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RESEARCH ARTICLE

Linking soil variability with plant community composition along a mine-slope topographic gradient: Implications for restoration

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Abstract Soil heterogeneity generated during the topographic restoration of opencast coalmines determines important differences in vegetation dynamics. The relationship between soil and vegetation along a reclaimed mine slope was assessed. Two vegetation patches (grassland and shrubland) were distinguished and compared with the adjacent forest. Seven sampling transects (3:3:1, grassland:shrubland:forest) were implemented for soil and vegetation characterization. Eleven years after reclamation significant differences between the reference community and the reclaimed communities, and along the reclaimed mine slope, were found. A topographic gradient was observed in the vegetation distribution associated with water and organic matter content: Grassland patches occupy the upper parts of the mine slope to where easily oxidizable-carbon/total-carbon ratio increases and shrubland patches occupy the lower parts towards where water retention capacity increases. The plant species segregation along the mine-slope topographic gradient was related to stages of different maturity of vegetation and soil properties. Novel aspects in plant-soil systems understanding in reclaimed mine slopes were addressed.

Keywords Coal mining · Ecological restoration · Floristic composition · Northern Spain · Soil properties · Topography

INTRODUCTION

Opencast mining is a major environmental disturbance worldwide that often leaves a barren landscape with very poor soil-forming material for subsequent ecosystem development (Pallavicini et al. 2015). In such damaged systems, ecological restoration may create a long-term self-sustaining ecosystem with fully functioning soil and vegetation (Alday et al. 2012). However, restoration approaches have not always been successful in reaching this target, and an inappropriate spatial variation in the physical and biological structure of plant communities is produced (Milder et al. 2013).

It is known that spatial heterogeneity plays an important role in the structure and dynamics of ecosystems (Tilman 1988). This fact is of particular relevance in Mediterranean environments where the vegetation distribution may be discontinuous partly due to the irregular distribution of some soil properties (Ettema and Wardle 2002). Under these environmental conditions, heterogeneity is a key factor conditioning vegetation regeneration after disturbance (Steen 1999). On the other hand, changes in vegetation composition and structure during succession can ameliorate soil conditions and assist further vegetation development (Alday et al. 2012).

Changes in soil properties and vegetation development during succession have been studied in various types of landscapes, including 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 the dynamics of vegetation and soil properties during succession after mining restoration (Alday et al. 2012). There is some detailed long-term work on ecological and soil restoration after bauxite mining in SW Australia (Koch and Hobbs 2007; Grigg 2017). Although some field studies have been carried out to elucidate the importance of abiotic limiting factors in the establishment and subsequent vegetation development on mining wastes (Martínez-Ruiz and Marrs 2007; González-Alday et al. 2008; Alday et al. 2010), there is still little information about the processes that occur in

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the soil and the changes in its physicochemical properties during succession after coal mining restoration (De Kovel et al. 2000).

In particular, the study of the spatial patterns of soil properties and vegetation is a key to understanding the ecohydrological behaviour of the slopes (Espigares et al. 2013), which explains how the run-off sources and sinks, and transitions between both, influence plant growth and the development of bare patches (Merino-Martín et al. 2012). Such dynamics is of particular interest in Mediterranean environments, where water deficit and the high impact of human activities make up a landscape characterized by sparse vegetation cover that influences the ecohydrological behaviour of the slopes (Moreno-de las Heras et al. 2008) and the success of revegetation.

The study of the spatial patterns of soil properties and vegetation along mine slopes may provide insights into the solution of practical problems in ecological restoration (Del Moral and Walker 2007). In this paper, we hypothesize that there is a relationship between soil heterogeneity and floristic composition of plant communities along an artificial slope derived from opencast coal mining in northern Spain. The aims were (1) to assess differences in topography, soil properties and vegetation between natural and reclaimed mine-slope communities as well as between the reclaimed mine-slope communities; (2) to relate species composition to topography and soil properties; and (3) to describe the plant species compositional change along the mine-slope gradient and its relation with stages of different maturity of the vegetation. Expanding our knowledge of the ecological processes involved in the dynamics of revegetation in slope systems can contribute to a more efficient design of mining restoration plans adapted to local particularities.

MATERIALS AND METHODS

Study area

This study examines 17 ha restored from an opencast coalmine (northern Spain; lat 42°47′18.4″N, long 4°50′59.2″W; ca. 1110 m a.s.l.; Fig. 1) in the 'Montaña Palentina' area. The climate is sub-humid Mediterranean (Milder et al. 2013), with 973 mm of annual rainfall and an annual mean temperature of 9.2 °C (1973–2007 means from Guardo Meteorological Station). Rainfall is irregularly distributed throughout the year, with a rainy season in autumn (October and November) and spring (April and May), and a dry season in July through August. Most of the area surrounding the site is forested with relatively diverse vegetation associated with sessile oak (*Quercus petraea* (Matt.) Liebl.) and Pyrenean oak (*Quercus pyrenaica* Willd.) forests. The most abundant tree species associated with this type of forest in this area are: *Ilex aquifolium* L. and *Corylus avellana* L., with an understory mainly composed of *Genista florida* L., *Cytisus scoparius* (L.) Link, *Erica australis* L., and the herbaceous *Linaria triornithophora* (L.) Cav. The natural soils are mainly inceptisols with an udic soil moisture regime and mesic soil temperature regime (sensu Soil-Survey-Staff 2014). The soil profile opened in the natural forest close to the mine (Table 1) indicates that it is a Typic Dystroudept.

The study site was reclaimed 11 years before our spring sampling in 2011. After coal mining stopped, the open pit was filled with coal wastes from nearby mines, and the surface regraded to approximately the original contour and covered with ca. 30 cm of fine-textured materials and a superficial layer of cattle manure (10 Mg ha^{-1}). The fine-textured materials were a mixture of topsoil and sediments from deeper parts of the nearest opencast pits; this mixture had a clay loam texture, with a pH of 6.5, electrical conductivity (EC) of 114.3 µS cm^{-1}, easily oxidizable carbon (OxC) of 19.8 g kg^{-1}, available phosphorous (P_{av}) of 9.7 mg kg^{-1} and an effective depth of 10–15 cm at the sampling time (López-Marcos 2012). These soils can be classified as Lithic Udorthents (sensu Soil-Survey-Staff 2014). In October 2000, the entire site was hydroseeded by the mining company (UMINSA) using a slurry containing soluble chemical fertilizer (200 kg ha^{-1}; NPK of 8:15:15), and a seed mixture (300 kg ha^{-1}) of grasses and legume herbs (74:26 by weight) composed of *Lotus corniculatus* L. (18%), *Trifolium repens* L. (8%), *Festuca rubra* L. (20%), *Bromus sterilis* L. (10%), *Poa trivialis* L. (10%), *Phleum pratense* L. (20%), *Avena sativa* L. (7%) and *Secale cereale* L. (7%). Nowadays, the reclaimed area, a south-facing slope with a steepness of 10–35°, has been colonized by native herbaceous and shrub species, mainly *Cytisus scoparius* and *Genista florida*, from the surrounding areas. The area is being grazed by wild animals (deer, roe deer and wild boar), cattle and horses. Two patches of two different plant communities (grassland and shrubland) were distinguished on the reclaimed slope and compared with that of the adjacent natural forest edge. Seven sampling transects were implemented: six transects in the reclaimed slope (three in the grassland patch and another three in the shrubland patch), and one transect in the nearby native forest due to its homogeneity (Milder et al. 2013).

Vegetation and soil sampling, and topography characterization

Transects for vegetation, soil and topography characterization were established from 'high' to 'low' altitude in each patch of vegetation on the reclaimed slope and in the native forest edge. An initial transect point was established at the

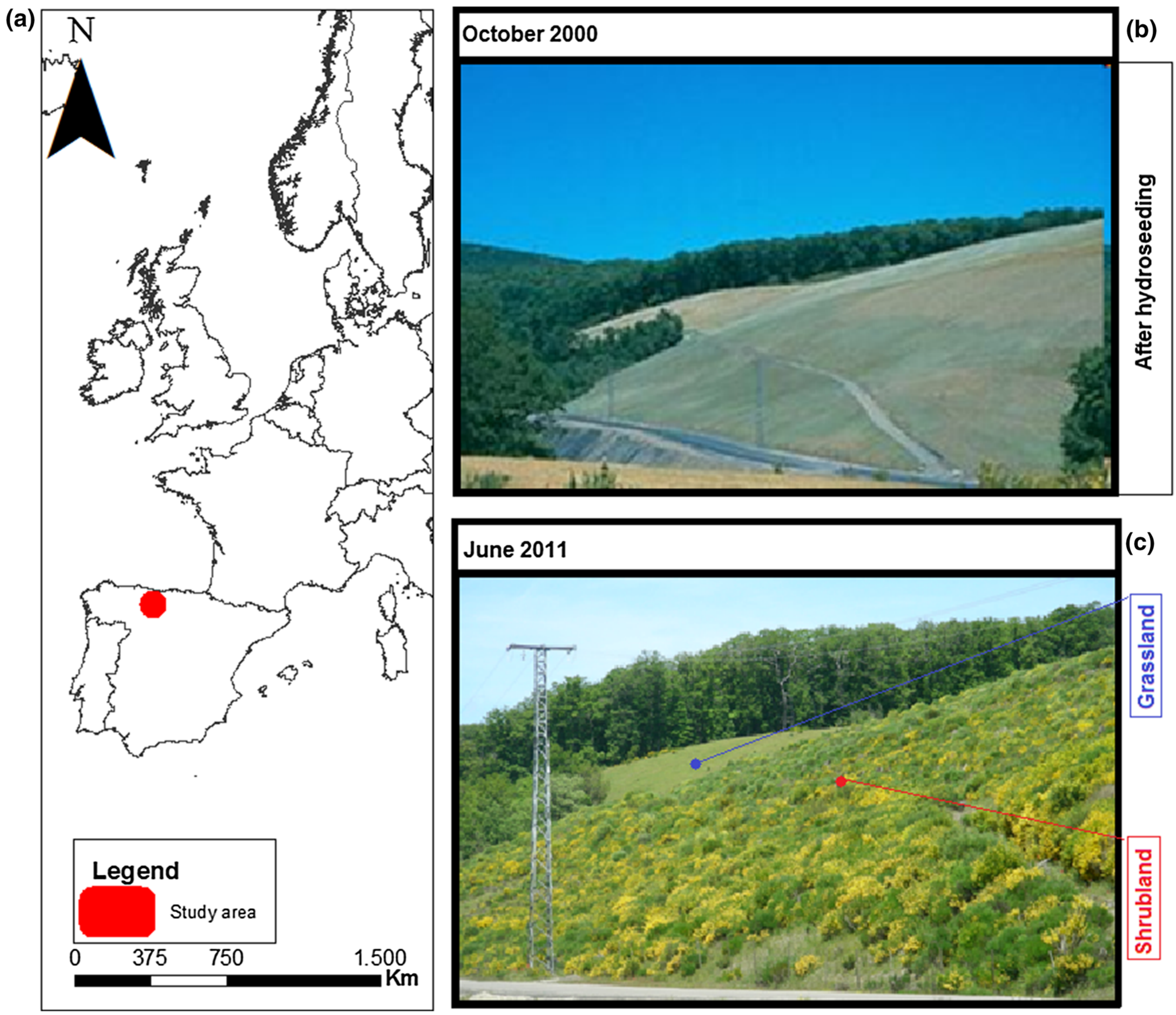

Fig. 1 **a** Location of study area in the north of Spain. **b** Picture of the study area on October of 2000 some days after the hydroseeding; and **c** picture of the study area on June of 2011, 11 years after the hydroseeding where the two different plant communities (grassland and shrubland) can be observed

Table 1 General soil properties of soil profile under natural oak forest. *Colour* wet matrix colour (value/chroma), *CM* coarse soil material (> 2 mm), *OxC* carbon easily oxidizable determined by K-dichromate oxidation method, *EC* electric conductivity, P_{av} available phosphorous determined by Olsen procedure

Horizon	Depth (cm)	Colour	CM (%)	Sand (%)	Silt (%)	Clay (%)	OxC (g kg^{-1})	pH	EC (µS cm^{-1})	P_{av} (mg kg^{-1})
Ah	0–10	10YR3/2	42.0	28.9	48.7	22.4	78.6	4.4	159.9	1.9
AC	10–25	7.5YR3/3	63.4	19.7	52.6	27.7	53.2	4.8	48.9	1.2

upper left corner of each vegetation patch, and subsequent transects were established to the right at 15-m intervals. The initial transect point was omitted from sampling in each vegetation patch to minimize possible bias in starting point selection (see Milder et al. 2013). Along each transect, six vegetation and soil sampling points were established around 2 m from each other (Fig. 2). At each point, basic site attributes including altitude (m a.s.l), steepness (°) and thickness (cm) of the soil down to the coal wastes, in the case of the reclaimed mine slope, were collected.

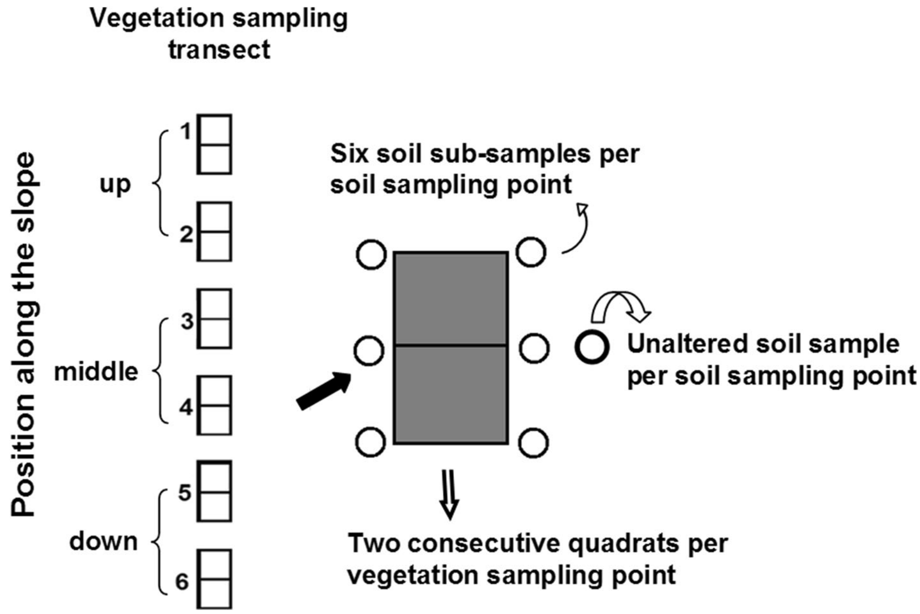

Fig. 2 Distribution of six vegetation and soil sampling points along each of seven transects implemented for study; sampling points separated 2 m from each other. Every two consecutive sampling points are belonging to each of the three parts distinguished along the slope (up, middle, down)

Each vegetation sampling point consisted of two consecutive quadrats (Fig. 2), whose size varied according to the type of vegetation sampled: 0.5 × 0.5 m plots for the grassland community (González-Alday et al. 2008; Alday et al. 2012) and of 2 × 2 m for the shrubland and forest communities (Milder et al. 2013); previous studies in the same area indicated that those are the optimum sampling sizes that balances the sampling effort and allow the whole plant diversity to be collected in each case (see González-Alday et al. 2008; Alday et al. 2012; Milder et al. 2013). The cover (%) of every vascular plant species present in each quadrat, as well as the bare soil and superficial stoniness percentages were estimated visually in June 2011.

For each soil sampling point, one composite soil sample was taken: it consisted of six soil sub-samples (Fig. 2), taken close to the vegetation sampling quadrats down until the presence of coal wastes were found (ca. 15 cm), and which were homogenized to obtain a uniform composite sample for soil characterization. Hence, there were 42 composited soil samples (6 samples/transect × 7 transects). An undisturbed soil sample was also collected at each soil sampling point with a steel cylinder of 98.18 cm^3 (Fig. 2), i.e. 42 undisturbed soil samples.

Soil analyses

The air-dried soil samples were sieved (≤ 2 mm) for the coarse soil material determination (CM %), and different chemical and physical soil properties were analysed in the fine earth fraction.

Soil chemical properties were measured as follows: soil pH and electrical conductivity (EC) using a conductivity meter in a 1:2.5 soil/deionized water slurry (Allen et al. 1974); easily oxidizable carbon (OxC) using the K-dichromate oxidation method (Walkley 1947); available phosphorous (P_{av}) using the Olsen method (Olsen and Sommers 1982); total carbon (C) and total nitrogen (N) with a LECO CHN-2000 autoanalyser; the ratio of easily oxidizable carbon to total carbon (OxC/C) and the ratio of total carbon to total nitrogen (C/N) were also calculated.

Soil texture (sand, silt and clay contents) was analysed using the pipette method, and bulk density (BuD), porosity, available water (UW) and water holding capacity (WHC) by MAPA (1994) methods; the last three physical properties were measured directly from the undisturbed soil samples.

Data analyses

First, we analysed the differences between the reclaimed communities and the reference community (grassland, shrubland and forest; fixed factor) for edaphic, topographic, and vegetation variables (see Table 2) by using linear mixed models (LMM; Pinheiro and Bates 2000); the restricted maximum likelihood method was used (REML; Richards 2005). Second, we analysed in more detail the

Table 2 The summary results of linear mixed models testing the effect of community type (grassland, shrubland and adjacent forest) on (1) topographic, (2a) physical edaphic, (2b) chemical edaphic and (3) vegetation variables (mean±standard error). *Depth* soil depth to the coal wastes in the case of mine communities, *CM* coarse soil material (> 2 mm), *BuD* bulk density, *UW* useful water, *WHC* water holding capacity, *EC* electrical conductivity, *OxC* carbon easily oxidizable, P_{av} available phosphorous. Different letters indicate differences between pairs of plant communities ($p< 0.05$)

	Variable	Community type			$F_{[2,16]}$	P
		Grassland	Shrubland	Forest		
1	Depth (cm)	8.39 ± 0.83 **a**	14.11 ± 0.66 **b**	–	145.30	< 0.001
	Altitude (m)	1213.22 ± 1.71 **b**	1196.39 ± 3.09 **a**	1214.83 ± 2.87 **b**	14.32	< 0.001
	Steepness (°)	19.78 ± 0.88 **a**	23.22 ± 1.64 **a**	21 ± 1.41 **a**	13.60	0.28
2a	CM (%)	60.47 ± 1.14 **b**	58.02 ± 1.83 **b**	42.01 ± 2.21 **a**	23.92	< 0.001
	Sand (%)	53.52 ± 0.81 **b**	54.48 ± 0.73 **b**	30.92 ± 1.25 **a**	87.60	< 0.001
	Silt (%)	28.24 ± 0.74 **a**	32.07 ± 1.3 **b**	48.78 ± 1.90 **c**	34.19	< 0.001
	Clay (%)	18.24 ± 1.13 **b**	13.45 ± 0.96 **a**	20.29 ± 0.95 **b**	58.63	0.01
	BuD (g cm^{-3})	1.05 ± 0.03 **a**	1.38 ± 0.03 **b**	0.7 ± 0.05 **a**	44.88	< 0.001
	Porosity (%)	54.14 ± 1.66 **b**	38.65 ± 1.60 **a**	49.92 ± 4.42 **b**	19.61	< 0.001
	UW (%)	12.51 ± 1.44 **a**	17.72 ± 1.22 **a**	25.84 ± 5.19 **b**	6.41	0.01
	WHC (g cm^{-2})	1.00 ± 0.10 **a**	3.55 ± 0.36 **b**	19.87 ± 1.52 **c**	289.39	< 0.001
2b	pH	6.51 ± 0.07 **b**	6.4 ± 0.09 **b**	5.1 ± 0.18 **a**	29.36	< 0.001
	EC (µS cm^{-1})	138.85 ± 8.74 **b**	89.79 ± 4.56 **a**	82.01 ± 7.15 **a**	16.85	< 0.001
	OxC (g kg^{-1})	42.5 ± 0.31 **b**	17.5 ± 0.14 **a**	78.9 ± 0.40 **b**	85.74	< 0.001
	C (g kg^{-1})	51.2 ± 0.43 **b**	37.2 ± 0.24 **a**	90.3 ± 0.30 **b**	30.54	< 0.001
	N (g kg^{-1})	4.2 ± 0.03 **b**	3.0 ± 0.02 **a**	5.2 ± 0.02 **b**	12.08	< 0.001
	OxC/C	0.87 ± 0.05 **b**	0.47 ± 0.03 **a**	0.87 ± 0.04 **b**	38.64	< 0.001
	C/N	11.87 ± 0.28 **a**	12.47 ± 0.28 **a**	17.53 ± 0.48 **b**	38.56	< 0.001
	P_{av} (mg kg^{-1})	15.64 ± 1.15 **b**	3.56 ± 0.25 **a**	2.77 ± 0.48 **a**	46.25	< 0.001
3	Bare soil (%)	14.91 ± 1.62 **b**	7.78 ± 1.93 **a**	0.00 ± 0.00 **a**	2.25	< 0.001
	Stoniness (%)	5.19 ± 1.46 **a**	6.36 ± 1.48 **a**	0.83 ± 0.53 **a**	2.18	0.145
	Plant cover (%)	107.845 ± 3.38 **a**	145.16 ± 5.65 **b**	150.92 ± 6.34 **b**	16.15	< 0.001

differences between the two reclaimed communities (grassland and shrubland), considering also as fixed factors the position on the slope (up, middle, down) and their interaction (see Table 3). In all analyses, transects and sampling points per position on the slope within each transect were considered as random factors. Finally, working over the model matrix, contrasts were calculated to test differences between fixed factor levels (Pinheiro and Bates 2000). Consequently, the Bonferroni correction was used to adjust for the significance level for each *t* test (Sokal and Rohlf 1995).

The matrix of species abundance used in the ordination analyses considered the mean value of the percentage of cover of all species present in every two quadrats of vegetation sampling; hence, there were vegetation data of six points along each transect, as well as of soil and topographic parameters. Detrended Correspondence Analysis (DCA) performed on the complete data set (reclaimed mine and native forest) produced an ordination with a first axis gradient length of 6.696 SD units suggesting that a unimodal approach was appropriate to describe the relationship between species and environmental variables (Ter-Braak and Similauer 2002). Therefore, the influence of constrained explanatory variables (soil and topographic variables) on floristic composition was then assessed within the whole data set, using a forward selection procedure in Canonical Correspondence Analysis (CCA). Forward selection was used to select significant variables and the Monte Carlo test was used to assess significance, with 9999 permutations (Legendre and Legendre 2003). In all permutation tests, an unrestricted permutation structure was used. This process was combined with an examination of inflation values, to remove those variables that were highly multicollinear.

The separation of sampling sites in two groups along CCA1 (Fig. 3a) justified analysing data of the reclaimed mine separately to assess in some more depth the relationship between site conditions and vegetation composition along the slope gradient (Fig. 3b), following the same procedure as for the whole data set.

Only species responses along the mine-slope topographic gradient associated with CCA1 (Fig. 3b) were

Table 3 The summary results of linear mixed models testing the effect of community type (grassland, shrubland), position in the slope (up, middle, down) and their interaction, into the reclaimed mine slope, on (1) topographic, (2) edaphic and (3) vegetation variables (mean±standard error); abbreviations as in Table 2. Different letters indicate differences pairs of positions within each plant community and between communities ($p < 0.05$)

	Grassland			Shrubland			Community		Position		Com × Pos	
	Up	Middle	Down	Up	Middle	Down	$F_{[2.4]}$	P	$F_{[1.8]}$	P	$F_{[2.8]}$	P
Depth(cm)	9.67 ± 1.82 a	8.67 ± 1.05 a	6.83 ± 1.33 a	12.17 ± 0.54 b	13.67 ± 0.92 b	16.5 ± 1.18 b	9.29	0.04	0.2	0.83	4.42	0.05
Altitude (m)	1220.33 ± 1.98 b	1212.67 ± 1.65 ab	1206.67 ± 2.11 a	1206.17 ± 5.08 b	1197 ± 4.38 ab	1186 ± 3.45 a	6.8	0.06	41.37	< 0.001	1.67	0.25
Steepness (°)	21.33 ± 1.33 a	22 ± 0.89 a	16 ± 1.03 a	21 ± 1.41 a	22.83 ± 1.97 a	25.83 ± 4.36 a	1.65	0.27	0.25	0.79	2.95	0.11
CM (%)	60.63 ± 0.88 a	57.26 ± 1.81 a	63.52 ± 2.28 a	51.71 ± 1.37 a	55.65 ± 1.51 b	66.71 ± 2.42 b	2.8	0.17	16.08	< 0.001	5.79	0.03
Sand (%)	53.57 ± 1.83 a	53.49 ± 1.03 a	53.52 ± 1.49 a	57.02 ± 1.59 a	54.02 ± 0.68 a	52.41 ± 0.47 a	0.18	0.69	3.79	0.07	3.59	0.08
Silt (%)	27.77 ± 0.72 a	27.93 ± 1.62 a	29.03 ± 1.5 a	29.67 ± 2.01 a	31.45 ± 2.03 a	35.09 ± 2.46 a	1.43	0.3	4.21	0.06	1.57	0.27
Clay (%)	18.66 ± 1.47 a	18.58 ± 2.05 a	17.46 ± 2.56 a	13.31 ± 1.39 a	14.53 ± 1.43 a	12.5 ± 2.24 a	2.02	0.23	0.8	0.48	0.14	0.87
BuD (g cm^{-3})	1.02 ± 0.05 a	1.06 ± 0.06 a	1.06 ± 0.05 a	1.36 ± 0.09 b	1.36 ± 0.03 b	1.43 ± 0.03 b	12.52	0.02	0.7	0.52	0.7	0.74
Porosity (%)	56.38 ± 2.72 b	54.76 ± 2.71 b	51.28 ± 3.28 b	39.68 ± 3.85 a	39.52 ± 2.5 a	36.75 ± 1.95 a	42.87	< 0.001	1.06	0.39	0.07	0.93
UW (%)	14.06 ± 2.92 a	11.72 ± 1.95 a	11.74 ± 2.85 a	13.35 ± 1.7 a	19.37 ± 2.05 a	20.45 ± 1.52 a	5.68	0.08	0.67	0.54	2.87	0.11
WHC (g cm^{-2})	1.23 ± 0.19 a	1.05 ± 0.14 a	0.72 ± 0.13 a	2.24 ± 0.37 b	3.62 ± 0.53 b	4.8 ± 0.47 c	74.68	< 0.001	4.54	0.05	9.99	0.01
pH	6.64 ± 0.08 b	6.64 ± 0.08 b	6.26 ± 0.11 a	6.21 ± 0.05 a	6.3 ± 0.06 a	6.7 ± 0.24 b	0.63	0.47	0.15	0.87	8.75	0.01
EC (μS cm^{-1})	129.32 ± 17.32 b	137.1 ± 14.18 b	150.12 ± 15.3 b	98.74 ± 8.13 a	86.31 ± 6.76 a	84.31 ± 8.71 a	18.8	0.01	0.1	0.9	1.06	0.39
OxC (g kg^{-1})	32.6 ± 0.28 b	49.9 ± 0.72 b	45.2 ± 0.30 c	20.8 ± 0.2 c	18.7 ± 0.22 a	13.2 ± 0.19 a	69.27	< 0.001	2.21	0.17	4.85	< 0.001
C (g kg^{-1})	36.8 ± 0.41 b	54 ± 0.64 b	62.8 ± 0.80 c	40.6 ± 0.58 c	39.4 ± 0.3 a	31.5 ± 0.24 a	10.47	0.03	1.61	0.26	5.45	0.03
N (g kg^{-1})	3.3 ± 0.03 b	4.5 ± 0.05 b	4.9 ± 0.06 c	3.3 ± 0.04 c	3 ± 0.01 a	2.5 ± 0.01 a	16.45	0.02	0.8	0.48	4.81	0.04
OxC/C	0.91 ± 0.07 b	0.93 ± 0.08 b	0.76 ± 0.08 c	0.53 ± 0.05 c	0.47 ± 0.04 a	0.41 ± 0.04 a	61.7	< 0.001	2.76	0.12	0.4	0.68
C/N	11.01 ± 0.32 a	11.78 ± 0.3 a	12.81 ± 0.51 a	12.08 ± 0.34 a	13.03 ± 0.58 a	12.3 ± 0.51 a	1.98	0.23	2.19	0.17	1.74	0.24
P_{av} (mg kg^{-1})	11.38 ± 1.74 b	15.83 ± 1.42 b	19.72 ± 1.23 c	4.46 ± 0.42 a	2.92 ± 0.26 a	3.31 ± 0.34 a	78.25	< 0.001	5.46	0.03	9.65	0.01
Bare soil (%)	12.83 ± 1.47 b	14.17 ± 1.24 b	17.75 ± 4.53 b	16.25 ± 2.21 a	6.25 ± 2.80 a	0.83 ± 0.83 a	10.19	0.03	3.75	0.07	10.6	0.01
Stoniness (%)	2.33 ± 0.38 a	6.50 ± 1.55 a	6.75 ± 4.09 a	4.17 ± 0.83 a	4.17 ± 0.83 a	10.75 ± 3.89 a	0.34	0.59	2.58	0.14	0.87	0.46
Plant cover (%)	106.25 ± 2.30 a	111.83 ± 7.88 a	105.46 ± 6.64 a	138.4 ± 6.57 b	141.03 ± 9.88 b	156.05 ± 12.18 b	15.43	0.02	0.51	0.62	0.97	0.42

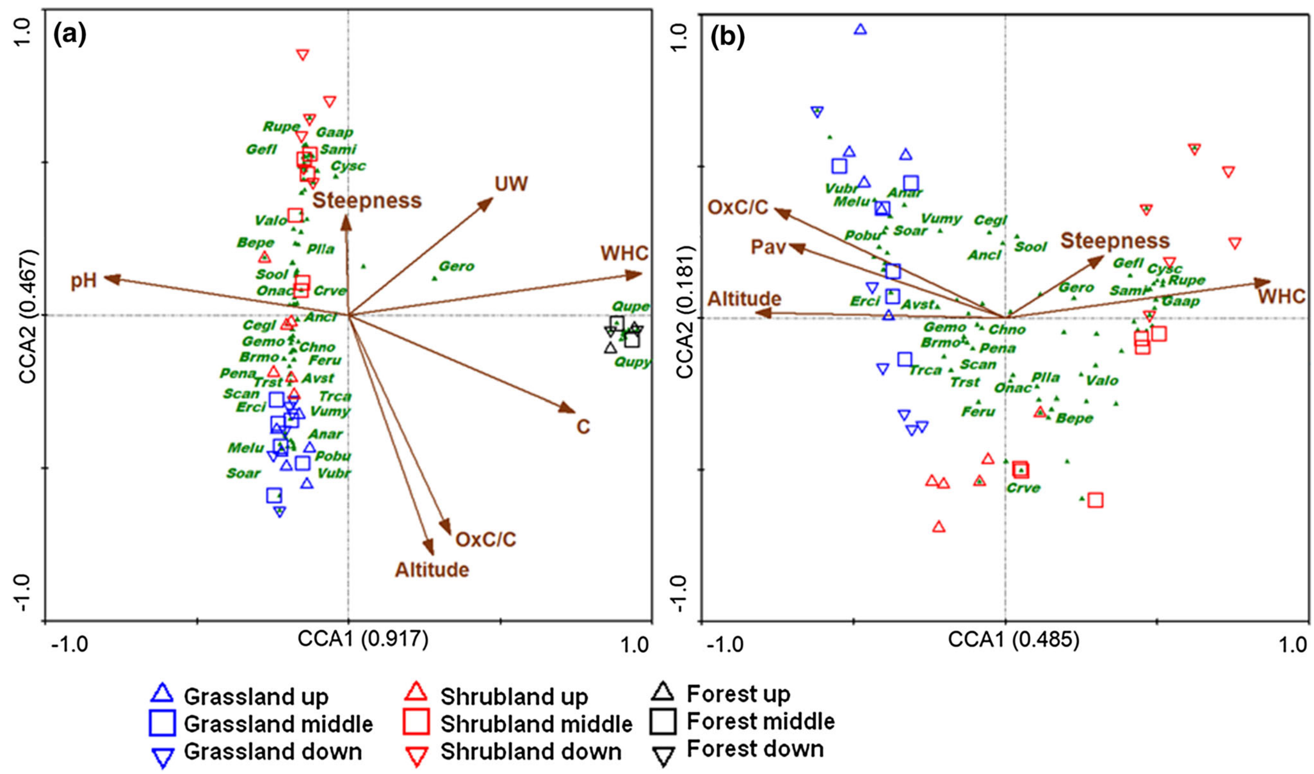

Fig. 3 CCA triplot with significant explanatory variables, sampling points and species **a** for the whole data set (native forest and reclaimed mine slope), and **b** for data of the reclaimed mine slope only. Sampling points in the different positions along the slope identified as follows: open triangle (up), open square (middle), open inverted triangle (down); in blue, red or black colour for grassland, shrubland and forest communities, respectively. Full species complement (small green triangles) and identification of those species with cover > 1%, listed by first two letters of genus and species name. Species codes: Ancl (*Anacyclus clavatus*), Anar (*Anthemis arvensis*), Avst (*Avena sterilis*), Bepe (*Bellis perennis* L.), Brmo (*Bromus mollis*), Cegl (*Cerastium glomeratum*), Crve (*Crepis vesicaria* L.), Cysc (*Cytisus scoparius*), Chno (*Chamaemelum nobile*), Erci (*Erodium cicutarium* (L.) L'Hér*)*, Feru (*Festuca rubra*), Gaap (*Galium aparine* L.), Gefl (*Genista florida*), Gemo (*Geranium molle* L.), Gero (*Geranium robertianum*), Melu (*Medicago lupulina* L.), Onac (*Onopordum acanthium* L.), Pena (*Petrorhagia nanteuilli*), Plla (*Plantago lanceolata* L.), Pobu (*Poa bulbosa*), Qupe (*Quercus petraea*), Qupy (*Q. pyrenaica*), Rupe (*Rubia peregrine* L.), Sami (*Sanguisorba minor* Scop.), Scan (*Scleranthus annuus* L.), Soar (*Sonchus arvensis*), Sool (*Sonchus oleraceus*), Trca (*Trifolium campestre* Schreb), Trst (*Trifolium striatum* L.), Valo (*Valerianella locusta* (L.) Laterr.), Vubr (*Vulpia bromoides*), Vumy (*Vulpia myuros* (L.) C.C.Gmel.)

modelled by Huisman–Olff–Fresco (HOF) models (Huisman et al. 1993). These are a hierarchical set of five response models, ranked by their increasing complexity (Model I, no species trend; Model II, increasing or decreasing trend; Model III, increasing or decreasing trend below maximum attainable response; Model IV, symmetrical response curve; Model V, skewed response curve). The Akaike information criterion (AIC; Akaike 1973) was used to select the most appropriate response model for each species (Johnson and Omland 2004); smaller values of AIC indicate better models. HOF response curves were computed for 38 species, those present in more than 52% of the sampling points on the reclaimed mine slope to illustrate the broad trends of compositional change.

DCA and CCA were carried out using CANOCO 4.51 (Ter-Braak and Similauer 2002), with standard options and no down-weighting of rare species. Linear mixed models and HOF models were carried out using the NLME (version 3.1-137; Pinheiro et al. 2018) and the eHOF (version 3.2.2; Jansen and Oksanen 2013) packages, respectively, both implemented in the R software environment (version 3.3.3; R-Core Team 2015).

RESULTS

Comparing the reclaimed sites with the reference community

Differences in topography, soil properties and vegetation cover

All variables, except for steepness and superficial stoniness percentage, differed among communities (Table 2). Soil depth to the coal wastes was 1.7 times higher in the shrubland than in the grassland. Sand content, CM and pH were lower in the nearby forest than in the reclaimed mine slope, whereas UW and C/N were higher in the forest, and silt content and WHC increased from the grassland to the forest. In the shrubland, altitude, clay content, porosity, N, C, OxC and OxC/C were lower than in the other two communities, but BuD was higher. EC, P_{av} and bare soil percentage were higher, and total plant cover was lower, in the grassland than in the other two communities.

Relating species composition with environmental factors

The CCA forward selection procedure applied to the complete data set (Fig. 3a), identified, in this order, WHC ($F = 14.46$, $p = 0.002$, 35.10% of variance explained), altitude ($F = 6.99$, $p = 0.002$, 14.84%), OxC/C ($F = 3.06$, $p = 0.002$, 6.17%), steepness ($F = 2.51$, $p = 0.002$, 4.87%), C ($F = 1.89$, $p = 0.006$, 3.44%), UW ($F = 1.74$, $p = 0.008$, 2.98%) and pH ($F = 1.63$, $p = 0.016$, 2.82%) as the main influential factors on floristic composition. The first two axes of the CCA explained 59% of the variation. The eigenvalues (λ) for the first two CCA axes were 0.917 and 0.467, and the model was significant according to the Monte Carlo test, for both the first axis ($F = 8.232$, $p = 0.002$) and all canonical axes ($F = 2.780$, $p = 0.002$). Correlation between species and environmental variables were 99.6% and 96.5% for the first and second axes, respectively. Axis 1 separated the sampling points in the native forest surrounding the mine, in the right half area of the diagram, from those on the reclaimed mine in the left-hand area. The forest community was dominated by *Quercus pyrenaica* and *Quercus petraea* and included 74% of exclusive species, mostly characteristic of the reference community. Four soil variables, i.e. WHC, OxC/C, C, and UW, increasing to the forest community and pH increasing to the reclaimed mine were related to these differences in floristic composition. Axis 2 was related to altitude and steepness, and suggests a topographic gradient in the composition of plant communities along the reclaimed mine slope, with grasslands located at higher altitudes (CCA2 negative end) and shrublands on steeper slopes (CCA2 positive end).

Assessing differences between the two reclaimed mine-slope communities

Differences in topography, soil properties and vegetation cover

The grassland community occupied the sites with higher altitude on the mine slope (Table 3). Soil depth to the coal wastes, BuD, and total plant cover were higher in the shrubland community. CM did not vary among communities, but there was an effect on position, with different effects in shrubland vs. grasslands: being higher in the lower and medium shrubland slope parts and with the upper shrubland slope part being similar to all grassland slope positions. WHC was higher in soils under the shrubland community than under grassland, increasing to the lower part of the slope in the shrubland. P_{av} was higher in the grassland than in the shrubland at all positions, increasing to the lower part of the grassland patch. Porosity, EC and OxC/C were higher in the grassland community independent of the position on the slope. Bare soil, C, N and OxC were higher in the grassland than in the shrubland at the medium and low positions of the slope, the last three increasing to the lower part of the slope in the grassland and to the upper part in the shrubland. There was no main effect of either community or position on soil pH content, but a significant interaction effect, with higher pH values in the lower position of shrubland communities.

Relating species composition with environmental factors

The CCA forward selection procedure applied to sampling sites on the reclaimed mine slope, identified, in this order, WHC ($F = 7.72$, $p = 0.002$, 24.84% of variance explained), OxC/C ($F = 2.59$, $p = 0.002$, 7.95%), steepness ($F = 2.74$, $p = 0.004$, 6.70%), altitude ($F = 2.28$, $p = 0.002$, 6.52%) and P_{av} ($F = 1.61$, $p = 0.02$, 4.38%) as the main environmental variables responsible for differences in floristic composition within the reclaimed mine slope (Fig. 3b). The first two axes of the CCA explained 44.4% of the variation. The eigenvalues for the first two CCA axes were 0.485 and 0.181, and the model was significant according to the Monte Carlo test for both the first axis ($F = 4.451$, $p = 0.002$) and all canonical axes ($F = 1.821$, $p = 0.002$). Correlations between species and environmental variables were 97% and 91% for the first and second axes, respectively. Axis 1 showed the same topographic gradient drawn before by CCA2 in the global analysis, with altitude increasing to the sites occupied by the grassland communities, where steepness was lower but soils had higher values of OxC/C and P_{av}; in contrast, the soil of shrubland communities had higher WHC.

Compositional change through the mine-slope topographic gradient

Responses of individual species along the topographic gradient associated with CCA1 of Fig. 3b separated the species into four groups (Fig. 4). Group 1 (HOF model I) included 13 species, mostly with a short life-span (annuals) and anemochorous dispersion, with Asteraceae being the best-represented family. These species showed no response to the topographic gradient and are not shown in Fig. 4; six of them had cover $\leq$ 1% (*Anacyclus clavatus* (Desf.) Pers., *Cerastium glomeratum* Thuill., *Filago pyramidata* L., *Hordeum vulgare* L, *Leontodon hispidus* L., *Leontodon*

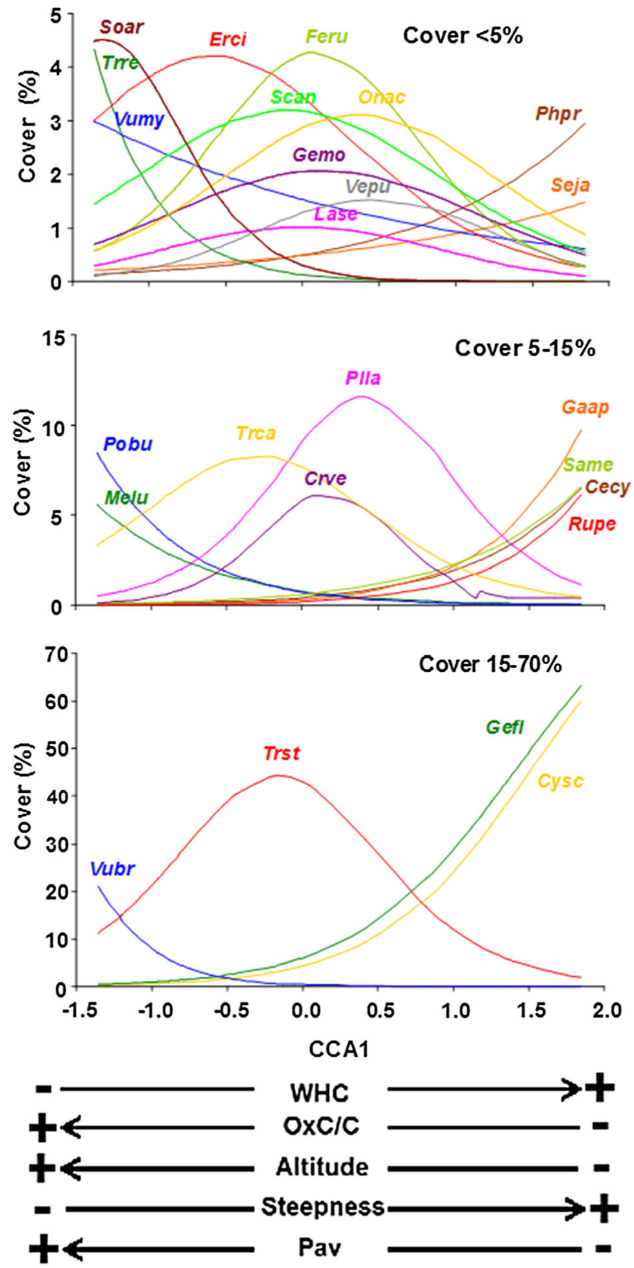

Fig. 4 HOF-derived response curves showing the response of the most common species, relative to the topographic gradient from the upper (negative axis 1) to the lower (positive axis 1) part of the reclaimed mine slope. Graphs separated for clarity of scale. Species codes in Fig. 2, with the additional species Cecy (*Centaurea cyanus* L.), Lase (*Lactuca serriola* L.), Phpr (*Phleum pratense*), Trre (*Trifolium repens*), Seja (*Senecio jacobaea* L.), Vepu (*Verbascum pulverulentum* Vill.)

taraxacoides (Vill.) Mérat.). The cover of four species ranged from 1 to 2.8 (*Anthemis arvensis* L., *Bromus mollis* L., *Geranium robertianum* L., *Sonchus oleraceus* L.), and the most abundant species were *Chamaemelum nobile* (L.) All., *Avena sterilis* L. and *Petrorhagia nanteuilli* (Burnat) P.W. Ball & Heywood with a cover of 8.8, 5.7 and 3.6%, respectively. Group 2 (HOF model II, decreasing trend) included six species, mainly grasses and legumes, with three of them being perennial herbs (*Poa bulbosa* L., *Sonchus arvensis* L. and *Trifolium repens*), whose cover decreased towards the lower part of the slope. Group 3 (HOF model II, increasing trend) included eight species from a greater variety of families, mostly perennial herbs, and two woody species (*Cytisus scoparius* and *Genista florida*), whose cover increased towards the lower part of the slope. Lastly, 11 species in Group 4 exhibited symmetrical response curves (HOF Model IV) with optima at different points along CCA1, suggesting a gradual turnover of these species through the topographic gradient.

DISCUSSION

Results showed significant differences in the floristic composition between the reference community and the plant communities established on the mine slope 11 years post-reclamation, and a topographic-successional gradient in the distribution of plant communities and plant species abundance along the reclaimed mine slope; some soil properties, related to soil water and soil organic matter, seem to be responsible for these differences.

Differences between the reclaimed sites and the reference community

Five soil properties point to being responsible for the differences in the floristic composition between the reference community (forest surrounding the mine) and the plant communities established on the mine slope, 11 years post-reclamation. Properties related to soil water (water holding capacity, WHC and useful water, UW) and soil organic matter (easily oxidizable carbon, OxC and total carbon, C) had higher values in the forest soils, whereas pH was higher in the reclaimed mine-slope soils. These soil differences might be due to the different origin and time of development of soils. In this sense, it would be wise to ask whether we are able to restore soils that are closer in origin to those of the reference community or, on the contrary, if we agree that this is not possible and millennial timeframes are required for reference community development. Natural soils in the study area (nearby forest) had an udic soil moisture regime, which means moisture storage exceeding the evapotranspiration losses. However, the lack of soil structure in the mining substrates greatly hinders its ability to retain moisture, even though the mean annual precipitation was almost 1000 mm. Regarding the chemical soil properties, a temporal plant successional progress could be related to the decrease in soil pH levels towards the reference community, since pH was lower in the native nearby forest than in the reclaimed mine slope (Fig. 3a); contrary to that found on the acid soils of the Teruel coalfield area in central-eastern Spain (Moreno-de las Heras et al. 2008), where pH was higher in the reference community than in the reclaimed area.

Distribution of plant communities along the reclaimed mine slope

The distribution of plant communities along the reclaimed mine slope responded to their position on the slope, categorized here by altitude. The grassland patches occupied the upper parts of the slope and shrubland patches the lower parts, and plant communities with greater species richness in the middle parts. These differences in floristic composition along the reclaimed mine slope might be related to environmental stochasticity (Bradshaw 1983) and soil heterogeneity generated during restoration works (White and Jentsch 2004). Nonetheless, the ecohydrological behaviour of the mine slope may play a critical role in vegetation dynamics, since run-off is expected to be higher in the upslope areas (Moreno-de las Heras et al. 2008; Merino-Martín et al. 2012; Espigares et al. 2013). Although measuring run-off was not a target of our study, we found a decreasing tendency in the bare soil percentage from the grassland patches compared to shrubland patches that could be explained by a decreasing of rate of run-off in the down-slope direction (sensu Berga 1988), in accordance with the run-off source and sink model proposed by Merino-Martín et al. (2012). Higher rates of run-off are related to lower rates of water infiltration that, in turn, are associated with lower leaching of salts and correspond to higher salinity and thus electrical conductivity in the soil, as we found in the grassland community soil, where bare soil and soil porosity values were higher. Probably, after the first post-restoration rainfall events, there were drags from the upper parts of the mine slope that produced the accumulation of fine material in the lower parts, despite their greater slope, allowing in turn the establishment of the more mature plant communities.

In our study, the water holding capacity was revealed as one of the variables most related to the dynamics of the vegetation towards more mature stages, reaching higher values in the lower parts of the mine slope where, despite their greater steepness, phanerophytes shrub species such as *Cytisus scoparius* and *Genista florida* reached cover close to 100% (Fig. 5). On the other hand, the lower water holding capacity values were found in the upper parts of the slope, where xerophytic grasslands dominated by *Poa bulbosa* and *Vulpia bromoides* (L.) Gray were established. A similar successional gradient in the distribution of plant communities along the mine-slope gradient was previously described for semi-arid Mediterranean conditions (Moreno-de las Heras et al. 2008; Espigares et al. 2013). The lower values of the rate of easily oxidizable carbon to total carbon (OxC/C) found in the soils on the lower parts of the mine slope were also consistent with the greater cover of woody vegetation found there. In particular, lower OxC/C values in the soils under shrubs indicate a higher rate of recalcitrant organic matter (Chabrerie et al. 2003) due to the higher lignin content of woody species, which reduces the decomposition rate of the soil organic matter by microorganisms (Clark and Paul 1970) and the speed of carbon incorporation into the soil (Condron and Newman 1998). As for the available phosphorus (P_{av}), similar values were expected in grassland and shrubland soils, since the restoration of the terrain and subsequent management was the same. However, the lower values of P_{av} in the shrubland soils could be explained by the fact that the P_{av} is closely linked to the dynamics of the soil organic matter (Turrión et al. 2007), as we found in our study (significant positive correlation between P_{av} and all variables related to soil organic matter).

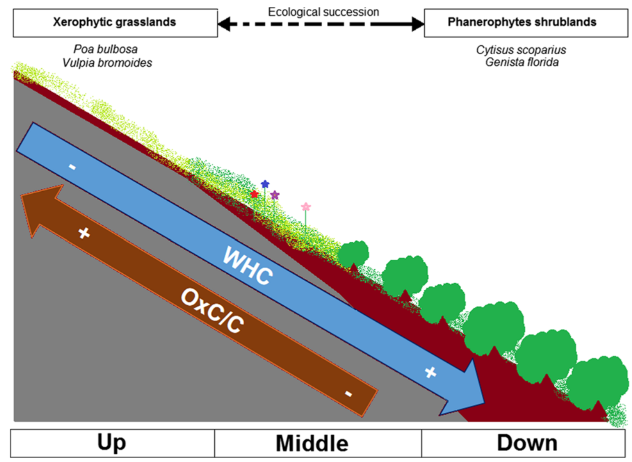

Fig. 5 Graphical abstract of the relationship between soil properties and plant communities distribution along the reclaimed coalmine slope. The increase in water retention capacity (WHC) and the decrease in oxidizable-carbon/total-carbon ratio (OxC/C) from the upper to the lower parts of the slope determine a segregation in the distribution of plant communities from typical of xerophytic grasslands dominated by *Vulpia bromiodes* and *Poa bulbosa* to Phanerophytes shrublands dominated by *Cytisus scoparius* and *Genista florida*

Distribution of plant species along the reclaimed mine slope

According to the changes in soil properties along the mine-slope topographic gradient, segregation in the abundance of individual plant species was observed, which mainly responded to the gradient of water availability and organic matter content in the soils. The species whose cover remained constant along the gradient were mostly annual ruderal herbs, able to grow with modest nutritional requirements. The species whose coverage decreased from the upper parts (grassland) to lower parts (shrubland) of the mine slope, i.e. from high values of the ratio of easily oxidizable carbon to total carbon (OxC/C) and low values of water holding capacity (WHC), were annual and perennial herbs typical of xerophytic grasslands on soils with low soil moisture such as *Poa bulbosa* and *Vulpia bromoides* (García et al. 1991). Species with symmetric unimodal response showed greater cover in the middle part of the topographic gradient, i.e. in the lower parts of the grassland patches and in the upper parts of the shrubland patches, for intermediate values of the ratio of OxC/C and WHC; they were annual and perennial herbs typical of early stages of succession, but on soils with an intermediate soil moisture such as *Plantago lanceolata* L. and *Trifolium striatum* L. (Pastor et al. 1992). Finally, species whose cover increased towards the lower parts of the mine slope, dominated by shrubland, where low values of the ratio of OxC/C and high values of the WHC were found, were mostly perennial herbs and woody species characteristic of the nanophanerophytes shrub community dominated by leguminous shrubs such as *Cytisus scoparius* and *Genista florida* belonging to the association *Cytiso scoparii-Genistetum polygaliphyllae* S. which is one of the early stages of substitution of the climax community in the study area (Navarro-Andrés and Valle-Gutiérrez 1987).

Implications for ecological restoration

The great differences in the floristic composition and soil properties along the restored mine slope, 11 years post-reclamation, appear to be related to the run-off source-sink dynamics in the down-slope direction. Thus, in sites where soil depth to the coal waste was lower, vegetation succession was slower and plant communities remained in a pioneer grassland stage, whereas in sites where soil depth to the coal waste was higher the plant community achieved a more mature stage (shrubland). The water holding capacity was the soil property most strongly related to the vegetation dynamics towards more mature stages. Therefore, the results emphasize the importance of designing efficient restoration plans, whose objective is to achieve long-term self-sustaining ecosystems, with fully functioning soil and vegetation (Alday et al. 2012), through control of the topsoil properties and depth on which the water holding capacity depends. The improvement of the properties (depth, water holding capacity, carbon content…) of the topsoils used for mining restoration contributes to accelerating plant succession, allowing more mature plant communities to settle earlier; if not, grasslands are attained in the study area instead of shrublands.

These findings have important implications for ecological restoration since vegetation plays an important role in the stabilization of degraded systems (Moreno-de las Heras et al. 2008), and the low capacity to store water in mine soils is one of the most limiting factors for plant growth (Barnhisel et al. 1987). It is strongly recommended to consider local topographic conditions when restoring mine slopes. Plant succession advances at different rates on different parts of the slope and, in turn, the plant species compositional change along the mine-slope topographic gradient is related to stages of different maturity of vegetation and soil properties. The improvement of soil properties, such as topsoil depth and soil organic matter, which affect the available soil water storage capacity, could be considered as a restoration strategy to accelerate plant succession and favour the establishment of a more mature plant community on the mine slopes.

CONCLUSIONS

The study showed that the water and organic matter content in the soil revealed the maturity status of reclaimed plant communities along the mine-slope gradient. The most labile carbon forms were related to early successional stages such as pastures, which occupied the upper parts of the restored slope, whereas the higher water holding capacity content was related to late vegetation stages such as shrubland communities, which occupied the lower parts of the restored slope.

Small differences in soil properties are revealed as a constrain of important ecological processes that determine different paths in the dynamics of plant communities and different individual species response patterns. Therefore, this study encourages using topsoils for mining restoration with the best possible properties (depth, water holding capacity, carbon content…). It will compensate (pay off?) by accelerating plant succession. Otherwise, a long-term ruderal grassland would be installed as an almost permanent seral stage, particularly in the upper slope areas.

Given that the Spanish Framework of Action for the coal mining and mining regions in the period 2013–2018 aims to precipitate an orderly closure of non-competitive coal mines, provision has been made for the closure of 10 opencast coal mines in the coming years (IRMC 2013); the research work carried out in these environments can contribute to the success of the restoration plans currently envisaged.

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