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REGULAR ARTICLE

Soil and vegetation development during early succession on restored coal wastes: a six-year permanent plot study

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Abstract

Aims Little is known about how soil parameters change during early stages of revegetation dynamics on newly-restored coal mines, particularly in a Mediterranean climate. Our aim was to explore the short-term interactions of changes in soil physico-chemical properties and vegetation succession (composition and structure) in these newly-forming ecosystems, and discuss potential functional relationships.

Methods Between 2004 and 2009, we monitored soil and vegetation changes in nine permanent plots (20 m^2 each one) at a restored open-pit coal mine annually; these plots were set up in a structured way to account for site aspect (north, south and flat). We used linear mixed models and multivariate analysis to derive patterns of soil parameters changes through time and to relate soil variables with vegetation structure or floristic compositional changes.

Results Soil variables showed a general trend over time of increasing soil organic matter, total carbon and nitrogen, sand content and exchangeable calcium, but a reduction in soil pH, clay and lime contents, whereas electrical conductivity, P, Mg^{2+} and K^+ showed no change through time. More importantly, these changes in soil properties were independent of aspect, whereas vegetation functional/structural changes were related to the accumulation of organic matter and sand content, and pH reduction. Surprisingly, floristic compositional changes had little relationship with soil factors.

Conclusions The results indicate that age since restoration was the main driving agent, at least in the short-term, of soil and vegetation compositional changes during ecosystem development through the restoration of a coal mine, whereas vegetation functional/structural changes are involved in the mechanism that induce some soil changes, favouring the increase of plant community complexity in such mined areas. Finally, these results suggest that if soil-forming material is sufficiently good for vegetation development, floristic compositional differences are mainly driven by a combination of abiotic and stochastic factors in the short-term.

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Introduction

Open-cast mining is a major environmental disturbance which often leaves a landscape with no vegetation and very poor soil-forming materials for subsequent ecosystem development (Herath et al. 2009). In such damaged systems, the objective of ecological restoration should be the restoration of a healthy, long-term, self-sustaining ecosystem (Hobbs and Norton 1996), with good vegetation cover (Dazy et al. 2008) and a fully-functioning soil (Moreno-de las Heras 2009; Dölle and Schmidt 2009), including appropriate soil biota and microbial processes (Frouz et al. 2008). Ideally, a self-sustaining restored ecosystem should have at least a semblance of the original soil dynamics (Walker and del Moral 2009). Therefore, knowledge of how soil develops during restoration is of particular importance to guide future ecological restoration (Abreu et al. 2009).

When a mine is restored the initial restoration treatment provides a starting soil material, although the physico-chemical properties of these new soils usually hinder plant growth (Alday et al. 2011b). During succession, changes in vegetation composition and structure occur, which can ameliorate soil conditions and assist further vegetation development (Isermann 2005). Vegetation development enhances the accumulation of carbon and nutrients in the soil (Marrs and Bradshaw 1993; De Kovel et al. 2000; Walker and del Moral 2009), and these processes improve the soil conditions for subsequent species colonization and ecosystem development (Frouz et al. 2008). Therefore, in order to predict medium-term change in ecosystem development, knowledge of the likely changes (rates of change) in organic matter content and the proportion of nutrients in the soil during the initial restoration period are needed.

Changes in soil parameters and vegetation development during succession has been studied in various types of landscapes including china clay wastes (Marrs et al. 1980a,b; Roberts et al. 1980), abandoned fields (Knops and Tilman 2000), urban sites (Schadek et al. 2009), glaciers (Hodkinson et al. 2003) and forests (Matlack 2009). However, there have been few attempts to study vegetation succession and soil change together in restoration projects of coal mined sites under Mediterranean climates (e.g. Moreno-de las Heras 2009).

In northern Spain, particularly in the provinces of León and Palencia, open-cast coal mining has caused an extensive impact on the landscape (affecting ca. 5,000 ha), and a post-mining restoration strategy has been implemented. Recently, the most common mine restoration approach within this region has been to reshape the mined landform, improve the baseline soil-forming materials, and then introduce herbaceous seeds by hydroseeding. Although, this approach has been validated experimentally, and specifically to elucidate the importance of abiotic factors limiting vegetation establishment and development (González-Alday et al. 2008; Alday et al. 2010), little is known about soil processes or changes in the soil physico-chemical properties during the post-restoration succession.

In this paper, we attempt to address these issues. We followed the changes in vegetation and soil in permanent plots for 6 years after restoration was implemented on a coal mine in northern Spain. Permanent plot studies often offer valuable insights into soil, nutrient and vegetation changes during succession (Dölle and Schmidt 2009). The aims were to explore the interactions of changes in soil physico-chemical properties and vegetation succession (composition and structure), and discuss potential functional relationships. Specifically, we aimed to: (1) describe the changes in soil physico-chemical properties through the first 6 years of post-restoration succession, identifying the main processes and patterns, (2) determine the relationship between the soil parameters and the vegetation structure variables (richness, diversity and cover), and (3) assess what determines the early floristic compositional dynamics (changes in soil properties, aspect, time-effect). It was hoped that this information would lead to improve methods for ecological restoration, increasing their effectiveness, and help to gain a more predictive understanding of mine restoration dynamics.

Methods

Site description and restoration treatment

The study was carried out at ‘Pozo Sell’, a 10 ha reclaimed open-cast coal mine near Villanueva de la Peña, Palencia, northern Spain (1.185 ma.s.l.; lat 42°50′N, long 4°38′W). The climate of the area is sub-humid Mediterranean with a mean annual temperature of 9°C and an average annual precipitation of 980 mm seasonally distributed, i.e. with a rainy season in autumn and spring and a pronounced dry summer season. The vegetation surrounding the site comprises a complex matrix of grasslands (*Arenaria montana*, *Bromus mollis*, *Plantago alpina*, *Vulpia myuros*), crop fields (*Avena sativa*, *Secale cereale*), remnants of natural shrubland (*Cistus laurifolius*, *Erica cinerea*, *Juniperus communis*, *Rosa canina*) and *Quercus pyrenaica* woodland (Alday et al. 2010).

After mining stopped, the open pit was filled with coal wastes from nearby mines and the surface was covered with 50–100 cm of fine-textured materials and a superficial layer of cattle manure using a manure spreader (30 tha^{-1}). The fine-textured materials were a mixture of topsoil and sediments from deeper parts of the nearest open-cast pits. This mixture had a clay loam texture, the pH was moderately alkaline (pH=8.2), organic matter content below 2% and there was a very sparse seed bank (González-Alday et al. 2008, 2009). In October 2003, the entire site was hydroseeded using a slurry containing soluble chemical fertilizer (150 kg ha^{-1}; 8 N:15P:15 K), and a seed mixture (210 kg ha^{-1}) of grasses and herbaceous legumes (81:19 by weight). The seed mixture included *Festuca* spp., *Avena sativa*, *Secale cereale*, *Lolium perenne*, *Phleum pratense*, *Poa pratensis*, *Trifolium pratense*, *Lotus corniculatus*, *Medicago sativa* and *T. repens* in 9:3:3:2:1.75:1.5:1.25:1.25:1.25:1 proportions.

Previous studies on this area have demonstrated that vegetation structural parameters (total plant cover, hydroseeded and native species plant cover, diversity and richness) converged rapidly with the reference community, whereas compositional convergence needed a much longer time (Alday et al. 2011a). However there was a lack of knowledge about the interactions between changes in soil physico-chemical properties and vegetation succession (composition and structure). In this paper we attempt to answer these questions relating the vegetation with soil processes and changes in the soil physico-chemical properties during the post-restoration succession.

Vegetation sampling

As aspect is a major factor controlling vegetation development in Mediterranean climates (Martínez-Ruiz and Marrs 2007; Alday et al. 2010), this study investigated the development of soil and vegetation in three separate areas of different aspect: (1) a north-facing slope, (2) a south-facing slope, and (3) a flat area; both sloped areas were approximately 25°. In each of these areas three permanent plots of 20 m^2 (5×4 m) were randomly located (n=9). Within each plot, eight 0.25 m^2 (0.5×0.5 m) quadrats were positioned randomly in January 2004 and marked permanently (Alday et al. 2010; Alday et al. 2011a). The cover (from 0 to 100%) of all vascular plant species present in each quadrat was estimated visually by the same observer every spring (May–June) for 6 years from 2004 to 2009. The mean cover values of each species in the eight quadrats per plot were used to obtain an estimate of the cover of vascular plant species in each plot on each sampling occasion.

Soil sampling and analysis

In the spring of each year from 2004 to 2009, eight soil sub-samples were taken with a soil auger (diameter=8 cm; depth=10 cm) in the vicinity of each 0.25 m^2 quadrats. These sub-samples were pooled and thoroughly mixed to obtain a uniform sample of the soil characteristics for each of the nine permanent plots (n=9). The soils were shallow and the sample depth included the developing A (organo-mineral) and the rooting layer of the herbaceous species present.

In the laboratory the soil samples were air-dried, sieved (≤ 2 mm mesh) and soil texture (clay, sand and lime proportions) was analysed using the Bouyoucos-method (Day 1965). Soil chemical properties were then measured as follows: soil pH and electrical conductivity (EC) using a conductivity meter in a

1:2.5 soil:deionized water slurry (Allen 1989); total nitrogen concentration using the Kjeldahl-method (Bremner and Mulvaney 1982); available phosphorus concentration using the Olsen method (Olsen and Sommers 1982); total organic matter and total carbon concentration using the Walkley-Black method (Walkley 1947); and finally exchangeable cations as calcium (Ca^{2+}), potassium (K^{+}) and magnesium (Mg^{2+}) with atomic absorption spectroscopy after extraction with 1 N ammonium acetate (pH 7) (Allen 1989; Anderson and Ingram 1993).

Data analysis

Changes in soil parameters through time

Linear Mixed Models (LMMs) were used to evaluate soil parameters changes (12 soil variables) between areas and time. In this analysis, area (north-, south-facing, flat) was treated as categorical fixed factor, time (age since reclamation) was treated as a continuous fixed factor, and time nested within plot was included as random factor to account for temporal and spatial autocorrelation (Pinheiro and Bates 2000). Model simplification guidelines followed Crawley (2007) using the Akaike information criterion (AIC, Pinheiro and Bates 2000). The reduction of AIC (ΔAIC) was calculated as: $\Delta\mathrm{AIC} = 100 \times (\mathrm{AICn} - \mathrm{AICmin})/\mathrm{AICn}$, where AICn and AICmin are AIC of the null and minimal adequate models respectively (Burnham and Anderson 2002). For each model the r^2 was calculated following the Likelihood ratio test proposed by Magee (1990) which is calculated as: $r^2_{\mathrm{lr}} = 1 - \exp\left\{-2n^{-1}\left(L(\theta;y) - L(\theta_0;y)\right)\right\}$, for $L(\theta;y)$ the log-likelihood of the model of interest and $L(\theta_0;y)$ of the null model with only an intercept and random effects, whereas n is the length of y. Models were fitted using REML method. All values are reported as the mean±standard error of the fixed factors.

Vegetation structure and soil variables

Plant community diversity was assessed using the Shannon-Wiener index (H′) and richness (S). Plant species were categorized into functional types in two ways: (1) type (hydroseeded, ruderal and native species typical of the region), and (2) by functional groups and life-forms (annuals and perennials, and the perennials were further sub-divided into grasses, legumes and forbs). The mean plant cover and richness of each type in each plot were then calculated, whereas for functional groups only plant cover was calculated.

Principal component analysis (PCA) was used to provide an integrated analysis of the patterns of variation for soil and vegetation structure variables and to evaluate successional trends. PCA was carried out over the correlation matrix of data considering 12 vegetation structural variables; ten soil variables and age since reclamation (see Table 2 for detailed list). All variables were standardized before analysis to correct for different scales of measuring units. In order to avoid autocorrelation two soil variables and four vegetation structural variables were excluded from the analysis, e.g.: lime fraction, total carbon, total cover, native species richness, annual forbs and perennial legumes cover.

Floristic composition and soil variables

Ordination analysis was used to relate plant community species composition (log(x+1) transformed) to soil variables. Here, Detrended Correspondence Analysis (DCA) was performed using the quadrat compositional data (n=432) with down-weighting to reduce the influence of rare species (Hill 1979). For interpretability of the graphical output the centroids for each plot (n=9) for each year were used in the sites biplot. Thereafter, each of the four ordination axis were interpreted using Linear Mixed Models (LMMs) with a separate environmental dataset, including area (north-, south-facing, flat), age since reclamation and the 12 soil variables (see Table 3 for detailed list). DCA quadrat scores for each axis were used as the response variable and each environmental variable tested as explanatory variables (fixed factors). The random structure of the data was defined to account for temporal and spatial autocorrelation using quadrats nested within plot nested within area and time. However, in the models where area was considered as fixed factor only time nested within plot and quadrat were including as random factors. Model simplification guidelines, fitting methods and r^2 calculations were as described above.

All statistical analyses were implemented in the R software environment (version 2.10; R Development

Core Team 2009), using the NLME package for LMM (Pinheiro et al. 2009) and the VEGAN package for multivariate analyses (Oksanen et al. 2010).

Results

Soil development through time

The soil variables were separated into four groups based on the type of significant response to successional age. Group 1 (Fig. 1, Table 1) comprised three variables (pH, clay content and lime content) that showed no difference between areas (common intercept) but negative linear slopes with respect to age. These variables decreased over the 6 years from 8.19±0.03 to 7.74±0.09 for pH, from 27.88±0.82% to 22±0.76% for clay content, whereas lime content decreased from 26.12±0.71% to 14±0.74%.

Group 2 comprised five variables that also showed no significant differences between areas (common intercept) but here the variables showed a significant increasing linear trend with age; the variables included in this group were sand content, organic matter content, total carbon and nitrogen concentrations and exchangeable Ca^{2+} concentration (Fig. 2, Table 1). These

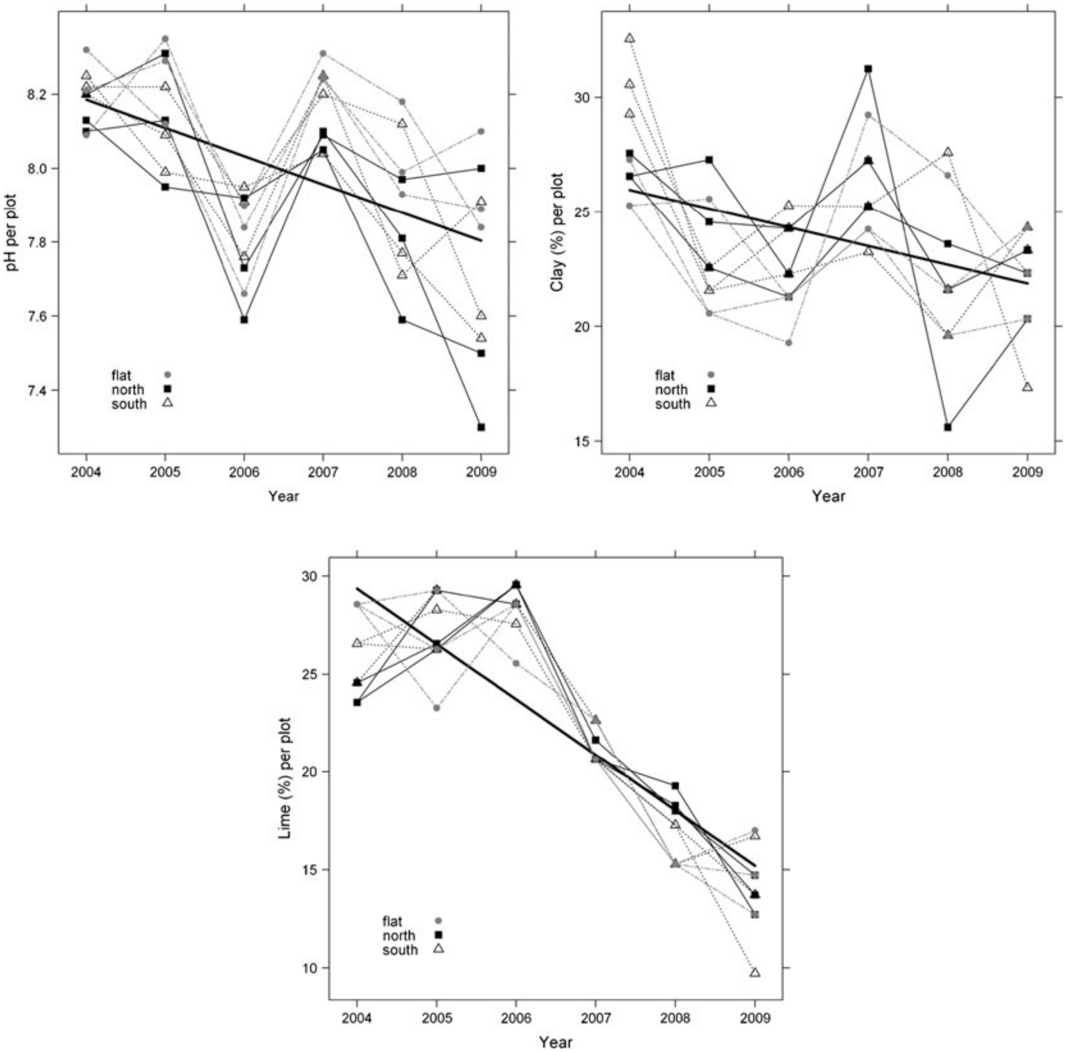


Fig. 1 Decreasing soil variables (pH, clay and lime contents) over time at 9 permanent plots distributed in three areas (flat, north- and south-facing slopes) at the restored 'Pozo Sell' mine. *Dark line* is the best fixed effect model. The parameters of the *fitted lines* are available in Table 1

Table 1 Parameters from the linear mixed effects analysis of soil variables with respect to age since restoration at the restored ‘Pozo Sell’ mine. Three responses were noted: Group 1 showed negative relationships with age, Group 2 showed positive relationships and Group 3 showed aspect effect and no relationship with age. All of these variables had a linear relationship and Group 1 and 2 had no significant effect of sample area (aspect effect). Parameters description; β_0= intercept, β_1 age=age slope, ΔAIC=AIC reduction

Group	Variable	β_0	Parameter estimates					ΔAIC=%	r^2
			t	*P*-value	β_1 age	t	*P*-value		
1	pH	8.26±0.06	127.73	<0.001	−0.08±0.02	−4.86	<0.001	74.9	0.32
	Clay content (%)	27.78±0.97	27.44	<0.001	−0.82±0.25	−3.26	<0.01	1.2	0.16
	Lime content (%)	32.20±0.94	34.28	<0.001	−2.83±0.24	−11.74	<0.001	18.0	0.71
2	Sand content (%)	41.67±0.92	45.50	<0.001	3.5±0.24	14.84	<0.001	22.3	0.80
	Organic matter (%)	0.29±0.45	0.65	0.521	1.0±0.11	8.58	<0.001	17.2	0.54
	Total C (%)	0.16±0.26	0.65	0.520	0.58 ±0.07	8.58	<0.001	22.0	0.55
	Total N (%)	0.05±0.03	1.97	0.055	0.06±0.01	9.27	<0.001	73.0	0.56
	Exchangeable Ca^{2+}	11.34±0.72	15.65	<0.001	1.13±0.16	6.99	<0.001	10.6	0.45
3	Exchangeable K^+							3.21	0.32
	Flat	142.16±12.90	11.03	<0.001	–	–	–	–	–
	North	184.42±13.84	3.05	<0.05	–	–	–	–	–
	South	189.34±13.84	3.41	<0.05	–	–	–	–	–

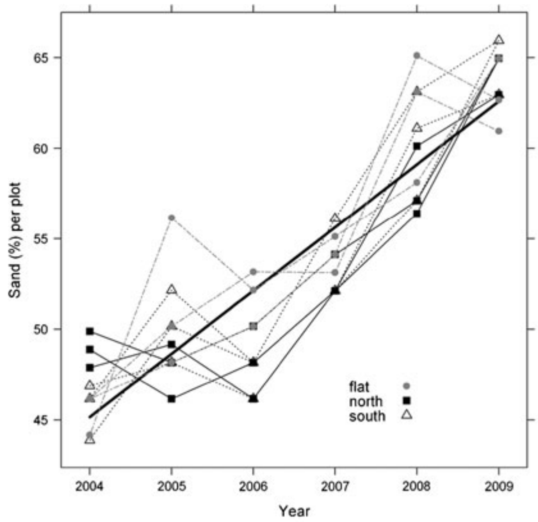
variables increased over the 6 years as follows: sand content showed an important increase of 2.9% yr^{-1}, organic matter increased at 1% yr^{-1}, total carbon at 0.6% yr^{-1}, total nitrogen at 0.07% yr^{-1} and the available calcium concentration increased at 1.12% yr^{-1}.

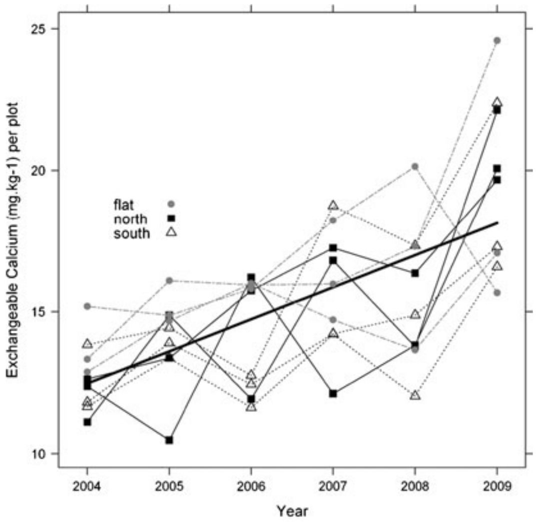
Group 3 comprised just the exchangeable potassium concentration where significant differences were found between areas but no effect of successional age, suggesting lower exchangeable potassium concentrations in the flat area (Flat = 142.16 ± 12.9 *vs.* North = 184.42 ± 13.84 and South = 189.34 ±3.84). Finally, Group 4 contained soil variables which showed no significant differences between areas and any relationship with successional age, i.e. with stable values along the sequence (EC = $0.22 \pm 0.01 mmhos.cm^{-1}$, $P = 56 \pm 3.9$ $mg.kg^{-1}$ and $Mg^{2+} = 1.43 \pm 0.08$ $mg.kg^{-1}$).

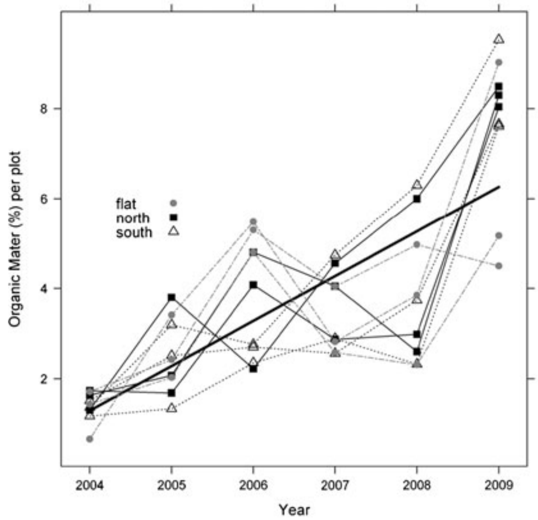
Vegetation structure and soil variables

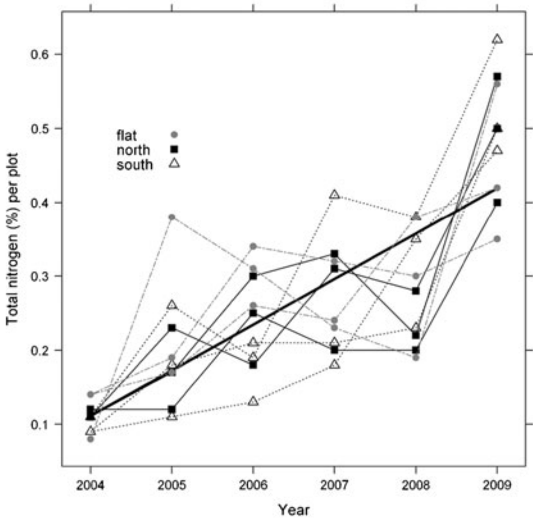
The integrated analysis of soil parameters, vegetation structure variables and age since reclamation using a PCA (Table 2, Fig. 3) explained 60.4% of the variation (axis 1=44%, axis 2=16.4%), revealing four main groups of correlated variables. There was a strong positively correlation between axis 1 and age, diversity (H′, S), sand content, organic matter and total nitrogen, ruderal richness and the cover of ruderal, native and annual species, and negative correlation between axis 1 and cover and richness of hydroseeded species, pH and clay content and cover of perennial grasses. Axis 2 was correlated positively with pH and negatively with electrical conductivity and exchangeable cations (K^+, Mg^{2+}). The PCA ordered the plots along the first axis according to age since reclamation (successional trajectories), increasing from left to right (Fig. 3b, c, d), whereas the second axis produced a differentiation between the plots on the basis of aspect (north, south and flat). Therefore, the first two axes seem to be responding to two different gradients: the main one (PCA axis 1) associated with a successional gradient that showed a close relationship between vegetation structural changes and the changes in physical and organic related soil properties; and the second one (PCA axis 2) related to pH, electrical conductivity and soil cations (K^+, Mg^{2+}).

Fig. 2 Increasing soil variables (sand content, Ca, organic matter, N, C) over time at 9 permanent plots distributed in three areas (flat, north- and south-facing slopes) at the restored ‘Pozo Sell’ mine. *Dark line* is the best fixed effect model. The parameters of the *fitted lines* are available in Table 1 ▶


Sand (%) per plot
45
50
55
60
65
2004
2005
2006
2007
2008
2009
Year
flat ●
north ■
south △


Exchangeable Calcium (mg.kg-1) per plot
10
15
20
25
2004
2005
2006
2007
2008
2009
Year
flat ●
north ■
south △


Organic Mater (%) per plot
2
4
6
8
2004
2005
2006
2007
2008
2009
Year
flat ●
north ■
south △


Total nitrogen (%) per plot
0.1
0.2
0.3
0.4
0.5
0.6
2004
2005
2006
2007
2008
2009
Year
flat ●
north ■
south △

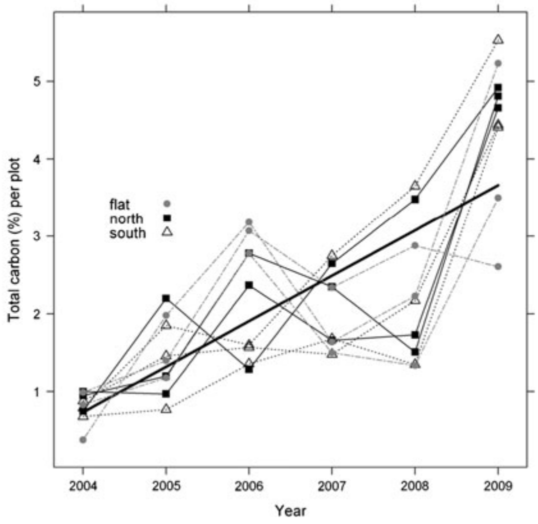

Total carbon (%) per plot
1
2
3
4
5
2004
2005
2006
2007
2008
2009
Year
flat ●
north ■
south △

Table 2 Correlation coefficients of plot scores along axes 1 and 2 from a Principal Components Analysis (PCA) of soil and vegetation variables; significant correlations at $p<0.01$ and $r>0.50$ are displayed in bold

	Code	Variable units	Axis 1	Axis 2
Age	Age	Age since reclamation (years)	**0.87**	0.06
Vegetation variables	Soil	Bare soil (%)	−0.11	0.39
	CovH	Hydroseeded species cover (%)	**−0.84**	−0.39
	RichH	Hydroseeded species richness	**−0.81**	−0.28
	CovR	Ruderal species cover (%)	**0.66**	0.20
	RichH	Ruderal species richness	**0.73**	0.03
	CovNa	Native species cover (%)	**0.76**	0.04
	Ga	Annual grasses cover (%)	0.43	0.12
	La	Annual legumes cover (%)	**0.56**	0.39
	Fp	Perennial forbs cover (%)	**0.54**	0.44
	Gp	Perennial grasses cover (%)	**−0.57**	−0.26
	S	Richness	**0.93**	0.14
	H′	Shannon diversity	**0.85**	0.26
Soil variables	Sand	Sand (%)	**0.84**	0.02
	Clay	Clay (%)	**−0.56**	0.24
	pH	pH	**−0.58**	**0.60**
	EC	Electrical conductivity (mmhos.cm^{-1})	0.44	**−0.71**
	OM	Organic matter (%)	**0.83**	−0.41
	N	Total nitrogen (%)	**0.86**	−0.22
	P	Available phosphorus (mg.kg^{-1})	0.36	−0.45
	K^+	Exchangeable potassium (mg.kg^{-1})	0.09	**−0.80**
	Ca^{2+}	Exchangeable calcium (mg.kg^{-1})	**0.77**	−0.20
	Mg^{2+}	Exchangeable magnesium (mg.kg^{-1})	0.05	**−0.88**
		Eigenvalues	10.09	3.75
		Explained variance	44%	16.4%

Floristic composition and soil variables

In total, 87 vascular plant species were recorded at the restored mine during the 6-year period. All of the ten hydroseeded species were found, especially during the first 3 years, but their cover declined with age. The remaining 77 species included some early colonizers or ruderals (22 species; e.g. *Brassica nigra*, *Capsella bursa-pastoris*, *Lactuca* spp., *Malva sylvestris*) and native species (55 species; e.g. *Avenula sulcata*, *Helianthemun hirtum*, *Hieracium pilosella*, *Trifolium campestre*) the cover of all of these species increased with successional age.

The DCA of species composition produced eigenvalues (λ) of 0.25, 0.10, 0.10 and 0.06, and gradient lengths (GL) of 2.21, 1.34, 1.50 and 1.00 for the first four axes respectively. The species and sites biplots (Fig. 4a,b) showed a clear trend in the distribution of plots from 2004 with negative scores in axis 1 and characterized by hydroseeded species such as *Avena sativa*, *Secale cereale*, *Festuca* spp., *Lotus corniculatus*, *Trifolium pratense* and *T. repens*, to 2009 plots which had positive values on axis 1and species characteristic of the reference community, including *Arenaria montana*, *Avenula sulcata*, *Bromus mollis* and *Helianthemun hirtum*. The majority of the variation in DCA axis 1 was, therefore, explained by age since reclamation ($r^2=0.81$; Table 3). Although several soil parameters also had a significant negative or positive correlation with the DCA axis 1 (sand, clay, lime, pH, OM, C, N, Ca^{2+}; Table 3), they explained less variation than age and showed the same sign of relationship with DCA axis 1 as they did in the analysis of soil parameters changes through time (Table 1) and in PCA axis 1 (Fig. 3a). Thus axis 1, which represents the main vegetation variation in the data set, appears to represent a successional gradient.

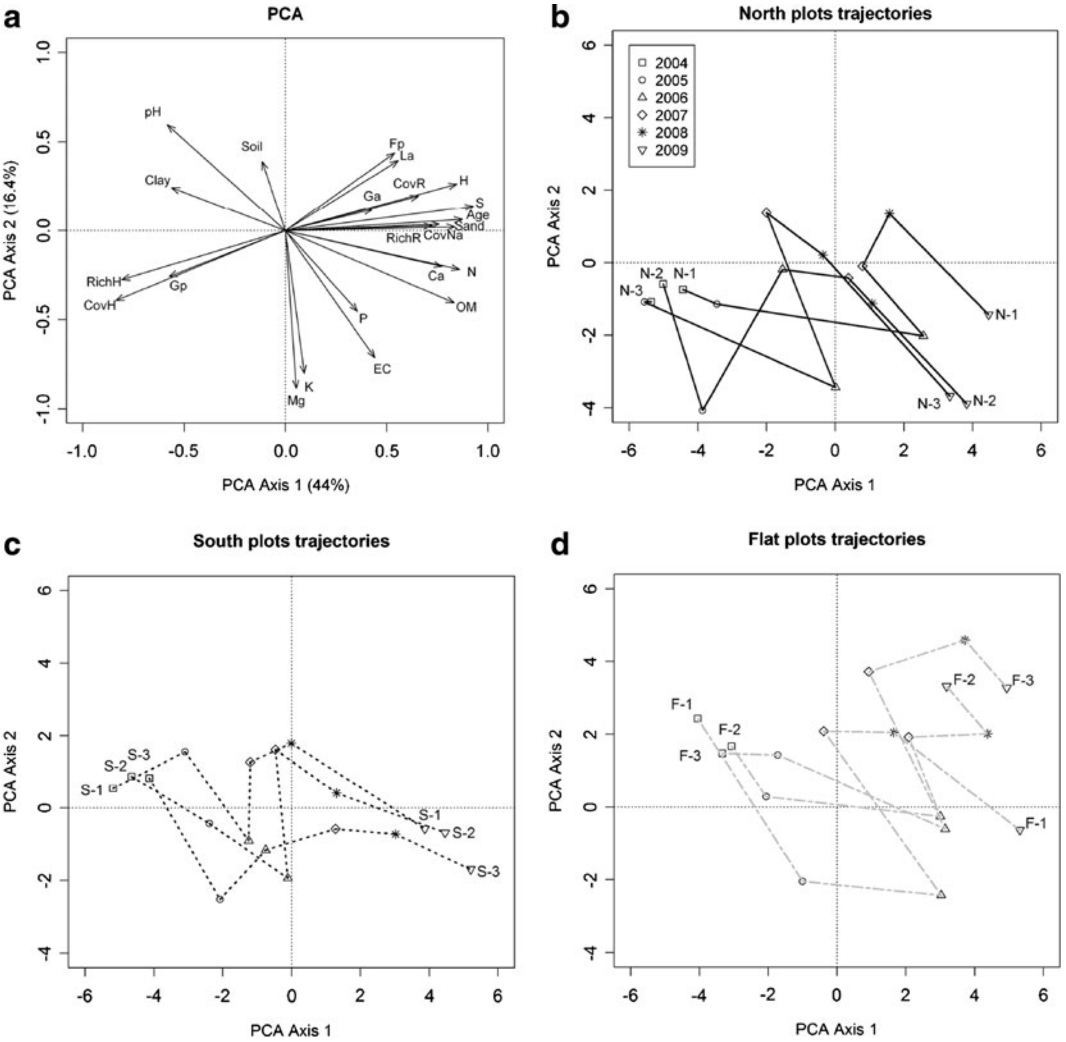
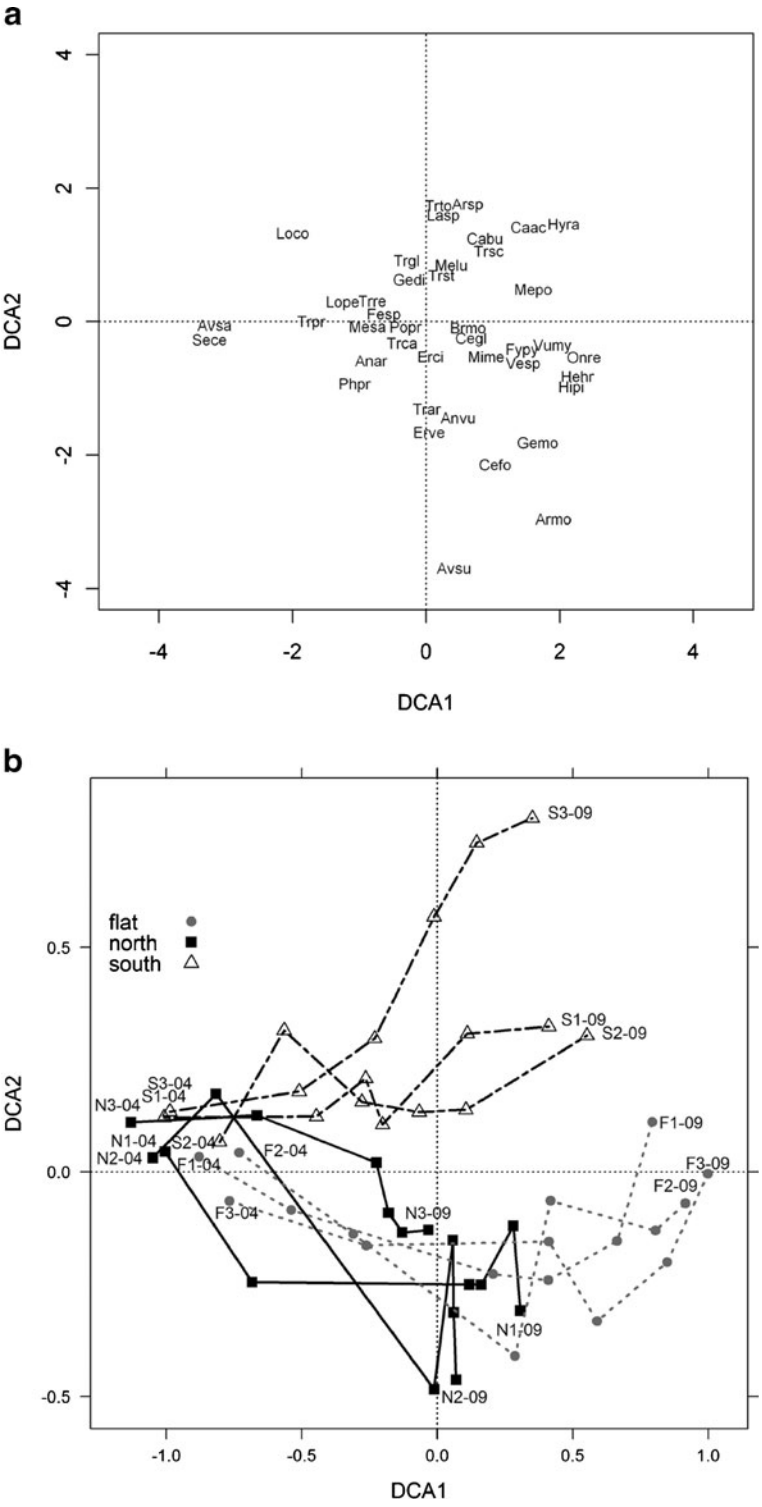


Fig. 3 PCA ordination for the first two axes of soil and vegetation structure variables; data from 9 permanent plots monitored from 2004 to 2009 at the 'Pozo Sell' reclaimed open-pit coal mine at Palencia, northern Spain. **a** Variables ordination diagram; the distance of variables points from centre indicates the strength of the correlations between variables; for abbreviations see Table 2. **b**, **c** and **d** Ordination of the plots ($n=3$ per area); points of the same plot are connected by successional vectors

The DCA axis 2 showed a clear divergence with the age trajectory of south-facing plots characterized by species such as *Arenaria* spp., *Carduus acanthium*, *Hypochoeris radicata* and *Trifolium tomentosum* clearly separated from north-facing plots characterized by *Arenaria montana*, *Avenula sulcata*, *Erophila verna*, *Geranium molle* and flat plots which *Ononis repens*, *Hieracium pilosella*, and *Helianthemun hirtum* as common species. The main variation along axis 2 was explained by differences in aspect (north-, south-facing, flat; $r^2=0.13$; Table 3), suggesting that axis 2 represents an aspect gradient.

Several explanatory variables were significantly correlated with DCA axis 3, being the most important one pH ($r^2=0.25$), followed by total carbon, organic matter and total nitrogen content correlated negatively with axis 3 (Table 3). Therefore, DCA axis 3 showed a clear distribution of plots which represents a gradient of pH reduction and organic matter increased from the positive end of DCA axis 3to the negative one. However, age since reclamation and aspect also explained part of this axis variation ($r^2=0.05$ and 0.09, respectively), with the soil parameters showing the same sign of relationship


a
DCA2
DCA1
4
2
0
-2
-4
Trto
Arsp
Lasp
Caac
Hyra
Loco
Cabu
Trsc
Trgl
Melu
Gedi
Trst
Mepo
LopeTrre
Fesp
Avsa
Trpr
Mesa
Popr
Brmo
Cegl
Sece
Trca
Fypy
Vumy
Anar
Erci
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south
DCA2
DCA1
0.5
0.0
-0.5
-1.0
-0.5
0.0
0.5
1.0
S3-09
S1-09
S2-09
S3-04
S1-04
N3-04
N1-04
S2-04
N2-04
F1-04
F2-04
F3-04
F1-09
F3-09
F2-09
N3-09
N1-09
N2-09

◀ **Fig. 4** DCA ordination for the first two axes of floristic composition data (432 quadrats) from the nine permanent plots between 2004 and 2009 at the 'Pozo Sell' reclaimed open-pit coal mine. **a** Species ordination. **b** Ordination of centroids for each plot ($n=3$ per area) for each year were used; points of the same plot are connected by successional vectors to enhance the interpretability (04–09 indicate the last two digits of monitoring year). Species codes: Anar=*Anthemis arvensis*; Anvu=*Anthyllis vulneraria*; Armo=*Arenaria montana*; Arsp=*Arenaria* spp.; Avsa=*Avena sativa*; Avsu=*Avenula sulcata*; Brmo=*Bromus mollis*; Cabu=*Capsella bursa-pastoris*; Cefo=*Cerastium fontanum*; Cegl=*C. glomeratum*; Caac=*Carduus acanthium*; Erci=*Erodium cicutarium*; Erve=*Erophila verna*; Fesp=*Festuca* spp.; Fypy=*Filago pyramidata*; Gedi=*Geranium disectum*; Gemo=*Geranium molle*; Hehr=*Helianthemun hirtum*; Hipi=*Hieracium pilosella*; Hyra=*Hypochoeris radicata*; Lasp=*Lactuca* spp.; Lope=*Lolium perenne*; Loco=*Lotus corniculatus*; Melu=*Medicago lupulina*; Mepo=*M. polymorpha*; Mesa=*M. sativa*; Mime=*Minuartia mediterranea*; Onre=*Ononis repens*; Phpr=*Phleum pratense*; Pllan=*Plantago lanceolata*; Popr=*Poa pratensis*; Sece=*Secale cereale*; Trar=*Trifolium arvense*; Trca=*T. campestre*; Trgl=*T. glomeratum*; Trpr=*T. pratense*; Trre=*T. repens*; Trsc=*T. scabrum*; Trst=*T. striatum*; Trto=*T. tomentosum*; Vesp=*Veronica* spp.; Vumy=*Vulpia myuros*

with DCA axis 3 as they did in the PCA axis 1 and in the analysis of soil parameter change through age (Table 1). Therefore, it is likely that this gradient had also some relationship with the successional gradient. Finally, only two explanatory variables, age since reclamation and exchangeable calcium were significantly correlated with DCA axis 4. However, the plant species compositional variation explained by these variables on axis 4 was negligible ($r^2=0.09$ and 0.07, Table 3).

Discussion

Age since restoration drove the short-term soil changes during ecosystem development on a coal mine due to vegetation functional/structural successional changes. In contrast, species compositional changes were mainly driven by age and aspect (north-, south- facing slopes and flat area), whereas some soil factors (pH, total nitrogen and organic matter), which were correlated with changes in plant cover, were related to vegetation composition at the plot-level.

Soil development through time

The influence of time on soil parameters during primary succession is well known (Jenny 1980; Marrs and Bradshaw 1993; Knops and Tilman 2000; Hodkinson et al. 2003), with changes in soil texture and accumulation of organic matter and both carbon and nitrogen. Our results for the first 6 years of ecosystem development after the restoration of an open-cast coal mine in a sub-humid Mediterranean climate confirmed these general trends, with an increase through time of soil organic matter, total carbon and nitrogen, sand content and exchangeable calcium, but a reduction in soil pH, and clay and lime contents. Importantly for this site, these changes in soil properties were independent of the three aspects considered; a factor that has been shown to be very important in determining the outcome of species composition at this site (Alday et al. 2010). As a result, age since restoration alone is, therefore, the agent driving change in these soil variables at least in short-term. This result differs from mine vegetation succession where aspect has been shown to have an important influence on subsequent soil changes (Martínez-Ruiz et al. 2001; Martínez-Ruiz and Marrs 2007).

Although the increase in organic matter, total carbon and nitrogen with successional age is consistent with other studies on successional development on mineral wastes (Marrs et al. 1980a,b; Marrs and Bradshaw 1993; De Kovel et al. 2000; Banning et al. 2008; Frouz et al. 2008), here the accumulation of organic matter was relatively rapid, increasing by 1% year^{-1} and reaching a mean value of 6% after 6 years. In other studies of post-agricultural successions in Mediterranean climates organic matter increases were much slower, between 5 and 20% in 50 years (Cortez et al. 2007). This rapid accumulation of organic matter at our study site may be caused by a combination of two factors. First, the manure layer applied before hydroseeding would act as an initial boost to organic matter content, but this could only account for the immediate increase over the raw waste material and not the ongoing accumulation. Second, there was a very rapid vegetation development and a proportion of the carbon fixed would be recycled

Table 3 Sign of the significant relationships and significance of vegetation gradients obtained from linear mixed models of the four DCA axis quadrat scores (n=432) with respect to the explanatory variables tested (soil properties, aspect and age). Aspect sign is not included since it is a factor with 3 levels

	Sign	r^2	*F*	*P*-value	Sign	r^2	*F*	*P*-value
	DCA1				DCA2			
Aspect			0.34	0.728		0.13	14.75	0.005
Age	+	0.81	270.14	<0.001			0.18	0.675
Sand	+	0.53	71.72	<0.001			2.06	0.158
Clay	−	0.07	10.75	0.002			0.20	0.657
Lime	−	0.33	40.29	<0.001			2.69	0.108
pH	−	0.18	16.50	<0.001			0.33	0.566
EC			2.38	0.130			0.50	0.484
OM	+	0.36	43.64	<0.001			1.95	0.169
C	+	0.38	43.70	<0.001			1.94	0.170
N	+	0.49	53.16	<0.001			2.40	0.129
P			2.40	0.129			2.64	0.610
K^+			0.01	0.949			2.30	0.167
Ca^{2+}	+	0.28	29.82	<0.001			1.33	0.254
Mg^{2+}			2.26	0.140			0.15	0.702
	DCA3				DCA4			
Aspect		0.09	9.31	0.015			0.88	0.461
Age	−	0.05	10.39	0.002	+	0.09	5.10	0.029
Sand	−	0.11	6.88	0.012			2.35	0.133
Clay	+	0.08	5.10	0.029			2.48	0.123
Lime			3.22	0.080			1.45	0.236
pH	+	0.25	21.20	<0.001			2.16	0.149
EC		0.06	2.38	0.130			2.96	0.093
OM	−	0.14	17.82	<0.001			2.89	0.096
C	−	0.16	17.84	<0.001			2.87	0.097
N	−	0.16	12.44	<0.001			3.31	0.075
P			2.71	0.107			3.49	0.069
K^+			0.77	0.386			0.48	0.493
Ca^{2+}	−	0.02	9.37	0.004	+	0.07	4.16	0.047
Mg^{2+}			3.64	0.063			0.03	0.875

into the soil organic matter (Marrs et al. 1980a; Frouz et al. 2008). On the other hand, the total carbon and nitrogen accumulation in the soil was produced at lower rates than organic matter (total carbon 0.6% yr^{-1} and total nitrogen 0.07% yr^{-1}), although being comparable with other post-mining landscapes (Šourková et al. 2005). The accumulation of organic matter and carbon follows a similar relationships and is a function of the inevitable increase in soil organic matter in very young soils (Marrs et al. 1980a,b; Dölle and Schmidt 2009). In contrast, nitrogen accumulation in the soil may result from several pathways; (1) from fertilizer applied during hydroseeding, and (2) from legumes nitrogen fixation (García et al. 2007), which where the dominant plant types during the first 6 years of the succession (Alday et al. 2010). The evidence we collected suggested that both processes could be important; the positive correlation of both organic matter and nitrogen content on axis 1 of the PCA suggests that they are connected.

In any case, the increase in organic matter, total carbon and nitrogen with age is a very important result from the soil dynamics restoration point of view, since the accumulation of these parameters is a key factor in the activation of soil biological processes (Moreno-de las Heras 2009), providing a food source and habitat for soil fauna (Frouz et al.

2008), and promoting soil fertility for vegetation establishment. Nitrogen, in particularly, has been shown to be a limiting factor in many early successions, and especially on mine wastes (see Marrs and Bradshaw 1993; De Kovel et al. 2000).

It is also well known that clay and organic matter are the main soil bonding agents (Bronick and Lal 2005), and exchangeable calcium has a role in the stabilization of soil structure (Oades 1988). Our results showed that the increase in organic matter with age was accompanied by an increase in sand content and exchangeable Ca^{2+} concentrations and a reduction in clay and lime contents. The decrease in clay content may have been brought by small soil particles settling through the profile, and the lime may have been lost by leaching or through vegetation uptake (Oades 1988). As the lime was dissolved, the exchangeable Ca^{2+} concentrations would be expected to increase. As the clay and lime decreased the sand proportion would increase, which coupled with the increased organic matter would improve soil aeration and water-holding capacity in these clay-loam textured soils, further enhancing biological soil processes (Porta et al. 1994).

Soil reaction showed a decrease of 0.45 pH units during the 6 years, and this result is similar to those found on other restored sites. However, our results are lower than the reduction of 1–1.5 pH units over 15 years on restored mines in the Czech Republic (Frouz et al. 2008), but larger than the reductions of 0.2 and 0.5 pH units over 36 and 100 years after abandonment in old-field successions in Germany and Pennsylvania respectively (Dölle and Schmidt 2009; Matlack 2009). The decrease in pH reported here might be caused by the greater increase of organic matter, which continuously extracted base cations from the soil minerals, releasing protons into the soil (van Breemen et al. 1984). In any case, the changes in soil reaction during succession depend on the initial pH and the buffering capacity of each soil (Dölle and Schmidt 2009); it seems that the buffering capacity of these newly-forming soils is lower than that of well-developed soils.

An interesting result was that four soil variables (EC, available P, and exchangeable Mg^{2+} and K^{+}) did not show any successional trend, even though phosphorus and potassium were included as fertilizers within the hydroseeding slurry. It seems that the clay loam soil forming material used for restoration in this area maintained a large enough supply of these elements for vegetation development, e.g. they are not limiting *sensu* Marrs (2004).

Vegetation structure and soil variables

The soil changes during succession have been generally attributed to vegetation functional/structural changes, since plants determine the amount of soil organic matter, nitrogen and nutrients influencing soil conditions directly (Marrs and Bradshaw 1993; Isermann 2005). In our case, there was a clear relationship between some soil variables, age and vegetation structural/functional components during this short-term succession. These results suggested that though age was the driving agent, vegetation is involved in the mechanisms that induce these soil changes.

The soil variables could be viewed as two distinct groups based on the PCA results, and since these groups corresponded with different axes, this results suggests that they vary independently. The first group can be understood in terms of accumulation of organic matter through time and increase of sand proportion, which favoured the reduction of pH and clay content. Only vegetation structural changes were correlated with this group of soil variables, mainly because vegetation cover (plant biomass) helped in the accumulation of soil organic matter (Marrs et al. 1980a; Frouz et al. 2008). The accumulation of organic matter and the increase in sand proportion led to increased soil aeration and water retention (Matlack 2009); these increases created better conditions for subsequent ruderal and native species establishment and development, increasing complexity of plant communities (increasing species richness (S) and biological diversity index (H′)). The second group of soil variables was related to the concentration of exchangeable cations (K^{+} and Mg^{2+}), electrical conductivity and their negative relation with soil pH. Although, potassium and magnesium are considered key factors for plant growth (Cañadas et al. 2010), our results showed that these cations were not related to structural changes during succession. Cations showed only a plot trend, possibly reflecting the soil cation differences at plot scale. In fact, soil cations have been reported as highly site-specific upon the initiation of succession (Cañadas et al. 2010).

Floristic composition and soil variables

The results of this study showed that the first two main gradients that determines compositional dynamics of vegetation in the short-term, were age since reclamation (successional gradient) and aspect (abiotic differences between areas). The importance of these factors was identified in previous studies at this mine (Alday et al. 2010; Alday et al. 2011a). The successional variation along DCA axis 1 can be seen as a species turnover from hydroseeded species to early colonizers and ruderal and some native species at positive end, whereas DCA axis 2 variation is related with abiotic differences produced by aspect (Alday et al. 2010). The species composition in the three restored areas was more similar in 2004 than it was in 2009 (Alday et al. 2011a), almost certainly reflecting the effect of the hydroseeding at the start with divergence thereafter, as different successional rates were detected (DCA axis 1 age × aspect interaction; $p=0.01$). This result indicates that within-area constraints play an important role in succession, producing diverse trajectories even in close locations (Alday et al. 2011a). These results emphasized also the importance of spatial heterogeneity for the initiation of multiple trajectories (Turner et al. 1998), highlighting the significance of monitoring in a structured way to account for the spatial heterogeneity of individual sites (Legendre and Legendre 2003).

Typically, successional studies of vegetation on mined lands have demonstrated that floristic compositional changes were conditioned by variation in edaphic factors (Prach et al. 2007; Moreno-de las Heras et al. 2008). Similarly, Alday et al. (2011b) in a study of succession on 31 restored coal mines in the same geographical area as this research found that among 16 soil variables only pH was correlated with the floristic composition over the medium time-scale. Our results here showed that vegetation variation on DCA axis 3 was correlated with certain soil variables, showing a gradient of pH reduction (acidification) and organic matter and sand accumulation, which was very similar to the PCA axis 1 successional gradient. Therefore, it is possible that this gradient may be masking a successional gradient similar to that detected on first gradient, since age also had a significant correlation with DCA axis 3.

In any case, and considering that pH and organic matter content were not influenced by aspect, it is likely that pH and organic matter relationships with species composition were associated with differences at plot scale that exhibit both parameters in 2008 and 2009 (variation explained by plot differences pH=89% and organic matter=94%, Figs. 1 and 2). This suggest, that although age since restoration and aspect are the main drivers of compositional dynamics of vegetation at short-term, there are some within-plot factors (here, pH and organic matter) that are related with vegetation composition at plot level. In any case, as we commented before, our results suggest that the mechanisms that induce organic matter accumulation and pH reduction, which have an influence in compositional changes at plot scale, are mainly related to vegetation functional/structural variations such as plant biomass production (Frouz et al. 2008; Meriläa et al. 2010).

The main cause of lack of clear influence of edaphic factors in composition may be because the soil-forming material was sufficiently good to prevent soil factors controlling species development, with the soil development preceded at a similar rate on all areas (an exception of K^+ in the flat area). These findings add evidence to the idea that compositional differences in short-term are mainly driven by age and a combination of abiotic factors (i.e. slope aspect (González-Alday et al. 2008), distance to surroundings species pool (González-Alday et al. 2009)) and stochastic factors (i.e. colonization chance, climate (Alday et al. 2010)). However, there are other factors that worth considers such as the potential role of soil biota on vegetation development and soil properties, which have been described as influential factors for vegetation and soil formation on reclaimed mines (Frouz et al. 2008; Halingerová et al. 2010).

Conclusions

The present work showed that age since restoration was the driving agent, at least in short-term, of soil changes during ecosystem development during the restoration of a coal mine in the Palencia region, under Mediterranean climate. This is in contrast to species compositional changes which are also affected by aspect. Some soil changes, for example the accumulation of organic matter, total nitrogen and sand content were correlated with vegetation functional/structural changes such as vegetation cover (biomass production), which suggested that they might be involved in the mechanism that induce these soil changes, favouring the increase of plant community complexity in such mined areas. However, even where some soil changes were produced, the levels of most measured parameters indicate that the soils studied are in the early stages of successional development (Šourková et al. 2005). At the same time, this study showed little relationship between floristic compositional dynamics and soil parameters, which supported the idea that compositional differences in short-term are mainly driven by a combination of abiotic and stochastic factors. To determine the relative importance of these findings supplementary experiments would be necessary to: (a) determine the cause of soil element changes and their relationships with vegetation functional/structural components; (b) assess the role of soil biota on vegetation and soil development; and (c) identify soil changes over the longer-term time scale.

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