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The effects of farming system and soil management on floristic diversity in sloping olive groves

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Abstract

The effects of the farming system (conventional-organic-abandoned) and soil management (native cover crop *vs* tillage) on vascular plant species were analyzed in sloping olive groves (>20%) in 20 different locations in Andalusia, SE Spain. The soil management techniques included Organic Tillage (OT), Organic Cover Crops (OC), Conventional Tillage (CT), Conventional Non-Tillage (CNT), Abandoned Cover Crops (AC) and Abandoned Woody (AW). Data for the vascular plant species were recorded through three line transects of 30 m with a bar perpendicularly touching every 1 m of the measuring tape. Environmental variables were also recorded at plot level to assess their influence. Dependent variables, such as species abundance, richness and diversity indexes were studied using univariate analysis (one-way ANOVA, Kruskal–Wallis test) while multivariate statistics (ANOSIM, SIMPER, DCA) were used for analyzing the data matrices. We found that the different combinations of farming system and soil management affect biological diversity in terms of individual abundance, plant cover, species richness and diversity, species and family composition. Life forms and species distribution patterns are also affected. The main environmental variables affecting the plant taxa were those related with soil and climate characteristics, slope, olive age and intensive land uses at landscape level, including the percentage of artificial surfaces. The lowest levels of biodiversity (e.g., species richness) were found in the tilled olive groves (CT = 8.1 sp. ± 2.2, OT = 10.0 sp. ± 5.4). Surprisingly, the organic tilled groves (OT) were very poor in species compared to those with native plant cover (OC = 27.9 sp. ± 3.0). The latter, however, showed similar species richness to the abandoned olive groves (AC = 21.2 sp. ± 3.7, AW = 27.2 sp. ± 3.0). Possible solutions for increasingly uncompetitive sloping olive groves include conversion to organic with native plant cover or abandonment for rewilding.

Introduction

Olive groves play a fundamental role in the production system of the southern regions of Europe. In 2020, the gross value of olive production was 6762 million US$ in Spain, 19,349 in Europe and 23,891 worldwide (FAOSTAT, 2022).

Most of these earnings come from traditional olive groves. This type of olive grove has long been considered a typical Mediterranean agroecosystem of great importance in the maintenance of biodiversity and the control of soil erosion, and as part of the ancient Mediterranean cultural heritage and landscape identity (Loumou and Giourga, 2003).

However, the traditional olive grove, like other Mediterranean agroecosystems, is currently undergoing dramatic changes due to intensification, changes in soil management techniques and, in many cases, abandonment. All these processes are being mediated by globalization (Guzmán-Álvarez and Navarro-Cerrillo, 2008; Lozano-García *et al.*, 2017). These changes are having significant effects on the ecosystem services provided by olive farming and on crop sustainability. In recent times, new intensive olive groves have been planted in areas where cereals or traditional olive groves once dominated. This, combined with the progressive increase in production costs, the increasing average age of farmers, and the lower value of the olives and olive oil, are making traditional olive groves less profitable. Sloping olive groves are particularly vulnerable to changes of this kind (Duarte *et al.*, 2008) because mechanization of farm work is limited by problems of accessibility and drivability of agricultural machinery on steep hillsides (Blanco, 2009; CAPDR, 2018).

In Spain, olive groves cover a total area of 2,770,424 ha., of which 1,673,657 ha are in Andalusia (ESYRCE, 2021). There are adult plantations of olives on surfaces with many different degrees of slope. 29.6% of Andalusian olive groves are on slopes of over 20%, the threshold above which total mechanization is considered impossible (Blanco, 2009; CAPDR, 2018). With the current trend toward mechanization, these olive groves are becoming less and less viable and are therefore at serious risk of being abandoned. Surveys on land use (ESYRCE,

2021) indicate that the percentage of 'unmaintained' olive groves in Spain is 6.6%, and 3.4% in Andalusia. Many of these 'unmaintained' olive groves may in fact have been abandoned. That makes it difficult to quantify the 'real' area of abandoned olive groves and how this has changed over time.

Traditional olive groves are based on a conventional farming system in which the soil is tilled to control ground cover. For the last several decades, tillage has been complemented by the use of inorganic fertilizers and synthetic pesticides. Tillage is especially detrimental in strongly sloping areas, where it can lead to severe soil erosion. That is why soil management must be taken into account when assessing the environmental services provided by agroecosystems, in which it can be just as or even more important than the farming system applied (Soriano *et al.*, 2014; Sánchez-Fernández *et al.*, 2020).

On the other hand, although little research has so far been conducted into what happens to olive groves once they have been abandoned, it seems that the flora undergo a rapid secondary succession process, and a phenomenon known as 'renaturalization' or rewilding (Rühl *et al.*, 2011) occurs, as happens in other types of agricultural land, in which pastures are progressively transformed into scrublands, shrub formations and later into woodland (di Pietro and Blasi, 2002; Loumou and Giourga, 2003; Rühl *et al.*, 2011; Maccherini *et al.*, 2013; Romero-Díaz *et al.*, 2016). The herbaceous flora in the early grassland and scrub seasons show high diversity and are dominated by *Poaceae* and *Fabaceae* species (Lasanta *et al.*, 2020). This process depends on the time elapsed since the grove was abandoned (García, *et al.*, 2007; Solomou and Sfougaris, 2015), as well as on flora composition and the soil seed bank. Other important factors include the plant communities that surround it (Solomou and Sfougaris, 2015; Rey *et al.*, 2019) and any isolated trees within the olive grove which can act as perches (Rühl *et al.*, 2011). Rewilding is also affected by edaphic issues, stoniness, slope, soil penetration resistance, the presence of terraces (García *et al.*, 2007; Maccherini *et al.*, 2013; Perrino *et al.*, 2014), overgrazing -which prevents succession and encourages erosion- (Arhonditsis *et al.*, 2000; Maccherini *et al.*, 2013), and fires (Rühl, *et al.*, 2011).

In order to understand more about the patterns and processes affecting plant diversity (as an indicator of biodiversity) in sloping olive groves at high risk of abandonment and how they are affected by farming system (conventional-organic-abandonment) and soil management (native cover crop *vs* tillage), 20 different locations were studied across Andalusia. The ultimate goal is to provide data that will be useful for taking decisions about the future of sloping olive groves in line with the European Green Deal and the Biodiversity Strategy for 2030. We predict that the way an olive grove is managed will be reflected in the biodiversity. The following hypotheses were tested: (i) organic farming and abandonment will provide more biodiversity than conventional farming; (ii) soil management practices such as native cover crops will also have a significant influence on biodiversity, although it will be strongly mediated by environmental variables such as climate, soil features or landscape structure.

Material and methods

Study site

We selected 20 locations with sloping olive groves situated on slopes with a gradient of over 20% within a total area of 1 million ha in the provinces of Granada, Jaén, Córdoba and Málaga (Andalusia, Spain) (Fig. 1). Three adjacent or very close plots were selected in each locality, one from each of the three farming systems: organic (O), conventional (C) and abandoned (A). They were all mature olive groves, with more than one trunk per tree, an average age of 55 years, from 100–139 trees ha^{-1} and a canopy volume ranging between 1019–5350 m^3 ha^{-1} (Table 1). We contacted the owners of the plots to find out about the farming systems used and how long the abandoned groves had been in that condition. We then classified each plot according to the farming system and soil management technique applied (Pastor *et al.*, 2004; ESYRCE, 2021, see Fig. 2), as follows:

- Organic Tillage (OT): certified-organic management with soil tillage ($n = 4$).
- Organic Cover Crops (OC): certified-organic management with a cover crop controlled by mowing ($n = 16$).
- Conventional Tillage (CT): traditional soil tillage. Depending on the intensity of the tillage, soil can have some weed cover in autumn and early spring ($n = 11$).
- Conventional Non-Tillage (CNT): application of pre- and post-emergence herbicides over the soil surface. Some later-emerging weeds may escape the effects of the herbicides ($n = 9$).
- Abandoned Cover Crops (AC): Sloping olive groves abandoned between 2000 and 2015, with herbaceous vegetation covering the soil surface (i.e., first stages of abandonment) ($n = 5$).
- Abandoned Woody (AW): Sloping olive groves abandoned between 1950 and 2000, with woody vegetation established by secondary succession (i.e., consolidated abandonment) ($n = 15$).

In the treatments involving tillage, this was done twice a year, in the autumn and the spring. In these cases, plant sampling was always carried out before the spring tillage. In all cases, the same soil management technique was applied in each plot from at least 2009 onwards. When we use the term 'cover crops', we are referring to native or spontaneous cover crops.

Plant sampling

Plant sampling was carried out during spring 2017. Data about the vascular plants were recorded through three line transects of 30 m in length, with a bar perpendicularly touching every 1 m of the measuring tape. Transects were always arranged perpendicular to the slope. The selection of the starting point of each transect inside the plots was randomly selected. Starting at 0.5 m, 30 points per transect and 90 per plot were monitored using an adapted version of the point-quadrat sampling technique (Chalmers *et al.*, 1989). All the species from the different layers touching the bar at the same point were registered. Each vascular plant was counted only once, even if the bar touched the same individual several times. Bare ground, litter, gravels (rock <4 mm), rock (rock >4 mm) and bryophytes were recorded when no plants were found. The contacts with the canopy of the olive tree were also counted. From these data, we calculated the total and partitioned cover (%) of both vascular plant species and the other surface layers (litter, gravels, rocks, bryophytes, bare ground).

From the floristic data we estimated plant species richness (S), i.e., the total number of species per sample; abundance (N), i.e., the number of individuals of each species per sample; and species diversity calculated from the above using the Shannon–Wiener

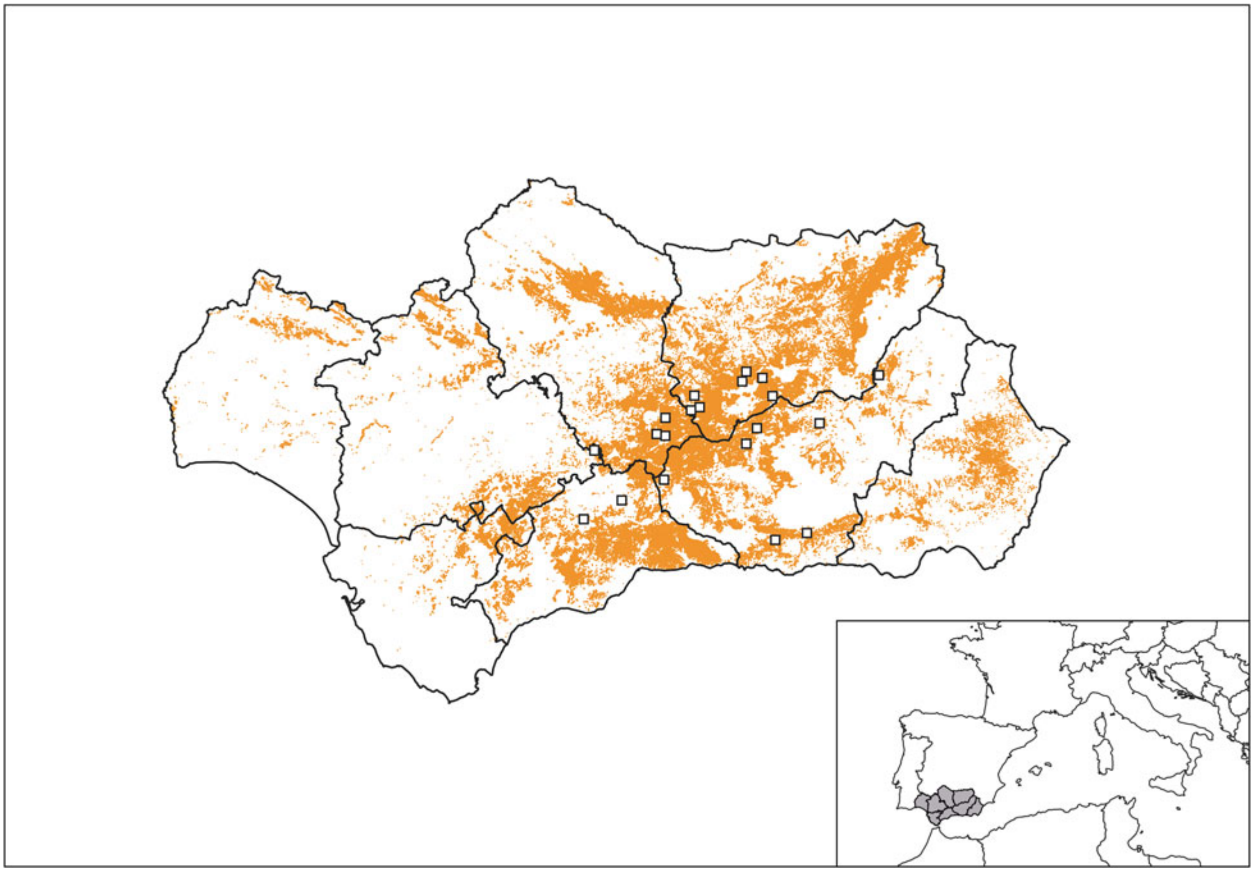

Fig. 1. Location of the study places (☐) in Andalusia (South Spain). In orange distribution of olive groves with slope > 20%.

(H'), Simpson (D) and Margalef indexes (Magurran, 1988). The Shannon–Wiener index measures the uncertainty of a category in a particular set. The Simpson index represents the probability that two randomly selected individuals from the habitat will belong to the same species, and the Margalef index provides a measure of species richness that is roughly normalized for sample size without using more complex rarefaction techniques. These indexes are widely used in studies of plant species and composition in olive groves and higher index values mean higher diversity (Solomou and Sfougaris, 2011, 2013, 2015; Al Harbi, 2017; Gómez *et al*., 2018; Carpio *et al*., 2020) The species abundance by plant families, Raunkiaer life forms (therophytes, geophytes, hemicryptophytes, chamaephytes, nanophanerophytes and phanerophytes), life cycle (annual and perennial) and distribution range were also analyzed. The methods for identifying species and families, life form, life cycle and distribution were based on Castroviejo (1986), and Blanca *et al.* (2009).

Environmental data

We recorded geographic and topographic variables (latitude, altitude, slope), climatic variables (mean annual temperature and precipitation, potential insolation), soil features (shear stress, soil organic carbon, N, P and K contents, C:N ratio, pH, cation exchange capacity, gravel content, clay content and water resource depletion), tree status at plot level (soil coverage at tree level, olive tree age and years since abandonment), and data registered at landscape level (mean data recorded at 1-km buffer around the plots to analyze landscape complexity and cover surface areas of olive groves, shrubland, grasslands, broadleaf-forest, conifer, rainfed cereals, woody-crop, water-body and artificial surface).

Climate date such as altitude (m), mean annual air temperature (°C), mean annual precipitation (mm) and potential insolation (total hours of sunlight per year) were extrapolated from REDIAM (2019), while the slope (%) was measured with a clinometer. Tree age and year since abandonment were obtained directly from land owners and Orthoimages of REDIAM (2019). Trunk perimeter (at 30 cm above the soil) and height was measured manually, and canopy volume (m^3_ha^{-1}) and tree cover (m^2 ha^{-1}) were calculated from tree height and spread according to Gálvez *et al.* (2004). Tree mound (soil loss around trunk, m^3_ha^{-1}) was obtained using the Stocking and Murnaghan (2001) soil degradation index.

Soil bulk density (g_cm^3) was calculated according to Grossman and Reinsch (2002), and soil parameters such as gravels (%), clay (%), pH, CEC ($cmol^+$_kg^{-1}), soil phosphorus (Mg_ha^{-1}), soil potassium (kg_ha^{-1}) and water resource depletion (mm) according to MAPA (1986). The C:N ratio was also analyzed to a soil depth of 30 cm. C was analyzed by wet oxidation with the dichromate method (Nelson and Sommers, 1996), and N using the Kjeldahl method (Bremner, 1996).

At landscape level we established a buffer of 1-km radius around the centroid of each sampling plot following the methodology of Scalercio *et al.* (2012) to analyze the vegetation cover and land use based on the Andalusian Map of Land Uses and Vegetation Covers from 2017 (E 1:25,000; REDIAM, 2019). We obtained 55 different land uses and vegetation covers, which were then grouped into these broad categories: olive groves,

Table 1. Information about the localities studied, including mean data recorded at plot level for geographical coordinates (X, Y), slope, mean air temperature (Tavg), mean annual precipitation (Pavg), altitude, potential insolation, canopy volume, soil coverage tree canopy, tree mound, years of abandonment (applicable for abandoned plots), olive tree age, soil shear stress, pH, bulk density, soil organic carbon, soil nitrogen, C:N ratio, soil potassium, cation exchange capacity, gravels, clay, water resource depletion and variables measured at 1-km buffer cover surface area (ha) around the plots

Locality	X	Y Y	Slope (%)	Tavg (°C)	Pavg (mm)	Altitude (m)	Total sun hours year	Canopy volume (m^{3}ha^{-1})	Soil coverage tree canopy (m^{2}ha^{-1})	Tree mound (m^{3}ha^{-1})	Years of abandonment
Colomera	438,019	4,136,060	38	14.8	570	783	3791	4404	2074	25	13
Venta de Andar	444,224	4,145,022	31	14.1	643	923	4036	2411	1200	21	13
Venta del Carrizal	411,212	4,156,955	29	15.4	627	625	4076	1414	1045	37	40
Cortijo Solis	408,065	4,163,863	26	14.5	598	792	3862	1415	989	41	17
Las Madrilas	390,795	4,115,683	35	15.6	719	600	4102	4248	2041	30	20
Las Cabreras	406,081	4,155,352	38	15.3	611	605	4021	1174	856	26	40
Esparragal	391,613	4,150,983	36	14.7	673	698	3937	2180	1212	41	33
Los Bermejos	391,471	4,140,624	46	14.1	727	844	3762	3096	1781	38	61
Carcabuey	386,590	4,141,632	31	14.3	775	832	3796	3309	1867	46	40
Cambil	447,333	4,173,863	25	13.5	596	1174	3789	1378	931	23	6
La Guardia	437,946	4,177,485	38	15.1	613	781	3908	1019	805	14	20
Puertoalto	435,737	4,171,825	40	15.2	673	781	3698	1878	1284	12	20
Arbuniel	453,304	4,163,499	27	13.2	635	1201	3914	2047	1230	19	24
Gobantes	344,340	4,093,153	22	17.0	528	379	4005	5350	2506	29	33
Peñon Enamorados	366,414	4,103,918	29	16.3	523	531	4109	1575	1034	18	20
Campocámara	514,293	4,175,504	27	14.2	714	894	4131	1097	670	15	8
Pedro Martínez	480,168	4,147,852	29	14.2	458	943	4086	1237	805	15	20
Badolatosa	350,816	4,132,435	38	17.0	487	284	4129	4529	2251	19	33
Ízbor	455,174	4,081,108	29	16.0	578	570	3681	1923	1558	34	13
Almegijar	472,770	4,084,258	31	14.5	671	938	3772	3018	1869	22	40

Olive tree age (mean locality)	Shear stress (kPa)	pH	Bulk density (Mg.m-^{3})	Soil Organic Carbon (Mgha^{-1})	N soil kgha’$^{-1}$	C:N	K soil kgha^{-1}	P soil kgha^{-1}	CEC cmolc kg^{-1}	Gravels %	Clay (%)
41	59	7.9	1.1	4.5	0.5	9.1	98	2.0	7.8	23	29
39	46	7.8	1.1	10.6	1.5	7.2	141	8.0	10.0	16	35
52	141	8.1	1.2	11.4	1.0	11.1	135	2.4	7.8	35	25
60	117	8.1	1.0	12.5	1.2	10.2	130	4.0	9.6	38	25
60	76	8.3	1.1	8.7	0.8	9.7	107	1.4	10.3	28	33
65	48	8.3	1.0	9.6	1.0	9.3	98	2.2	11.7	53	32

(*Continued*)

Table 1. (*Continued.*)

Olive tree age (mean locality)	Shear stress (kPa)	pH	Bulk density (Mg.m-^{3})	Soil Organic Carbon (Mgha^{-1})	N soil kgha’$^{-1}$	C:N	K soil kgha^{-1}	P soil kgha^{-1}	CEC cmolc kg^{-1}	Gravels %	Clay (%)
62	47	8.0	0.8	16.1	1.6	10.2	157	2.7	15.5	58	34
60	51	8.2	0.9	8.4	0.8	10.2	157	1.1	14.6	50	52
62	57	8.0	0.8	13.1	1.3	10.2	208	5.1	18.4	38	42
55	57	8.0	0.9	12.9	1.2	10.8	187	2.7	14.1	49	37
65	47	8.1	0.8	11.7	1.1	10.5	159	1.4	18.6	64	39
60	55	8.1	1.0	12.5	1.2	10.6	85	1.6	15.6	32	31
41	54	8.0	0.9	12.0	1.3	9.4	242	3.7	16.8	46	44
55	67	8.2	1.0	6.0	0.7	8.6	180	1.3	21.7	28	43
65	38	8.1	0.9	8.3	0.7	12.3	63	1.8	8.2	41	22
45	17	8.4	1.0	4.4	0.4	11.9	80	0.8	5.2	30	30
60	19	8.4	1.1	3.8	0.4	11.0	82	1.7	7.6	32	24
65	71	8.2	1.1	5.6	0.6	9.8	81	5.3	6.5	13	31
41	28	8.2	0.9	4.1	0.5	8.6	23	1.1	6.3	54	13
49	73	8.1	1.1	5.2	0.6	9.5	36	1.6	5.4	53	11

Water resource depletion (mm)	Landscape complexity	Olive groves	Shrublands	Grasslands	Broadleaf forests	Conifers	Rainfed cereals	Woody crops	Water bodies	Artificial
4.8	20	216	47.4	1.1	19.6	0.0	1.6	25.5	2.0	1.1
4.6	14	190	0.0	0.7	1.5	0.0	101	6.1	1.8	13.3
3.9	7	269	18.2	0.0	8.7	0.0	0.0	1.4	16.6	0.0
3.3	16	158	69.4	0.0	56.3	16.0	0.0	2.2	12.1	0.0
3.3	16	145	53.5	1.4	98.5	0.0	5.3	3.7	5.5	1.3
2.5	14	193	10.5	30.6	0.0	56.7	0.0	6.9	16.5	0.0
1.2	10	156	17.7	93.2	33.2	0.0	0.0	12.4	0.0	1.6
2.0	11	146	50.4	2.7	103	0.0	0.0	12.3	0.0	0.5
2.0	11	145	146.0	13.1	3.3	0.0	0.0	7.0	0.0	0.0
2.7	12	117	132.9	0.0	0.0	60.1	0.0	4.7	0.0	0.0
1.2	23	180	46.8	47.3	0.0	0.0	1.8	14.2	7.7	16.3
4.4	12	188	79.2	0.0	0.2	0.0	0.0	28.1	16.1	2.0
2.7	24	95	64.3	17.1	32.4	77.5	2.4	16.9	5.9	2.5
3.7	14	120	71.6	11.9	21.9	0.0	0.0	4.2	84.6	0.3
2.5	10	149	60.2	12.3	0.0	0.0	73.0	8.9	0.0	10.8

(*Continued*)

Table 1. *(Continued.)*

Water resource depletion (mm)	Landscape complexity	Olive groves	Shrublands	Grasslands	Broadleaf forests	Conifers	Rainfed cereals	Woody crops	Water bodies	Artificial
4.0	10	176	3.9	0.0	0.0	69.0	13.3	47.1	5.3	0.0
3.4	11	56	195.0	0.0	0.0	0.0	39.4	23.5	0.0	0.0
6.0	15	164	21.4	7.4	3.0	47.6	11.1	3.8	44.6	11.4
2.1	14	36	70.5	9.3	0.0	12.7	1.7	184	0.0	0.0
2.7	19	47	99.5	3.2	0.0	2.3	4.2	141	7.5	9.0

shrubland, woody crops, broadleaf forests, grasslands, conifers, rainfed cereals, water bodies and wetlands and artificial surface. On the basis of the number of categories found in each buffer and the number of different patches from each category, we then measured landscape complexity using the Shannon index.

Data analysis

The diversity of vascular plants was estimated through the number of species, the number of individuals from each species, and the diversity indexes in order to determine the specific structure and richness of the population of plant species and to analyze the effects of the different treatments (Magurran, 1988). For this purpose, one-way ANOVAs or Kruskal–Wallis tests were applied with treatments as the independent variable. Normality and homogeneity of variance tests were carried out, after which one-way ANOVAs were applied to the biodiversity-related parameters, and Kruskal–Wallis tests were applied to soil covers.

To analyze the effects of the different treatments on the whole species composition, we used cluster analysis in Q-mode and UPGMA (unweighted pair-group method using the arithmetic average based on the Bray–Curtis similarity index). For this purpose, we used the presence-absence of species and aggregated the data by treatments.

A dissimilarity analysis (ANOSIM), which was also based on the Bray–Curtis similarity index (Clarke, 1993), was performed as a non-parametric test that allows significant differences between two or more groups to be identified. The *R*-test statistic expresses dissimilarity between the groups, over a range of 0 to 1. When *R* values are close to or equal to 1 and $P \leqslant 0.05$, this is a sign of significant dissimilarity (Legendre and Legendre, 1998). This analysis was carried out for species, family, chorology and life form for all the treatments analyzed globally and by pairs of treatments.

We also carried out a SIMPER analysis (percentage similarity procedure; Clarke, 1993) on the pairs that showed significant differences in ANOSIM. Species, family, chorology and life form were also analyzed.

The effect of the environmental variables was analyzed via redundancy analysis (RDA), a constrained ordination method proposed by Ter Braak and Smilauer (2002) for linear data, which was verified by the length of the gradient of the first axis (<2) of a Detrended Correspondence Analysis (DCA) made with the species matrix. The individual significance of the environmental variables was analyzed through the marginal effects ($\lambda 1$) obtained using automatic forward selection, although the variables finally included in the RDA were those showing higher conditional effects (λA) and $P \leqslant 0.05$ (the effect contributed by each variable over and above the combined effect of all the other variables already selected, so avoiding collinearity). The variability in the species and samples due to environmental variables was tested using the Monte Carlo permutation test (499 permutations) for the first and all canonical axes.

Index calculation and statistical analysis were performed on the data using Past software ver. 3.2 (Hammer *et al.*, 2001), and the Statistix 9.0 software package. Multivariate analyses (DCA, RDA) were carried out using CANOCO 4.5 (Analytical Software, Tallahassee, FL, USA) (Lepš and Šmilauer, 2003).

Results

The OC treatment showed the highest mean cover of vascular plant species (54.5% ± 1.8 SE), especially compared to the

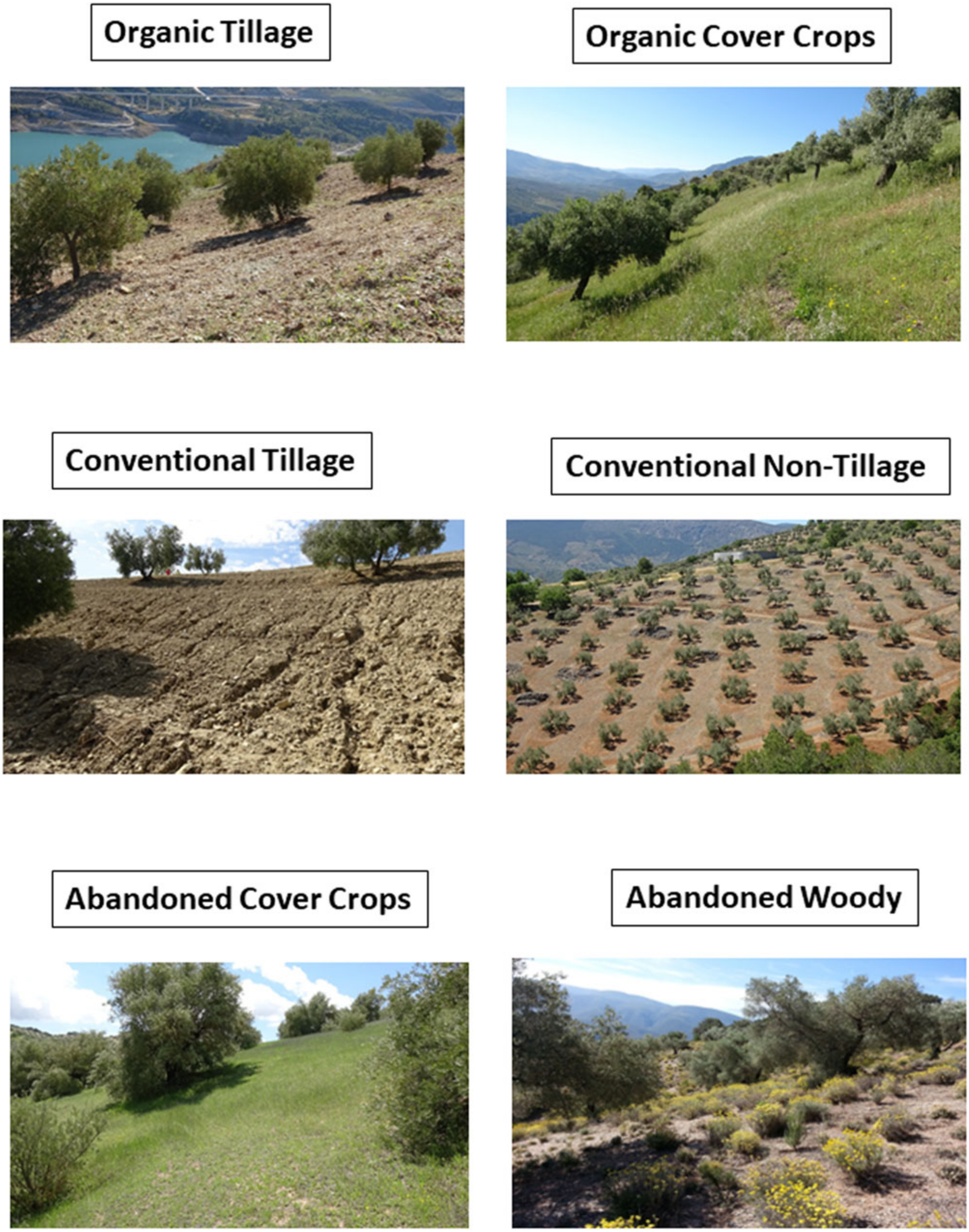

Fig. 2. Combinations of farming system and soil management analyzed in this study.

treatments involving tillage (OT = 23.1% ± 5.4, and CT = 18.1% ± 3.4). Bare ground also obtained higher values in these last two variables than OC, AC and AW, while CNT obtained intermediate values (Table 2). Litter cover was minimal in the tilled treatments, while it was higher in the abandoned olive groves (AW and AC) and in organically farmed groves with a native cover crop (OC).

Table 2. Mean percentage (%) ± standard error (SE) for the area covered by different soil covers in each treatment

	OT	OC	CT	CNT	AC	AW	All	
Soil Cover	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Signif.	Mean
Vascular plants	23.1 ± 5.4bc	54.5 ± 1.8a	18.1 ± 3.4c	28.5 ± 3.6bc	43.0 ± 4.4ab	42.4 ± 1.2b	0.0001	37.7
Litter	5.3 ± 1.8bc	19.3 ± 1.4a	3.1 ± 0.7c	13.5 ± 2.1ab	24.6 ± 3.0a	21.1 ± 1.5a	0.0001	15.4
Gravels	15.0 ± 3.9abc	9.6 ± 1.4bc	12.6 ± 2.5bc	25.9 ± 3.0a	3.6 ± 1.0c	13.7 ± 1.6ab	0.0001	13.5
Rocks	2.6 ± 0.8ab	1.9 ± 0.5b	1.2 ± 0.5b	4.3 ± 0.9ab	1.2 ± 0.4b	5.5 ± 0.7a	0.0001	3.0
Bryophytes	0.0 ± 0.0b	2.3 ± 0.9b	0.7 ± 0.5b	1.5 ± 0.9bc	8.5 ± 3.6ab	6.2 ± 1.0a	0.0001	3.2
Olive canopy	8.8 ± 1.6	6.5 ± 0.8	10.1 ± 1.8	6.9 ± 1.4	9.3 ± 2.1	6.5 ± 1.0	0.5	7.6
Bare ground	45.1 ± 6.5ab	5.8 ± 0.9d	54.1 ± 4.5a	19.4 ± 3.2bc	9.9 ± 2.8cd	4.6 ± 0.9d	0.0001	19.5

OT, organic tillage; OC, organic cover crops; CT, conventional tillage; CNT, conventional non-tillage; AC, abandoned cover crops; AW, abandoned woody.
The Kruskal–Wallis test was performed at $P \leqslant 0.05$. Different letters show significant differences in the Kruskal–Wallis All-Pairwise Comparisons Test. The last column shows the mean for each soil cover.

Bryophyte cover was significantly higher in the abandoned olive groves (AC and AW) while in the treatments involving tillage, either no bryophytes were found (OT) or the value was very low (CT). Gravels and rocks on the surface of the soil were particularly high in AW and CNT (Table 2).

A total of 294 species from 45 plant families were accounted for in this study. For most of the treatments analyzed, the flora was dominated by annual species ranging from 84% in CT to 91% in OC, with the exception of AW olive groves, where perennial species dominated with 53% (Supplementary Table S1).

At plot level, the highest mean species richness was found in OC (27.9 ± 3.0), AC (21.2 ± 3.7) and AW (27.2 ± 3.0), and the lowest in OT (10.0 ± 5.4) and CT (8.1 ± 2.2) (Table 3). The highest individual abundance was also found in OC (146.6 ± 17.9) and the lowest in CT (25.8 ± 10.4) and OT (21.8 ± 14.1). CT obtained the lowest values in both the Simpson index and the Shannon index (0.63 ± 0.1; 1.4 ± 0.3 respectively). These values were significantly different from the highest values, which were obtained by OC, AC and AW. In general, CNT obtained intermediate values while the lowest values were obtained by the treatments involving tillage (Table 3). The treatments involving tillage (OT and CT) showed significantly lower values on the Margalef index, while AW scored the highest value (5.7 ± 0.5).

Cluster analysis separated the combinations involving tillage (CT and OT) from all the others (Fig. 3). Of these, AW and OC were most similar to each other and were different from the cluster formed by CNT and AC.

The analysis of similarity (ANOSIM) for plant species composition, plant family, chorology and life form based on abundance data was statistically significant when globally analyzed (Table 4). Analyzed by pairs of treatments, AW showed significant *P* values for all pairwise comparisons, showing the highest *R* (dissimilarity) values when compared to the tilled treatments (especially OT). In all the variables studied, significant *P* values were obtained in the comparison between OC and OT and the highest *R* values. In general, at species and family composition level, OT was different from all the other treatments except CT and CNT. As regards chorological distribution and life form, OC and AW showed dissimilarity from all the other treatments, and the highest *R* value (0.7) was obtained in the AW-OT pair for life form (Table 4) (Supplementary Table S2).

According to the SIMPER analysis (Table 5), the dominant life form was the therophyte (with a 64.8% contribution to dissimilarity), which was most abundant in OC (44.3). By contrast, AW showed high abundance values for chamaephytes, hemicryptophytes and nanofanerophytes. The main families contributing to the dissimilarity between the treatments were *Poaceae, Fabaceae* and *Asteraceae* (64%). *Poaceae* species were especially abundant in OC, AC and to a lesser extent AW, while *Fabaceae* and *Asteraceae* species were most abundant in OC. The abundance of *Fabaceae* species was especially low in the tilled olive groves (OT and CT). CT was the only treatment with an abundance of *Fumariaceae* and *Papaveraceae* species, while AW had the greatest abundance of *Lamiaceae, Cistaceae, Rhamnaceae,*

Table 3. Mean values ± standard error of species richness (S), abundance (N) and diversity indices

	OT	OC	CT	CNT	AC	AW		
Indices	Mean±SE	Mean±SE	Mean±SE	Mean±SE	Mean±SE	Mean±SE	Signif.[1]	Transf.[2]
S	10.0 ± 5.4bc	27.9 ± 3.0a	8.1 ± 2.2c	17.2 ± 4.5bc	21.2 ± 3.7ab	27.2 ± 3.0a	***	#
N	21.8 ± 14.1c	146.6 ± 17.9a	25.8 ± 10.4c	52.1 ± 15.4bc	101.8 ± 33.5ab	94.5 ± 9.9b	***	
Simpson_1-D	0.71 ± 0.1ab	0.87 ± 0.02a	0.63 ± 0.1b	0.75 ± 0.1ab	0.88 ± 0.01a	0.87 ± 0.03a	**	
Shannon_H	1.7 ± 0.5bc	2.6 ± 0.1a	1.4 ± 0.3c	2.1 ± 0.4abc	2.5 ± 0.1ab	2.7 ± 0.2a	**	
Margalef	2.9 ± 1.1cd	5.4 ± 0.5ab	2.3 ± 0.4d	4.0 ± 0.9bcd	4.5 ± 0.5abc	5.7 ± 0.5a	***	#

OT, organic tillage; OC, organic cover crops; CT, conventional tillage; CNT, conventional non-tillage; AC, abandoned cover crops; AW, abandoned woody.
Different letters denote Tukey's HSD post hoc significant differences ($P \leqslant 0.05$) for the treatment factor in each parameter (one-way ANOVA).

[1] Values followed by different letters in the same row show significant differences at levels: NS = No Signif.; *$P \leqslant 0.05$; ** $P \leqslant 0.01$; *** $P \leqslant 0.001$.

[2] # Transf. log(x).

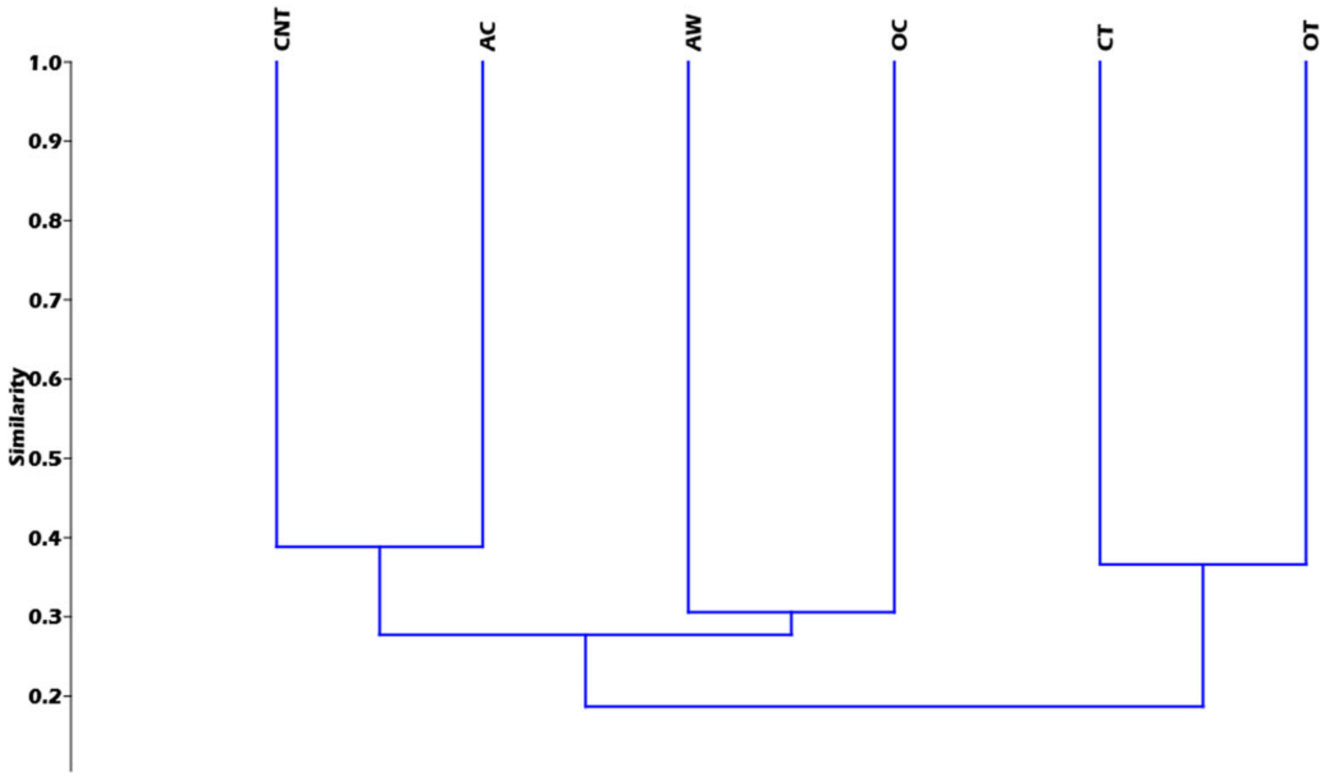

Fig. 3. Hierarchical clustering using the Bray–Curtis similarity index and cluster analysis in Q-mode and UPGMA for each treatment. OT = organic tillage; OC = organic cover crops; CT = conventional tillage; CNT = conventional non-tillage; AC = abandoned cover crops; AW = abandoned woody.

Fagaceae (*Quercus* species), and typical families of geophytes such as *Orchidaceae, Iridaceae* and *Liliaceae,* which were not found in the other treatments. According to this analysis, the Mediterranean, Iberian and Paleartic species were the ones that encompassed most of the dissimilarity between the treatments (81.7%). Of these, the Mediterranean species make the greatest contribution to dissimilarity (56.7%) and were dominant in all the treatments, especially OC, while the Iberian and Baetic species dominated in AW (Supplementary Table S2).

The contribution of the main plant species to dissimilarity (up to 68.5%) was especially notable in OC and AW (Table 6). Annual grasses and legumes were dominant in OC. AW had a quite different plant species composition, with higher abundance of perennial and woody species (Supplementary Table S2), while the treatments involving tillage were dominated by ruderal species such as *Lolium rigidum, Diplotaxis virgata* and *Eruca vesicaria.*

Species richness (S) was also influenced by a range of different environmental variables. In particular, it was highly and positively correlated with soil organic carbon content ($r = 0.617$, $P = 0.000$), soil nitrogen content ($r = 0.516$, $P = 0.000$), soil shear stress ($r = 0.404$, $P = 0.001$), and to a lesser extent with soil gravel percentage, cation exchange capacity, C:N ratio, age of the olive grove, and mean annual precipitation (Table 7). By contrast, species richness was negatively correlated with the presence of woody crops (olive groves) and the area of rainfed cereal calculated at landscape level, soil pH, water resource depletion, olive canopy volume, mean annual temperature and tree mound (Table 7). Abundance (N) was also highly correlated with the soil organic carbon ($r = 0.757$, $P = 0.000$), nitrogen ($r = 0.684$, $P = 0.000$), potassium and phosphorus contents and with cation exchange capacity (Table 7), as well as with soil shear stress and mean annual precipitation. It was negatively correlated with soil pH ($r = -0.461$, $P = 0.000$), and with the presence of patches of woody crops (olives) at landscape level.

RDA conducted using the abundance of individuals by plant families clearly segregated the conventional combinations (C) from the organic combinations (O) and the abandoned olive groves (A). More specifically, the AW and OC combinations showed a higher abundance of individuals belonging to families such as *Fabaceae, Poaceae and Asteraceae*, etc., while families such as *Fumariaceae, Polygonaceae* and *Papaveraceae* were more abundant in OT and CT (Fig. 4). AC and CNT appeared in an intermediate position between OC and OT-CT. The effects of the explanatory variables (Monte Carlo test with 499 permutations) were highly significant for the first canonical axis (Eigenvalue = 0.166, *F*-ratio = 9.744, $P = 0.002$) and for all the canonical axes (Trace = 0.339, *F*-ratio = 2.509, $P = 0.002$). The total variance explained by all the variables used in the RDA was 69.6%. The main variables explaining the total variance in the data regardless of their interactions (singly analyzed, marginal effects) were soil organic carbon and nitrogen, soil shear, mean annual temperature and precipitation and olive age. When these effects were taken into account (conditional effects), the significant variables were soil organic carbon ($\lambda = 0.11$, $F = 7.44$, $P = 0.002$), soil phosphorous content ($\lambda = 0.04$, $F = 2.53$, $P = 0.010$), soil shear ($\lambda = 0.03$, $F = 2.17$, $P = 0.018$), mean annual temperature ($\lambda = 0.04$, $F = 2.38$, $P = 0.010$), slope ($\lambda = 0.03$, $F = 2.24$, $P = 0.006$), artificial surface ($\lambda = 0.02$, $F = 1.69$, $P = 0.052$) and soil clay ($\lambda = 0.02$, $F = 1.67$, $P = 0.040$). In addition to having a higher abundance of individuals belonging to the main plant families, both OC and AW were influenced by and positively correlated with the soil organic carbon, nitrogen and phosphorous contents, as

Table 4. Analysis of similarities (ANOSIM) for species, family, chorology and biotype both globally for all treatments and for pairs of treatments

	Flora				Family				Chorology				Biotype			
Global test			*R*	*P*			*R*	*P*			*R*	*P*			*R*	*P*
Treatments	All		0.30	0.0001	All		0.30	0.0001	All		0.3	0.0001	All		0.4	0.0001
Pairwise test																
Treatments	OT	AW	0.6	0.002	OT	OC	0.6	0.002	OC	OT	0.6	0.002	AW	OT	0.7	0.002
	CT	AW	0.5	0.002	OT	AC	0.6	0.002	OC	CT	0.5	0.002	OC	OT	0.6	0.002
	OT	OC	0.4	0.002	OT	AW	0.6	0.002	AW	OT	0.5	0.002	OC	CT	0.5	0.002
	OT	AC	0.4	0.002	CT	OC	0.4	0.002	AW	CNT	0.5	0.002	AW	OC	0.5	0.002
	CNT	AW	0.4	0.002	CT	AW	0.4	0.002	OC	CNT	0.4	0.002	AW	CT	0.5	0.002
	OC	AW	0.3	0.002	CNT	AW	0.4	0.002	AW	AC	0.4	0.002	AW	CNT	0.5	0.002
	AC	AW	0.3	0.003	CNT	OC	0.3	0.002	AW	CT	0.4	0.002	OC	CNT	0.4	0.002
	CNT	OT	0.2	0.005	AC	AW	0.3	0.05	AW	OC	0.3	0.002	AW	AC	0.4	0.002
	CNT	OC	0.2	0.003	OC	AW	0.1	0.002	OT	AC	0.2	0.04				
	CNT	CT	0.1	0.003												

OT, organic tillage; OC, organic cover crops; CT, conventional tillage; CNT, conventional non-tillage; AC, abandoned cover crops; AW, abandoned woody.
Only the *R* values that showed significance at a level of $P \leqslant 0.05$ are shown.

well as with soil clay, slope, shear and olive age. By contrast, OT, CT and CNT were correlated with mean annual temperature, and the presence of artificial surfaces at landscape level (Fig. 4).

Finally, the ordination diagram obtained through the DCA run for the individual abundance of the 'species × plot' matrix showed the similarity between treatments according to their species composition and species richness (Fig. 5). In that biplot, treatments including tillage (OT, CT) were poorer in species and had different species composition than non-tilled treatments (OC, CNT). In fact, in terms of species richness and species composition, OC and CNT had more in common with the abandoned olive groves (AW, AC) than with the tilled ones (OT, CT).

Discussion

In this study, we evaluate the ground cover and the composition and diversity of the plant species in 20 sloping olive groves (in Andalusia, SE Spain) tended using different farming and soil management systems. These olive groves are subject to a range of different environmental conditions and are at high risk of being abandoned.

Independently of the farming system (organic or conventional) applied in each olive grove, tillage (OT, CT) resulted in a low percentage of vegetation cover, litter and bryophytes on the soil surface. This is because most of these components are either destroyed or buried during tillage. By contrast, very high percentages were recorded in abandoned or untilled olive groves. This contrasts with the results obtained by Maccherini *et al.* (2013), who observed an impoverishment of the bryophyte cover in abandoned olive groves with a strong presence of woody species. Vegetation cover assessment shows that OT and CT had soil coverage of less than 30%, the minimum level considered for conservation agriculture systems (Lal, 2015). The highest value was obtained by OC with coverage of 73.8%. Meyer *et al.* (1970) recorded a 1/3 reduction in soil water erosion compared to bare soil when plant debris was used to provide 31% soil cover. Espejo-Pérez *et al.* (2013) found practically zero erosion with covers of 70% in olive groves, and Sastre *et al.* (2018) noted a decrease of 80% in soil erosion with *Trachynia dystachia* coverage of over 80%. Therefore, in the cultivation conditions being studied here, on slopes of 20% or above, which are highly vulnerable to erosion, OC, AC and AW offer very satisfactory levels of soil protection.

In general, the flora of the olive grove is dominated by annual species (Pujadas Salvá, 1986; Perrino *et al.*, 2014; Simoes *et al.*, 2014), since one of the main objectives when managing the weedy vegetation that appears in olive groves is to eliminate the perennial species that are considered the greatest competition for the main crop (Pujadas Salvá, 1986; Fernández-Quintanilla *et al.*, 1991). Indeed, the only treatment in which the species with perennial life forms (chamephytes, hemicryptophytes, phanerophytes) were the most abundant was AW, as reported by Fernández-Quintanilla *et al.* (1991) and Simoes *et al.* (2014). That means that all the vegetation control operations involving tillage (OT, CT) or herbicide application (CNT) tended to reduce the vascular plant diversity. In short, although from an agronomic point of view, vegetation control has traditionally been considered advisable as a means of increasing olive production (Huqi *et al.*, 2009), it has a high environmental cost, especially in sloping agriculture where the topsoil is more vulnerable to erosion.

The dominance of species from the *Poaceae, Fabaceae* and *Asteraceae* families was also noted in previous studies of the flora in Mediterranean olive groves (Huqi *et al.*, 2009; Solomou

Table 5. SIMPER analysis for biotypes, families and chorological types

Biotypes	Dissimilarity Avg·	Contribution %	Cumulative %	OT	OC	CT	CNT	AC	AW
Therophyte	44.5	64.8	64.8	9.0	44.3	7.1	14.7	29.2	12.8
Camephyte	11.3	16.4	81.2	0.3	1.7	0.5	0.6	2.2	9.7
Hemicriptophyte	8.9	13.0	94.2	0.9	2.5	0.6	1.8	2.3	7.4
Nanofanerophyte	2.8	4.1	98.3	0.1	0.1	0.0	0.1	0.1	3.0
Macrofanerophyte	0.8	1.1	99.4	0.0	0.3	0.2	0.0	0.0	0.3
Geophyte	0.4	0.6	100	0.0	0.0	0.0	0.19	0.1	0.2
Family									
Poaceae	22.2	29.1	29.1	4.4	16.0	3.4	3.2	16.6	11.3
Fabaceae	16.6	21.7	50.8	1.1	14.7	1.9	6.2	7.1	6.5
Asteraceae	10.1	13.2	64.0	0.7	7.2	0.5	2.9	4.3	4.6
Lamiaceae	3.7	4.9	68.8	0.1	1.0	0.0	0.3	0.0	3.0
Brassicaceae	3.0	4.0	72.8	1.0	1.8	0.5	0.3	0.3	0.6
Rubiaceae	2.7	3.6	76.3	0.1	1.2	0.2	1.3	0.3	1.5
Apiaceae	2.2	2.9	79.2	0.1	0.9	0.2	0.6	1.3	1.1
Primulaceae	1.8	2.4	81.6	0.1	0.9	0.2	0.3	0.5	0.5
Convolvulaceae	1.7	2.2	83.8	0.6	0.7	0.5	0.2	0.4	0.2
Caryophyllaceae	1.7	2.2	86.1	0.6	0.7	0.1	0.6	0.4	0.0
Linaceae	1.6	2.1	88.2	0.1	0.5	0.1	0.1	0.5	0.9
Rosaceae	1.2	1.6	89.7	0.0	0.3	0.3	0.4	0.5	0.3
Plantaginaceae	1.1	1.4	91.2	0.3	1.0	0.0	0.0	0.7	0.3
Malvaceae	1.0	1.3	92.5	0.0	0.1	0.2	0.0	0.0	0.6
Euphorbiaceae	0.7	0.9	93.4	0.00	0.35	0.09	0.11	0.20	0.33
Geraniaceae	0.6	0.8	94.2	0.13	0.63	0.12	0.07	0.00	0.00
Veronicaceae	0.6	0.8	94.9	0.00	0.46	0.00	0.22	0.07	0.05
Cistaceae	0.4	0.6	95.5	0.00	0.04	0.00	0.00	0.07	0.43
Polygalaceae	0.4	0.5	96.0	0.13	0.13	0.00	0.00	0.07	0.17
Dipsacaceae	0.3	0.4	96.4	0.53	0.04	0.00	0.00	0.00	0.07
Campanulaceae	0.3	0.4	96.8	0.00	0.10	0.00	0.15	0.13	0.00
Resedaceae	0.3	0.4	97.2	0.33	0.02	0.06	0.07	0.00	0.00
Gentianaceae	0.2	0.3	97.5	0.00	0.00	0.00	0.00	0.33	0.00
Ranunculaceae	0.2	0.3	97.8	0.00	0.02	0.00	0.00	0.13	0.17
Asparagaceae	0.2	0.3	98.1	0.00	0.04	0.00	0.04	0.07	0.12
Hyacinthaceae	0.2	0.2	98.4	0.00	0.02	0.03	0.11	0.07	0.02
Rhamnaceae	0.2	0.2	98.6	0.07	0.00	0.00	0.00	0.00	0.17
Fumariaceae	0.1	0.2	98.8	0.00	0.00	0.09	0.00	0.00	0.00
Pinaceae	0.1	0.2	99.0	0.00	0.17	0.00	0.00	0.00	0.02
Smilaceae	0.1	0.1	99.1	0.00	0.00	0.00	0.00	0.00	0.10
Fagaceae	0.1	0.1	99.2	0.00	0.00	0.00	0.00	0.00	0.07
Papaveraceae	0.1	0.1	99.3	0.00	0.00	0.09	0.00	0.00	0.00
Clusiaceae	0.1	0.1	99.4	0.00	0.06	0.00	0.00	0.00	0.00
Orobanchaceae	0.1	0.1	99.5	0.00	0.02	0.00	0.00	0.00	0.07
Scrophulariaceae	0.1	0.1	99.6	0.00	0.00	0.00	0.22	0.00	0.00
Thymelaeaceae	0.1	0.1	99.7	0.00	0.00	0.00	0.00	0.00	0.10

(*Continued*)

Table 5. (*Continued.*)

Biotypes	Dissimilarity Avg·	Contribution %	Cumulative %	OT	OC	CT	CNT	AC	AW
Crassulaceae	0.1	0.1	99.7	0.00	0.02	0.00	0.04	0.00	0.00
Anacardiaceae	0.05	0.1	99.8	0.00	0.00	0.00	0.00	0.00	0.05
Capparaceae	0.04	0.1	99.9	0.00	0.00	0.03	0.00	0.00	0.00
Globulariaceae	0.03	0.03	99.9	0.00	0.00	0.00	0.00	0.00	0.02
Caprifoliaceae	0.02	0.03	99.9	0.00	0.00	0.00	0.00	0.00	0.02
Orchidaceae	0.02	0.02	99.9	0.00	0.00	0.00	0.00	0.00	0.02
Cyperaceae	0.02	0.02	99.97	0.00	0.00	0.00	0.00	0.00	0.02
Iridaceae	0.02	0.02	99.99	0.00	0.02	0.00	0.00	0.00	0.00
Liliaceae	0.01	0.01	100	0.00	0.00	0.00	0.00	0.00	0.02
Chorology									
Mediterranean	36.6	56.7	56.7	7.7	32.2	6.6	10.6	21.3	20.8
Iberian	8.2	12.6	69.4	0.9	2.7	0.5	0.8	2.0	7.0
Paleartic	8.0	12.4	81.7	0.9	7.6	0.8	2.9	3.9	1.0
Cosmopolitan	6.6	10.3	92.0	0.1	4.8	0.6	2.2	5.3	1.9
Holartic	2.7	4.2	96.2	0.6	1.1	0.1	0.7	0.6	0.4
Euroasian	2.2	3.5	99.7	0.0	0.4	0.0	0.2	0.8	2.1
Baetic	0.2	0.3	99.9	0.0	0.0	0.0	0.0	0.0	0.2
Atlantic	0.05	0.07	100	0.1	0.0	0.0	0.0	0.0	0.0

OT, organic tillage; OC, organic cover crops; CT, conventional tillage; CNT, conventional non-tillage; AC, abandoned cover crops; AW, abandoned woody.
The dissimilarity average (Bray–Curtis distance), the contribution of each type, and the accumulated contribution are presented. The highest values that contribute most to the differentiation appear in shading.

and Sfougaris, 2011; Perrino *et al.*, 2014; Simoes *et al.*, 2014). When vegetation is controlled exclusively by the application of pre-emergence herbicides (CNT), this favored the establishment of annual legumes, such as *Medicago minima, M. orbicularis, M. polymorpha, Scorpiurus muricatus* and *Astragalus hamosus*, which germinate well in the fall without the need to bury the seeds (Siles *et al.*, 2016). The widespread presence of annual legumes was reported by Saavedra *et al.* (1992) when studying untilled olive groves where the vegetation was controlled with herbicides. The floristic composition of OC (Table 5) presented a balanced composition of *Poaceae* and *Fabaceae*, which according to Simoes *et al.* (2014) is the ideal cover for soil health and agronomic purposes. This is because the *Poaceae* species generally produce more biomass and fix more soil carbon due to their fasciculated root system and root renewal rate (Márquez-García *et al.*, 2013), while the *Fabaceae* species increase inorganic N in the soil (Rodrigues *et al.*, 2013). A mixture of *Poaceae* and *Fabaceae* with a balanced C:N ratio is therefore highly recommended in this sense. In our case, this occurs naturally in the OC treatment, which is also the one with greatest biodiversity.

The species *Trachynia distachya* was dominant (spontaneously) in AW, OC and AC (Table 6), which explains why so many research studies refer to it and why it has been chosen as a suitable option for those wishing to plant vegetation covers in their olive groves. *T. distachya* has been used as a cover crop because it germinates in the field without having to be planted under the soil (Jiménez-Alfaro *et al.*, 2018). It has also been used as a cover crop in olive groves on gypsum soils (Sastre *et al.*, 2017, 2018). Its carbon sequestration capacity in olive grove soils has also been analyzed (Repullo-Ruibérriz de Torres *et al.*, 2018), and it has been used as a cover crop in conservation agriculture to prevent soil degradation and ensure sustainability (Rodríguez-Lizana *et al.*, 2018).

The dominant species in the tilled olive groves (CT and OT) was *Lolium rigidum*. Trials with *Lolium* in which seeds were buried by tillage showed that seeds buried at 10–20 cm have more persistence, deteriorate less and come out before dormancy (Cechin *et al.*, 2021). This explains the dominance of this species and other similar ruderal species in tilled olive groves (Cohen *et al.*, 2015). In untilled groves, *Lolium* seeds remain on the surface, where they become a food source for predatory ants (Baraibar *et al.*, 2017). Tillage, however, tends to bury the seeds, which in this way escape their predators. The ants themselves are also affected by tillage, even when tine farrows are used (Campos *et al.*, 2011; Hevia *et al.*, 2019).

Finally, it is known that frugivorous bird species are responsible for high seed dispersal of fleshy fruit species. It is possible that these birds use olive trees as perches (Rühl *et al.*, 2011; González-Varo *et al.*, 2017). That would explain the existence of perennial species with fleshy fruit in the area under the olive tree canopy in AW. Species such as *Sylvia atricapilla* show a preference for abandoned olive trees rather than those that are intensively cultivated (Assandri *et al.*, 2017). That could explain why some species were only found in the AW olive groves. Those include *Pistacia lentiscus, P. terebintus, Quercus rotundifolia, Rubus ulmifolius, Smilax aspera, Asparagus acutifolius, Rhamnus alaternus* and *Rubia peregrina* among others, characteristic species of the Mediterranean forest and of endozoochorous seed dispersal (Bonet and Pausas, 2004). As expected, they are also more abundant in abandoned olive groves because they

Table 6. Results of SIMPER analysis showing the dissimilarity average (Bray–Curtis distance), and the contribution (%) made by the different plant species (total, cumulative and for each treatment).

Taxa	Dissimilarity Avg.	Contribution %	Cumulative %	OT	OC	CT	CNT	AC	AW
Trachynia distachya	6.4	6.8	6.8	0.07	4.33	0.39	0.37	3.07	2.88
Medicago minima	4.4	4.7	11.4	0.33	4.50	0.30	1.81	2.07	0.33
Lolium rigidum	3.8	4.1	15.5	1.60	1.44	2.03	0.41	1.13	0.02
Bromus madritensis	3.4	3.6	19.1	0.47	2.54	0.33	0.96	2.47	0.38
Avena sativa	3.1	3.3	22.4	0.07	1.88	0.15	0.59	4.53	0.43
Aegilops geniculata	3.0	3.1	25.5	0.93	1.83	0.36	0.19	1.87	0.36
Medicago rigidula	2.9	3.0	28.5	0.13	2.02	0.21	1.37	1.27	0.24
Scorpiurus muricatus	2.6	2.8	31.3	0.07	2.17	0.42	1.19	0.33	0.19
Leontodon longirrostris	2.6	2.7	34.0	0.13	1.90	0.03	0.37	1.47	1.02
Helichrysum italicum	1.8	1.9	35.9	0	0.17	0	0	0.67	0.79
Dactylis glomerata	1.8	1.9	37.8	0	0.35	0	0	0.80	1.64
Anagallis arvensis	1.5	1.6	39.4	0	0.81	0.03	0.22	0.33	0.38
Brachypodium retusum	1.4	1.4	40.8	0	0.19	0	0	0	1.38
Macrochloa tenacissima	1.3	1.4	42.3	0	0	0	0	0	1.36
Retama sphaerocarpa	1.3	1.4	43.7	0.07	0.02	0	0	0.07	1.55
Medicago truncatula	1.3	1.3	45.0	0.07	1.35	0	0.33	0	0
Silene latifolia	1.2	1.2	46.2	0.60	0.21	0.03	0.48	0	0
Linum suffruticosum	1.2	1.2	47.4	0.13	0.38	0.06	0	0	0.60
Avena barbata	1.0	1.1	48.5	0.07	0.48	0.03	0.56	0.13	0.48
Bromus diandrus	1.0	1.1	49.6	0.07	1.27	0	0	0.60	0.05
Aegilops triuncialis	0.9	1.0	50.5	0	0.50	0	0	1.47	0.21
Avenula bromoides	0.9	0.9	51.5	0	0.02	0	0	0	0.91
Galium verticillatum	0.9	0.9	52.4	0	0.35	0.06	0.52	0.07	0.24
Trifolium scabrum	0.8	0.9	53.3	0	0.92	0.12	0.04	0.73	0.10
Sanguisorba verrucosa	0.8	0.9	54.2	0	0.19	0.06	0.41	0.47	0.21
Diplotaxs virgata	0.8	0.9	55.0	0.20	0.44	0.06	0.19	0.13	0.02
Convolvulus meonanthus	0.8	0.9	55.9	0.53	0.40	0.15	0.07	0.40	0.10
Calendula arvensis	0.8	0.8	56.7	0.07	0.54	0	0.67	0	0.02
Teucrium pseudochamaepytis	s 0.8	0.8	57.6	0	0.13	0	0	0	0.71
Sherardia arvensis	0.7	0.8	58.3	0	0.54	0.12	0.33	0.20	0.26
Thymbra capitata	0.7	0.8	59.1	0	0.31	0	0	0	0.24
Medicago polymorpha	0.7	0.8	59.9	0	0.88	0	0.41	0	0.02
Scandix pecten-veneris	0.7	0.8	60.6	0	0.58	0	0	0.93	0
Glossopappus macrotus	0.7	0.7	61.4	0	0.46	0	0.19	0.33	0.24
Phagnalon rupestre	0.7	0.7	62.1	0	0.02	0	0.07	0.40	0.26
Thymus mastichina	0.6	0.7	62.8	0.07	0	0	0	0	0.67
Bituminaria bituminosa	0.6	0.6	63.4	0	0.25	0.09	0.04	0.07	0.41
Ulex parviflorus	0.6	0.6	64.1	0	0	0	0	0	0.60
Vicia lutea	0.6	0.6	64.7	0	0.23	0.12	0.07	0.60	0.02
Euphorbia exigua	0.6	0.6	65.2	0	0.27	0.09	0.11	0.13	0.24
Eruca vesicaria	0.5	0.6	65.8	0.27	0.19	0.15	0.04	0	0
Cistus albidus	0.5	0.6	66.4	0	0	0	0	0	0.55

(*Continued*)

Table 6. (*Continued.*)

Taxa	Dissimilarity Avg.	Contribution %	Cumulative %	OT	OC	CT	CNT	AC	AW
Sonchus oleraceus	0.5	0.6	67.0	0	0.52	0.03	0.15	0.07	0.07
Cuscuta sp.	0.5	0.6	67.5	0.07	0.10	0.27	0	0	0.02
Crepis foetida	0.5	0.5	68.1	0	0.63	0	0.11	0.20	0.05
Hordeum murinum	0.4	0.5	68.5	0	0.63	0.03	0.04	0	0

OT, organic tillage; OC, organic cover crops; CT, conventional tillage; CNT, conventional non-tillage; AC, abandoned cover crops; AW, abandoned woody.
The highest values that contribute most to the differentiation appear in shading. The cumulative contribution (%) made by all these species comes to 68.5%.

Table 7. Pearson's correlation coefficients between soil/agro-environmental variables with abundance of individuals (N) and species richness (S). The asterisks show significant differences at 0.05 (*); 0.01 (**); and 0.001 (***).

Flora abundance (N)		
Pearson's Sig. (bilateral)		
PH	−0.461	***
Soil organic carbon (Mg-ha^{-1})	0.757	***
Soil nitrogen (Mg-ha^{-1})	0.684	***
Shear stress (kPa)	0.373	**
Soil potassium (kg-ha^{-1})	0.38	**
CEC (cmol^{+}-kg^{-1})	0.336	**
Soil phosphorus (Mg-ha^{-1})	0.314	*
Woody crops (ha)	−0.287	*
Average precipitation (mm)	0.283	*
Average temperature (°C)	−0.253	*
Grassland surface (ha)	0.253	*
Flora richnes (S)		
Pearson's Sig. (bilateral)		
Soil organic carbon (Mg-ha^{-1})	0.617	***
Soil nitrogen (Mg-ha^{-1})	0.516	***
Shear stress (kPa)	0.404	***
Soil coverage tree canopy (m^{2}-ha^{-1})	−0.346	**
Olive age (y)	0.34	**
Grassland surface (ha)	0.324	*
Woody crops (ha)	−0.308	*
Gravels (%)	0.304	*
pH	−0.297	*
Water resource depletion (mm)	−0.283	*
Average precipitation (mm)	0.278	*
Olive tree surface (ha)	0.275	*
Canopy volume (m^{3}-ha^{-1})	−0.27	*
Average temperature (°C)	−0.268	*
Tree mound (m^{3}-ha^{-1})	−0.269	*
CEC (cmol^{+}-kg^{-1})	0.266	*
C:N	0.258	*
Rainfed cereal surface (ha)	−0.258	*

disappear or are rarer in areas where the vegetation is returned to the early stages of natural succession by soil management (e.g., tillage). In any case the presence of olive trees, which also grow wild in the Mediterranean region, could facilitate the return to the native forest.

In this paper we demonstrate how different farming systems and soil management techniques can affect biological diversity at different levels, in terms of individual abundance, plant cover, species richness and diversity, species and family composition, as well as life forms and species distribution patterns. The soil management systems involving soil tillage (CT, OT) showed the least biodiversity, even in organic olive groves, where the tilled groves (OT) were much poorer in species than those with native plant cover (OC). Similar plant biodiversity results were recorded by Carpio *et al.* (2020), albeit only in terms of species richness. However, in a study by Terzi *et al.* (2021) of olive groves in Apulia (Italy), tillage was not the worst culprit in terms of reducing biodiversity, in that herbicides produced even lower levels, probably due to a more intensive use of herbicides than in our plots (CNT).

In view of our results, there are two possible alternatives to conventional olive cultivation. The first would be the abandonment of marginal sloping olive groves and their conversion into woodland spaces (as has happened in AC and especially AW); and the second would be the conversion to organic farming with native plant cover (OC). The latter could reconcile agricultural activity in sloping olive groves with the conservation of biodiversity and its associated ecosystem services, therefore increasing the sustainability of olive production.

AW and OC were the treatments that showed the greatest coverage and therefore protection of the soil by native vegetation, together with litter and bryophytes. They also favored the coexistence of the greatest abundance of individuals, species and families of vascular plants, and had higher diversity index values and more life forms. The tilled (CT and OT) and conventional non-tilled (CNT) treatments gave rise to unprotected soils and very low biodiversity values, which is quite unsustainable. Despite being organic, OT could be considered 'non-bioinclusive', which contradicts the essential principles of organic farming.

In this regard, the combination of farming system and soil management technique in olive groves has rarely been addressed in the literature. Solomou and Sfougaris (2011) pointed out that the organic olive grove (grazed and cleared) increases the alpha and beta diversity of herbaceous plants compared to conventional systems (with and without herbicides). In addition, the best chemical and microbiological properties of the soils are obtained in organic olive groves with cover crops of *Fabaceae* species whose remains are left on the surface (Herencia, 2018). Increases in solitary bees (Martínez-Núñez *et al.*, 2019), Lepidoptera Rhopalocera (Sánchez-Fernández *et al.*, 2020), and birds (Martínez-Núñez

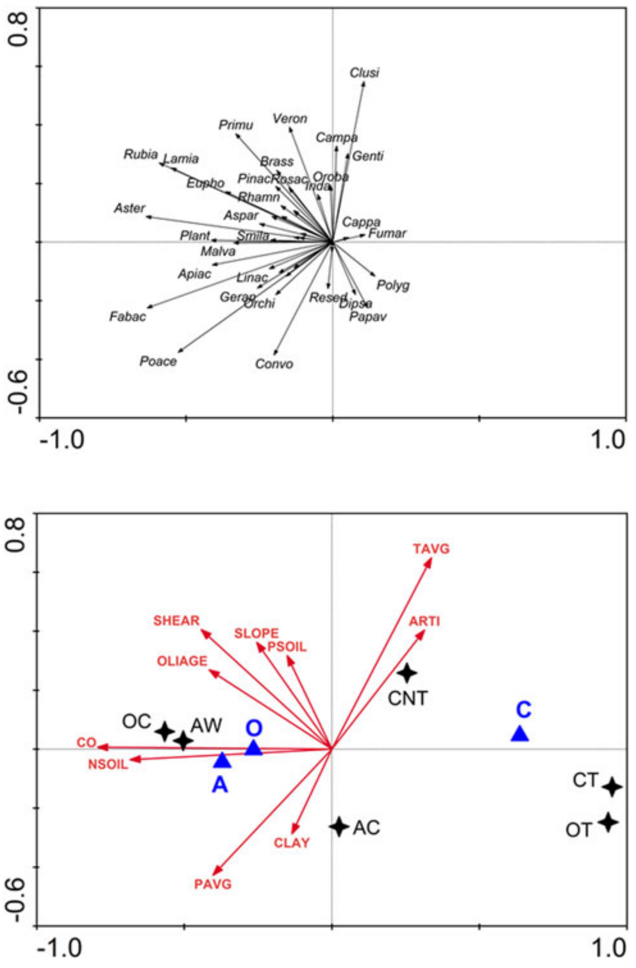

Fig. 4. RDA biplot made with species-abundance data showing the spatial distribution of the plant families (above), and the main environmental variables influencing the accumulated variation (below). In the latter, the treatments are also projected as nominal variables. A = Abandoned, O = Organic, C = Conventional. OT = organic tillage; OC = organic cover crops; CT = conventional tillage; CNT = conventional non-tillage; AC = abandoned cover crops; AW = abandoned woody. CO = soil organic carbon (Mg ha^{-1}), NSOIL = soil organic nitrogen (Mg ha^{-1}), PSOIL = soil phosphorous content (Mg ha^{-1}), PAVG = mean annual precipitation, TAVG = mean annual temperature, SHEAR = soil shear stress (kPa), OLIAGE = olive age, ARTI = artificial surface in the 1 km-radius buffer zone.

et al., 2020) have also been reported in organic olive groves with cover crops. In fact, the improved sustainability of organic olive groves with plant cover and mechanical mowing as compared to those with conventional tillage is widely recognized, bringing a range of benefits such as reduced soil erosion and soil organic carbon depletion (Soriano *et al.*, 2014). In this way, organic olive groves with cover crops could provide a solution for enhancing ecosystem services (Keesstra *et al.*, 2018).

However, the abandonment of sloping olive groves could have a number of disadvantages, such as the loss of direct economic income, which might encourage people to leave rural areas, the loss of the associated sociocultural heritage and the increased risk of fires (Allen *et al.*, 2006). At the same time, it could also be seen as a great opportunity to regenerate patches of forest inside agricultural landscapes, so creating islands of biodiversity of enormous interest as green infrastructure that provides ecosystem services to nearby crops (i.e., biological control of pests), wildlife refuges for endemic or local species and ecological corridors (Paredes *et al.*, 2013). In fact, Guzmán-Álvarez and Navarro (2008) estimated that 75% of marginal olive groves in Andalusia could be afforested solely by natural processes. Our results show that: (i) the abandonment of sloping olive groves would be beneficial from a biological and environmental point of view (unlike other studies which suggested otherwise) and (ii) that in certain landscape contexts it might be advisable to offer farmers financial incentives to encourage them to do so.

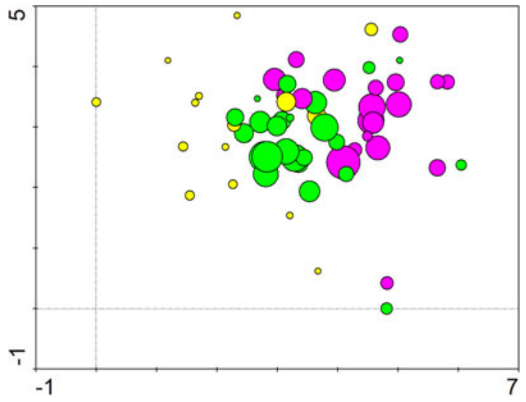

Fig. 5. DCA biplot made with species-abundance data showing the spatial ordination of plots according to their similarity in species composition and species richness (indicated by the circle size). Organic tillage (OT) and conventional tillage (CT) are shown with yellow circles, organic cover crop (OC) and conventional non-tillage (CNT) with green circles, and the abandoned treatments (AW, AC) with purple circles.

For its part, the conversion to organic agriculture with spontaneous or native plant cover could be a very interesting solution to reconcile socioeconomic activity with environmental and biodiversity protection. This could increase the added value of the products and make these marginal olive groves more viable. This would reduce the risk of abandonment, so maintaining the sociocultural and economic benefits for rural areas. It could also improve biodiversity and ecosystem services. Likewise, if farmers were ‘remunerated or encouraged’ to adopt certain soil management techniques that entail improvements in biodiversity, erosion control or carbon sequestration (e.g., native cover crops), that could help prevent the loss of the sociocultural and economic benefits produced by sloping olive groves (CAPDR, 2018; ESYRCE, 2021).

The introduction of plant cover is currently prioritized and subsidized by governments, as is the conversion to organic agriculture, and this could be a great opportunity to monetize sloping olive groves. In this case, plant cover should be mandatory for olive groves (and other woody crops) on slopes of over 20% or perhaps even less, regardless of the farming system. In organic woody crops, tillage should not be allowed, especially on slopes (at present it is permitted under European organic farming regulations, despite being considered harmful for the soil). To this end, we suggest that organic certification schemes should incorporate additional or more specific criteria on farm soil and vegetation management, as proposed by De Leijster *et al.* (2020). The higher prices of organic olive oil (and other organic products such as almonds), together with EU subsidies for organic agriculture, should also help make these sloping olive groves more economically viable.

Finally, the richness, composition and abundance of species and plant families were shown to be influenced by local abiotic characteristics such as mean annual precipitation and temperature, and by certain physical-chemical properties of the soil and landscape complexity, as was quantified by Allen *et al.* (2006) in olive groves in Crete (Greece). These authors found that elevation (related to temperature (−) and precipitation (+)), slope, soil pH, organic matter and soil N and P contents were good predictors of plant data variability. For their part, Baessler and Klotz (2006) established a clear relationship between landscape complexity and plant diversity, which is in line with our results in the sense that more homogeneous, more intensively-farmed landscapes (abundance of woody crops, rainfed cereal or artificial surfaces) had a negative correlation with plant diversity. That is probably because simplified landscapes of this kind have less plant diversity, fewer seed sources and more barriers to dispersal. In turn, the environment can be improved by the richness and abundance of the species themselves, which can lead to higher concentrations of soil organic carbon, nitrogen, phosphorous, cation exchange capacity, etc. These aspects should be taken into account in the design of incentive policies aimed at encouraging farmers to convert to certain specific land uses, soil management or farming systems.

Conclusions

In this paper, we have shown that, for biological conservation in sloping olive groves, the soil management techniques used by farmers are more important than the farming system, a finding that partially contradicts hypothesis 1. Specifically, on both conventional and organic farms, treatments involving tillage should not be considered as bio-inclusive or environmentally sustainable. By contrast, treatments with native cover crops had a significant, positive influence on plant diversity, so confirming hypothesis 2. According to this hypothesis, plant diversity was also affected by the environment, especially by climate, soil features and landscape complexity. From an environmental perspective and in the face of increasing competition from intensive olive farming, our recommendation is that the marginal sloping olive groves which are normally managed by tillage should either be abandoned or converted to organic agriculture with spontaneous or native plant cover. The first solution could entail various disadvantages, especially in terms of loss of income, but it could also provide a great opportunity to recover ecosystem services. The second could be a very interesting solution for reconciling socioeconomic activity with environmental and biodiversity protection.

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References

Al Harbi NA (2017) Diversity and taxonomic composition of weeds in olive orchards in Tabuk Region, Saudi Arabia. *Arid Ecosystems* **7**, 203–208.

Allen HD, Randall RE, Amable GS and Devereux BJ (2006) The impact of changing olive cultivation practices on the ground flora of olive groves in the Messara and Psiloritis regions, Crete, Greece. *Land Degradation and Development* **173**, 249–273.

Arhonditsis G, Giourga C and Loumou A (2000) Ecological patterns and comparative nutrient dynamics of natural and agricultural Mediterranean-type ecosystems. *Environmental Management* **265**, 527–537.

Assandri G, Morganti M, Bogliani G and Pulido F (2017) The value of abandoned olive groves for blackcaps (*Sylvia atricapilla*) in a Mediterranean agroecosystem: a year-round telemetry study. *European Journal of Wildlife Research* **63**, 26.

Baessler C and Klotz S (2006) Effects of changes in agricultural land-use on landscape structure and arable weed vegetation over the last 50 years. *Agriculture, Ecosystems and Environment* **115**, 43–50.

Baraibar B, Canadell C, Torra J, Royo-Esnal A and Recasens J (2017) Weed seed fate during summer fallow: the importance of seed predation and seed burial. *Weed Science* **654**, 515–524.

Blanca G, Cabezudo D, Cueto M, Fernández López C and Morales Torres C (eds) (2009) *Flora Vascular de Andalucia Oriental*, 4 vols. Consejería de Medio Ambiente. Junta de Andalucía. Sevilla.

Blanco G (2009) Tractores utilizados en explotaciones forestales, características e innovaciones. *Vida Rural* **291**, 48–54.

Bonet A and Pausas JG (2004) Species richness and cover along a 60-year chronosequence in old-fields of southeastern Spain. *Plant Ecology* **174**, 257–270.

Bremner JM (1996) Nitrogen-total. In Sparks DL (ed). *Methods of Soil Analysis: Part. 3. Chemical Methods*. SSSA, pp. 1085–1121, Book Series no. 5.

Campos M, Fernández L, Ruano F, Cotes B, Cárdenas M and Castro J (2011) Short term response of ants to the removal of ground cover in organic olive orchards. *European Journal of Entomology* **1083**, 417–423.

CAPDR (2018) Consejería de Agricultura, Pesca y Desarrollo Rural. Costes en explotaciones de olivar. Campaña 2015/2016. Secretaría General de Agricultura y Alimentación. https://juntadeandalucia.es/export/drupaljda/estudios_informes/18/01/Costes_en_explotaciones_de_olivar.pdf.

Carpio AJ, Lora A, Martín-Consuegra E, Sánchez-Cuesta R, Tortosa FS and Castro J (2020) The influence of the soil management systems on aboveground and seed bank weed communities in olive orchards. *Weed Biology and Management* **20**, 12–23.

Castroviejo S (ed.) (1986) *1986–2012. Flora iberica 1–8, 10–15, 17–18, 21*. Madrid: Real Jardín Botánico, CSIC.

Cechin J, Schmitz MF, Hencks JR, Monge AA, Agostinetto D and Vargas L (2021) Burial depths favor Italian ryegrass persistence in the soil seed bank. *Scientia agricola* **78**, e20190078.

Chalmers N and Parker P (eds) (1989) *The OU Project Guide. Fieldwork and Statistics for Ecological Projects*. Field studies Council. No. 9. UK: The Open University and Field Studies Council.

Clarke KR (1993) Non-parametric multivariate analysis of changes in community structure. *Australian Journal of Ecology* **18**, 117–143.

Cohen M, Bilodeau C, Alexandre F, Godron M, Andrieu J, Grésillon E, Garlatti F and Morganti A (2015) What is the plant biodiversity in a cultural landscape? A comparative, multi-scale and interdisciplinary study in olive groves and vineyards Mediterranean France. *Agriculture, Ecosystems and Environment* **212**, 175–186.

De Leijster V, Verburg RW, Santos MJ, Wassen MJ, Martínez-Mena M, de Vente J and Verweij PA (2020) Almond farm profitability under agroecological management in south-eastern Spain: accounting for externalities and opportunity costs. *Agricultural Systems* **183**, 102878.

di Pietro R and Blasi C (2002) A phytosociological analysis of abandoned olive-grove grasslands of Ausoni mountains (Tyrrhenian district of Central Italy). *Lazaroa* **23**, 73–93.

Duarte F, Jones N and Fleskens L (2008) Traditional olive orchards on sloping land: sustainability or abandonment? *Journal of Environmental Management* **892**, 86–98.

Espejo-Pérez AJ, Rodríguez-Lizana A, Ordóñez R and Giráldez JV (2013) Soil loss and runoff reduction in olive-tree dry-farming with cover crops. *Soil Science Society of America Journal* 776, 2140–2148.

ESYRCE (2021) Encuesta sobre superficies y rendimientos de cultivos de España. Resultados 2019. Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente. https://www.mapa.gob.es/es/estadistica/temas/estadisticas-agrarias/agricultura/esyrce (Accessed March 2022).

FAOSTAT (2022) Food and Agriculture Organization of the United Nations FAOSTAT Online Database. https://www.fao.org/faostat/es/#data (Accessed June 2022).

Fernández-Quintanilla C, Mesa García J and García-Torres L (1991) Control de malas hierbas en diversos cultivos. In García-Torres L and Fernández-Quintanilla C (eds). *Fundamentos sobre malas hierbas y herbicidas*. Madrid: MAPA & Mundi-Prensa ED, pp. 307–328.

Gálvez M, Parra MA and Navarro C (2004) Relating tree vigour to the soil and landscape characteristics of an olive orchard in a marly area of southern Spain. *Scientia Horticulturae* **101**, 291–303.

García H, Tarrasón D, Mayol M, Male-Bascompte N and Riba M (2007) Patterns of variability in soil properties and vegetation cover following abandonment of olive groves in Catalonia (NE Spain). *Acta Oecologica* **313**, 316–324.

Gómez JA, Campos M, Guzmán G, Castillo-Llanque F, Vanwalleghem T, Lora Á and Giráldez JV (2018) Soil erosion control, plant diversity, and arthropod communities under heterogeneous cover crops in an olive orchard. *Environmental Science and Pollution Research* **25**, 979–989.

González-Varo JP, Carvalho CS, Arroyo JM and Jordano P (2017) Unravelling seed dispersal through fragmented landscapes: frugivore species operate unevenly as mobile links. *Molecular Ecology* **2616**, 4309–4321.

Grossman RB and Reinsch TG (2002) Bulk density and linear extensibility. In Dane H and Clarke Topp G (eds). *Methods of Soil Analysis: Part. 4. Physical Methods*. Soil Science of Society of America, Book Series no. 5., pp. 201–225.

Guzmán-Álvarez JR and Navarro-Cerrillo RM (2008) Modelling potential abandonment and natural restoration of marginal olive groves in Andalusia south of Spain. *Journal of Land Use Science* **3**, 113–129.

Hammer Ø, Harper DAT and Ryan PD (2001) PAST: Paleontological Statistics Software.

Herencia JF (2018) Soil quality indicators in response to long-term cover crop management in a Mediterranean organic olive system. *Biological Agriculture and Horticulture* **344**, 211–231.

Hevia V, Ortega J, Azcárate FM, López CA and González JA (2019) Exploring the effect of soil management intensity on taxonomic and functional diversity of ants in Mediterranean olive groves. *Agricultural and Forest Entomology* **211**, 109–118.

Huqi B, Dhima K, Vasilakoglou I, Keco R and Salaku F (2009) Weed flora and weed management in established olive groves in Albania. *Weed Biology and Management* **94**, 276–285.

Jiménez-Alfaro B, Hernández-González M, Fernández-Pascual E, Toorop P, Frischie S and Gálvez-Ramírez C (2018) Germination ecology of winter annual grasses in Mediterranean climates: applications for soil cover in olive groves. *Agriculture, Ecosystems and Environment* **262**, 29–35.

Keesstra S, Nunes J, Novara A, Finger D, Avelar D, Kalantari Z and Cerdà A (2018) The superior effect of nature based solutions in land management for enhancing ecosystem services. *Science of the Total Environment* **610–611**, 997–1009.

Lal R (2015) Sequestering carbon and increasing productivity by conservation agriculture. *Journal of Soil and Water Conservation* **70**, 55–62.

Lasanta T, Sánchez-Navarrete P, Medrano-Moreno LM, Khorchani M and Nadal-Romero E (2020) Soil quality and soil organic carbon storage in abandoned agricultural lands: effects of revegetation processes in a Mediterranean mid-mountain area. *Land Degradation and Development* **31**, 2830–2845.

Legendre P and Legendre L (1998) *Numerical Ecology. Second English Edition. Developments in Environmental Modelling 20*. Amsterdam: Elsevier Science B. V., 853 pp.

Lepš J and Šmilauer P (2003) *Multivariate Analysis os Ecological Data Using CANOCO*. UK: Cambridge University Press.

Loumou A and Giourga C (2003) Olive groves: "The life and identity of the Mediterranean.". *Agriculture and Human Values* **201**, 87–95.

Lozano-García B, Muñoz-Rojas M and Parras-Alcántara L (2017) Climate and land use changes effects on soil organic carbon stocks in a Mediterranean semi-natural area. *Science of the Total Environment* **579**, 1249–1259.

Maccherini S, Santi E, Bonini I, Amici V, Pruscini S, Palazzo D and Selva FC (2013) The impact of land abandonment on the plant diversity of olive groves. *Biodiversity and Conservation* **22**, 3067–3083.

Magurran A (1988) *Diversidad ecológica y su medición*. Barcelona: Vedrá.

Márquez-García F, González-Sánchez EJ, Castro-García S and Ordoñez-Fernández R (2013) Improvement of soil carbon sink by cover crops in olive orchards under semiarid conditions. Influence of the type of soil and weed. *Spanish Journal of Agricultural Research* **112**, 335–346.

Martínez-Núñez C, Manzaneda AJ, Isla J, Tarifa R, Calvo G, Molina JL and Rey PJ (2019) Low-intensity management benefits solitary bees in olive groves. *Journal of Applied Ecology* **57**, 111–120.

Martínez-Núñez C, Rey PJ, Manzaneda AJ, Tarifa R, Salido T, Isla J, Pérez AJ, Camacho FM and Molina JL (2020) Direct and indirect effects of agricultural practices, landscape complexity and climate on insectivorous birds, pest abundance and damage in olive groves. *Agriculture, Ecosystem and Environment* **304**, 107145.

Meyer LD, Wischmeier WH and Foster GR (1970) Mulch rates required for erosion control on steep slopes. *Soil Science Society American Procedure* **34**, 928–931.

Ministerio de Agricultura, Pesca y Alimentación (1986) Métodos oficiales de análisis. MAPA, 3, Madrid, 532 pp.

Nelson DW and Sommers LE (1996) Total carbon, organic carbon, and organic matter. In Sparks DL (ed). *Methods of Soil Analysis: Part. 3. Chemical Methods*. Soil Science Society of America (SSSA), pp. 961–1010, Book Series no. 5.

Paredes D, Cayuela L and Campos M (2013) Synergistic effects of ground cover and adjacent vegetation on natural enemies of olive insect pests. *Agriculture, Ecosystems and Environment* **173**, 72–80.

Pastor M, Castro J, Vega V and Humanes MD (2004) Sistemas de manejo del suelo. In Barranco D, Fernández-Escobar R and Rallo L (eds), *El Cultivo del Olivo*. Mundi-Prensa S.A: Consejería de Agricultura Junta de Andalucía, pp. 230–285.

Perrino EV, Ladisa G and Calabrese G (2014) Flora and plant genetic resources of ancient olive groves of Apulia Southern Italy. *Genetic Resources and Crop Evolution* **611**, 23–53.

Pujadas Salvá A (1986) *Flora arvense y ruderal de la provincia de Córdoba* (Tesis Doctoral ETSIA). Universidad de Cordoba.

REDIAM (2019) Red de Información Ambiental de Andalucía. http://www.juntadeandalucia.es/medioambiente/rediam (Accessed 12 December 2018).

Repullo-Ruibérriz de Torres MA, Ordóñez R, Giráldez JV, Márquez-García J, Laguna A and Carbonell-Bojollo R (2018) Efficiency of four different seeded plants and native vegetation as cover crops in the control of soil and carbon losses by water erosion in olive orchards. *Land Degradation and Development* **298**, 2278–2290.

Rey PJ, Manzaneda AJ, Valera F, Alcántara JM, Tarifa R, Isla J, Molina-Pardo JL, Calvo G, Salido T, Gutiérrez JE and Ruiz C (2019) Landscape-moderated biodiversity effects of ground herb cover in olive groves: implications for regional biodiversity conservation. *Agriculture, Ecosystems and Environment* **277**, 61–73.

Rodríguez-Lizana A, Repullo-Ruibérriz de Torres MA, Carbonell-Bojollo R, Alcántara C and Ordóñez-Fernández R (2018) *Brachypodium distachyon, Sinapis alba*, and controlled spontaneous vegetation as groundcovers: soil protection and modelling decomposition. *Agriculture, Ecosystems and Environment* **265**, 62–72.

Rodrigues MÂ, Correia CM, Claro AM, Ferreira IQ, Barbosa JC, Moutinho-Pereira JM and Arrobas M (2013) Soil nitrogen availability in olive orchards after mulching legume cover crop residues. *Scientia Horticulturae* **158**, 45–51.

Romero-Díaz A, Ruiz-Sinoga JD, Robledano-Aymerich F, Brevik EC and Cerdà A (2016) Ecosystem responses to land abandonment in Western Mediterranean Mountains. *Catena* **1493**, 824–835.

Rühl J, Caruso T, Giucastro M and La Mantia T (2011) Olive agroforestry systems in Sicily: cultivated typologies and secondary succession processes after abandonment. *Plant Biosystems* **145**, 120–130.

Saavedra M, Pastor M, Arquero O and Salas J (1992) Malas hierbas del olivar no labrado y degradación de la simazina en el suelo. Información Técnica 17/92. DGITFAP. Consejería de Agricultura y Pesca. Junta de Andalucía.

Sánchez-Fernández J, Vílchez-Vivanco J, Navarro FB and Castro-Rodríguez J (2020) Farming system and soil management affect butterfly diversity in sloping olive groves. *Insect Conservation and Diversity* **135**, 456–469.

Sastre B, Barbero-Sierra C, Bienes R, Marques MJ and García-Díaz A (2017) Soil loss in an olive grove in Central Spain under cover crops and tillage treatments, and farmer perceptions. *Journal of Soils and Sediments* **173**, 873–888.

Sastre B, Marques MJ, García-Díaz A and Bienes R (2018) Three years of management with cover crops protecting sloping olive groves soils, carbon and water effects on gypsiferous soil. *Catena* **171**, 115–124.

Scalercio S, Brandmayr P, Iannotta N, Petacchi R and Boccaccio L (2012) Correlations between landscape attributes and ecological traits of Lepidoptera communities in olive groves. *European Journal of Entomology* **109**, 207–216.

Siles G, Torres JA, Ruiz-Valenzuela L and García-Fuentes A (2016) Germination trials of annual autochthonous leguminous species of interest for planting as herbaceous cover in olive groves. *Agriculture, Ecosystems and Environment* **217**, 119–127.

Simoes MP, Belo AF, Pinto-Cruz C and Pinheiro AC (2014) Natural vegetation management to conserve biodiversity and soil water in olive orchards. *Spanish Journal of Agricultural Research* **123**, 633–643.

Solomou A and Sfougaris A (2011) Comparing conventional and organic olive groves in central Greece: plant and bird diversity and abundance. *Renewable Agriculture and Food Systems* **26**, 297–316.

Solomou AD and Sfougaris AI (2013) Herbaceous plant diversity and identification of indicator species in olive groves in central Greece. *Communications in Soil Science and Plant Analysis* **441**, 320–330.

Solomou AD and Sfougaris AI (2015) Determinants of woody plant species richness in abandoned olive grove ecosystems and maquis of central Greece. *Communications in Soil Science and Plant Analysis* **46**, 317–325.

Soriano MA, Álvarez S, Landa BB and Gómez JA (2014) Soil properties in organic olive orchards following different weed management in a rolling landscape of Andalusia, Spain. *Renewable Agriculture and Food Systems* **291**, 83–91.

Stocking MA and Murnaghan N (2001) *A Handbook for the Field Assessment of Land Degradation*. London: Earthscan (Routledge).

Ter Braak CJF and Smilauer P (2002) CANOCO reference manual and CanoDraw for Windows user's guide: Software for Canonical Community Ordination version 4.5. Biometris, Wageningen.

Terzi M, Barca E, Cazzato E, D'amico FS, Lasorella C and Fracchiolla M (2021) Effects of weed control practices on plant diversity in a homogenous olive-dominated landscape (South-east of Italy). *Plants* **106**, 1–12.