Acta Oecologica 38 (2012) 58–65

Contents lists available at SciVerse ScienceDirect

Acta Oecologica

journal homepage: www.elsevier.com/locate/actoec

Original article

Soil chemical properties in abandoned Mediterranean cropland after succession and oak reforestation

B. Cuesta[a,*], J.M. Rey Benayas[a], A. Gallardo[b], P. Villar-Salvador[a], M. González-Espinosa[c]

[a] *Departamento de Ecología, Universidad de Alcalá, 28871 Alcalá de Henares, Spain*
[b] *Departamento de Sistemas Físicos, Químicos y Naturales, Universidad Pablo de Olavide, 41013 Sevilla, Spain*
[c] *División de la Conservación de la Biodiversidad, El Colegio de la Frontera Sur (ECOSUR), Apartado Postal 63, 29290 San Cristóbal de las Casas, Chiapas, Mexico*

ARTICLE INFO

Article history:
Received 15 December 2010
Accepted 12 September 2011
Available online 2 October 2011

Keywords:
Ammonium
Inorganic nitrogen
Nitrate
Old fields
Quercus ilex
Soil fertility
Tree planting

ABSTRACT

Large extents of cropland have been abandoned in recent decades and more may be abandoned in the near future. These may undergo secondary succession or reforestation. We experimentally tested the response of soil chemical properties to secondary succession (old field) and to *Quercus ilex* plantation (reforested cropland) in a Mediterranean cropland that was abandoned 13 years ago. We also evaluated the relevance of previous reforestation management (four combinations of presence and absence of irrigation and shading) in addition to current environmental conditions (herbaceous community and cover of oak canopy) on soil chemistry in the reforested cropland. Carbon and NH_4^+−N concentrations and availability of mineral N were higher in the reforested cropland than in the old field. However, soil pH, total N, P, K and NO_3^-−N concentrations, mineralization rates, and available PO_4^{3-}−P were similar in the reforested cropland as well as in the old field. Previous reforestation management practices, particularly irrigation, and current environmental conditions, mostly biomass and composition of the herbaceous community, affected soil chemistry. Irrigation increased K and P concentrations and NH_4^+−N availability. This study highlights the overall slow dynamics of soil chemistry in Mediterranean ecosystems, which has resulted in little variation of soil properties in reforested cropland after more than a decade. Reforestation can accelerate the recovery of some soil properties of abandoned cropland in comparison with secondary succession, but these effects will be more noticeable in longer time periods.

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1. Introduction

Large extents of cropland have been abandoned during the last decades due to a number of ecological and socio-economic factors (Bakker et al., 2005; Rey Benayas et al., 2007). Further, a considerable amount of cropland may be abandoned in the near future due to human migration from rural areas (Grau and Aide, 2008) or subsidies for cropland reforestation such as those from the EU Community Agrarian Policy or China's Grain to Green project (Cao et al., 2009). These areas can be left to undergo secondary succession (passive restoration) or be subjected to active restoration that mostly consists of tree and shrub planting and their management. At present, more abandoned agricultural land area is being restored by tree plantations than by secondary succession (FAO, 2011).

In semiarid ecosystems, recruitment of woody species is usually slow because it is hindered by factors such as extreme climatic conditions, poor soil fertility, and competition from herbaceous vegetation (Rey Benayas, 2005; Vallejo et al., 2006). Thus, Mediterranean abandoned cropland under secondary succession is initially colonized by herbaceous vegetation which persists for a long time before woody vegetation establishes (Bonet and Pausas, 2004). Restoration of these systems usually requires reforestation practices in order to reduce soil erosion, increase biological diversity and create carbon sinks.

There is evidence that reforestation not only alters aboveground vegetation, but also leads to significant changes in the physical and chemical properties and biochemical cycles of soils (Alriksson and Olsson, 1995; Côté et al., 2000; Paul et al., 2010b). After cropland abandonment, soil chemical properties may differ from natural soil properties due to previous agricultural practices such as fertilization, plowing, and harvesting (Koerner et al., 1997; Compton and Boone, 2000; Hooker and Compton, 2003). Generally, soil carbon increases with time after abandonment due to biomass accumulation, whereas available phosphorous decreases because of its

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[*] Corresponding author. Current address: Centro de Investigación Forestal, Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria–INIA, Carretera de La Coruña Km 7.5, 28040 Madrid, Spain. Tel.: +34 913476773; fax: +34 913476767.

E-mail address: cuesta.barbara@inia.es (B. Cuesta).

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doi:10.1016/j.actao.2011.09.004

immobilization in the living plant biomass (Du et al., 2007; Dölle and Schmidt, 2009). There is also a general consent that vegetation recovery can successfully restore soil nitrogen stocks (Alriksson and Olsson, 1995; Silver et al., 2005; Paul et al., 2010b). Since vegetation recovery differs between secondary succession and reforestation, soil chemical properties are expected to be different under these contrasting scenarios of Mediterranean woodland restoration.

Several studies have shown that plant species differ in their capacity to modify soil properties (Gallardo and Merino, 1993; Vinton and Burke, 1995; Cornelissen et al., 1999) since plant functional traits such as growth form, biomass allocation, tissue chemistry, and lifespan can significantly affect organic matter decomposition and nutrient dynamics (Hooper and Vitousek, 1998; Carrera et al., 2009). Plants with fast growth rates, such as herbaceous vegetation that usually proliferates on recently abandoned cropland, show high N concentration in green tissues and low content of secondary compounds which turn into high quality litter that decomposes rapidly (Carrera et al., 2009). In addition, some plants such as the legumes have N-fixing capacity, which increase soil N content (Hooper and Vitousek, 1998; Oelmann et al., 2007; Davies et al., 2009). In contrast, plants with slow growth rates such as Mediterranean evergreen species exhibit high concentration of secondary compounds and chemical defenses against herbivores (e.g. phenol–protein complexes) which promote slow decomposition (Aerts and Chapin, 2000; Satti et al., 2003).

Quercus ilex (Holm Oak) is a slow-growing, sclerophyllous evergreen oak that is a major structural component of the natural woodlands in Western Europe and Northern Africa. Holm Oak produces large amounts of litter which can potentially incorporate considerable quantities of organic matter and nutrients to the soil (Gallardo, 2003; Moreno et al., 2007). In addition, the microclimatic conditions generated under tree canopies in dry climates, namely lower soil temperature and higher soil moisture, enhance microbial activity and increase litter decomposition and mineralization of organic matter (Muscolo et al., 2007; Sariyildiz, 2008). Thus, the presence of Holm Oak canopy may have both positive and negative effects on soil nutrient dynamics.

In this study, we analyze soil chemical properties associated with early secondary succession (hereafter referred to as old field) and reforestation with *Q. ilex* (hereafter referred to as reforested cropland) in a Mediterranean cropland that was abandoned 13 years ago. As the response of soil to the environment is usually slow, most of this type of soil research is based on chronosequences or “space for time” studies (e.g. Alriksson and Olsson, 1995; Compton and Boone, 2000; Falkengren-Grerup et al., 2006; Paul et al., 2010a,b). However, we used an experimental approach rather than a phenomenological approach to test the effects of environmental manipulation on soil properties. Our study is part of long-term research aiming to investigate the effects of environmental manipulation on ecosystem processes in relation to restoration of Mediterranean woodland (Cayuela et al., 2008; Rey Benayas et al., 2008a). In this context, we also evaluated the relevance of previous management in addition to current environmental conditions on soil chemistry of the reforested woodland. Based on the contrasting effects of canopy of Holm Oaks on soil nutrient dynamics, we asked whether nutrient concentration and availability would be higher in the reforested woodland than in the old field or *vice-versa*. We hypothesized that current soil chemical properties of actively reforested woodland will reflect both a carry-over effect of previous management and a response to current environmental conditions. Most tree plantations in Mediterranean environments are based on pine species (MAPA, 2006), and little attention has been given to how plantations of native oak species modify soil chemical properties. Our research will help to forecast effects of cropland reforestation on soil properties in comparison to secondary succession in Mediterranean environments, as well as offer an opportunity to test how previous environments resulting from reforestation management affect the current soil chemical properties.

2. Materials and methods

2.1. Study site

The study site was located in 1 ha of abandoned cropland in central Spain (40°3′N, 4°24′W, altitude 450 m), which had been cultivated for grain for at least four decades until the experiment started. It has a typical Mediterranean continental climate, with mean annual precipitation of 480 mm and mean annual temperature of 15 °C. Summer is hot and dry while winter is cold with frequent frosts. The soil is a luvisol type derived from sandstone arkoses and is classified as loamy sand (62% sand, 23% silt, and 15% clay). Before abandonment, the cropland was fertilized following a standard scheme in the area: application of a fertilizer with inorganic nitrogen, phosphorous and potassium (70:35:35, 400 kg ha^{-1}) once a year plus another annual application of just inorganic nitrogen (27% concentration, 150 kg ha^{-1}).

In this abandoned cropland, we assessed two contrasted strategies of vegetation restoration, namely secondary succession and cropland reforestation. We assessed 20 10 × 10 m-plots in total, four of which were under secondary succession (old field plots) and 16 were reforested (reforested cropland plots). The old field plots were located close to reforested cropland (<20 m apart). Soil parent material and depth were identical in all 20 plots, which were also subjected to identical soil preparation (plowing) before the reforestation took place in 1993. The 16 reforested plots were planted with 50 one-year-old seedlings of *Q. ilex* subsp. *ballota* planted at regular intervals of 2 m (Rey Benayas, 1998). During the first three years, the planted seedlings were subjected to one of four treatments from the factorial combination of summer irrigation and artificial shading (control, irrigation, shading, and irrigation and shading) with four replicate plots per treatment. Irrigation was applied uniformly with sprinklers at the peak of the dry season (60 mm in July and August; 120 mm in total per year) and added across the whole plot area. The shading treatment consisted of a 68% reduction in incident radiation by placing a black polyethylene net 2 m above ground. The shading and irrigation treatments were stopped in the winter of 1996 and all plots have experienced natural rainfall and light conditions since then. The plots were protected from herbivores (sheep, rabbits and hares) with appropriate fencing.

2.2. Characterization of vegetation and litter

Variables related to vegetation structure and composition and plant litter were measured both in the old field and in the reforested cropland plots. In May 2006, five 50 × 50 cm quadrats were established in each plot. In these quadrats, herbaceous aboveground biomass and herbaceous and Holm Oak litter mass were collected and weighed after drying at 60 °C for two days. All vascular plant species were identified and recorded in these five quadrats and in four additional quadrats. All species were classified into groups according to their functional attributes as graminoids, legumes and forbs (see Cayuela et al., 2008 for species composition details). We calculated the mean value of each measured variable (herb biomass, Holm Oak and herb litter mass, and total herbaceous, graminoid, legume and forb cover) per plot. In December 2005 the volume of Holm Oak canopies in reforested cropland plots was calculated as the sum of the individual volumes, estimating the volume of each tree as its height × crown projected area. The crown projected area of each Holm Oak was estimated as the elliptical surface of the crown projected onto the ground.

2.3. Soil chemical properties

Soil samples were taken from the four old field and 16 reforested cropland plots in March 2006. We systematically collected three 20 cm deep soil samples per plot at one of the plot diagonals; the location of the three sampling points divided the diagonal in four segments of similar length. These samples were combined into one single soil composite sample per plot (20 composite samples in total). Fresh soil composite samples were sieved to separate plant material and fragments >2 mm in size. For each composite sample, soil pH, carbon (C), total nitrogen (N), total phosphorous (P), and potassium (K) were measured. Soil pH was determined in a 1:2.5 mass:volume soil and water suspension. Carbon was analyzed using $K_2Cr_2O_7$ in a H_2SO_4 environment (Nelson and Sommers, 1982). Total N was determined by Kjeldahl analysis with $SeSO_4{-}K_2SO_4$ as catalyst in a Tecator 20 digestion system and a Kjeltec-auto 1030 analyzer (Tecator, Sweden). For total P, we used the method reported by Burriel and Hernando (1950). Potassium was analyzed according to MAPA (1986) using an Optic PLASMA ICP (Perkin-Elmer, model 4300 DV).

Potential rates of ammonification, nitrification and mineralization were determined by aerobic incubation of 5 g of dry soil of each composite sample with 15 g of pure sand and 6 ml of water for 14 days in the dark at 30 °C. Mineral N was extracted with 100 ml of KCl 2 N (soil:KCl 2 N ratio, 1:4), shaken for 1 h and the suspension filtered through 0.45 mm millipore filters. Ammonium ($NH_4^+{-}N$) and nitrate ($NO_3^-{-}N$) in the extract were measured by colorimetry, using a microplate reader (Sims et al., 1995). Potential net mineralization rate was calculated as the difference between the $NH_4^+{-}N + NO_3^-{-}N$ concentration before and after the incubation period. Potential net nitrification was the difference of $NO_3^-{-}N$ concentration over the same period. Potential ammonification rate was the difference between potential net mineralization rate and potential nitrification rate.

In May 2006, the availability of $NH_4^+{-}N$, $NO_3^-{-}N$, total N ($NH_4^+{-}N + NO_3^-{-}N$) and phosphate ($PO_4^{3-}{-}P$) in soils were assessed using anionic and cationic exchange membranes (types I-100 and I-200, Electropure Excellion, Laguna Hills, California). We used two anion and two cation exchange resin membranes that were placed at the two external sampling points of each plot diagonal and the mean value per plot was calculated. Resin membranes were previously conditioned in the lab by immersing them in demineralized water at 82–90 °C for 48 h. After conditioning, 2.5 × 2.5 cm resin membranes were glued on a plastic holder to facilitate insertion into the soil. A plastic rod joined to the plastic holder helped to locate the resin membranes in the field. This design kept the membrane ionic exchange capacity unaltered (Cain et al., 1999). Exchange resin membranes were introduced in the soil at a ca. 10 cm depth and remained in the soil for 20 days. After being removed, the membranes were dried at ambient temperature. The attached soil was removed, the plastic rod was cut and an extraction was performed with 50 ml of 2 M KCl (5 cm^2 of resin membrane per 50 ml of 2 M KCl) by orbital spinning for 1 h at 200 rpm in 125 ml flasks. These extracts were used to calculate the quantity of $NH_4^+{-}N$, $NO_3^-{-}N$, and total N-mineral by the indophenol blue method (Sims et al., 1995) and $PO_4^{3-}{-}P$ by the molybdenum blue method (Allen et al., 1986) with a microplate reader.

2.4. Effects of previous and current environmental conditions

The management treatments (irrigation and shading) applied to the 16 reforested cropland plots between 1993 and 1995 were used to account for the environmental conditions during early establishment of the introduced *Q. ilex* seedlings.

We measured different variables to describe the effect of current environmental conditions in each reforested cropland plot. In addition to the volume of Holm Oak canopy, herbaceous aboveground biomass and litter mass, we estimated the canopy openness and soil moisture. Canopy openness was assessed by means of hemispherical (or fish-eye) digital photographs taken just before sunrise with a Nikon Coolpix 4500 camera with a Nikon Fisheye Converter FC-E8 0.21x and analyzed with WinPhot 5.00 software (Hans ter Steege, Utrecht University, 1996). We took photographs at nine sampling points per plot set with a regular distribution and the mean value per plot was calculated. Soil moisture in the first 10 cm was measured in each plot at five sampling points regularly spaced within the plot. We used a time domain reflectometer (TDR, Topp et al., 1980) on three dates (13 May, 23 May and 7 June 2006), and the mean value per plot was calculated. To account for the effect of current environmental conditions, we used volume of Holm Oak canopy, herbaceous mass, and composition of the herbaceous communities as explanatory variables. Across reforested cropland plots, volume of Holm Oak canopy was negatively correlated with canopy openness ($r = -0.74$; $p = 0.001$; $n = 16$) and soil water content ($r = -0.52$; $p = 0.041$; $n = 16$), and positively correlated with Holm Oak litter ($r = 0.73$; $p = 0.001$; $n = 16$). Since these four variables were highly correlated, we only used canopy volume in the statistical analyses. In order to reduce the dimensionality of the species composition of the herbaceous community data set into one single variable, a non-metric multidimensional scaling (NMDS) was performed and the values for the first axis were selected as values of species composition.

2.5. Data analysis

Differences among soil chemical properties, vegetation cover and litter mass between old field and reforested cropland plots were analyzed with Student's *t* tests. For these analyses, we used only the control reforested plots, where irrigation and artificial shading treatments were not applied.

In the reforested cropland plots, differences in soil chemical properties, vegetation cover and litter mass among the four previous management treatments (control, irrigation, shading, and irrigation and shading) were analyzed by means of two-way ANOVA, in which irrigation and shading were the factors analyzed.

To test the simultaneous responses of soil properties to previous and current environmental conditions, the variance of soil properties was partitioned into different components by means of redundancy analysis (RDA) (Borcard et al., 1992). We differentiated direct effects of previous management, direct effects of current environmental conditions (i.e. Holm Oak canopy and herbaceous community), indirect effects of previous management through effects on current environmental conditions, and indirect effects of Holm Oak canopy through effects on the herbaceous community. The partitioning of the variance analysis allows estimation of the effects of each single variable or the effects of a group of variables; thus, the effects of the herbaceous community refer to both herb community composition and biomass. Indirect effects do not have degrees of freedom and, therefore, they cannot be tested for significance.

Data were checked for normality and homogeneity of variance, and were transformed when necessary to correct deviations from these assumptions. Differences between the levels of significant explanatory factors were determined using post-hoc Tukey's tests. All statistical analyses were performed with Statistica 6.0. Package (StatSoft, Inc., Tulsa, OK, USA) and R 2.8 (R Development Core Team 2008).

3. Results

3.1. Vegetation structure and litter mass

Holm Oak canopy was relatively closed in the reforested cropland (mean of 56.1% in the four reforested control plots), whereas not a single Holm Oak was established in the old field plots after 13 years of cropland abandonment. Consequently, there was a relatively high quantity of Holm Oak litter in the reforested cropland (Table 1), but not in the old field. The old field had higher herbaceous cover (62.1 ± 4.6%), herbaceous biomass (143.9 ± 12.3 g m^{-2}) and herbaceous litter (126.2 ± 20.7 g m^{-2}) than the reforested cropland (Table 1; $p = 0.035$, $p = 0.024$ and $p = 0.042$ for these variables, respectively). Leguminous ($p = 0.113$) and graminoid ($p = 0.661$) cover were similar in the old field (3.7 ± 1.1% and 24.6 ± 4.8%, respectively) and in the reforested cropland (Table 1), but forb cover was higher in the old field (33.8 ± 3.8%) than in the reforested cropland (Table 1, $p = 0.048$).

Volume of Holm Oak canopy did not differ among reforested cropland plots subjected to previous management treatments (Table 1). However, canopy openness and Holm Oak litter in control plots were lower than in both irrigated plots and shaded plots (Table 1). Herbaceous biomass and cover were lower in shaded plots, but there were no differences in herbaceous litter among plots subjected to different management treatments (Table 1). Irrigation increased legume cover and shading reduced graminoid cover, but the treatments did not affect forb cover (Table 1).

3.2. Effects of vegetation restoration on soil chemical composition

Soil pH was similar in the reforested cropland (5.71 ± 0.22) and in the old field (5.70 ± 0.16). Concentration of soil C (Fig. 1a) was 25% higher in the reforested cropland than in the old field. Neither, N, P or K concentrations in the soil differed between the reforested cropland and the old field (Fig. 1b–d). The C:N ratio of soil was similar in the reforested cropland (10.71 ± 0.39) and in the old field (10.37 ± 0.36).

The concentration of soil NH_4^+–N was almost twice in the reforested cropland than in the old field, whereas no differences were found for the concentrations of NO_3^-–N or total mineral N (Fig. 2a). Availability of NH_4^+–N, NO_3^-–N and total mineral N were 65–77% higher in the reforested cropland than in the old field (Fig. 2b). In both old field and reforested cropland, the availability of NH_4^+–N in the soil was higher than that of NO_3^-–N (78% and 67%, respectively). Soil ammonification, nitrification, and mineralization rates did not differ between reforested cropland and old field (Fig. 2c). Similarly, no differences were found for availability of PO_4^{3-}–P in the soil (6.06 ± 0.41 and 6.39 ± 1.28 μg dm^{-2} day^{-1}, respectively; $p = 0.917$).

3.3. Effects of previous and current environmental conditions on soil chemical properties in reforested cropland

Neither C, total N or the C:N ratio differed among soil collected from reforested cropland plots subjected to different previous management treatments. Soil K was the highest in irrigated plots (either shaded or not) and lowest in shaded plots, whereas control plots had intermediate values (Table 1). Irrigated plots showed the highest concentration of soil P, shaded and control plots the lowest, and the plots that were both irrigated and shaded had intermediate values. Concentrations of NH_4^+–N, NO_3^-–N and total mineral N in the soil did not differ among previous treatment plots. In contrast, availability of NH_4^+–N, NO_3^-–N, and total mineral N differed among treatments (Table 1). Soil from irrigated plots and shaded plots had higher availability of NH_4^+–N than plots that were both irrigated and shaded, whereas control plots had intermediate values. Availability of NO_3^-–N and total mineral N were lower in plots that were both irrigated and shaded compared to other treatment plots. The four management treatments did not have any effect on availability of PO_4^{3-}–P or on potential rates of ammonification,

Table 1
Vegetation cover, litter and soil variables measured in the reforested cropland plots under different treatments of previous management. Data are means ± standard error. Different letters mean statistical differences at $p \leq 0.05$.

	Control	Irrigation	Shading	Irrigation and shading
Vegetation cover and litter mass				
Volume of Holm Oak canopy (m^3 ha^{-1})	103.1 ± 41.1	209.8 ± 90.7	171.1 ± 42.1	137.8 ± 42.6
Holm Oak canopy openness (%)	68.5 ± 5.9^a	45.9 ± 3.4^b	45.4 ± 5.2^b	59.1 ± 3.9^{ab}
Holm Oak litter mass (g m^{-2})	66.7 ± 24.0^b	127.5 ± 27.1^a	135.1 ± 7.7^a	83.1 ± 30.2^{ab}
Herbaceous biomass (g m^{-2})	82.8 ± 15.6^a	54.9 ± 12.2^{ab}	35.1 ± 5.6^b	62.7 ± 18.4^{ab}
Herbaceous litter biomass (g m^{-2})	78.1 ± 12.6	68.4 ± 11.8	74.5 ± 5.9	65.5 ± 11.1
Herbaceous cover (%)	58.2 ± 4.2^a	45.1 ± 4.7^{ab}	32.0 ± 3.6^b	51.0 ± 10.6^{ab}
Legume cover (%)	1.25 ± 0.8^{bc}	4.19 ± 1.1^{ab}	0.75 ± 0.2^c	4.71 ± 1.7^a
Graminoid cover (%)	24.3 ± 3.6^a	15.9 ± 1.2^{ab}	11.5 ± 2.0^b	14.1 ± 2.8^{ab}
Forb cover (%)	31.4 ± 2.7	25.0 ± 4.0	19.8 ± 2.9	24.8 ± 2.3
Soil properties				
pH	5.71 ± 0.22^b	6.49 ± 0.19^a	5.52 ± 0.05^b	6.55 ± 0.14^a
C concentration (%)	0.63 ± 0.02	0.53 ± 0.08	0.44 ± 0.06	0.55 ± 0.06
Total N concentration (%)	0.05 ± 0.01	0.05 ± 0.01	0.04 ± 0.005	0.06 ± 0.01
C:N ratio	10.71 ± 0.39	10.60 ± 0.20	10.11 ± 0.40	9.70 ± 0.08
K concentration (μg g^{-1})	172.3 ± 14.4^{ab}	256.8 ± 38.4^a	107.3 ± 6.29^b	230.4 ± 54.5^a
Total P concentration (μg g^{-1})	15.81 ± 0.97^b	36.72 ± 8.15^a	14.30 ± 1.44^b	25.79 ± 5.92^{ab}
NH_4^+–N concentration (μg g^{-1})	3.31 ± 0.24	1.88 ± 0.66	2.40 ± 0.43	2.83 ± 0.41
NO_3^-–N concentration (μg g^{-1})	0.25 ± 0.49	0.47 ± 0.80	0.11 ± 0.87	0.78 ± 1.24
Total mineral N (μg g^{-1})	3.56 ± 0.54	2.35 ± 1.43	2.51 ± 1.17	3.61 ± 1.49
NH_4^+–N availability (μg dm^{-2} day^{-1})	19.1 ± 2.7^{ab}	24.3 ± 4.9^a	21.7 ± 1.0^a	10.7 ± 3.2^b
NO_3^-–N availability (μg dm^{-2} day^{-1})	6.1 ± 0.4^a	6.1 ± 0.8^a	4.9 ± 1.4^a	1.9 ± 0.1^b
Total mineral N availability (μg dm^{-2} day^{-1})	25.2 ± 3.2^a	30.4 ± 5.4^a	26.6 ± 2.2^a	12.5 ± 3.3^b
PO_4^{3-}-N availability (μg dm^{-2} day^{-1})	6.1 ± 0.4	6.02 ± 0.8	7.5 ± 1.9	4.31 ± 0.3
Nitrification rate (μg g^{-1} day^{-1})	0.30 ± 0.03	0.21 ± 0.10	0.23 ± 0.09	0.21 ± 0.08
Mineralization rate (μg g^{-1} day^{-1})	0.22 ± 0.03	0.15 ± 0.09	0.23 ± 0.07	0.15 ± 0.08
Ammonification rate (μg g^{-1} day^{-1})	−0.08 ± 0.01	−0.05 ± 0.01	−0.01 ± 0.06	−0.06 ± 0.01
Water content (%)	5.09 ± 0.86^b	7.70 ± 0.70^a	4.71 ± 0.41^b	5.97 ± 0.80^b

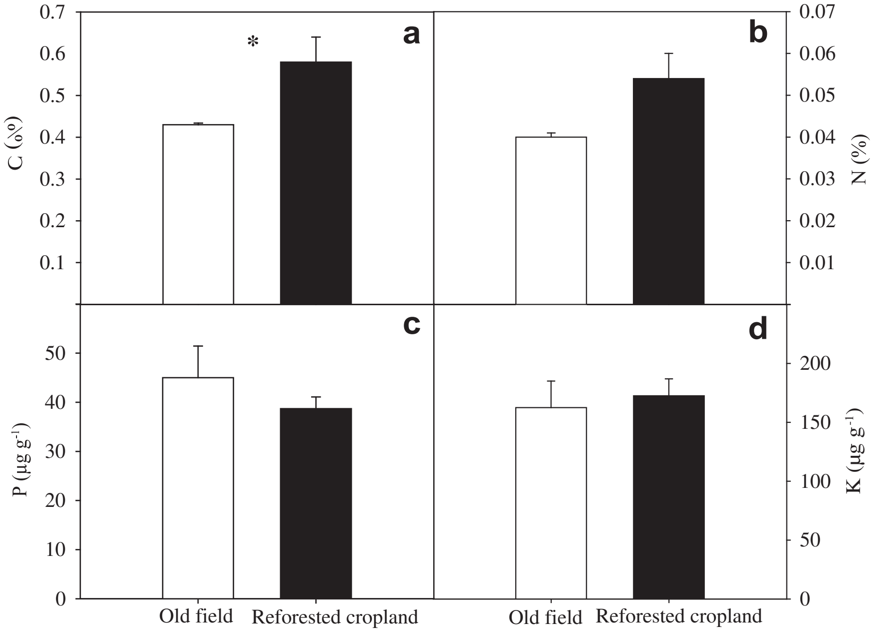

Fig. 1. Soil C (a), total N (b), total P (c), and K (d) concentration measured in the old field and reforested cropland plots. Data are means ± standard error. * means statistical differences at $p \leq 0.05$.

nitrification and mineralization (Table 1). Soil water content was higher in irrigated plots than in the other treatment plots (Table 1).

Direct effects of previous treatments at the time of seedling establishment ($p = 0.032$, D1 in Fig. 3) and of the herbaceous community ($p = 0.499$, D3) explained most of the variation in soil chemical properties in reforested cropland plots (15 and 20% of variance accounted for, respectively). In contrast, the volume of the Holm Oak canopy explained only 2% of the variance ($p = 0.345$, D2). Similarly, the indirect effects of management treatments on the herbaceous community (I2 in Fig. 3) explained 16% of the variance, whereas indirect effects on the Holm Oak canopy (I1) explained only 2% of the variance. The effect of the Holm Oak canopy on the herbaceous community (I3) indirectly explained 1% of the variance.

4. Discussion

4.1. Secondary succession versus Holm Oak reforestation

Our results showed that only few soil chemical properties, namely concentration of C and NH_4^+—N and availability of mineral N, differed between two types of vegetation restoration possible for abandoned cropland regardless on their clearly different vegetation structure (i.e. development of a dense Holm Oak canopy in the reforested plots). Thus, soil changes induced by agricultural practices may persist or exhibit a legacy for a long time after cropland abandonment (Koerner et al., 1997; Compton and Boone, 2000). Other studies, particularly those in temperate prairies and forests,

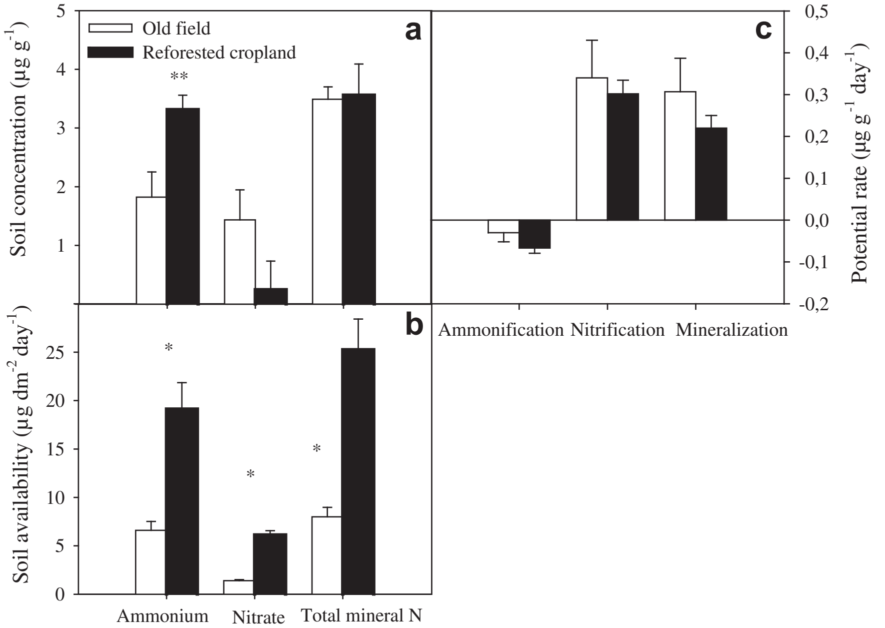

Fig. 2. a) Concentration of soil ammonium, nitrate and total mineral N, b) availability of soil ammonium, nitrate and total mineral N, and c) rates of soil potential ammonification, nitrification and mineralization measured in the old field and reforested cropland plots. Data are means ± standard error. * means statistical differences at $p \leq 0.05$.

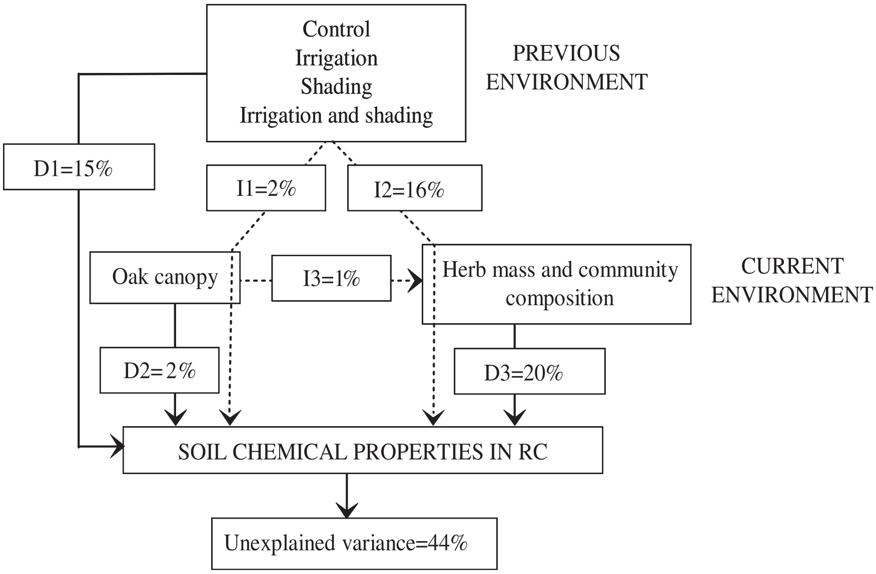

Fig. 3. Contribution of direct effects (solid arrows) and indirect effects (dotted arrows) of previous and current environmental conditions to explain the variance (56%) of soil chemical properties in the reforested cropland plots (RC). D1: direct effects of previous management practices (control, irrigation, shading, and irrigation and shading); D2: direct effects of current Holm Oak canopy; D3 direct effects of current herb community (herb mass and species composition); I1 and I2: indirect effects of previous management through their effects on oak canopy and herb community, respectively; and I3: indirect effects of oak canopy through its effect on herb community.

have reported restoration of soil fertility only after a few decades of cropland abandonment (Rey Benayas et al., 2009).

Thirteen years after cropland abandonment, the old field was colonized by a dense herbaceous community where no woody species has established. The recovery of woody vegetation in Mediterranean old fields is usually hindered by summer drought and herbaceous competition (Bonet and Pausas, 2004; Rey Benayas, 2005; Vallejo et al., 2006). Reforestation in this study created a closed Holm Oak canopy, which reduced herbaceous cover and biomass, probably because of water, nutrient and light deprivation (Ludwig et al., 2004; Pecot et al., 2007). Herbaceous community composition differed between old field and reforested plots, forb cover was higher in the old field. Differences in vegetation structure and composition between the old field and the reforested plots are likely to contribute to the differences observed in some of the studied soil chemical properties (Vinton and Burke, 1995; Cornelissen et al., 1999; Cornwell et al., 2008; Guo et al., 2008).

Soil from reforested cropland showed higher concentration of C than soil from old field which is in agreement with previous studies (Compton and Boone, 2000; Falkengren-Grerup et al., 2006). Carbon accumulation in soils under secondary succession after crop abandonment is slow in Mediterranean environments (Berg et al., 1993; Couteaux et al., 1995), whereas reforestation can accelerate the incorporation of C into the soil (Zhang et al., 2010).

Concentration of total N, P and K, and pH did not differ between reforested cropland and old field plots. Some studies have reported increases in total soil N after agriculture abandonment and woody vegetation recovery (Alriksson and Olsson, 1995; Côté et al., 2000), but other studies have failed to detect such increases (Camill et al., 2004; Marcos et al., 2007). Agricultural land use increases the concentration of N, P and K in the soil due to application of fertilizers and this effect usually persists for long time after crop abandonment (Compton and Boone, 2000; Smal and Olszewska, 2008). It is likely that our experiment has not run a sufficient period of time to override such effects of agricultural fertilization.

Potential rates of mineralization were very low, or even negative, indicating a high potential of soil biota to immobilize N in our study (Gallardo and Merino, 1998). The lack of differences in ammonification, nitrification and mineralization rates between old field and reforested plots can again be explained by the relatively short time since cropland abandonment in an environment that has low productivity. Changes in litter quality due to different plant composition may require a longer time to modify mineralization rates, since decomposition and incorporation of organic matter into the soil is usually slow (Berendse et al., 1989), particularly in Mediterranean environments (Berg et al., 1993; Couteaux et al., 1995). Moreover, mineralization rates were measured at standard environmental conditions in the laboratory and, consequently, the indirect effects of large plants on micro-climatic conditions were omitted. Actual rates of mineralization in the field could well differ between old field and reforested plots.

Soils from old field and reforested cropland showed similar concentrations of total mineral N and NO_3^-–N. However, reforested plots displayed higher concentration of NH_4^+–N and higher availability of mineral N than old field plots. The amount of mineral N in the soil depends mainly on the balance between rates of mineralization and immobilization (Killham, 1994; Accoe et al., 2004). Since net N mineralization was similar in the old field and reforested plots, the lower amount of NH_4^+–N and the lower availability of mineral N found in the old field suggest that immobilization of N was higher here than in reforested cropland. This means that N uptake by plants and/or soil microorganism exceeds the rate at which N is released through decomposition of organic matter. Fast growing species such as herbs are more nutrient demanding than slow growing Holm Oak and therefore have greater potential to uptake nutrients (Poorter et al., 1990), which may explain the lower concentration of NH_4^+–N in old field plots. Furthermore, previous studies demonstrated that N immobilization in the soil microbial biomass is higher in grassland than in forest soils (Davidson et al., 1990, 1992; Hart et al., 1993), which can explain the greater availability of soil mineral N in reforested cropland. Differences in cover of functional groups in the herbaceous community between the old field and the reforested cropland may also explain differences in soil chemistry (Tilman et al., 1997). Legumes usually increase N availability in the soil, because of N_2 fixation and higher N input via litter decomposition, whereas grasses and forbs reduce it, generally due to their high root production (Hooper and Vitousek, 1998; Oelmann et al., 2007; Davies et al., 2009).

4.2. Carry-over effects of reforestation management

In agreement with our hypothesis, soil chemical properties in the studied reforested cropland reflected both carry-over effects of previous reforestation management, particularly irrigation, and effects of current environmental conditions that were mostly related to herb community composition and biomass. This pattern may be explained by the mitigation of water stress on soil fauna, microbes and fungi that stimulate organic matter decomposition (Couteaux et al., 1995; Austin et al., 2004). Soil chemical properties were also indirectly affected by previous management practices mainly through its influence on the herbaceous community, as indirect effects through Holm Oak canopy were low. The reforestation treatments applied determined the structure and composition of the herb community (Cayuela et al., 2008), resulting in differences in litter quality and quantity which may have influenced soil properties (Vinton and Burke, 1995). For example, greater cover of legumes in irrigated plots may explain the higher availability of N in these plots.

The relative effects of Holm Oak canopy were small compared to the effects of the herbaceous community. Holm Oak litter has a high lignin and tannin content (Allen et al., 1974), which results in slower rates of decomposition and ultimately incorporation of nutrients into the soil (Gallardo and Merino, 1993; Couteaux et al., 1995; Satti et al., 2003). The unexplained variation found in this study may be due to a combination of stochastic processes and mechanisms related to microclimate, tree root development and soil biota (Davidson et al., 1992; Couteaux et al., 1995; Aerts and Chapin, 2000).

To complement this research, it would have been desirable to study the soil chemical properties in nearby mature native woodland, as a reference ecosystem. However, this was not possible as there are no remaining patches of mature woodland in or near the study area.

This study provides further evidence of the overall slow dynamics of soil processes in Mediterranean ecosystems after cropland abandonment, even in reforested sites that are actively managed to facilitate the establishment of native woody vegetation. Yet experimental evidence allows us to highlight that reforestation with native woodland species may accelerate the recovery of soil properties such as the concentration of C and NH_4^+—N and the availability of mineral N, and rehabilitation options take advantage of management techniques used to facilitate early establishment of introduced seedlings. Thus, the reintroduction of woodland into agricultural landscapes may contribute in the long term to enhance both biodiversity and ecosystem services linked to soil function (Rey Benayas et al., 2008b; Paul et al., 2010a and 2010b).

Acknowledgments

We are grateful to L. Muñoz and R. Álvarez for their help with field work. This study was supported by a FPI-MEC grant to B. Cuesta and by projects CGL2010-18312, CGL2007-60533/BOS, AGL2006-12609-C02-01/FOR (Ministry of Science and Education), S-0505/AMB/0355 and S2009AMB-1783 REMEDINAL (Madrid Government).

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