diversity of spontaneous grass covers than the environmental site conditions (annual/seasonal patterns).

The specific objectives of this work were (1) to describe and compare the biodiversity indicators associated with spontaneous grass covers in two olive orchards with contrasting management intensities, environmental conditions and yields; (2) to analyze the seasonal patterns of these indices, as a result of meteorology and soil management; and (3) to evaluate their relevance as indicators for soil quality, in terms of soil loss and soil degradation.

2 Materials and methods

2.1 Study sites

The study catchments are located in the province of Córdoba (Fig. 1), in Southern Spain. Both of them have been described in detail by Gómez et al. (2014) and Taguas et al. (2013) to evaluate the erosive patterns during the periods 2006–2011 and 2005–2011, respectively, and the results were considered as an accurate evaluation of the soil degradation state.

The "Conchuela" catchment (Con; 37.6° N, −5.0° W, Spain) is situated in a fertile area along the old terraces of the River Guadalquivir. The drainage area of the catchment is 8.0 ha, and it presents an average elevation of 142 m and a mean slope equal to 9 %. The climate is classified as Mediterranean with an average annual precipitation of 642 mm, which is mainly concentrated from October to March (about 76 % of the precipitation). The average annual temperature is 17.5 °C. The maximum daily mean temperature is usually recorded in July (27.8 °C) while the minimum is generally observed in January (8.1 °C). The soil is a Vertisol, according to the FAO classification. It is a deep soil, very plastic when wet, but when dry, the presence of cracks induces high infiltration rates. The predominant soil texture is clay-loam (Table 2). The olive trees were planted in 1993 with 6 × 7 m tree spacing. The mean olive yield in the catchment is 8000 kg ha^{-1} During the study period, the farmer allowed the growth of natural weed vegetation in the lanes from the end of winter until April. Herbicide (glyphosate and oxifluorfen) treatments were applied to control their growth in the tree line from March to September (Table 1). Occasionally surface tillage was made at selected locations within the catchment to cover rills and small gullies obstructing machinery traffic within the orchard. Mowing in the tree lane was performed in areas of excessive grass cover from late winter to early spring. Harvesting is semi-mechanized using tree-vibrators from late autumn to mid-winter, depending on weather conditions and when the fruit ripens (Gómez et al., 2014; Table 1).

The "Puente Genil" catchment (PG; 37.4° N, −4.8° W) represented a marginal olive orchard with a very low production. Management operations are kept to a minimum in order to reduce costs. It is located in an area with a long tradition of olive cropping in the upper reaches of the Guadalquivir Valley. The catchment has a drainage area of 6.1 ha and the mean elevation is 239 m. The average slope is equal to 15 %. As for the climate type, the catchment is located in a Mediterranean area with a mean annual precipitation is of 400 mm. The average temperature in the hottest month (July) is 26.5 °C, while in the coldest month (January) it is 8.4 °C. The main soil category of the catchment is Cambisol (FAO classification) with sandy-loam texture (Table 2). Calcic parental material is located at different points of the catchment with a very shallow soil, mainly on the Western hillslope (Fig. 1b). In contrast, on the Eastern hillslope, soil depth is more than 3 m. The areas closer to the catchment outlet are old terraces with abundant coarse calcarean material. The mean olive yield is 1300 kg ha^{-1}. The olive trees' age is 17 years. They were planted on a 7 m × 7 m grid. No-tillage with spontaneous grass cover growing from winter to spring was the management type corresponding with the first few years. Spontaneous grass is removed once (only in spring) or twice a year (September or October and March, April or May), mechanically or using phytosanitary products under the canopies (or combining both; see also Taguas et al., 2013). The details of the management applied during the study period are summarized in Table 1.

2.2 Weed sampling

Four weed surveys were performed per year (1 per season) during 2011, 2012 and 2013. Survey dates were based on the preceding climatological conditions that determined the germination periods, as well as the development of the spontaneous grass cover. A grid was established in each catchment (Fig. 1) with a sampling density between 4 and 6 points ha^{-1}. In each geo-referenced grid point, a 0.5 × 0.5 m frame was used to delimit the survey area (Fig. 2). These sampling points were always placed in the lanes between the lines of trees away from the olive canopy and the areas of drip irrigation and herbicide application. Plant samples were taken in order to identify the species present at each grid point. In addition, pictures of each point were taken (Reflex Olympus E-420, ED 14–42 mm; height 1.4–1.7 m; Fig. 2) to check the annual and seasonal differences of the herbaceous vegetation.

2.3 Data analyses: biodiversity indices, meteorological variables and soil quality indicators

2.3.1 Biodiversity indices

The indices considered to evaluate the biodiversity associated to the grass spontaneous grass cover were richness (R), Sorensen's index (I_s), transformed Shannon's (H_{mod}) and Pielou's indices (J_{mod}), absolute and relative frequency of occurrence and biological spectrum. R was determined for the total number of species found per catchment per season and per point.

I_s indicates the degree of similarity of two samples (study sites) as regards the species composition (Eq. 1). It ranges from 0 to 1, where 0 means that both samples are completely different and 1 completely equal.

$$I_s = \frac{2 \cdot C}{A + B} \quad (1)$$

Where: A is the number of species identified in PG; B: number of species identified in Con; C is the number of species present on both farms.

Shannon's index , H, (Eq. 2; Shannon and Weaver, 1949) indicates the probability of finding an individual within an ecosystem. It usually produces values of between 1.5 and 4.5. Minimum values are obtained when most of the individuals belong to the same species or to a limited group of (less diverse) species, while the highest values are produced in communities where all the species have the same number of individuals.

$$H = \sum_{i:1\ldots n} (pi.Ln(pi)), \tag{2}$$

where: $p_i = n_i/N$; n_i is the number of individuals corresponding to the species i; N is the total number of individuals. In this case, a modification of Shannon's index, H_{mod}, was used, which was based on picture analysis in order to simplify the the analysis. Therefore, n_i was substituted by the number of grid points where a species was present and N, the total number of grid points considered. The suitability of the transformations associated to H_{mod} and J_{mod} was verified with the samples taken in spring 2013 in both catchments.

Pielou's equity index (Eq. 3; Pielou, 1969) measures the ratio of the observed diversity and the maximum expected diversity. It varies between 0 and 1, which would describe systems where all species are equally abundant.

$$J = \frac{H}{Ln(S)}, \tag{3}$$

where: H is Shannon's index; S is the number of species. If H (Eq. 3) is substituted by H_{mod}, then J_{mod} is obtained.

Finally, the biological spectrum or life-form (Raunkiaer, 1934) was identified for each species according to its behavior during the unfavorable season (June–September): Epiphytes; Phanerophytes Chamaephytes; Hemicryptophytes: Therophytes; Cryptophytes.

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2.3.2 Meteorological variables to describe temporal variability of biodiversity indicators

In order to evaluate the influence of the annual climatology on the biodiversity indices H_{mod}, J_{mod} and R, a correlation analysis was carried out with meteorological features: cumulative precipitation (P), cumulative reference evapotranspiration (ETP), average minimum daily temperatures (T_m). They were checked for the values weighted for previous 5, 15, 30, 60 and 365 days. The precipitation was recorded in the gauging stations of the catchments, while the daily values of ETP and T_m were collected from "La Reina" and "Santaella-CSIC" meteorological stations for Con and PG, respectively (CSIC, 2014).

2.3.3 Soil degradation indicators: soil loss, runoff, organic matter and bulk density

The relationships between the mean values of soil losses, runoff coefficients and organic matter content (0–10 cm) in the catchments with R, J_{mod} and H_{mod} were explored to discuss the role of biodiversity indices as a proxy of soil quality indicators. Soil loss (SL) and runoff coefficient (R_c) were measured in the catchments over 5 years (Taguas et al., 2013; Gómez et al., 2014).

The organic matter content (OM) was determined following the Walkley–Black procedure (Nelson and Sommers, 1982) with samples (2 mm sieve) obtained on regular grids with a density of 6–10 samples ha^{-1} The samples were taken between 0–10 cm combining the inter-row and the area under the tree canopies. The number of samples was 90 and 65 in Con and PG, respectively. Bulk density (BD) was measured in the same grid using undisturbed soil cores of approximately 250 cm^3. A t test for independent samples was used to identify significant differences between the attributes of the catchments.

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3 Results

3.1 Variability of the biodiversity indicators

The mean values of richness, H_{mod} and J_{mod}, were higher in Con than in PG, which probably shows that site-specific conditions have greater importance than long term management effects (Table 3). A lower diversity was identified in PG, which was probably associated with worse environmental conditions in terms of water deficit, as compared to Con (Table 3), coupled with coarser soil texture and lower soil water holding capacity (Table 2). Precipitation was on average 25 % lower in PG while ETP was slightly higher, with respect to Con (Table 3). The soils at PG were also shallower than at Con and of coarser texture, leading to a smaller water storage capacity which might limit the development of vegetation in PG.

With the exception of J_{mod}, the highest coefficients of variation were also observed in PG. Despite the extremely simplified landscapes of both catchments, H_{mod} values were notably high for agricultural systems, particularly in the driest year (2011) with values near to 2.2 and 1.9 in Con and PG, respectively (Table 3). On the other hand, J_{mod} values indicated that there were no dominant species in either of the catchments. These features are common in Mediterranean environments, characterized by a high inter-annual and intra-annual variability of precipitation and temperature, with a wide range of colonizing species awaiting their optimal development conditions without any clear dominant pattern. In spite of the selective herbicide treatments (Table 1), differences in J_{mod} between both catchments were small.

Sorensen's index numerically illustrated the notable differences of species existing in the catchments (Tables 3–5). It is worth noting how winter was the period when the floristic composition was the most similar while the spring, the most different. Although close species spectra were found (Table 5), a different floristic catalogue was observed in both catchments, and the lack of Monocotyledonous in PG is remarkable (Table 5). From the soil protection point of view, the current spectrum is not appropriate because most of the species are not permanently present for a long period of the year. However,

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most of the species constitute the nutritional base for insects and birds. Enrichment of the biological spectrum with Hemicryptophytes and Chamaephytes is suggested in locations where e.g. hedges are compatible with agricultural operations.

The coefficients of correlation between weather variables (T_m, ETP and P) and seasonal biodiversity indicators (H_{mod}, J_{mod} and R) were in general low (Table 7). Significant correlations were only found for PG as a result of the shallow sandy soil with short-term water availability controlling vegetation. In contrast, the deep clay soil at Con enhanced long-term water availability (Table 3) and weakened the correlations between weather variables and biodiversity indicators. Significant negative correlations for ETP15, ETP60 (and T_m60) are related to water stress, whereas the positive correlations for short-term indicators such as T_m15 and ETP5 might indicate optimal conditions for the seed germination and the growth of grass.

3.2 Relationships between biodiversity indices and indicators of soil quality

In addition to R, J_{mod} and H_{mod}, the mean annual values of SL and R_c, measurements of OM and BD are also shown in Table 8 and Fig. 3. R, J_{mod} and H_{mod} were not correlated with soil indicators. The highest values of soil losses and the lowest values of organic matter were found in Con. The differences in OM and BD between the catchments were significant as is shown in Table 8 and Fig. 3a–b (average OM-Con = 1.1 g cm^{-3}; average OM-PG = 1.4 g cm^{-3}). A large quantity of coarse elements was found in PG, which must be taken into account when understanding the differences in BD (Table 8). Substantial higher mean soil loss in Con (16.1 t ha^{-1}) was found with respect to PG (1.8 t ha^{-1}; Fig. 3c), Likewise, the mean R_c in Con (15.3 %) tripled the value of PG (5.1 %; Fig. 3d),

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4 Discussion

Indicators of weed biodiversity were not correlated with soil losses and organic matter. The role of cover crops in soil erosion is related with dissipation of energy from rainfall and runoff. It was expected that a wider ecological niche would allow for a more efficient occupation of space and a higher efficiency in the flow control on the hillslopes. However, in Con, other factors such as precipitation, soil hydrologic characteristics and the possible dominance of concentrated flow (gullies and rills; Gómez et al., 2014) accounted for higher soil losses and runoff coefficient (much higher than PG values). Lewis et al. (2013) highlighted the potential for soil erosion to impinge the weed seedbank increase and to improve the biodiversity in agro-ecosystems of Northern Europe. In natural Mediterranean systems, authors such as Cerdá and García-Fayos (2002) and García-Fayos et al. (2010) also described the susceptibility to seed removal by water erosion according to seed and landscape features. In this context, an annual sediment delivery ratio of 4 % was found in the PG catchment using the SEDD model (Taguas el al., 2011) while in Conchuela, the value was over 90 % indicating an efficient rate of transport, as calculated by Burguet (2015). Both the different values of soil losses and the annual sediment delivery ratios might illustrate the very different sediment dynamics which contribute towards explaining the greater biodiversity in Con.

As for the values of organic matter content, these might be explained by the management systems. No tillage operations were applied in PG from 2005 and machinery traffic was usually minimal (Table 1), which implies less mechanical soil disturbance than in Con, where productive farm management is carried out. In two sites with a silt loam texture in the Ebro Valley in Spain, Fernández-Ugalde et al. (2009) also described an increase in soil organic carbon content associated with non-tillage practices.

Although non-tillage management to maintain bare soil in olive orchards led to larger soil losses, runoff coefficients and soil compaction as compared to conventional tillage and cover crops (Gómez et al., 2004), larger carbon and organic matter contents were found in the topsoil, particularly under the canopy (Gómez et al., 1999). Márquez-

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García (2013) also found lower values of organic carbon in the topsoil of olive orchards under conventional tillage as compared to cover crops (spontaneous and sown). Near the study catchments, in other agricultural land uses under conservation agriculture, smaller amounts of crop residues, lower soil water contents and larger CO_2 emissions were observed in managements where tillage operations were applied (Cid, 2013).

Despite the annual and seasonal variations of meteorological conditions, overall a larger availability of water was observed in Con, as a result of the higher annual precipitation and the notably deeper soil. More extensive management did not lead to greater weed biodiversity. Similarly, Albrecht and Mattheis (1998) found that a management change from conventional to integrated farming in dicotyledonous crops in Germany did not lead to a substantial increment of the number of rare weeds. Hyvönen et al. (2003) found that differences in weed species numbers between organically and conventionally cropped fields in Finland were small. Similar results were highlighted under Mediterranean conditions by Graziani et al. (2012) for a sequence of six rotations in Italy. They found that the number of weed species and biodiversity were only slightly higher in organic systems as compared to low-input conventional systems.

Although single measures, such as the application of fertilizers or certain herbicides, may lead to a strong correlation with species diversity, such as the case of monocotyledoneous in Con, no clear sensitivity to the management was found, as described by Albrecht (2003) in Germany or Pysek et al. (2005) in Central Europe for different crops. This is likely to be a result of the site conditions in Con being substantially better for vegetation growth, which becomes evident from the olive yields at both catchments (Con, 5000–8000 $kg\,ha^{-1}$ and PG $< 2000\,kg\,ha^{-1}$).

5 Conclusions

Sorensen's index for two olive orchard catchments in the province of Cordoba (Spain) showed notable differences in composition, which were probably associated with the different site conditions. Although Con had a more intense management, its better site

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conditions (higher precipitation, deeper soils and less steep slopes) can explain the higher values in richness, Pielou's index and Shannon's index. Water stress is a limiting factor for the development of vegetation in the Mediterranean area, so the notable differences in annual precipitation (400 mm in PG versus 600 mm in Conchuela) account for the differences observed. In addition, a more active sediment transport dynamic might contribute to seed dispersal and to increasing the biodiversity indices.

In absolute terms, the diversity indices were high in both catchments, in spite of the major simplifications derived from the agricultural systems. This can be related with the typical Mediterranean dynamics where temporal variability allows different individual species to be incorporated each year according to certain climatological features. The impact of land-use and management in both catchments explains the dominance of short cycle Therophytes, Hemicryptophites and Cryptophytes, which are extremely resistant to mechanical/chemical treatments, since their buds are kept underground. On the other hand, Therophytes and Hemicryptophytes do not provide efficient soil protection, since their aerial parts are not present during autumn and winter seasons. However, these species are ecologically important for feeding numerous insects and local birds such as partridge (*Alectoris rufa* L).

Higher contents of organic matter were determined in PG, the catchment with the worst site conditions in terms of water availability and the least intense management. Additionally, low soil losses have been measured in this catchment. Therefore, biodiversity indicators associated to weeds were not appropriate to describe the soil degradation.

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Table 1. Management operations applied during the study periods in both catchments.

Catchment	Month	2011	2012	2013
Con	January		Harvesting: Mechanical vibrators combined with a buggy with an umbrella to collect the olives.	Harvesting: Mechanical vibrators combined with a buggy with an umbrella to collect the olives.
	February			
	March	Herbicide treatments around trees (glyphosate and oxifluorfen in infested areas)		Herbicide treatments around trees (glyphosate and oxifluorfen in infested areas) Mowing of lane areas
	April	Mowing of lane areas	Herbicide treatments around trees (glyphosate and oxifluorfen in infested areas) Mowing of lane areas	
	May	Drip irrigation	Drip irrigation	Drip irrigation
	June	Drip irrigation	Drip irrigation	Drip irrigation
	July	Drip irrigation Herbicide treatments around trees (glyphosate and oxifluorfen in infested areas)	Drip irrigation	Drip irrigation Herbicide treatments around trees (glyphosate and oxifluorfen in infested areas)
	August	Drip irrigation	Drip irrigation Herbicide treatments around trees (glyphosate and oxifluorfen in infested areas)	Drip irrigation
	September	Drip irrigation	Drip irrigation	Drip irrigation
	October			
	November			
	December	Harvesting: Mechanical vibrators combined with a buggy with an umbrella to collect the olives.	Harvesting: Mechanical vibrators combined with a buggy with an umbrella to collect the olives.	
PG	January			
	February			
	March			
	April	4 tractor passes to mechanically clear the weeds.		
	May	Foliar fertilization (N, Mg & Fe)	4 tractor passes to mechanically clear the weeds. Herbicide treatments around trees (glyphosate)	
	June			
	July			
	August			
	September			4 tractor passes to mechanically clear the weeds. Herbicide treatments around trees (glyphosate)
	October			
	November	Harvesting: Mechanical vibrators combined with a buggy with an umbrella to collect the olives.	Harvesting: Mechanical vibrators combined with a buggy with an umbrella to collect the olives.	Harvesting: Mechanical vibrators combined with a buggy with an umbrella to collect the olives.
	December			

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Table 2. Example of soil properties in two profiles of the catchments (PG = Puente Genil; Con = Conchuela).

Catchment	Horizon	Width (cm)	% Coarse elements	% sand	% silt	% clay	Texture class	pH	OM (%)
PG	A	10	22.7	59.5	35.2	5.3	Sandy-loam	8.8	1.59
	C	40	24.4	60.8	34.3	4.9	Sandy-loam	8.8	1.59
Con	A	0–56	0.36	5.9	45.1	49.0	Clay	8.6	0.96
	B	56–110	0.00	5.9	46.4	47.7	Clay	8.7	0.53
	BC	110–138	0.00	–	–	–	Clay-loam	–	–
	C	> 138	0.00	–	–	–	Clay-loam	–	–

Table 3. Annual values of biodiversity indices: Richness, modified Shannon's (H_{mod}) and Pielou's indices (J_{mod}); and climatological attributes: average minimum temperature (T_m), annual evapotranspiration (ETP) and precipitation (P) for both catchments. (CV = coefficient of variation).

Year	Richness		H_{mod}		J_{mod}		T_m (°C)		ETP (mm)		P (mm)	
	Con	PG	Con	PG	Con	PG	Con	PG	Con	PG	Con	PG
2011	23	24	2.194	1.880	0.897	0.840	11.7	12.4	1270.5	1383.7	401.0	376.8
2012	26	14	1.947	1.213	0.839	0.834	11.6	11.6	1310.2	1359.8	610.0	434.4
2013	28	24	1.826	1.751	0.850	0.817	11.1	11.7	1230.4	1355.1	621.1	423.8
Mean	25.7	20.7	1.989	1.614	0.862	0.830	11.5	11.9	1270.4	1366.2	544.0	411.7
SD	2.5	5.8	0.187	0.354	0.031	0.012	0.3	0.4	39.9	15.3	124.0	30.7
CV(%)	9.7	28.0	9.4	21.9	3.6	1.4	2.6	3.4	3.1	1.1	22.8	7.5

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Table 4. Annual and seasonal Sorensen's indices for the species identified in both catchments.

Sorensen's index Year	Winter	Spring	Summer	Autumn	Annual average
2011	0.231	0.231	0.320	0.166	0.237
2012	0.571	0.100	0.000	0.333	0.251
2013	0.333	0.087	0.363	0.000	0.196
Mean	0.378	0.139	0.228	0.166	0.228
SD	0.174	0.080	0.198	0.167	0.029

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Table 5. Mean values of biological spectrum during the period 2011–2013 in both catchments.

Biological	Con		PG	
Spectrum	*n*	Frequency (%)	*n*	Frequency (%)
Therophytes	27	62.8	21	60.0
Geophytes	4	9.3	3	8.6
Hemicryptophytes	12	27.9	10	28.6
Chamaephytes			1	2.9

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Table 6. Species identified in the study catchments present in Puente Genil (PG), Conchuela (Con) or both catchments (Both) for the study period.

Species Scientific name	Biological Spectrum	Location
	Dicotyledonous	
	APIACEAE (UMBELLIFERAE)	
Daucus carota L.	Hemicryptophites	Con
	ASTERACEAE(COMPOSITAE)	
Anacyclus clavatus (Desf.) Pers.	Therophytes	Both
Anthemis arvensis L.	Therophytes	Both
Calendula arvensis L.	Therophytes	Con
Centaurea melitensis L.	Therophytes	Both
Cirsium arvense (L.) Scop.	Geophytes	Both
Cichorium intybus L.	Hemicryptophites	Con
Conyza sumatrensis (Retz) E. Walker	Therophytes	PG
Chrysanthemum segetum L.	Therophytes	Both
Picris echoides L.	Hemicryptophites, Therophytes	Both
Senecio vulgaris L.	Therophytes	Both
Silybum marianum (L.) Gaerth	Hemicryptophites	Con
Sonchus asper (L.) Hill	Hemicryptophites, Therophytes	Both
Sonchus oleraceus L.	Hemicryptophites, Therophytes	Both
Taraxacum officinale Weber ex F.H. Wiss	Hemicryptophites	Both
Taraxacum obovatum (Willd) D.C	Hemicryptophites	PG
Pulicaria paludosa Link	Hemicryptophites, Therophytes	Both
	BORAGINACEAE	
Anchusa azurea Mill	Hemicryptophites	PG
Echium plantagineum L.	Hemicryptophites, Therophytes	Both
Heliotropium europaeum L.	Therophytes	Both
	BRASICACEAE(CRUCIFERAE)	
Diplotaxis virgata (Cav) DC	Therophytes	PG
Raphanus raphanistrum L.	Geophytes, Therophytes	Both
Rapistrum rugosum (L.) Bergeret	Therophytes	Both
Sinapis arvensis L.	Therophytes	Con

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Table 6. Continued.

Species Scientific name	Biological Spectrum	Location
	Dicotyledonous	
	CARYOPHYLLACEAE	
Spergula arvensis L.	Therophytes	PG
Stellaria media (L.) Vill	Therophytes	Both
	CISTACEAE	
Fumana ericoides (cav) Gand. In Magnier	Chamaephytes	PG
	CONVOLVULACEAE	
Convolvulus arvensis L.	Geophytes, Hemicryptophites	Con
	CRASSULACEAE	
Umbilicus rupestris (Salisb.) Dandy	Hemicryptophites	PG
	CUCURBITACEAE	
Ecballium elaterium	Hemicryptophites	Con
	FABACEAE(LEGUMINOSAE)	
Ononis punescens L.	Therophytes	PG
Trifolium repens L.	Hemicryptophites	Con
Trifolium campestreScreb.	Therophytes	Con
	GERANIACEAE	
Erodium cicutarium (L.) L'Her	Therophytes	Both
Erodium moschatum (L.) L'Her	Therophytes	Con
Erodium malacoides (L.) L'Her	Therophytes, Hemicryptophites	PG
Geranium molle L.	Therophytes	Con
	LAMIACEAE	
Lamium amplexicaule L.	Therophytes	Both
	MALVACEAE	
Malva sylvestris L.	Hemicryptophites	Both

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Table 6. Continued.

Species Scientific name	Biological Spectrum	Location
	Dicotyledonous	
	PAPAVERACEAE	
Fumaria officinalis L.	Therophytes	Con
	POLYGONACEAE	
Polygonum aviculare L.	Therophytes	PG
	PRIMULACEAE	
Anagallis arvensis L.	Therophytes	Both
	RANUNCULACEAE	
Ranunculus arvensis L.	Therophytes	Both
	RUBIACEAE	
Galium aparine L.	Therophytes	Both
	SCROPHULARIACEAE	
Veronica arvensis L.	Therophytes	PG
Veronica heredifolia L.	Therophytes	PG
	URTICACEAE	
Urtica urens L.	Therophytes	PG
	Monocotyledonous	
	LILIACEAE	
Muscari comosum (L.) Miller	Geophytes	PG
	POACEAE	
Bromus hordaceus L.	Therophytes	Con
Bromus madritensis L.	Therophytes	Con
Bromus squarrosus L.	Therophytes	Con
Hordeum murimum L.	Therophytes	Con
Hordeum leporinum (Link)	Therophytes	Con
Lolium rigidum Gaudin	Therophytes	Con
Poa annua L.	Therophytes	Con

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Table 7. Matrix of correlation between diversity indices (seasonal values) and climatological features: H_{mod} = Shannon's modified index; J_{mod} = Pielou's modified index; R = richness; P = cumulative precipitation; T_m = average of minimum daily temperatures; ETP = cumulative evapotranspiration. Numbers indicate the interval of previous days (5, 15, 30 and 60).

		$P5$	$P15$	$P30$	$P60$	T_m5	T_m15	T_m30	T_m60	ETP5	ETP15	ETP30	ETP60
Con	H_{mod}	0.12	0.33	0.40	0.39	−0.28	−0.26	−0.25	−0.31	−0.35	−0.36	−0.42	−0.43
	J_{mod}	−0.19	−0.25	−0.20	−0.10	0.55	0.52	0.41	0.17	0.29	0.54	0.55	0.44
	R	0.35	0.52	0.49	0.45	−0.16	−0.17	−0.20	−0.29	−0.25	−0.32	−0.36	−0.37
PG	H_{mod}	0.23	0.29	0.11	0.39	−0.12	−0.05	−0.42	**−0.64**	−0.27	**−0.58**	−0.39	**−0.58**
	J_{mod}	−0.19	−0.29	−0.42	−0.18	0.40	**0.60**	0.29	−0.01	**0.61**	0.26	0.51	0.36
	R	0.29	0.38	0.16	0.36	−0.22	−0.09	−0.42	**−0.61**	−0.35	**−0.62**	−0.46	**−0.61**

$N = 12$ – Bold indicates correlations are significant at $p < 0.05$

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Table 8. Means and standard deviations of the annual biodiversity indicators and parameters of soil quality: H_{mod} = Shannon's modified index; J_{mod} = Pielou's modified index; R = richness; OM = organic matter content in upper horizon (0–10 cm); BD = bulk density of upper horizon (0–10 cm); SL = annual soil loss; R_c = runoff coefficient (ratio of the annual values of precipitation and runoff).

Catchment	Stat.	R	J_{mod}	H_{mod}	OM[a] (%)	BD[b] (g cm^{-3})	SL[c] (t ha^{-1})	R_c^c (%)
Con	Mean	25.7	0.86	1.99	1.14	1.61	16.1	15.3
	SD	2.5	0.03	0.19	0.28	0.17	20.8	12.7
PG	Mean	20.7	0.83	1.61	1.39	1.51	1.8	5.1
	SD	5.8	0.01	0.35	0.49	0.15	2.3	4.2

[a] t test showed $p = 0.00052$ (see also Fig. 3a). [b] t test showed $p = 0.002936$ (see also Fig. 3b). [c] See Fig. 3c–d, t test was not carried out because the number of samples was very low. Con ($n = 5$ years), PG ($n = 6$ years).

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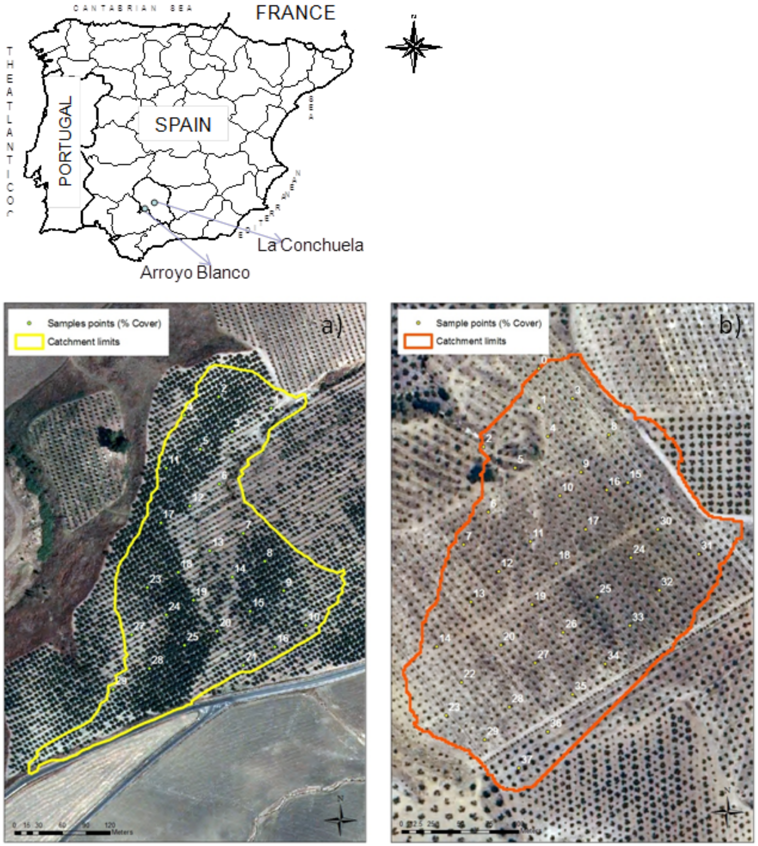

Figure 1. Locations of the study catchments and sample grids: **(a)** La Conchuela (Con); **(b)** Puente Genil (PG).

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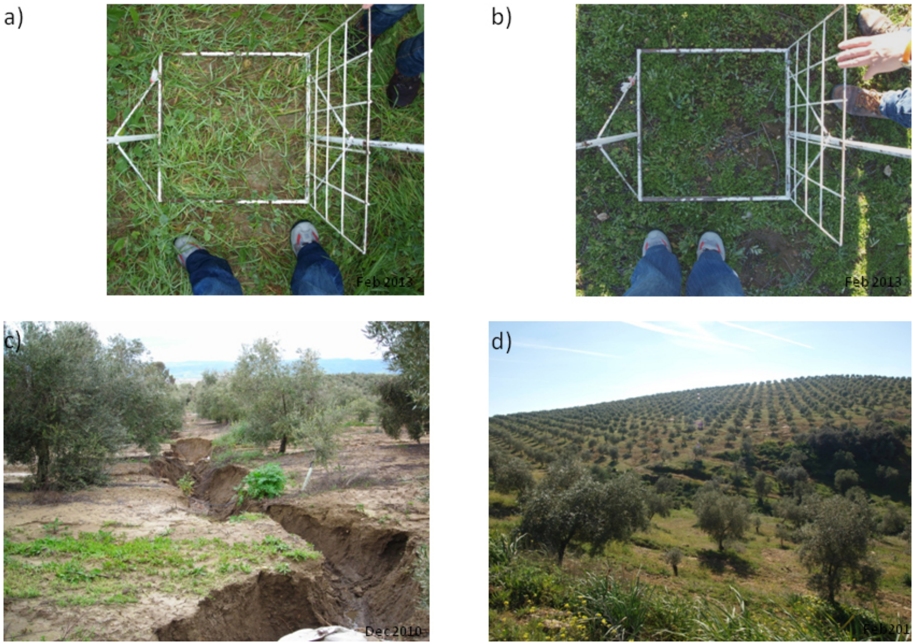

Figure 2. Examples of weed sample plots and view of the catchments: **(a)** a plot in La Conchuela; **(b)** gully with cover crop; **(c)** a plot in Puente Genil; **(d)** view of a hillslope in PG.

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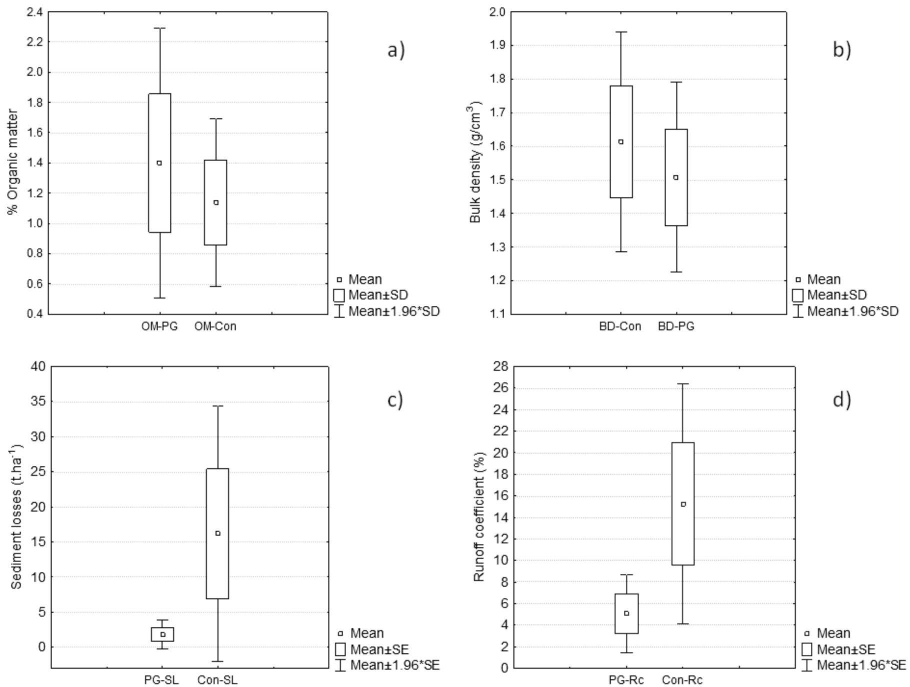

Figure 3. Box and whisker plots of the measurements of soil degradation indicators: **(a)** organic matter content in the upper horizon ($n = 90$ in La Conchuela (Con); $n = 65$ in Puente Genil (PG); **(b)** bulk density in the upper horizon ($n = 90$ in La Conchuela (Con); $n = 65$ in Puente Genil (PG); **(c)** annual soil losses in the catchment outlets ($n = 5$); **(d)** annual runoff coefficients ($n = 5$). (SE = Standard error).