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Vegetation succession on reclaimed coal wastes in Spain: the influence of soil and environmental factors

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Keywords
Age; Constrained ordination; HOF modeling; pH; Restoration method; Species responses; Topsoiling

Abbreviations
AIC = Akaike Information Criterion;
CCA = Canonical Correspondence Analysis;
DCA =Detrended Correspondence Analysis;
GAM =Generalized Additive Models;
HOF = Huisman-Olff-Fresco models;
MRPP = Multiresponse Permutation Procedure

Nomenclature
Tutin et al. (1964–1993)

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Abstract

Question: How is vegetation succession on coal mine wastes under a Mediterranean climate affected by the restoration method used (topsoil addition or not)? How are plant successional processes influenced by local landscape and soil factors?

Location: Reclaimed coal mines in the north of Palencia province, northern Spain (42°47′-42°50′ N, 4°32′-4°53′ W).

Methods: In Jun–Jul 2008, vascular plant species cover was monitored in 31 coal mines. The mines, which had been restored using two restoration methods (topsoil addition or not), comprised a chronosequence of different ages from 1 to 40 yr since restoration started. Soil and environmental factors at each mine were monitored and related to species cover using a combination of ordination methods and Huisman–Olff–Fresco modeling.

Results: Plant succession was affected by restoration method . Where topsoil was added, succession was influenced by age since restoration and soil pH. Where no topsoil was added, soil factors seem to arrest succession. Vegetation composition on topsoiled sites showed a gradient with age, from the youngest, with early colonizing species, to oldest, with an increase in woody species. Vegetation on non-topsoiled sites comprised mainly early-successional species. Response to age and pH of 37 species found on topsoiled mines is described.

Conclusions: Restoration of coal mines under this Mediterranean climate can be relatively fast if topsoil is added, with a native shrub community developing after 15 yr. However, if topsoil is not used, it takes more than 40 yr. For topsoiled mines, the species found in the different successional stages were identified, and their tolerance to soil pH was derived. This information will assist future restoration projects in the area.

Introduction

Succession provides a temporal framework in which to understand ecological processes such as species assembly (Walker & del Moral 2008), vegetation dynamics (Marrs & Bradshaw 1993) and ecosystem development (Odum 1969). At the same time, studies of vegetation succession can supply insights into solving practical problems in ecological restoration (del Moral & Walker 2007), for example the relative importance of biotic and abiotic conditions (Walker & del Moral 2008). Indeed, it has been suggested that ecological restoration should be considered as the practical implementation of management actions using successional concepts and processes to restore self-sustaining ecosystems on degraded lands (Walker et al. 2006; Hobbs et al. 2007). Within this general context, it is crucial to base restoration decisions and programs on a sound understanding of successional mechanisms and ecological processes (Prach et al. 2007a; Tischew & Kirmer 2007). It is, therefore, necessary to identify those abiotic and biotic factors that limit succession when it occurs (Walker et al. 2006; Walker & del Moral 2009).

Open-cast mining is one of the most severe disturbances produced by human activities; it generates highly localized impacts and anthropogenic habitats on sites where there is statutory or planning requirements to ensure vegetation restoration (Moreno-de las Heras et al.

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2008). In northern Spain (León and Palencia) open-cast coal mining affects around 5000 ha of land surface. The restoration approach to the land degraded during mining operations has evolved over the last 40 yr. At the start of this period no management intervention was carried out, and vegetation had to develop through natural colonization. More recently, active restoration management has been implemented, initially through reshaping the landscape and improving the baseline soil-forming materials, and thereafter through the use of a more technical restoration with seed introduction. Usually, herbaceous species have been seeded or hydroseeded (González-Alday et al. 2008) to surmount the lack of seeds in the soil bank (González-Alday et al. 2009). However, these approaches have not always been successful in creating self-sustaining ecosystems. Therefore, a better understanding of mechanisms that govern successional processes after open-pit coal mining in this area is urgently needed to inform management decisions. These decisions should be based on both scientific knowledge (Prach et al. 2007a) and economic considerations (Bradshaw 2002). An initial challenge is to identify the soil and environmental factors that impede or restrict ecosystem succession (del Moral et al. 2009).

The aim of this study was, therefore, to characterize the early vegetation succession in restored coal mines in northern Spain in the 40 yr after abandonment, and relate this to potential successional constraints. Specifically, we tried to answer the following questions: (1) How is vegetation succession affected by the restoration method used (addition of topsoil or not)? (2) How are successional processes influenced by local landscape and soil factors, and if so which are the most important? (3) Do individual species responses reflect these changes during succession and do they respond to local and landscape factors?

Methods

Site selection

Initially, historical information derived from mining company records (UMINSA, Unión Minera del Norte S.A., Guardo, ES) was collated for all coal mines in the north of Palencia province, northern Spain (42°47′-42°50′ N, 4°32′-4°53′ W); data were abstracted on the type of restoration methods used and the time of implementation. Every coal mine was visited and only mines with at least two sides in contact with seral stages of *Quercus pyrenaica* woodland were selected (i.e. mines mainly surrounded by arable land were excluded). As a result, 31 open-cast coal mines were selected for detailed study. These sites ranged in size from 0.5 to 3 ha, and provided a chronosequence of elapsed time since abandonment of 1-40 yr, which was further classified into three successional stages: young (1- 10 yr, $n = 10$), middle (11-20 yr, $n = 11$), and late (> 21 yr, $n = 10$). Three different restoration methods were used at these sites: (1) topsoil addition followed by hydroseeding (Top-H; $n = 16$; 1-25 yr), (2) topsoil addition followed by natural regeneration (Top; $n = 10$; 14-32 yr); and (3) no topsoil addition and natural regeneration (No-Top; $n = 5$; 15-40 yr). The sites showed a sequence of treatments; generally, the hydroseeded sites were the more recent, the topsoiled sites were intermediate and sites with natural regeneration were the oldest. The hydroseeding seed mixture included grasses and herbaceous legumes (81:19 by weight; 200 kg ha^{1}), such as *Lolium perenne*, *Lotus corniculatus*, *Medicago sativa*, *Phleum pratense*, *Poa pratensis*, *Trifolium pratense* and *Trifolium repens*.

Site description

The 31 coal mines selected for study were located relatively close together (within 30 km^2) to minimize geographic, altitudinal (1165-1419 m a.s.l.) and climatic variability. The climate is sub-humid Mediterranean, with an annual mean temperature of 9°C and average annual precipitation of 980 mm. Rainfall is distributed irregularly throughout the year; most rain falls during spring and autumn with a dry season in summer. The natural vegetation surrounding the studied mines is composed of *Q. pyrenaica* woodlands with vestiges of *Quercus petraea*, remnants of natural shrubland (*Crataegus monogyna*, *Cytisus scoparius*, *Genista florida*, *Rosa canina*), and grasslands containing *Agrostis castellana*, *Arenaria erinacea*, *Arenaria montana*, *Bromus mollis* and *Vulpia myuros*.

Sampling

Sampling was carried out in Jun–Jul of 2008. At each mine 10 1 m × 1 m quadrats were located randomly (Krebs 1999), and within each one the cover (%) of every vascular plant species was estimated visually by the same observer. The mean cover values of each species in 10 quadrats per mine were used to obtain a uniform sample of the vascular plant cover of the mine. In addition, a range of landscape variables were characterized for each mine (Table 1).

At each mine, a soil sample was taken from each 1 m × 1 m quadrat using a soil auger (diameter = 8 cm, depth = 10 cm). The 10 subsamples per mine were homogenized to obtain a uniform sample of the soil characteristics of the mine. Soil samples were air-dried, sieved (≤ 2 mm) and analysed for texture using the Bouyoucos method (Day 1965). Soil chemical properties were measured as follows: organic matter using the k-dichromate oxidation method (Walkley 1947); soil pH and electrical conductivity using a conductivity meter in a 1:2.5 soil–deionized water slurry (Allen 1989); total nitrogen concentration using the Kjeldahl method (Bremner & Mulvaney 1982); available

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Table 1. Environmental variables measured for each of 31 coal mines selected in Palencia province, northern Spain. Three sets of environmental variables were measured: (1) age since restoration was implemented; (2) landscape variables, measures of the processes that could affect restoration success from the surrounding landscape; and (3) local, site-specific variables of soil physico-chemical status. The asterisks in soil parameters indicate significant differences ($P < 0.05$) between Top (topsoiled mines; $n = 26$) versus No-Top (non-topsoiled mines; $n = 5$) restoration methods.

	Variable	Units	Median or mean (± S.E)	
			Top	No-Top
Age	Age since restoration was implemented	Years	15 (± 2)	25 (± 5)
Landscape environmental variables	Grazing	(y/n)	n	n
	Grazing Intensity	Number of faecal pellets in a randomly selected 100 m^2 plot	7 (± 2)	2 (± 2)
	Grazing Animal	Faecal pellets of the most important species. Factor 3 levels: N = none; C = cow; S = sheep	N	N
	Runoff	Counting the number of rills and cover and then transformed in a ordered factor (0–4): 0 = no runoff; 4 > 75% of soil eroded	1	2
	Runoff type	Factor 3 levels: N = no; R = reger; C = landslide	R	C
	Border type	Factor 4 levels: N = nothing; W = woodland; G = grassland; S = shrubland	W	W
	Slope	°	18 (± 1.9)	20.60 (± 5.94)
	Altitude	Meters above sea level	1250 (± 14.5)	1225 (± 23.40)
	Orientation	Factor 5 levels: N, S, E, W, Flat	N	E
Local soil variables	Sand	%	63 (± 1.18)	72 (± 2.40)*
	Silt	%	16 (± 0.5)	14 (± 1.60)
	Clay	%	21 (± 0.96)	14 (± 1.80)*
	pH		6.60 (± 0.24)	7.34 (± 0.33)
	Electrical conductivity	mmhos cm^{-1}	0.18 (± 0.02)	0.11 (± 0.02)
	Organic mater	%	5.54 (± 0.54)	3.86 (± 1.13)*
	Total nitrogen	%	0.32 (± 0.03)	0.31 (± 0.08)
	Available phosphorus	mg kg^{-1}	11.01 (± 2.05)	7.46 (± 2.70)
	Exchangeable potassium	mg kg^{-1}	175.36 (± 13.73)	177 (± 44.43)
	Exchangeable iron	mg kg^{-1}	69.45 (± 10.03)	23.60 (± 5.04)*
	C/N ratio		12.90 (± 0.82)	16.32 (± 1.80)*
	Cation exchange capacity	meq.100 g^{-1}	16.90 (± 1.10)	12.84 (± 1.54)*
	Exchangeable calcium	meq.100 g^{-1}	11.18 (± 1.11)	10.13 (± 1.63)
	Exchangeable magnesium	meq.100 g^{-1}	1.50 (± 0.12)	1.57 (± 0.52)
	Exchangeable manganese	meq.100 g^{-1}	47.05 (± 6.90)	16.54 (± 5.04)*
	Exchangeable sodium	meq.100 g^{-1}	0.02 (± 0.01)	0.08 (± 0.02)*

phosphorus (P) concentration using the Olsen method (Olsen & Sommers 1982); exchangeable potassium (K) by atomic absorption spectroscopy after extraction with 1 N ammonium acetate (pH 7) (Allen 1989). The carbon (C):N ratio, cation exchange capacity (CeC), and exchangeable concentrations of calcium (Ca), magnesium (Mg), manganese (Mn), iron (Fe) and sodium (Na) were determined using methods outlined by MAPA (1994).

Data analysis

All statistical analyses were implemented in the R software environment (version 2.10.1; R Development Core Team, Vienna, Austria, http://www.r-project.org), using the VEGAN (R package version 1.15-1, http://vegan.r-forge.r-project.org/) and GRAVY (R package version 0.0-21, http://cc.oulu.fi/~jarioksa/softhelp/softalist.html) packages for multivariate analyses and HOF (Huisman–Olff–Fresco; Huisman et al. 1993) models, respectively.

Initial data exploration and the effect of restoration methods

Multivariate exploratory analysis was carried out to describe the plant community composition with a detrended correspondence analysis (DCA) (Hill & Gauch 1980) ($\lambda_1 = 0.41$, $\lambda_2 = 0.26$, $\lambda_3 = 0.18$, $\lambda_4 = 0.11$; $GL_1 = 3.92$, $GL_2 = 2.12$, $GL_3 = 2.15$, $GL_4 = 1.82$). The plant species cover dataset was reduced by removing all species that only occurred in one sample, and a log-transformation ($\log(x+1)$) was then applied. One no-topsoiled mine had a strong influence on the ordination, therefore, DCA was

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repeated excluding the no-topsoiled mine outlier ($\lambda_1 = 0.35$, $\lambda_2 = 0.23$, $\lambda_3 = 0.15$, $\lambda_4 = 0.11$; $GL_1 = 3.60$, $GL_2 = 2.04$, $GL_3 = 1.95$, $GL_4 = 1.97$).

Thereafter, to test if the three restoration methods (topsoil, topsoil-hydroseeding and no-topsoil addition) shared the same primary gradients (hypothesis 1) two analytical approaches were used. First, different restoration methods were fitted onto DCA ordination using the 'envfit' function with 1000 permutations. Their class centroids and bivariate standard error ellipses were then used to illustrate each restoration method on the biplots. Second, a multi-response permutation procedure (MRPP) was used over the first two DCA axes (function 'mrpp' in VEGAN, using Euclidean distances and 1000 permutations) to examine the differences in floristic composition between topsoil, topsoil-hydroseeding and no-topsoil restoration methods. Bonferroni correction was used to adjust for the significance level of each contrast; here, the critical probability level for detecting significance between contrasts was $\alpha = 0.017$.

Finally, a new DCA was produced using only topsoiled mines ($n = 26$; $\lambda_1 = 0.38$, $\lambda_2 = 0.23$, $\lambda_3 = 0.11$, $\lambda_4 = 0.09$; $GL_1 = 3.66$, $GL_2 = 2.15$, $GL_3 = 1.61$, $GL_4 = 1.18$) to identify if the sequence of successional ages (young, middle and late) was established enabling the joint comparison of topsoiled mines. To aid interpretation the mines age and successional groups (young, middle and late) were fitted onto the DCA ordination plot using the 'envfit' function with 1000 permutations. The compositional differences at middle successional age, where Top-H and Top mines mixed together, were also evaluated using MRPP as described above.

After inspection of the results from these analyses (Hypothesis 1; Figs 1 and 2) and of the differences in physicochemical soil variables between the topsoiled and non-topsoiled mines analysed using unbalanced ANOVAS (Table 1), the data were split into two groups: Group 1, the 26 topsoiled mines; and Group 2, the four non-topsoiled ones (eliminating the non-topsoiled outlier, a 15 years old mine). All subsequent analyses were applied to Group 1 only.

The low number of non-topsoiled mines considered ($n = 4$) limits the use multivariate constrained ordinations. Therefore, we included only a brief description of the non-topsoiled mines community for tentative comparison.

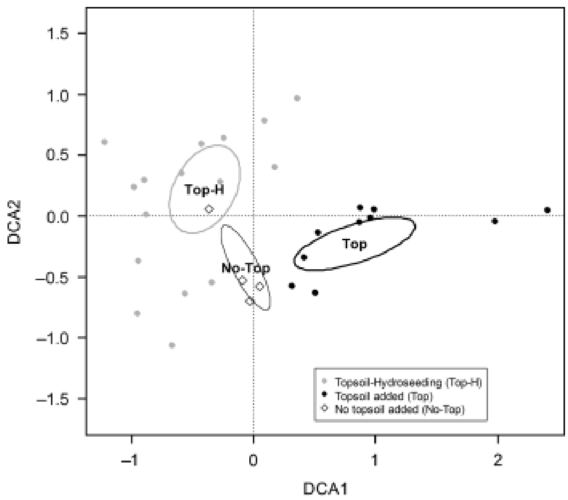

Fig. 1. Detrended correspondence analysis (DCA) ordination of floristic composition data from 30 coal mines in Palencia province, northern Spain. The positions of the three different restoration methods are illustrated as class centroids with overlain SE-ellipses for axis 1 and 2. Top-H, hydroseeding ($n = 16$; 1–25 yr); Top, topsoil addition followed by natural regeneration ($n = 10$; 14–32 yr); No-Top, no topsoil addition and natural regeneration ($n = 5$; 15-40 yr).

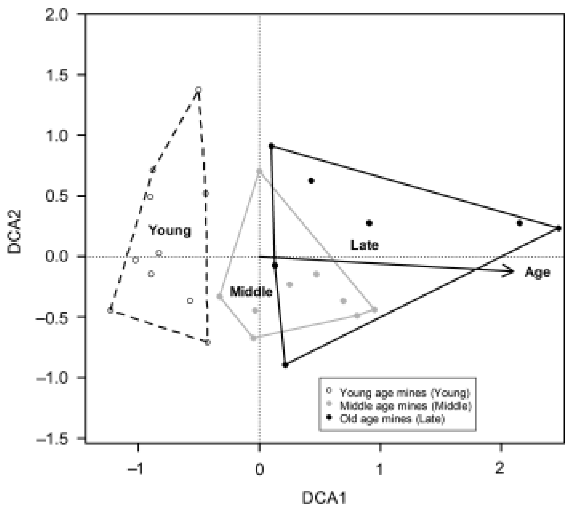

Fig. 2. Detrended correspondence analysis (DCA) ordination of floristic composition data from 26 topsoiled (Top-H, hydroseeding ; Top, topsoil addition followed by natural regeneration) coal mines in Palencia province, northern Spain. The three different successional stages are illustrated, and age since restoration fitted as passive variable over ordination.

Assessing effects of local soil factors and landscape factors on the succession

The effects of local landscape and soil factors on topsoiled mines succession were then evaluated using canonical correspondence analysis (CCA). The most significant uncorrelated environmental variables from those available in Table 1 were selected using the forward selection approach with the Akaike's information criterion (AIC) statistic as the selection criterion. Significance of the contrasts was assessed using permutation tests with the reduced model and 199 permutations. The large number of possible environmental variables ($n = 26$) compared with the number of

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topsoiled mines ($n = 26$) made selection difficult; therefore, selection was done within three subsets, {age}, {landscape variables} and {soil variables}. The final model was fitted using only the variables that reduced the AIC within each set. In order to check if the response of constrained variables response was really linear and vectors were appropriate to draw over the CCA biplots, surface models of each constraining variables (age and pH) were fitted over the CCA ordination results using GAM models and the 'ordisurf' function.

Species responses to age and pH

The cover of most important species were examined through time and over the pH gradient for the topsoiled mines ($n = 26$) using HOF models (Huisman et al. 1993). The HOF models allow testing of alternative responses to ecological gradients using a hierarchical set of five response models, ranked by their increasing complexity (Model I, no species trend; Model II, increasing or decreasing trend to the maximum; Model III, increasing or decreasing trend below maximum attainable response; Model IV, symmetrical response curve; Model V, skewed response curve). The HOF response models were fitted for species present in more than 11 mines (42% of topsoiled mines). The species cover data were transformed (arcsin(sqrt(x/100)) and a Gaussian error structure was used (Huisman et al. 1993). The AIC statistic was used to select the most appropriate model for each species.

Results

Community description and environmental variables

Two hundred and twenty three vascular plant species were recorded from the 31 coal mines. Of these 18 woody species and characteristics of the surrounding vegetation including *C. monogyna*, *C. scoparius*, *G. florida*, *Q. pyrenaica* and *R. canina* were found especially in mid- and late successional stages. The young successional stage was dominated by herbaceous species such as *B. mollis*, *Medicago polymorpha*, *Sonchus oleraceus*, *Trifolium campestre* and *V. myuros*, and there was also a high cover of some species included in the hydroseeding mixture (e.g. *L. perenne*, *T. repens*). At the same time, 61 species, including *Chamaespartium tridentatum*, *Lithodora diffusa* and *Silene conica* were found only once, and the 41% of this species group occurred only in the mid-successional stage.

The influence of restoration methods (Hypothesis 1)

The DCA of mine sites is shown (Fig. 1). The three restoration methods were overlain on this biplot and they occupied different regions of the ordination plot. The hydroseeded topsoiled mines (Top-H, most of them from the young successional stage) appeared in the left-hand area whereas the topsoiled mines (Top, most of them from middle- and late- successional stages) were in the right area of the plot. Surprisingly, the non-topsoiled mines (No-Top, most of them from the older sites) appeared in the central lower part of the plot, being closer to topsoiled young and middle sites than to older mines. Non-topsoiled mines showed significant compositional differences from Top-H (MRPP analysis, $A = 0.132$, $P = 0.011$) and Top ($A = 0.243$, $P = 0.002$). The composition of non-topsoiled mines was characterized by early-successional species (*Lactuca* spp., *Chondrilla* spp., *Cirsium arvense*, *Dianthus* spp., *Senecio jacobaea*, *S. oleraceus*, *Vicia hirsuta*), and species adapted to dry conditions (*Sedum sediforme*, *Filago pyramidata*, *Minuartia mediterranea*). Simultaneously, there were significant differences on soil properties between non-topsoiled and topsoiled mines; physical properties (sand and clay composition) and chemical properties (Organic matter, C:N ratio, CeC, Mn, Fe and Na) (Table 1).

The second DCA for hydroseeded topsoiled (Top-H) and topsoiled mines (Top) grouped the mines along the first axis according to their successional age (Fig. 2). A close relationship was revealed between the first axis and the age of the mine ($r^2 = 0.76$, $P < 0.001$). Young mines were plotted in the negative end of axis 1, middle mines from Top-H and Top appeared mixed in the central part showing no significant compositional differences (MRPP analysis, $A = 0.094$, $P = 0.103$), whereas the late successional mines were at the positive end.

Together, these two analyses suggest the presence of two distinct groups : the topsoiled mines (with and without hydroseeding) and the non-topsoiled mines.

Assessing effects of environmental factors (landscape versus local soil) on succession (Hypothesis 2)

For the topsoiled mines, age and pH were the only significant explanatory variables included in the model; local landscape factors had no significant effect. These variables reduced the AIC of the null model from 128.2 to 127, and were significant ($P = 0.005$). Age was the more influential factor on the course of vegetation succession (10% of the constrained inertia) followed by pH (7% of the constrained inertia). The CCA biplots (Fig. 3) showed that age was correlated with the first axis, reflecting a gradient from the youngest mines with hydroseeded species (*L. perenne*, *M. sativa*) and early colonizing species (*Erodium cicutarium*, *Hordeum murinum*, *M. polymorpha*, *Papaver rhoeas*) on the right of the diagram, to the oldest mines with typical woody species (*G. florida*, *Quercus pyrenaica*, *R. canina*) and late successional ones (*Viola riviniana*) on the left. The second axis was correlated negatively with pH; the mines with greater pH values and associated species (*Anthyllis vulneraria*, *Eryngium*

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campestre, *Vicia cracca* and *Xeranthemum inapertum*, all with Ellenberg *R*-values > 7; Ellenberg et al. 1991) appeared at lower scores, whereas the mines with lower pH values and associated species (*Aphanes microcarpa*, *Lepidium heterophyllum*, *Micropyrum tenellum*, *Myosotis discolor* and *Trifolium subterraneum*, all with Ellenberg *R*-values < 5; Ellenberg et al. 1991) were at the positive end.

Species responses to age and pH in topsoiled sites

The HOF response models were calculated for the 37 most common species for the two significant explanatory variables (age and pH) in the topsoiled sites. Plots are presented for those species which produced HOF model types III–V (Figs 4 and 5). Species with the null model (Type I) are not presented, and no species exhibiting the Type II model were found.

Four response groups were identified with respect to species response to age since restoration. Group 1 contained 14 species that showed no trend (HOF model I), which maintained stable cover values lower than 10%. The most important species in this group were *B. mollis* (10% of cover), *V. myuros* (8.3% of cover), *P. pratensis* (8% of cover), *Lotus corniculatus* (7% of cover) and *Plantago lanceolata* (6% of cover). Group 2 included two woody species (*G. florida* and *R. canina*) and a grass (*A. castellana*) increasing their cover through age according to HOF model III. Group 3 was the most abundant with 15 species; these species exhibited symmetrical or skewed response curves (HOF models IV and V) showing a gradual turnover of species from *S. oleraceus*, *T. campestre*, *T. scabrum*, *T. striatum*, which peaked in the young stages (< 10 years), through *Arrhenatherum elatius*, *Cerastium glomeratum* and *C. scoparius* which peaked between 10 and 20 yr, to *Dactylis glomerata*, *Hieracium pilosella* and *Rumex acetosella* which had their optima between 20 and 30 yr. Finally, Group 4 showed a decreasing trend (HOF model III) with age, and this group included five herbaceous species that had greatest cover values in the early stages and a subsequent reduction with age. This group included three species (*L. perenne*, *T. pratense*, *T. repens*) typically included in the hydroseeding mixture, as well as *Arenaria serpyllifolia* and *Festuca* spp.

The species responses to pH gradient could also be separated in the same way into four groups. Group 1 contained 18 species showing no response to pH (HOF model I), including *B. mollis*, *Festuca* spp., *T. repens* and *Veronica arvensis*. Group 2 contained only two species (*T. campestre* and *T. pratense*) that showed an increasing trend

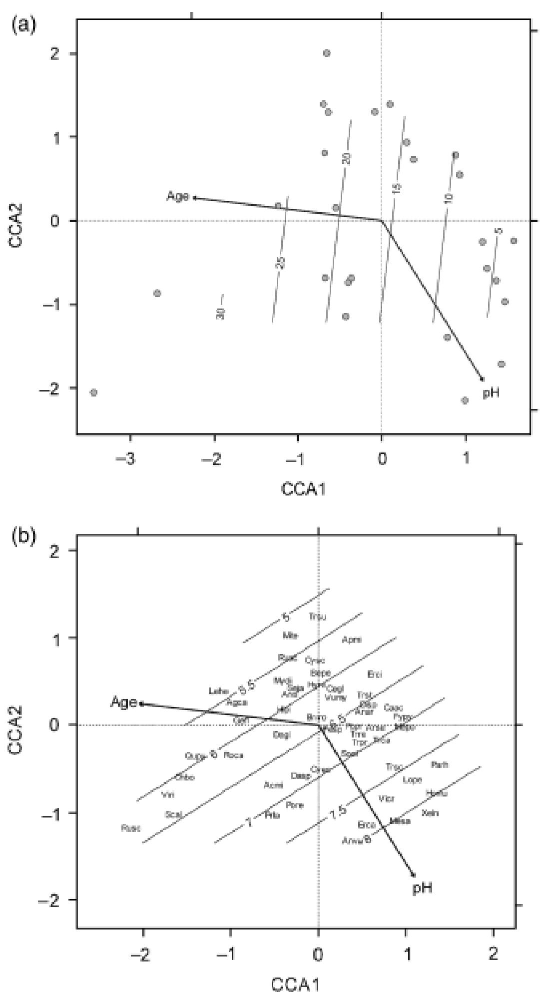

Fig. 3. Constrained canonical correspondence analysis (CCA) ordination biplots of 26 coal mines in Palencia province, northern Spain, where topsoiling restoration method was used. The ordination was constrained on age since restoration and soil pH and their fitted surface responses are overlain. (a) Sites biplot with age since restoration fitted as a response surface; (b) Species biplot with soil pH fitted as a response surface. Species codes: Acmi = *Achillea millefolium*; Agca = *Agrostis castellana*; Anar = *Anthemis arvensis*; Anvu = *Anthyllis vulneraria*; Arel = *Arrhenatherum elatius*; Arse = *Arenaria serpyllifolia*; Apmi = *Aphanes microcarpa*; Bepe = *Bellis perennis*; Brmo = *Bromus mollis*; Caac = *Carduus acanthoides*; Cegl = *Cerastium glomeratum*; Chbo = *Chenopodium bonus-henricus*; Cyec = *Cynosurus echinatus*; Cysc = *Cytisus scoparius*; Dagl = *Dactylis glomerata*; Dasp = *Daucus* spp.; Disp = *Dianthus* spp.; Erca = *Eryngium campestre*; Erci = *Erodium cicutarium*; Fesp = *Festuca* spp.; Fypy = *Filago pyramidata*; Gefl = *Genista florida*; Hipi = *Hieracium pilosella*; Homu = *Hordeum murinum*; Hyra = *Hypochoeris radicata*; Lehe = *Lepidium heterophyllum*; Lope = *Lolium perenne*; Mepo = *Medicago polymorpha*; Mesa = *Medicago sativa*; Mite = *Micropyrum tenellum*; Mydi = *Myosotis discolor*; Parh = *Papaver rhoeas*; Popr = *Poa pratensis*; Pore = *Potentilla reptans*; Prla = *Prunella laciniata*; Qupy = *Quercus pyrenaica*; Roca = *Rosa canina*; Ruac = *Rumex acetosella*; Rusc = *Rumex scutatus*; Scal = *Scrophularia alpestris*; Seja = *Senecio jacobaea*; Sool = *Sonchus oleraceus*; Trca = *Trifolium campestre*; Trpr = *Trifolium pratense*; Trre = *Trifolium repens*; Trsc = *Trifolium scabrum*; Trst = *Trifolium striatum*; Trsu = *Trifolium subterraneum*; Vicr = *Vicea cracca*; Viri = *Viola riviniana*; Vumy = *Vulpia myuros*; Xein = *Xeranthemum inapertum*.

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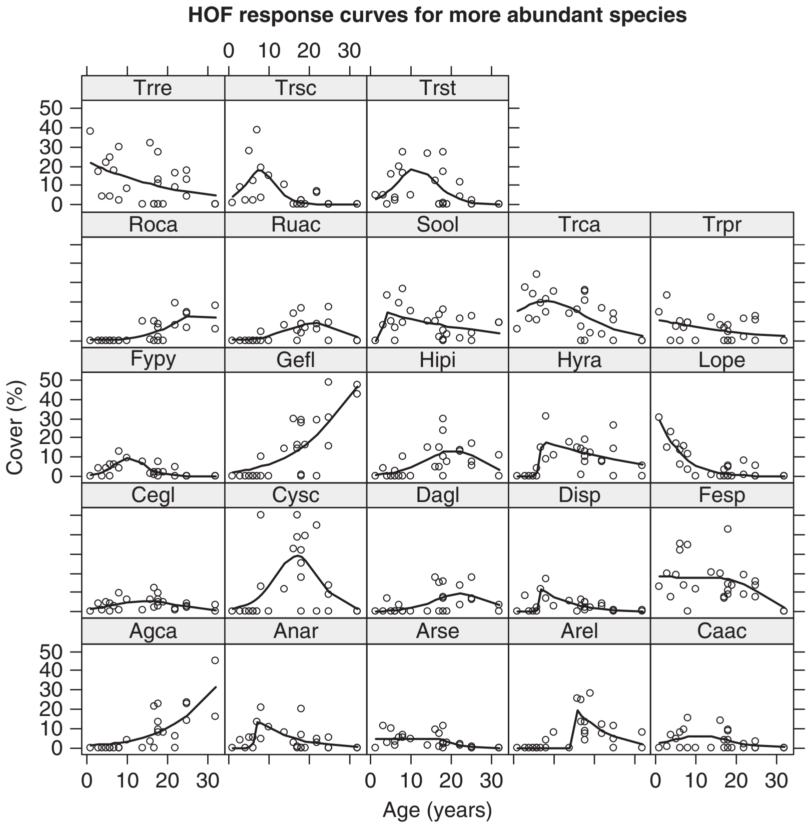

Fig. 4. Significant response curves of the most abundant species with respect to age since restoration started at 26 topsoiled coal mines in Palencia province, northern Spain. For species identification see Fig. 3. HOF, Huisman–Olff–Fresco model (Huisman et al. 1993).

with pH (HOF model III). Group 3 contained 12 species with an unimodal/skewed response; 11 species showed a skewed response (HOF model V) including *D. glomerata*, *P. pratensis* and *S. jacobaea*, but only *R. canina* showed unimodal one (HOF model IV); the optima for this group ranged from 5.5 to 8. Finally, Group 4 included six species that showed a decreasing trend with increasing pH (HOF model III), this group included *A. elatius*, *Hypochoeris radicata* and *V. myuros*.

Discussion

The results presented here clearly show that the vegetation succession was affected by the restoration method applied (i.e. whether topsoil was added or not). Simultaneously, the environmental factors that influence successional processes differed between the restoration methods : the vegetation on topsoiled mines showed a trend with age and pH, whereas on non-topsoiled mines substrate-based constraints seemed to limit succession.

The influence of restoration method (Hypothesis 1)

An important result was that restoration method influenced vegetation succession. In particular, the topsoiled mines (hydroseeded or not) shared the same primary gradients and the same direction of change in relation to age, whereas the older non-topsoiled mines were located among young- and mid-successional stages. This finding was expected given the importance of stable and fertile soil-cover to restore vegetation on mine wastes (Tordoff et al. 2000; Martínez-Ruiz & Marrs 2007). The vegetation on topsoiled mines included some native species (e.g. *B. mollis*, *T. campestre*, *V. myuros*) and showed an increase in native woody species with age (e.g. *G. florida*, *Q. pyrenaica*). These results are in agreement with previous studies that suggest topsoil spreading, especially under the extreme environmental conditions found on these mine sites, can enhance plant establishment by improving soil properties (Holl 2002), and therefore, increase the likelihood of re-establishment of native species of plants and microorganisms (Martínez-Ruiz & Marrs 2007).

It is well known that coal mine wastes present hostile soil conditions for plant establishment in terms of structure, physicochemical characteristics and instability (Felinks & Wiegand 2008). These aspects limit vegetation recovery by reducing the probability of the natural establishment of non-adapted native species (Prach et al. 2007b), thus slowing succession. The non-topsoiled

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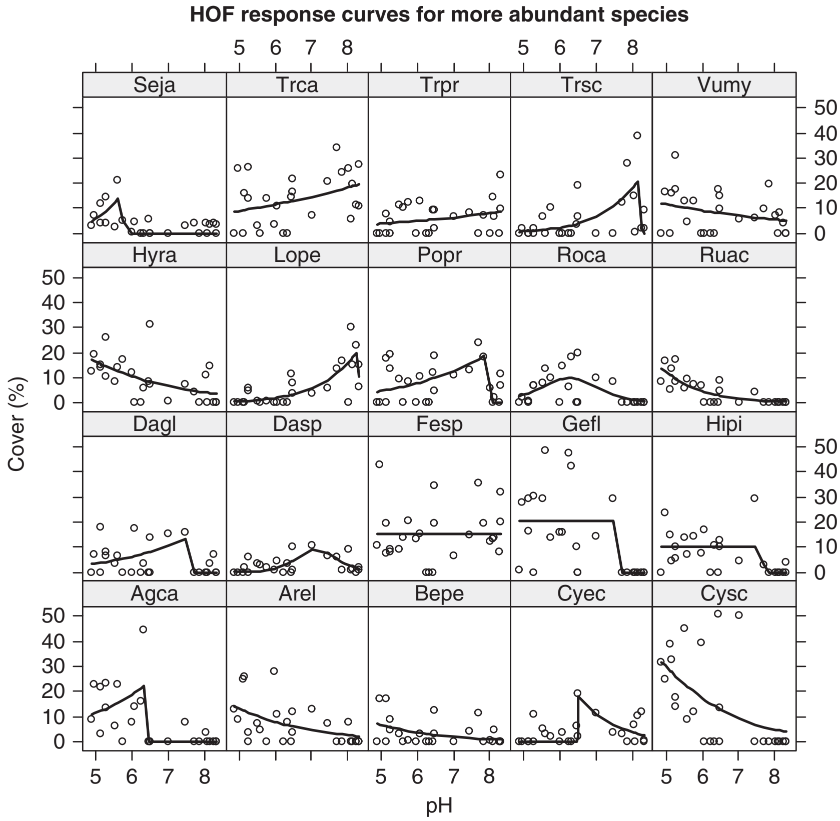

Fig. 5. Significant response curves of the most abundant species with respect to soil pH at 26 topsoiled coal mines in Palencia province, northern Spain. For species identification see Fig. 3. HOF, Huisman–Olff–Fresco model (Huisman et al. 1993).

mines conformed to this pattern, given that the constraints on succession on these mine wastes seem to be substrate-based, even though our analyses were based on few sites. Sand content and Na concentration have an impact on water-holding capacity; a high sand content (here $> 70\%$) will provide a low water-holding capacity and a high Na can increase clay dispersion, which will reduce water-holding capacity further (Southard 1999). The low water holding capacity will limit vegetation establishment and its effect will be accentuated by the regular and prolonged surface droughts in these Mediterranean areas (Blondel & Aronson 1999; Tordoff et al. 2000). At the same time, the lower organic matter, and Fe and Mn concentrations relative to the topsoiled mines are also factors that are likely to limit vegetation establishment and development (Bochet & García-Fayos 2004). Therefore, the vegetation of theses mines was characterized by early-successional species (e.g. *Cerastium* spp., *Chondrilla* spp., *Lactuca* spp.), those adapted to drought (e.g. *F. pyramidata*, *S. sediforme*) and with a few woody species establishing after 20 years (e.g. *C. scoparius*, *Thymus mastichina*).

The unbalanced design, caused by low number of non-topsoiled mines ($n = 4$, after the elimination of one outlier) in comparison with topsoiled mines ($n = 26$), reduced the strength of the evidence found. Therefore, further investigations are needed to quantify the relative importance of these findings. However, these results are in agreement with the hypothesis that improving soil conditions is important for improving plant establishment on coal wastes in Mediterranean ecosystems by overcoming physicochemical constraints (Bochet et al. 2010).

Assessing effects of environmental factors (landscape versus local soil) on the succession (Hypothesis 2)

The environmental factors driving the course of succession at the topsoiled mines were age since restoration was implemented and soil pH. Similar conclusions have been found on restored sites in central Europe (Prach et al. 2007b) and on coal mines in central Spain (Moreno de las Heras et al. 2008). The course of the succession reflected a gradient of species turnover from the early-successional stages (e.g. *A. serpyllifolia*, *S. oleraceus*), with hydroseeded species (e.g. *L. perenne*, *T. pratense*, *T. repens*) on young sites, to mid-successional stages (e.g. *A. elatius*, *C. glomeratum*, *C. scoparius*) and finally to late-successional stages where woody species (e.g. *G. florida*, *Q. pyrenaica*, *R. canina*) dominate. Analogous results of species turnover through age have been found in reclaimed coal mines in Virginia (USA), where the composition of the oldest reclaimed sites was approaching that of the adjacent natural vegetation (Holl & Cairns 1994). The vegetation of our study approaches the composition of native vegetation within 32 yr . This suggests that a longer time-frame is needed to achieve our ecological restoration objective.

Soil pH in topsoiled mines determined successional patterns across stages of the same age, separating the most acidic soils from the neutral and basic soils. The influence of pH on vegetation is well known (Ellenberg et al. 1991) and is often a reliable predictor of species composition in succession (Christensen & Peet 1981). In our study, this is an important result as understanding species niche space with respect to pH will help with species selection for future restoration planning (Young et al. 2005) and suggests that manipulation of soil pH might be a useful tool for accelerating or directing succession (Prach et al. 2007b).

In other regions, studies of succession on mine sites have reported the importance of a range of environmental and landscape factors driving succession (Moreno de las Heras et al. 2008; Rehounková & Prach 2008). Surprisingly our results did not support this, because we did not find that local landscape factors had significant effect on successional process. In any event, these findings are consistent with the hypothesis of Rehounková & Prach (2006), who suggest that the role of the environmental factors in succession depends on the scales and the systems studied.

Species response to age and pH in topsoiled sites

A large number of species (mainly therophytes) showed no response to age or pH; these species are presumably adapted to disturbance produced by the annual climatic cycles of the Mediterranean region (Lawesson & Oksanen 2002; Alday et al. 2010). Some of these species were native ones (e.g. *B. mollis*, *Medicago lupulina* and *V. arvensis*, and we suggest that these species might provide a useful additional option for improving hydroseeding mixtures in the future, where we might expect these species to persist for a very long time, facilitating the subsequent establishment of later-successional species (Malkinson et al. 2003; Walker & del Moral 2009).

The species response to pH showed that species optima ranged from 5.5 to 8, and tolerances within this range were generally large, indicating that these species are able to grow over a relative wide pH range (Wamelink et al. 2005). Some species showed optima at different parts of this range, for example *V. myuros* had lower optima than *T. pratense*. Information on the optima allows either species mixtures to be tailored to individual site conditions or conditions could be changed by liming to favor desired plant communities.

Conclusions

Wastes produced by surface coal mining in the Palencia region of northern Spain, under Mediterranean climate can, if topsoil is added, develop a native shrub community fairly quickly (ca. 15 yr). However, it will take more than 40 yr if topsoiling is not used. At the same time, these results identified the main species involved in the different stages of the colonization of coal mines in the region and will help guide future restoration strategies.

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