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ORIGINAL PAPER

Afforestation improves soil fertility in south-eastern Spain

**E. Fernández-Ondoño · L. Rojo Serrano · M. N. Jiménez ·
F. B. Navarro · M. Díez · F. Martín · J. Fernández ·
F. J. Martínez · A. Roca · J. Aguilar**

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Abstract In the 20th century, in the Mediterranean area, many extensive afforestation efforts were made with the primary objective of protecting soils from erosion and improving their fertility. This study evaluates the effects of the afforestation undertaken in the Guadalentín basin (SE Spain) with respect to the organic and inorganic soil constituents and physico-chemical soil properties. Given the phytoclimatic environments in the basin (sclerophyllous and hyperxerophyllous), paired samples were taken beneath the tree canopy of the pine plantations and in nearby open zones. With the same methodology, samples were taken from areas considered to be native forest. The data were submitted to different multivariate analyses of variance (two-way MANOVAs) in order to compare the effects and interactions of the factors CANOPY (with and without trees), PHYTOCLIMATE (sclerophyllous and hyperxerophyllous), and TYPE OF FOREST (afforested or native) on the dependent variables measured (soil variables). Significant differences were found at 0–10 cm in soil depth under pine afforestations in relation to adjacent open areas. Below this depth, differences were found only between phytoclimatic environments. No significant interactions were found between the variables analysed at any of the depths, indicating that the effects of the afforestations on the soil characteristics were independent of the phytoclimatic environment. The afforestation in the Guadalentín basin, in the two phytoclimatic environments considered increased the soil fertility. Nevertheless, the native forests presented the highest soil organic-carbon contents, mainly in the sclerophyllous phytoclimate type (*Quercus ilex* subsp. *ballota* forests). Therefore, although the afforestations improved the soil fertility in relation to the open areas, the maximum potential has probably not been reached in relation to that observed in the native forests. The effects that forest development (age, basal area) over time exerts on soil properties remain to be verified by further research.

Keywords Afforestation · Differential pedological characteristics · Organic carbon · Guadalentín basin

Introduction

The severe processes of erosion and desertification of large zones of the Mediterranean region have for decades worried governments and researchers (Albadalejo et al. 1988; United Nations 1992); and therefore, the protection of the soil currently constitutes a priority environmental policy in many countries and international organizations (Commission European Communities 2006). Erosion, the most important soil-degradation process, is related to human demographic pressure, the reduction in the plant cover, the special characteristics of the Mediterranean climate,

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E. Fernández-Ondoño (✉) · M. N. Jiménez · M. Díez ·
F. Martín · J. Fernández · F. J. Martínez · A. Roca · J. Aguilar
Departamento de Edafología y Química Agrícola, Facultad de
Ciencias, Universidad de Granada, 18071 Granada, Spain
e-mail: efernand@ugr.es

L. Rojo Serrano
Dirección General de Medio Natural y Política Forestal,
Ministerio de Medio Ambiente y Medio Rural y Marino,
Rios Rosas, 24, 28003 Madrid, Spain

F. B. Navarro
Grupo de Sistemas y Recursos Forestales, Área de Recursos
Naturales, IFAPA Centro Camino de Purchil
(Junta de Andalucía), Camino de Purchil s/no. Aptdo. 2027,
18080 Granada, Spain

topography, soil properties, and parent material (Cammeraat and Imeson 1998; van Wesemael et al. 2003; Imeson and Prinsen 2004; Boix-Fayos et al. 2007).

During the 20th century in the Mediterranean area, many extensive afforestation efforts were made with the primary objective of soil protection. The species most commonly used were conifers, especially *Pinus halepensis* Mill., as it is considered a species tolerant of many climates and soils. Afterwards, attention was placed on the contribution of these afforested areas in the biogeochemical evolution of the hydrographic basins in terms of nutrient cycle and microbial activity (Pinzari et al. 1999; Goberna et al. 2006), and most recently the focus has shifted to the conservation of the biodiversity and carbon sequestering (Castillo et al. 1997; Keller and Goldstein 1998; Hooke 2006).

Some authors indicate that afforestation increases the organic-carbon and nitrogen contents in the soil, although on occasions the differences found are minor or negligible (Romanyà et al. 2000; Maestre et al. 2003). These discrepancies in findings may be due to the species used, their density, and/or the degree of cover, as well as the time since planting. In addition, some topographic and pedological properties should be taken into account, such as slope, orientation, and lithology, as these affect both the characteristics of the vegetation as well as the soil properties (Kooijman et al. 2005).

Another factor to take into consideration is the planting technique used (Maestre and Cortina 2004). Preparations of the terrain such as terracing or subsoiling are employed preferentially over other manual techniques due to the lower economic cost and higher efficiency of planting (Serrada 1990; Rojo et al. 2002). The influence on soil properties has raised controversy in many studies. That is, some authors have pointed out that these techniques can negatively affect the water-retention capacity and the dynamics of spontaneous vegetation (Chaparro and Esteve 1996; Bellot et al. 1999; Navarro et al. 2005, 2006). On the other hand, other studies indicate that the terraces with subsoiling increase the water-storage capacity of the soil, compared with other techniques, and thereby encourage root penetration of trees, augmenting water availability (Quejereta et al. 2001). However, most of these works refer to early stages of afforestation development (Löf et al. 2006; Quejereta et al. 2008).

Despite the extensive afforested areas and the time occurred after the plantation, few studies offer a critical overall examination of the growth development and ecological consequences of afforestation in the Mediterranean environment (Maestre and Cortina 2004), especially those related to soil properties. In fact, the evaluation of afforestations is complex for the great number of factors involved: prior to the afforestation (choice of appropriate sites and species), during (planting techniques, density, interaction with natural vegetation of the zone, etc.), and afterwards (changes in the physico-chemical properties of the soils, impact on biodiversity, implications for the increase or reduction in erosion, changes in the landscape, etc.). In recent years, some works have been published on these issues (Andrés and Ojeda 2002; Chirino et al. 2006; Goberna et al. 2007), although few analyse the changes in soil properties at a basin scale in relation to nearby non-afforested areas (e.g. grassland, scrub, or bare soils) and the intrinsic characteristics of each soil. The aim of the present work was to ascertain the influence that afforestations in the Guadalentín river basin (SE Spain) exert on the soil characteristics in two different phytoclimatic environments and compare them to adjacent areas without trees and with native forests (*Quercus ilex* L. subsp. *ballota* (Desf.) Samp. and *Pinus halepensis* Mill.).

Materials and methods

Description of the study area

The study was conducted in the Guadalentín river basin, situated in the SE Iberian Peninsula (Fig. 1), covering approximately 3,300 km^2 (Boer et al. 1996). The highest altitude reaches 2,045 m in Sierra de María and the lowest 200 m in zones near the Guadalentín valley. Throughout the basin, slopes lower than 10% predominate, followed by slopes of 10–30%, with a low rate of slopes steeper than 30%.

The most representative bioclimatic regimes (*sensu* Rivas-Martínez and Loidi 1999) are dry and semiarid mesomediterranean and semiarid thermomediterranean. The average annual temperature is 13–19°C with annual precipitation of 200–400 mm (exceptionally 600 mm at specific high areas of the basin). The lithology is varied, with carbonate materials predominating (hard limestones, calcareous conglomerates, calco-schists, marly limestones, and limestone-dolomites), and more rarely sandstones, marls, schists, slates, and gypsums.

The oldest pine plantations of the basin are located in Sierra Espuña (Murcia) and began in 1891 by the famous forestry engineers R. Codorníu, J. Musso, and J.A. de Madariaga (Alonso 1982; García 1999) with three main objectives: land protection, especially watersheds and torrential rivers, intensive timber production, and reduction in unemployment among workers and farmers. The other pine stands of the basin were spaced in time but planted with special intensity from the 1950s to 1970s, lasting until 1986 (Boer et al. 1996). This latter effort, undertaken by the national programme of public afforestation, started with the implementation of *Ley de Patrimonio Forestal del Estado* (National Forest Estate Act) from 1941 to 2000 (Marey-Pérez and Rodríguez-Vicente 2008). Most of these

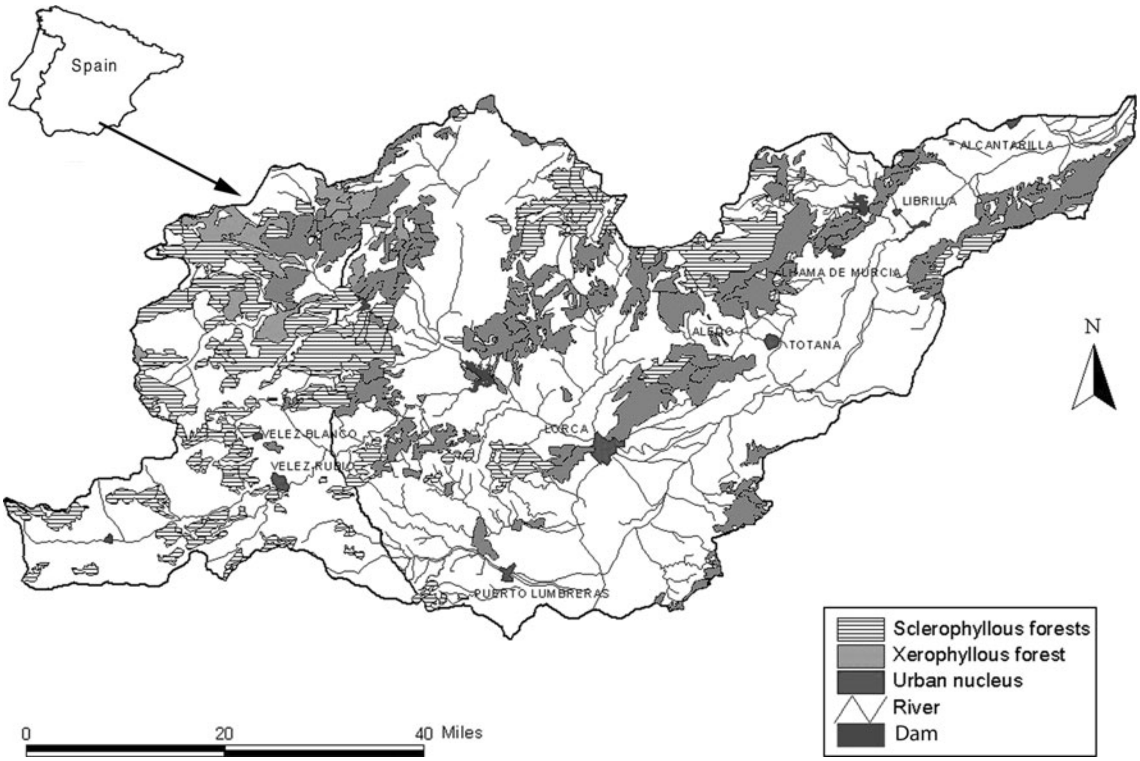

Fig. 1 Location of the Guadalentín Basin in SE Spain. Geographic distribution of sclerophyllous and hyperxerophyllous phytoclimates

afforestations were made with *Pinus halepensis* on degraded grasslands and shrublands previously deforested, using different soil-preparation techniques with a high plantation density (≈1,500–3,000 trees/ha). In general, forest management in these areas was restricted to minimum selective pruning and no thinning after planting. Today these pine plantations have a homogeneous structure and low species diversity.

Sampling

For the choice of the sampling points (Table 1), the climatic characteristics of the area were taken into account (phytoclimatic environment), the parent material on which the soils developed, the slope and altitude, the technique of soil preparation during the afforestation, and the height of the forest. These data were determined from the literature (Aguilar et al. 2004, 2006) and field observations. Other variables such as age, volume, or basal area of afforestations have not been considered in this study. Soil descriptions were made according to Guidelines for Soil Description (FAO 1990). From the phytoclimatic environments defined in the forest map of Spain (ICONA 1993) for the Guadalentín basin, two types were selected: sclerophyllous and hyperxerophyllous.

The phytoclimatic sclerophyllous type appears in mountains under average annual temperatures of 13–17°C and annual precipitation of 350–600 mm. Within the Guadalentín basin, this type is found well represented in Sierra María and Sierra Espuña. The parent materials were limestones and dolomites and occasionally a mixture of both. The native forest within this phytoclimatic environment was dominated by Holm oak (*Quercus ilex* L. subsp. *ballota* (Desf.) Samp.), generally with a mixture of shrubs including *Juniperus oxycedrus* L., *Quercus coccifera* L., *Phillyrea angustifolia* L., *Viburnum tinus* L., and vines such as *Lonicera etrusca* G. Santi, *Lonicera implexa* Aiton, *Tamus communis* L., *Asparagus acutifolius* L., and *Bryonia dioica* Jacq.

The phytoclimatic hyperxerophyllous type develops in broad areas at lower altitudes and with greater aridity, where the average annual temperature is 17–19°C and rainfall 200–350 mm. The geological materials are also varied, although marls, limestones, and marly limestones predominate. Also, soils that had developed over schists, slates, Triassic sandstones, and gypsums were sampled. The native forest within this phytoclimatic environment is composed of Aleppo pine (*Pinus halepensis*) accompanied by shrubs such as *Juniperus oxycedrus, Quercus coccifera, Rhamnus lycioides* L., and, in warmer areas, *Pistacia lentiscus* L. and *Chamaerops humilis* L.

The types of soils dominant in both phytoclimatic environments generally present little development of the soil profile. The most frequent types in the moderate-relief areas

Table 1 Summary of the general characteristics of the localities where the soils were sampled

Phytoclimatic types	Sample number	Locality	Elevation (m)	Parent material	Slope (%)	Forest type	Soil-preparation techniques	Canopy height (m)
Sclerophyllous	3	Sª María	940	Marly limestones	<5	Native	–	>7
	5	Sª María	900	Limestones	15	Afforestation	Hollows	>7
	28	Zarzilla de Ramos	840	Limestones	>30	Afforestation	Terraces	3–7
	33	Sª Carrascoy	800	Dolomites	>30	Native	–	3–7
	13	Sª María	1200	Limestones	<10	Afforestation	Hollows	>7
	14	Sª María	1300	Limestones	10–30	Native	–	3–7
	34	Sª Espuña	1300	Limestones	>30	Afforestation	Hollows	>7
	2	Sª María	900	Limestones- Dolomites	15	Afforestation	Hollows	>7
	25	Sª María	1200	Limestones	<2	Native	–	3–7
	1	Sª María	1200	Dolomites	>30	Afforestation	Hollows	3–7
Hyperxero-phyllous	7	Sª María	760	Limestones	>15	Afforestation	Terraces	>7
	11	Sª Espuña	300	Limestones	30	Afforestation	Hollows	3–7
	18	Sª de la Muela	480	Marls with gypsum	20	Afforestation	Terraces	3–7
	23	Sª de la Tercia	500	Conglomerates and marls	<2	Afforestation	Terraces	3–7
	31	Sª de Peña Rubia	600	Triassic sandstones	55	Afforestation	Terraces	>7
	19	Sª de Carrascoy	400	Schists, slates	20–25	Afforestation	Hollows	3–7
	30	La Alquería	700	Marly limestones	45	Afforestation	Hollows	3–7
	21	Sª de la Tercia	500	Marls and sandstones	>30	Afforestation	Terraces	<3
	9	La Muela	300	Sandstones and calcareous crusts	>30	Afforestation	Subsoiling	3–7
	27	Sª de las Cabras	740	Limestones	15	Afforestation	Terraces	>7
	17	Sª de la Muela	500	Calcareous conglomerates	20	Afforestation	Subsoiling	3–7
	15	Sª Espuña	700	Limestones and Triassic sandstones	20–30	Native	–	>7
	26	Sª de la Carrasquilla	700	Calco-schists	45	Afforestation	Hollows	>7
	16	Sª Espuña	700	Limestones	40	Native	–	>7
	22	Sª de la Tercia	400	Sandstones and calcareous conglomerate	>30	Afforestation	Hollows	3–7
	29	Zarzilla de Ramos	770	Calcareous conglomerates	4	Afforestation	Terraces	<3
	35	Sª Espuña	500	Triassic sandstones	20	Native	–	>7
	8	Sª de Carrascoy	400	Cuarcitic conglomerates, marls and sandstones	35	Afforestation	Hollows	>7
	10	Sª de la Muela	400	Sandstones with gypsum	>30	Afforestation	Terraces	>3
	20	Sª de Carrascoy	300	Limestones- Dolomites	>30	Native	–	3–7
	32	Sª de Carrascoy	500	Schists	>20	Afforestation	Terraces	>7
	4	Sª María	800	Marls with gypsum	10–15	Afforestation	Hollows	>3
	4bis	Sª María	800	Marls with gypsum	>30	Afforestation	Hollows	>3
	6	Sª María	500	Marls with gypsum	20–30	Afforestation	Hollows	>3
	12	Sª María	800	Marls with gypsum	10	Afforestation	Hollows	>3
	24	Sª María	840	Gypsum	7	Afforestation	Hollows	3–7

are regosols, in which a calcareous character dominates, and leptosols in the steepest zones, where a lithic character is dominant (WRBSR 1998). Due to the abundance of carbonate materials in the area, soils that develop a calcic horizon at depth are also relatively frequent. The most pronounced difference is in sclerophyllous native forest, which develops a superficial horizon rich in organic matter that can be mollic, especially in the northerly oriented areas.

In total, there were 36 sampling sites, in a stratified random sampling design. Paired samples were taken, one under the tree canopy (both for the afforested stands and for the native forests) and another in adjacent open areas. These open areas were composed of degraded dry grasslands and scrublands. At one of the sampling sites, three 100 cm × 50 cm trial pits were opened, and composite samples were taken at 0–5, 5–10, >10 cm in depth (prior to the soil sampling, the organic litter not mixed into the soils and deposited over them was removed). In total, $36 \times 2 \times 3 = 216$ samples were taken. Of the 36 sampling sites, 10 belonged to the phytoclimatic sclerophyllous type and 26 to the hyperxerophyllous type (Table 1). A total of 8 sites corresponded to native forests (4 in the phytoclimatic sclerophyllous type and 4 in the hyperxerophyllous) while 28 corresponded to high-density afforestations dominated by the pine species (*Pinus halepensis*, and on rare occasions *Pinus pinaster* Aiton and *P. nigra* J.F. Arnold). All of these chosen forests were planted between 1950 and 1970, and areas previously burnt were not sampled.

Analyses

The soil analyses were made with samples previously air dried and sieved. The gravels (>2 mm) and fine earth (<2 mm) were separated to calculate the percentage of each fraction. All analyses were made with the fine-earth fraction. The soil organic carbon (SOC) was determined by the wet oxidation with dichromate method (Tyurin 1951), and the total nitrogen was established by Kjeldahl method (Bremner 1965). The pH was measured potentiometrically in a soil:water suspension of 1:2.5, and the texture was estimated by the pipette method of Robinson after dispersion with sodium polyphosphate (Loveland and Whalley 1991). The calcium carbonate content ($CaCO_3$ equivalent) was determined by the method of Barahona (1984). The exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+, and K^+) were extracted with NH_4OAc 1 N, and the cation-exchange capacity (CEC) was established by saturation with sodium after washing with alcohol and extraction of the sodium adsorbed with NH_4OAc 1 N (SCS-USDA, 1972). The available water (AW) was established by the difference between the moisture content at field capacity on a pressure plate at −33 kPa and moisture at the wilting point measured at −1500 kPa (Cassel and Nielsen 1986).

Statistical treatment

Different multivariate analyses were made (two-way MANOVAs) to compare the effects and interactions of the factors CANOPY (under tree canopy *vs.* open areas), PHYTOCLIMATE (sclerophyllous and hyperxerophyllous) and TYPE OF FOREST (afforested or native) on the dependent variables measured (pedological variables). For statistical comparison, the Wilks lambda was used and the Tukey test for *post hoc* multiple comparisons. Despite the unbalanced subpopulation, the variable distribution fits the requirements of normality. These analyses were made for each of the depths separately in order to fulfil the requirements of independence. The program used was STATISTICA v. 6.

The correlations between the different pedological parameters selected were made using the Spearman correlation coefficient using the program SPSS v. 15.0.

Results

General soil characteristics

The soils presented loamy textures, clayey-loamy, or clayey, generally with a high content in calcium carbonate, frequently in the form of nodules, mycelia, or crusts of variable continuity. The structure in the afforested zones was crumbly on the surface, shifting to subangular blocks at successive depths. In the open areas, lacking the litter layer that protects against erosion, laminar structures predominated on the surface, especially in the areas in which the thickets were more or less dense.

Effects of the afforested stands within the two phytoclimates

Forest canopy and phytoclimatic type had significant effects on the soil variables measured at 0–10 cm soil depth (Table 2). From this depth on (10–30 cm), differences were found only between phytoclimates. No significant interactions were found between the factors analysed at any depth, indicating that the effects of the pine plantations on the soil characteristics were independent of the phytoclimate in which the afforestation was performed.

Significant differences appeared for the content in organic carbon, nitrogen, calcium, magnesium, and potassium, for CEC, and for moisture at −1.500 kPa at the three depths studied (Table 3). The clay content and moisture at −33 kPa differed significantly with respect to 5–10 cm in depth. Finally, differences were detected in the gravel content at more than 10 cm in depth. In all cases, the values found were higher in the sclerophyllous than in the phytoclimatic hyperxerophyllous type.

Differences in the pedological variables with depth

The afforestation stands of the Guadalentín basin, considering the two phytoclimates, significantly altered the organic-carbon values, the C/N relationship, the cation-

Table 2 Results of the two-way MANOVAs for each of the depths, with all the dependent variables measured and for the factors CANOPY (under tree canopy and open zones) and PHYTOCLIMATE (sclerophyllous and hyperxerophyllous types)

		Λ value	*F*	Effect *df*	Error *df*	*P*
0–5 cm ($N = 56$)	Intercept	0	4250	16	37	**0.0000**
	Canopy	0.4	3	16	37	**0.0014**
	Phytoclimate	0.4	3	16	37	**0.0014**
	Can. × Phytocl.	0.6	2	16	37	0.1025
5–10 cm ($N = 56$)	Intercept	0	1×10^{12}	18	35	**0.0000**
	Canopy	0	2×10^{13}	18	35	**0.0124**
	Phytoclimate	0	4×10^{13}	18	35	**0.0000**
	Can. × Phytocl.	1	1×10^{13}	18	35	0.0554
>10 cm ($N = 55$)	Intercept	0	5×10^{8}	18	34	**0.0000**
	Canopy	1	1	18	34	0.2458
	Phytoclimate	0	4	18	34	**0.0005**
	Can. × Phytocl.	1	1	18	34	0.1884

The Wilks lambda (Λ) was used as the comparison statistic

Bold indicates statistically significant value, $P < 0.05$

Can. Canopy, *Phytocl.* phytoclimate

exchange capacity, and the concentrations in calcium and magnesium (Table 4). The significant differences between the afforested and adjacent open zones were greater in the uppermost 5 cm. For the organic-carbon contents and the C/N relationship, significant differences were also noted at 5–10 cm in depth.

Differences with native forests

For soil comparisons of the pine plantations with respect to native forests, the results (Table 5) show significant differences in terms of the variables measured at all depths, regardless of the phytoclimate and the factor CANOPY (under tree canopy *vs.* open adjacent areas).

The native forests registered significantly higher values in gravels, SOC, N, K, Ca, Na, and CEC (Table 6). On the contrary, the afforested zones presented higher values for calcium carbonate and pH. These differences were found at all depths. Some of the parameters studied, such as organic carbon, N, K, or CEC, practically doubled in value in the native forests with respect to afforested areas.

Correlation analyses

Correlations between SOC and the main soil variables are similar either using combined data or considering the forest type and open/afforested areas separately (Table 7). The most significant variation between the correlations of combined and divided data is for calcium carbonate, clay, and silt.

With the consideration of divided data, strong correlations were established between the SOC and N. The K presented a similar relationship with SOC, although in some cases the significance level was lower. Also, the correlations with CEC and soil–water capability measured at −33 and −1500 kPa proved positive, although in some cases they were not significant. With pH, the correlations were negative, except in the native forests. With $CaCO_3$, a significant negative correlation resulted when using the data from the samples collected in the open zones within phytoclimatic sclerophyllous type. Practically, no significant correlations were found between the SOC content and the textural fractions of the soil underneath the tree canopy of any of the forest types considered. Among the samples collected in the open areas, positive correlations were found between SOC and clay within phytoclimatic sclerophyllous type ($r = 0.52$) and between SOC and the silt fraction in the samples collected in open areas of the native forests ($r = 0.66$).

Discussion

The results of the MANOVA indicate that afforestations altered the soil characteristics, increasing the fertility (mainly SOC, N, and CEC), in both phytoclimatic environments, at least in the uppermost 10 cm of the soil (Table 4). Nevertheless, SOC, N, C/N relationship, and exchangeable cations differed significantly within the two phytoclimatic environments considered. This could be related to the more favourable climatic conditions, especially rainfall (Zornoza et al. 2007), as well as the greater density of the vegetation associated with the phytoclimatic sclerophyllous types, together with the presence of superior colonization of the accompanying species. As in other studies in cold-temperate areas (Li et al. 2010; Rosenqvist et al. 2010), other variables such as age, basal area, volume could influence these results.

Regardless of the phytoclimatic environment, the afforested stands doubled the SOC values of the adjacent open areas in the upper 10 cm of soil. Maestre et al. (2003) also pointed out an increase in soil organic matter between pine plantations and open microsites, although the differences found were less marked than ours and in no case proved significant. Along the same lines, Sinsabaugh et al.

Table 3 Results for comparisons of soil characteristics in different phytoclimatic environments (ESC: sclerophyllous, HIP: hyperxerophyllous) at the depth studied (only at afforested sites)

	PHYTOCL.	−1500 kPa (%)	SOC (%)	N (%)	Ca	Mg	K	CEC	Clay (%)	−33 kPa (%)	Gravel (%)
					$\mathrm{Cmol_c\ kg^{-1}}$						
0–5 cm	ESC ($n = 12$)	23.64 ± 3.51*	6.23 ± 1.24**	0.35 ± 0.06***	21.07 ± 3.59***	3.91 ± 0.82**	1.16 ± 0.29***	26.26 ± 3.67***	–	–	–
	HIP ($n = 44$)	16.24 ± 1.26	3.28 ± 0.49	0.18 ± 0.02	11.76 ± 1.02	2.30 ± 0.21	0.51 ± 0.05	14.68 ± 1.15	–	–	–
5–10 cm	ESC ($n = 12$)	22.47 ± 2.08***	3.65 ± 0.61***	0.24 ± 0.04***	18.15 ± 3.69**	4.14 ± 0.93**	0.98 ± 0.25***	23.39 ± 3.58***	35.90 ± 4.70*	28.98 ± 1.97*	–
	HIP ($n = 44$)	14.85 ± 0.95	1.88 ± 0.22	0.12 ± 0.01	9.54 ± 0.83	2.22 ± 0.21	0.41 ± 0.04	12.27 ± 0.92	26.52 ± 1.63	23.03 ± 1.27	–
>10 cm	ESC ($n = 12$)	20.53 ± 1.90**	2.30 ± 0.39*	0.17 ± 0.03*	15.87 ± 3.94**	4.38 ± 1.04**	0.84 ± 0.22**	21.21 ± 3.82***	–	–	44.30 ± 5.34*
	HIP ($n = 43$)	15.07 ± 0.91	1.44 ± 0.16	0.11 ± 0.01	8.21 ± 0.68	2.41 ± 0.25	0.36 ± 0.04	11.12 ± 0.79	–	–	26.77 ± 3.38

The Tukey test was used to identify significant differences between phytoclimatic types. Data are mean ± SE

Phytocl. phytoclimate factor

* $0.05 > P > 0.01$, ** $0.01 > P > 0.001$, *** $P < 0.001$

(2004) reported a significant variation in the organic-matter content in the soil after different fertilization treatments of the soil and in different forest types. The C/N relationship in the afforested soils, higher than 20 at 0–5 cm in depth and higher than 15 at 5–10 cm in depth, indicates a predominance of humification processes in these areas (Cotrufo et al. 2000).

The relationship between the clay content and SOC fixation has been documented in many works (Hassink and Whitmore 1997; Álvarez and Lavado 1998; Percival et al. 2000; Arrouays et al. 2006). However, given the absence of correlations between the SOC and the textural fractions (Table 7), the supply of organic matter by plants is the main factor influencing the SOC content. Similar results were found by Castro et al. (2008) in olive-orchard soils with different supplies of organic matter.

The contents in N, Ca, Mg, and CEC presented significant differences only in the uppermost 5 cm of the soil. The CEC was positively correlated with the SOC (Table 7), this correlation being stronger under all the tree canopies. The increase in CEC related to the greater content in SOC may explain the higher quantity of cations retained. These results agree with those of Kutiel and Naveh (1987), who reported greater soil fertility under *Pinus halepensis* than in open areas or those covered by grass, as the environment supplied a higher quantity of organic wastes and had a lower nutrient demand.

Although the mean value of the content in exchangeable K was greater in the afforested zones than in the adjacent open zones, in many of the paired samples, this relationship was reversed, with contents higher in the open zones. In most cases, the differences were minor, although at certain sampling points, values were notable. Different works (Rhoton et al. 1993; Thomas et al. 2007) associate the increase in exchangeable K with the greater SOC in the soil; however, in our study, the correlations between SOC and K, although positive, presented *r* values lower than those established between SOC and N, elements also commonly associated. Lafleur et al. (2005) indicated that the increase in exchangeable K may be related to the higher mineralization index, which could explain the greater concentration in some open zones. Dames et al. (2002), studying the nutrient cycle of *Pinus patula* Schltdl. & Cham. afforestation stands, observed that the K pool of litter was threefold higher than the K pool of the soil. In our study, this litter was removed to take samples. The fact that pine litter tends to retain K could explain the lower values found in some soils. Kupfer et al. (2004) also found the importance of K sequestering in the regeneration of the vegetation.

The water-retention capacity of the soil at −33 and −1500 kPa was not correlated to the SOC content in the

Table 4 Results for comparisons of soil characteristics under the tree canopy (Below) and open sites (Open), only for afforestation sites at the depth studied

	CANOPY	SOC	C/N	N	Ca	Mg	CEC
0–5 cm	Below ($n = 28$)	5.59 ± 0.73***	20.6 ± 1.04***	0.26 ± 0.02*	17.09 ± 1.89**	3.15 ± 0.42*	21.02 ± 2.04***
	Open ($n = 28$)	2.24 ± 0.49	12.71 ± 0.49	0.17 ± 0.03	10.43 ± 1.24	2.14 ± 0.25	13.31 ± 1.44
5–10 cm	Below ($n = 28$)	2.77 ± 0.32*	15.76 ± 0.65***	–	–	–	–
	Open ($n = 28$)	1.75 ± 0.31	12.52 ± 0.53	–	–	–	–

The Tukey test was used to identify significant differences between canopy and open sites. Data are mean ± SE

Canopy canopy factor

* $0.05 > P > 0.01$, ** $0.01 > P > 0.001$, *** $P < 0.001$

Table 5 MANOVA results for all the depths studied, with all the dependent variables measured and for the factors FOREST TYPE (native forest and afforestation), CANOPY (under tree canopy and open sites), and PHYTOCLIMATE (sclerophyllous and hyperxerophyllous types)

The Wilks lambda (Λ) was used as the comparison statistic

Bold indicates statistically significant value, $P < 0.05$

		Λ value	*F*	Effect *df*	Error *df*	*P*
0–5 cm ($N = 71$)	Forest type	1	2	18	50	**0.0360**
	Phytocl. × Type	1	1	18	50	0.4781
	Can. × Type	1	2	18	50	0.1249
5–10 cm ($N = 71$)	Forest type	1	2.41	18	46	**0.0084**
	Phytocl. × Type	1	8.27	18	46	0.6609
	Can. × Type	1	1.32	18	46	0.2193
>10 cm ($N = 70$)	Forest type	1	2	18	49	**0.0223**
	Phytocl. × Type	1	1	18	49	0.6767
	Can. × Type	1	1	18	49	0.2698

samples under the tree canopy in the sclerophyllous phytoclimate (probably due to a lower number of samples in this type), but it was in the hyperxerophyllous setting and the native forests (Table 7). The organic matter increased the capacity of soil to store water (Franzluebbers 2002) by altering the size and distribution of the soil pores (Bescansa et al. 2006). However, the water-retention capacity of the soil was also affected by the texture itself. Bauer and Black (1981) reported that the effect of the SOC in the water-retention capacity was high in sandy soils but marginal in fine-textured soils. The soils sampled within the sclerophyllous phytoclimate showed generally a low correlation between the SOC and the water-retention capacity, probably due to the finer and relatively uniform textures. Similar results were reported by Rawls et al. (2003) studying the relationship between soil moisture and SOC content in soils of different textures.

The open zones presented very similar values in all the sites studied, somewhat lower in the phytoclimatic hyperxerophyllous type but without significant differences (Fig. 2). The native forests within the sclerophyllous phytoclimate (Holm oak forests) presented the highest SOC contents, probably due to the characteristics of the vegetation (age, biomass, basal area, etc.) or for better climatic conditions, which favour greater productivity. Also, the differences in accumulated SOC under the tree canopy of these native forests were greater with respect to the adjacent open zones (under tree canopy: 16.6% ± 3.5 SE; open: 3.2% ± 1.1 SE) than in the phytoclimatic hyperxerophyllous type (under tree canopy: 8.3% ± 1.2 SE; open: 3.4% ± 0.3 SE). The effect of the afforestation in the Guadalentín basin has increased the SOC content of the soils and altered, in a variable way, the soil properties, although these changes did not reach values found in native forests. In addition to the variables considered in this study, other parameters such as age, biomass, basal area can be decisive in the explanation of the results and should be considered in further studies.

Conclusions

The afforestation stands altered the soil characteristics under the tree canopy in the two phytoclimates studied, but the differences with respect to the soils of the adjacent open zones were greater in the sclerophyllous phytoclimate, where the climatic conditions were more favourable.

The protection of the soil against erosive processes, together with the organic-matter supply provided by afforestations improved the structure of the uppermost cm of the soil, augmenting the SOC content and, concomitantly, soil properties related to physico-chemical fertility, such as N and K contents, cation-exchange capacity, and water-retention capacity.

Table 6 Results for comparisons of soil characteristics in native forests and at afforestation sites (forest-type factor) at the depths studied

	Forest Type	Gravels	SOC	N	$CaCO_3$	pH	Ca	K	CEC	Na	Silt	AW
0–5 cm	NAT ($n = 15$)	49.31 ± 4.97*	8.20 ± 1.73**	0.48 ± 0.10***	16.85 ± 5.27	7.62 ± 0.06	24.36 ± 3.29***	1.33 ± 0.32**	28.89 ± 3.74***	0.17 ± 0.03*	–	–
	AFFOR ($n = 56$)	32.91 ± 3.05	3.92 ± 0.49	0.21 ± 0.02	39.84 ± 3.20**	7.92 ± 0.03***	13.76 ± 1.21	0.65 ± 0.08	17.16 ± 1.34	0.11 ± 0.01	–	–
5–10 cm	NAT ($n = 15$)	44.63 ± 6.09*	4.68 ± 1.24**	0.31 ± 0.08**	19.67 ± 6.13	7.74 ± 0.07	20.23 ± 2.78***	1.03 ± 0.28*	23.66 ± 2.97**	0.15 ± 0.02*	30.63 ± 2.30	–
	AFFOR ($n = 56$)	30.54 ± 2.78	2.26 ± 0.23	0.15 ± 0.01	42.82 ± 3.23**	7.96 ± 0.03**	11.38 ± 1.11	0.53 ± 0.07	14.66 ± 1.20	0.10 ± 0.01	37.44 ± 1.42*	–
>10 cm	NAT ($n = 15$)	53.65 ± 4.50***	2.70 ± 0.53**	0.22 ± 0.04**	26.09 ± 7.14	7.80 ± 0.07	17.72 ± 1.83**	0.96 ± 0.36*	20.76 ± 1.99**	–	30.72 ± 2.27	5.60 ± 0.54
	AFFOR ($n = 55$)	30.60 ± 3.03	1.63 ± 0.16	0.12 ± 0.01	44.61 ± 3.61*	8.02 ± 0.03**	9.89 ± 1.08	0.47 ± 0.06	13.32 ± 1.16	–	38.04 ± 1.44*	7.78 ± 0.46*

The Tukey test was used to identify significant differences. Data are mean ± SE

NAT native forests, *AFFOR* afforestation areas

* $0.05 > P > 0.01$, ** $0.01 > P > 0.001$, *** $P < 0.001$

Table 7 Spearman correlation coefficients between SOC and some soil parameters

Soil parameter	Combined data $n = 194$	Afforestations within sclerophyllous phytoclimate		Afforestations within hyperxerophyllous phytoclimate		Native forests	
		$n = 18$		$n = 66$	$n = 65$	$n = 24$	$n = 21$
		Under tree canopy	Open areas	Under tree canopy	Open areas	Under tree canopy	Open areas
N	0.94**	0.88**	0.97**	0.94**	0.94**	0.92**	0.91**
pH	−0.48**	−0.57*	−0.62**	−0.46**	−0.28*	−0.31	−0.26
K	0.51**	0.54*	0.51*	0.39**	0.45**	0.64**	0.50*
CEC	0.58**	0.47*	0.33	0.67**	0.45**	0.55**	0.53*
−33 kPa	0.44**	0.44	0.63**	0.44**	0.11	0.62**	0.54*
−1500 kPa	0.49**	0.25	0.68**	0.45**	0.17	0.56**	0.28
$CaCO_3$	−0.25**	−0.39	−0.48*	−0.15	0.01	−0.10	0.15
Clay	0.16*	0.05	0.52*	0.06	0.05	0.05	−0.33
Silt	−0.16*	0.19	−0.20	−0.25*	−0.14	0.10	0.66**
Sand	−0.01	−0.14	−0.38	0.11	0.21	−0.08	−0.16

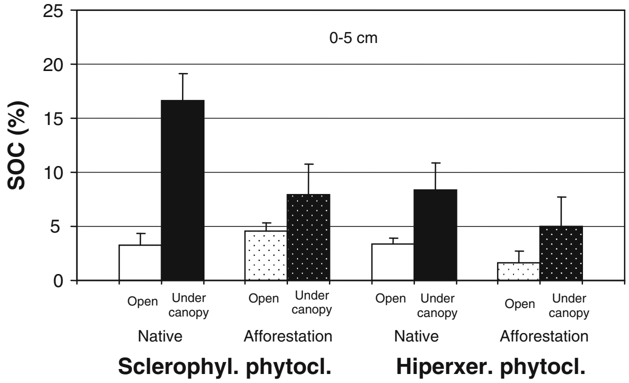

Fig. 2 SOC content in the native forests (under tree canopy and open areas) and at afforested sites within the two phytoclimates studied

The differences found with respect to the native forests appear to indicate that the afforested soils have not yet reached their maximum potential and are thus expected to improve further in quality. However, the effects that forest development (age, basal area, biomass) over time exerts on soil properties remain to be verified by further research.

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