

Original article

# Natural revegetation on topsoiled mining-spoils according to the exposure

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## Abstract

Comparative plant successional studies on derelict sites are providing significant insights into vegetation dynamics to ensure the success of future revegetation projects in these areas and, in the short-term, by using a space-for-time substitution. In this paper we describe, in relation to site exposure, vegetation development on waste rock materials covered with biologically active soil media, and compare this development with that from a previous study at the same mine (CW Spain) on non-biologically modified waste rock materials. The succession under study is faster on the North slope, as expected, and does not differ significantly from the general pattern of primary revegetation, although it was characterised by its own sequence of plant species. The topsoiling of waste increases richness and diversity from the first year of revegetation, reduces the time required for recovery of a terminal stage, and highlights the influence of slope orientation on vegetation dynamics. A total of 237 plant taxa were recorded, showing one of four patterns of change: (1) 'pioneer', (2) 'intermediate', (3) 'late coloniser' and (4) 'fluctuating'.

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## 1. Introduction

Restoration projects following mining usually consider vegetative cover as a means of stabilising the substrates. In practice, most efforts are concentrated on the early stages, when rapid establishment of vegetation is required to control erosion, and the long-term development of plant community is often overlooked (Luken, 1990). Nevertheless, to speed succession and the formation of a self-sustaining ecosystem, succession management should operate at all stages of plant community development (Luken, 1990). For this to occur, an understanding of the ecological principles involved is required (Piha et al., 1995).

Investigations into primary and secondary succession on new anthropogenic 'soils' are revealing significant facets of vegetation dynamics over a large range of environmental conditions (e.g. Gibson et al., 1985; Titlyanova and Mironycheva-Tokareva, 1990; Baig, 1992; Rebele, 1992; Marrs and Bradshaw, 1993; Prach and Pyšek, 1994; Hodge and Harmer, 1996;

Ursic et al., 1997; Jochimsen, 2001; Martínez Ruiz et al., 2001; Parrotta and Knowles, 2001). On the relationship between rates of species turnover and site conditions, some authors have referred to the influence of the original parent material (Tilman, 1988; Martínez Ruiz et al., 2001), availability of nutrients (Luken, 1990; Prach et al., 1993; Piha et al., 1995), artificial fertilisation (Luken, 1990; Piha et al., 1995), seed immigration (Parrotta and Knowles, 2001), climate (Major, 1974) or exposure (Martínez Ruiz et al., 2001). In semiarid Mediterranean areas, with low rainfall irregularly distributed throughout time and where water is the most limiting factor for plant growth, the influence of exposure in vegetation dynamic becomes especially relevant (Andrés et al., 1996).

In this paper, two 16-year-old successional series differing in slope orientation (North/South) are surveyed to analyse changes in the floristic composition during natural revegetation on uranium-mining spoils covered with an additional substrate. The discussion centres on the comparison of the pattern and duration of the succession under study with the primary revegetation development previously described at the same mine (Martínez Ruiz et al., 2001).

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## 2. Methods

### 2.1. Site description and sampling

The mine chosen for this study is located in centre-western Spain (40°37'N, 6°38'W). The climate is semiarid Mediterranean with 499 mm of mean annual rainfall and acute summer drought, with only 12% of annual rainfall and high evapo-transpiration from May to September; the mean annual temperature is 12.7 °C (Martínez Ruiz, 2000). The soils are acidic loam (pH 5.5–6.7) on slate bedrock, with the predominance of district cambisols (Dorransoro, 1992). The natural vegetation is a 'Dehesa' formation of open *Quercus ilex* subsp. *ballota* woodland with *Cytisus multiflorus* dominated mat-toral encroaching on the herbaceous layer. The Dehesa is utilised as a pasture for cattle and sheep, with moderate grazing pressure and extensive land use (Martínez Ruiz, 2000).

When opencast mining started in 1974, grazing was stopped within the study area, i.e. the uranium mine (700 ha) and the rest of the pre-existing Dehesa (300 ha). Topsoil covering the uranium bed was removed and stockpiled from 1974 to 1980 creating the so-called 'topsoil heap' (TH). This substrate was not subsequently used and underwent a process of natural revegetation.

Waste from the uranium-mining included 45,000 t of slate bedrock ( $U_3O_8 \leq 0.2\%$ ) that was heaped up into different dumps, with strata of 4–15 m high at an incline angle of 37°. It was not toxic, but low in organic matter (<0.2%) and plant nutrients, and extremely coarse (Martínez Ruiz, 2000). So, with the purpose of favouring vegetation establishment, some areas of the slag heaps (100–200 m<sup>2</sup>) were covered with finer textured sediments, obtained from a nearby arkose pit (depth of extraction from 10 cm to 1.5 m).

The covering substrate, with sandy-loam texture and loose-granular structure, favours soil aeration and prevents compaction. Its chemical properties are similar to the mine waste, except for cation exchange capacity (CEC) and pH, which are higher in the arkosic material and very similar to those of the Dehesa (D) soils (Martínez Ruiz, 2000). Moreover, the new top layer may be enriched with seeds and plant remains

that were previously growing on the material from the arkose pit. Small areas of 'natural' vegetation near the bases of the dumps chosen for study provide sources of propagules.

The mine chosen for study offered an opportunity to analyse, in a relatively small area with the same history and environmental conditions, two 16-year-old successional series derived from a hybrid approach (Martínez Ruiz et al., 2001). Twelve dump slope sites that varied between 0 and 14 years old in 1994, were monitored annually from 1994 to 1996 to provide a 16-year developmental sequence (Table 1). A sampling approach, hybrid between the synchronic and diachronic methods, has been also used in post-fire successional studies to examine vegetation succession using space-for-time substitution. The serial sequence is then obtained by re-sampling in successive years (Tárrega and Luis, 1989; Luis and Tárrega, 1993).

The dump slopes were of similar characteristics, except for exposure which was either north or south facing. For those ages with data from several sites (replicates), mean values and standard errors were calculated. The distance between sites of the same age but opposite exposure exceed 1 km, except for sites 2 and 8, and 5 and 11, which were separated by only 5 m. Vegetation on two slopes (north and south) on both TH and D were also sampled over the 3 sampling years. These were used as reference communities for the floristic composition of the final revegetation stage.

Eight squared areas of 0.25 m<sup>2</sup> were analysed on each site, as in the previous published study at the mine (Martínez Ruiz et al., 2001). These areas were located at random across the whole of each site and marked permanently in the first year. The suitability of this sampling size for all of the sites selected was previously checked by the "pooled quadrat" method of Pielou (1969), and made it possible to encompass 90% of all species from the plant community (Martínez Ruiz, 2000). The cover (%) of all species present in the 368 quadrats sampled was visually estimated in June. Due to overlapping strata, cover values frequently exceeded 100%. At least 237 vascular plant species from 37 families were encountered and identified using the *Flora Iberica* (Castroviejo, 1986–2003) or *Flora Europaea* (Tutin et al., 1964–1980).

Table 1  
Dump slopes sampled to derive the two successional series

		Age (years)															
North	Site 1 <sup>a</sup>	1	2														
	Site 2			3	4	5											
	Site 3						6	7	8								
	Site 4						6	7	8								
	Site 5										12	13	14				
	Site 6												14	15	16		
South	Site 7 <sup>a</sup>	1	2														
	Site 8			3	4	5											
	Site 9						6	7	8								
	Site 10						6	7	8								
	Site 11										12	13	14				
	Site 12												14	15	16		

<sup>a</sup> Sampled for the first time in 1995. The rest from 1994 to 1996.

## 2.2. Data analysis

Diversity ( $H'$ ), using the Shannon index (Shannon and Weaver, 1949) with logs to base 2, and its two components, richness ( $S$ ) and evenness ( $J'$ ) (Pielou, 1969), were calculated.

Changes in species composition were estimated using the qualitative similarity index of Sørensen (1948) and the quantitative similarity index of Motyka et al. (1950). Four forms of comparison were made: (1) cumulative changes in the floristic composition through time were grouped together, using the arithmetic average clustering, or UPGMA method (Sokal and Michener, 1958); only the quantitative similarity patterns are shown here because the qualitative ones were roughly the same but with higher similarity levels (Martínez Ruiz, 2000); (2) between slopes in the different years of revegetation; (3) between the first and the oldest revegetation stages and the reference communities (TH and D); and (4) the rate of succession, understood to be the time required for recovery of a terminal stage (Prach et al., 1993).

A multivariate gradient-analysis technique (DCA) was used to investigate the way and order in which site conditions (age and exposure) contribute to determining changes in the community composition, and to identify the taxa associated with them. The plotting technique employed was an HJ-Biplot, which is a variant of the biplot graphic display proposed by Gabriel (1971). After double-centring the data, samples and species were simultaneously represented as points on a two-dimension scatter diagram (Golub and Reinsch, 1970; Galindo, 1986) for their later interpretation. This ordination method has provided better results than other conventional techniques in several investigations including successional studies (Santos et al., 1991; Rivas et al., 1993; Martínez Ruiz et al., 2001), because the quality of plotting seems to be superior to that achieved by similar techniques (Galindo and Cuadras, 1986; Galindo et al., 1996). The HJ-Biplot was achieved by using the cover values of species present in more than one dump-slope-site with cover of at least 2% (80 species), and once sites were grouped by age to increase the discrimination power of the analysis. In general, data obtained from the same site during the three sampling years were grouped (3–5, 6–8, 12–13 and 15–16 years). The younger sites (1, 2 years) remained isolated because of the high variability between them, and the 14 years site because there were two replicates (Table 1).

## 3. Results

Diversity (Fig. 1) decreased during the first 3 years of revegetation because of the increased species dominance. It then increased to the fourth or seventh year on the north or south slope, respectively, and fluctuated afterwards. At older revegetation stages (14–16 years), diversity decreased again on the north slope but increased on the south slope. Thus, diversity values at older revegetation stages on the northern

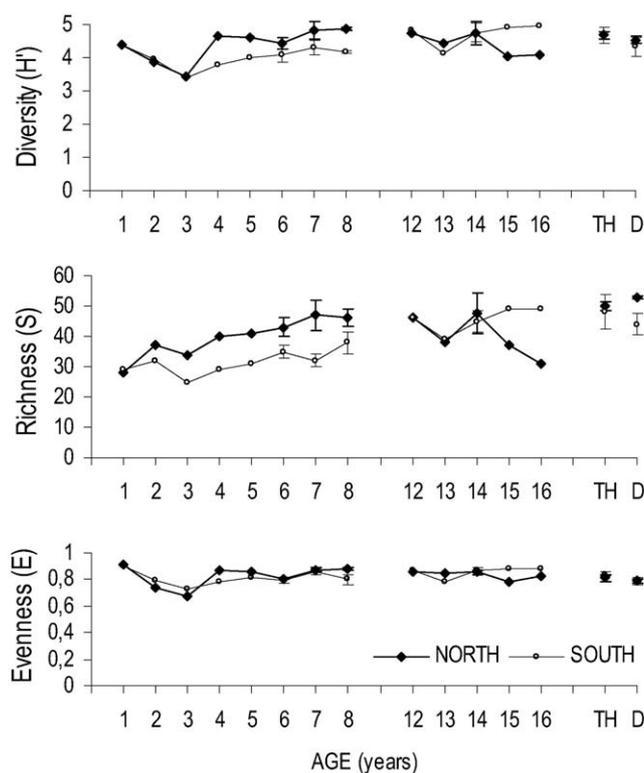


Fig. 1. Changes in the Shannon diversity index ( $H'$ ), plant species richness ( $S$ ) and evenness ( $E$ ) during succession.

slope were slightly lower than those found at TH and D, contrary to what happened on the southern slope. In general, diversity values on both exposures were similar, as in the reference communities, and occasionally higher for some ages on each slope (at 4, 5 or 8 years on the north, and at 15 or 16 years on the south). During the first 8 years of revegetation, fluctuations in diversity are more closely related to fluctuations in the evenness component. Richness increased gradually during the first 8 years, more clearly on the north slope, and ranged from 25 to 49 species per site with a maximum (48–49) at the 7th or 15th year of succession depending on exposure (north or south, respectively).

Total plant cover (Fig. 2) increased during the earlier years of revegetation. At the third year on the south slope or at the fourth year on the north one, cover values were already similar to those on TH or D. Later, fluctuations, particularly marked on the north slope, masked the successional tendency, which can be explained for this exposure by changes in cover of annual species. On the south slope, however, fluctuations in the total plant cover from ages 3–4, 4–5, 5–6, 7–8 and 15–16 years were more related to the changes in cover of perennial species. In any case, annual species were more abundant (both in number and cover) than perennials for every exposure and age, including TH and D (68–76% in number and 51–68% in cover), with no clear trend over time.

In the cluster analysis, samples from different years within the same site were, excepting for the two first years of revegetation on the south slope and 6–8 years on the north slope, more similar to each other than they were to samples from

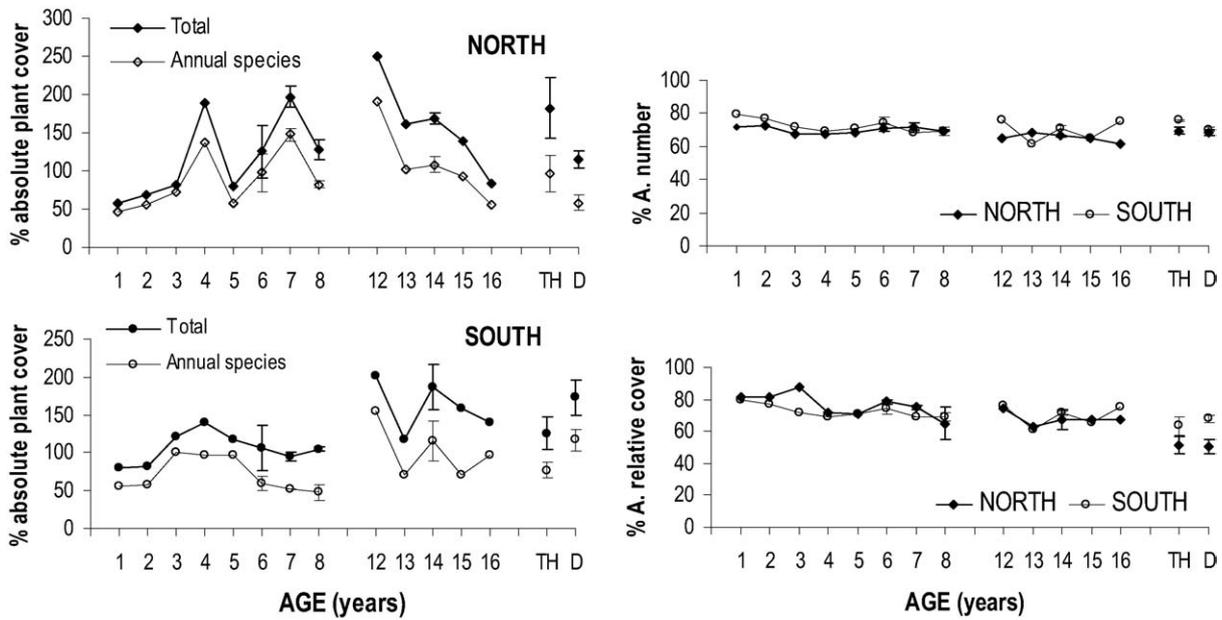


Fig. 2. Changes in total plant cover and relative proportions of annual species (A) (number and cover) over time on north and south slopes.

the same year but different site (Fig. 3a, b). Nevertheless, species similarity between different sites was low and temporal fluctuations in species composition at the one site could be of the order of 50–70%. In general, floristic similarity was slightly higher between years within the oldest sites (14–16 years) than between years within the younger ones (1–5 years).

Qualitative and quantitative similarity patterns were similar for every comparison, although the qualitative levels were always higher (Fig. 3c–e). The similarity between the first (1-year) and last (16-year) revegetation stages and the reference communities (TH, D) increased with succession age on both exposures, though more clearly on the northern one (Fig. 3c, d). Greater similarity between 16 years and TH than

between 16 years and D, suggested that TH was at a younger successional stage than D.

Floristic similarity between slopes increased in time (Fig. 3e), in spite of the fluctuations, and was due not only to the increase in the number but also in the cover values of species in common. However, similarity between slopes after 16 years can still be considered low (56% or 34% with S or M index, respectively). The highest similarities found after 3, 4, 5, 12 or 13 years of revegetation may partly be explained by the shorter physical distance between sites with opposite exposure at these ages.

The multivariate analysis showed (Fig. 4) that exposure was the first factor determining differences in the floristic composition on arkose (18% of variance explained by axis

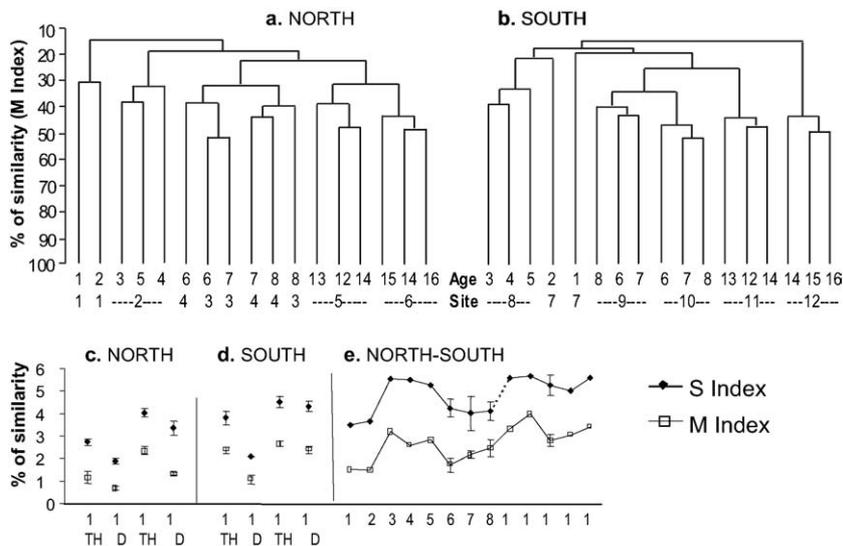


Fig. 3. Qualitative (S index) and/or quantitative (M index) similarity patterns within each successional series (a, b); between the first and the oldest revegetation stages and the reference communities (TH and D), on both exposures (c, d); and between slopes in the different years of revegetation (e).

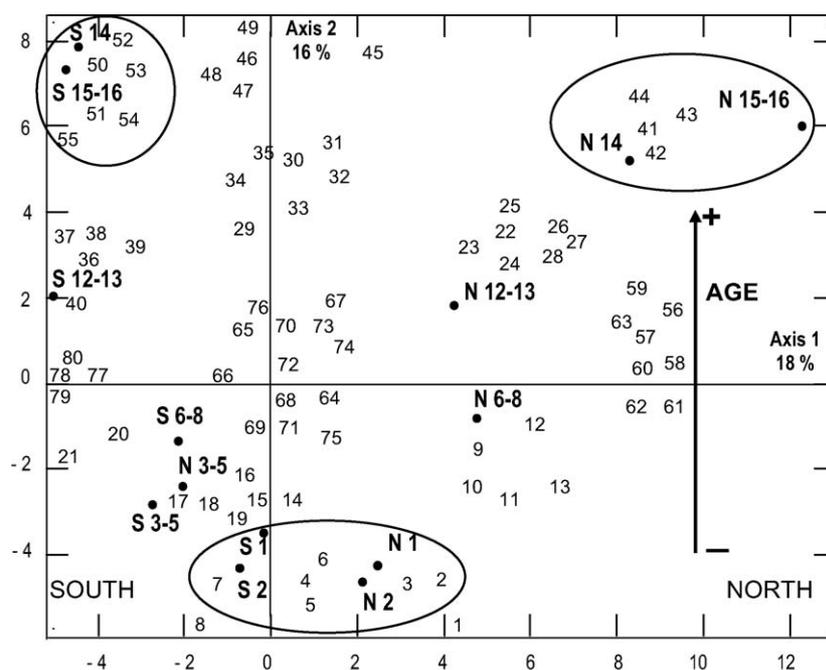


Fig. 4. Biplot of the 14 age groups (seven in each exposure; N = North and S = South) based on cover data for 80 species (see Table 2 for species names).

1), but closely followed by age (16% of variance explained by axis 2). It was also possible to identify the species associated with different combinations of age and exposure (Table 2). The changes in the cover of each species along the series (Fig. 4) allowed identification of four different colonising types (Table 2): (1) Pioneer (1–2 years), (2) Intermediate (3–13 years), (3) Late-colonising ( $\geq 14$  years) and (4) Fluctuating species (without a clear trend). All pioneer species on arkose were still present at intermediate stages and some of them at even later stages (*Herniaria glabra*, *Lactuca* sp.,

*Chamaemelum nobile*, *Conyza* sp.), albeit with lower cover. Intermediate species were mostly present from beginning to end, except *Bromus horceraceus*, *Q. ilex* subsp. *ballota*, *Pulicaria paludosa*, *Eryngium campestre* and *Gaudinia fragilis*, which first appeared at intermediate stages and persisted until the later stages. All the late-colonising species were present at intermediate stages except *Geranium molle* and *Rumex pulcher*, and some even from the beginning, for example, *Jasione montana*, *Agostis castellana*, *Chondrilla juncea* and *Leontodon taraxacoides*.

Table 2

Patterns of change of plant species according to exposure. Numbers in brackets identify species in the Biplot; species names in bold are named according to *Flora Iberica*, the rest according to *Flora Europea*

Pattern of change	Species		
	North	Indifferent of exposure	South
Pioneer (1–2 years)	<i>H. glabra</i> (1), <i>Papaver rhoeas</i> (2), <i>Lactuca</i> sp. (3)	<i>Silene inaperta</i> (4), <i>Conyza</i> sp. (5), <i>Lolium rigidum</i> (6)	<i>C. nobile</i> (7), <i>Polycarpon tetraphyllum</i> (8)
Intermediate (3–8 years)	<i>D. glomerata</i> (9), <i>Campanula lusitanica</i> (10), <i>Fumaria reuteri</i> (11), <i>Q. ilex</i> subsp. <i>ballota</i> (12), <i>T. angustifolium</i> (13)	<i>P. lanceolata</i> (14), <i>Evax carpetana</i> (15), <i>P. bulbosa</i> (16), <i>H. cornicina</i> (17), <i>H. lotoides</i> (18), <i>Spergularia rubra</i> (19)	<i>T. glomeratum</i> (20), <i>L. gallica</i> (21)
(12–13 years)	<i>Bromus horderaceus</i> (22), <i>B. rigidus</i> (23), <i>V. muiyros</i> (24), <i>D. carota</i> (25), <i>P. nanteuilli</i> (26), <i>Holcus setiglumis</i> (27), <i>R. induratus</i> (28)	<i>T. campestre</i> (29), <i>Bromus tectorum</i> (30), <i>Centaurea paniculata</i> (31), <i>Eryngium tenue</i> (32), <i>H. lanatus</i> (33), <i>Avena sterilis</i> (34), <i>A. bellidifolium</i> (35)	<i>B. rubens</i> (36), <i>P. paludosa</i> (37), <i>E. campestre</i> (38), <i>A. integrifolia</i> (39), <i>G. fragilis</i> (40)
Late coloniser ( $\geq 14$ years)	<i>J. montana</i> (41), <i>Briza maxima</i> (42), <i>Cerastium glomeratum</i> (43), <i>Taeniatherum caput-medusae</i> (44)	<i>C. arvensis</i> (45), <i>D. thapsi</i> (46), <i>A. castellana</i> (47), <i>C. juncea</i> (48), <i>S. minor</i> (49)	<i>G. molle</i> (50), <i>L. stoechas</i> (51), <i>C. corymbosa</i> (52), <i>R. pulcher</i> (53), <i>L. taraxacoides</i> (54), <i>S. jacobaea</i> (55)
Fluctuating	<i>Daucus durieua</i> (56), <i>Vicia lutea</i> (57), <i>Mycopirum tenellum</i> (58), <i>Galium aparine</i> (59), <i>Rumex acetosella</i> (60), <i>C. multiflorus</i> (61), <i>Crucianella angustifolia</i> (62), <i>Lathyrus angulatus</i> (63)	<i>Hypochoeris radicata</i> (64), <i>B. madritensis</i> (65), <i>L. perenne</i> (66), <i>Tolpis barbata</i> (67), <i>Linaria spartea</i> (68), <i>Lotus castellanus</i> (69), <i>Bellardia trixago</i> (70), <i>Logfia minima</i> (71), <i>Corrigiola litoralis</i> (72), <i>Vulpia ciliata</i> (73), <i>T. arvense</i> (74), <i>Cynosurus echinatus</i> (75), <i>Cynodon dactylon</i> (76)	<i>Anthemis arvensis</i> (77), <i>Echium plantagineum</i> (78), <i>Verbascum pulverulentum</i> (79), <i>P. coronopus</i> (80)

Overall only eight pioneer species were recorded, two of which were perennial herbs (*H. glabra*, *C. nobile*). The number of intermediate species was considerably higher (32). Among these species, three perennial herbs acquired importance at 3–8 years (*Dactylis glomerata*, *Plantago lanceolata*, *Poa bulbosa*) and another four at 12–13 years (*Holcus lanatus*, *Anarrhinum bellidifolium*, *E. campestre*, *Andryala integrifolia*). The latter remained at later stages, when another nine perennial herbs increased in cover (*Convolvulus arvensis*, *Digitalis thapsi*, *Agrostis castellana*, *C. juncea*, *Sanguisorba minor*, *Carlina corymbosa*, *Rumex pulcher*, *L. taraxacoides*, *Senecio jacobaea*). Thus, a tendency towards a steady increase in perennial herbs was revealed. The presence of woody species did not seem to be related to time, but more to exposure: *Rumex induratus*, *Q. ilex* subsp. *ballota* and *C. multiflorus* preferred the north slope and *Lavandula stoechas* the south one. It is noteworthy that 76% of fluctuating species were annual herbs.

#### 4. Discussion

The succession under study is different from the primary revegetation on uranium-mining spoils (Martínez Ruiz et al., 2001), because it proceeds on a substrate likely to contain plant residues and a seed stock, so that it has in part the character of a secondary succession. Also, the arkosic substrate can be considered as a physical agent, external to the mining waste itself and partly responsible for revegetation; so the successional process could be considered partially allogenic (Martínez Ruiz, 2000). As Rebele (1992) concluded, succession on depositional soils has characteristics of both primary and secondary succession, depending on the fertility of the substrate and the availability of propagules.

In any case, the pattern and duration of succession depends not only on climate, physical and chemical properties of the substrate, plant residues or seed stock, but also on the proximity of plant diaspores (Titlyanova and Mironycheva-Tokareva, 1990; Martínez Ruiz et al., 2001). In the study area the patches of 'natural' vegetation could be an important environmental factor determining, in part, availability of colonising species and the high richness values registered from the beginning (Rebele, 1992; Marrs and Bradshaw, 1993). Also, species with well-established medium to long distance dispersal mechanisms could be favoured (Gibson et al., 1985; Ash et al., 1994).

By comparing this succession with primary revegetation succession on uranium broken waste (Martínez Ruiz et al., 2001), we found that the covering of wastes with arkoses gave higher diversity values in the first year of revegetation. The amelioration of soil conditions, together with the initial space availability and the high spatial heterogeneity present in the dumps (Martínez Ruiz, 2000), made possible the establishment and coexistence of numerous species from covering substrate and/or the surrounds. Nevertheless, the high diversity value in the first year tended to decrease until the third year

because of the increase in dominance (as evenness decreased), and no later trend in the Shannon index with time was observed. Richness continued to increase over the first 8 years of revegetation then decreased markedly on the north slope. Increase in diversity during succession, at least up to advanced age, is generally accepted in undisturbed environments (Margalef, 1968), and it has also been shown in the primary revegetation of broken wastes in the study area (Martínez Ruiz et al., 2001).

In both successions, annual species were more abundant (in number and cover) than perennials for every stage, as well as in the reference communities. The strong influence of weather conditions on annual species (Madon and Médail, 1997) could explain in most cases plant cover fluctuations in time and mask any successional trends. Nevertheless, there are many instances on the south slope where cover fluctuations have arisen from perennial species, probably woody species whose importance seemed not to be related with time but to other site characteristics such as exposure or even other more severe environmental conditions (Martínez Ruiz, 2000). In spite of the higher abundance of annual species, perennial herbs gained importance with time (both in number and cover) as the multivariate analysis showed.

The similarity analysis revealed large differences in the composition of the vegetation between sites regardless age and exposure, as reported in a study of old-fields succession nearby (Puerto et al., 1984), and probably due to the high spatial heterogeneity registered in the dumps (Martínez Ruiz, 2000). However, the slightly higher similarity between years within the oldest sites, in comparison with the younger ones, suggest a tenuous decrease in the rate of species turnover with time, that might become more evident if the temporal series was longer (Puerto et al., 1984; Martínez Ruiz et al., 2001). A decrease in the rate of species turnover during succession is generally accepted (Titlyanova and Mironycheva-Tokareva, 1990; Prach et al., 1993) and, particularly, in the primary revegetation on broken waste in the study area (Martínez Ruiz et al., 2001).

On the other hand, both successions tend towards the floristic composition of the reference communities, albeit with different speed depending on the combined effect of site conditions (e.g. type of substrate, substrate-grain size or exposure). Thus, the multifactorial character of natural revegetation (Gibson et al., 1985; Prach et al., 1993) is revealed. The time required for recovery of a terminal stage seems to be lower on the north slope and lower where waste is covered with arkoses. This is deduced because the floristic similarity between the later revegetation stage and D on arkose is similar to that on broken waste (Martínez Ruiz et al., 2001); being the latest stages 16 or 21 years old, respectively.

However, the influence of slope orientation is not equally evident on both successions. The slow rate of soil formation in the primary succession probably reduces the importance of exposure that may influence floristic composition sooner on a more suitable substrate (arkose). Whereas during primary revegetation quantitative differences in floristic compo-

sition associated with exposure are only apparent after 14 years (late-coloniser stage), on arkose there are qualitative and quantitative differences in floristic composition associated with exposure from the beginning of vegetation re-establishment. This is so even when the physical distance between pairs of sites with opposite exposure is short. Some species are associated with exposure within all stages on arkose, although many species are indifferent to exposure.

The vegetation succession on topsoiled uranium-mining spoils described here has four pronounced successional stages: (1) a pioneer stage lasting only 2 years; (2) an intermediate stage from 2 years; (3) a later stage of more than 14 years; and (4) the disclimax pasture of a typical Dehesa. These successional stages have also been described in primary revegetation on uranium wastes (Martínez Ruiz et al., 2001), although they are now characterised by their own sequence of plant communities.

Nevertheless, as with primary revegetation on uranium-mining spoils, the best-represented species on the northern slopes are *Gramineae*, whereas rosette forming *Compositae* preferentially colonise the southern slopes. Among *Leguminosae*, *Trifolium angustifolium* and *C. multiflorus* are more abundant on the north slope but *T. glomeratum* is more so on the south one.

It is noteworthy that several late-colonising species on broken waste, including some perennial ones (\*), were intermediate (*P. lanceolata\**, *Hymenocarpos cornicina*, *Trifolium glomeratum*, *Logfia gallica*, *Bromus rubens*, *Daucus carota*, *Petrorhagia nanteuilli*, *A. bellidifolium\**, *A. integrifolia*, *Gaudinia fragilis*) or even pioneer species (*H. glabra\**) on arkose, suggesting that the covering of the original parent material accelerates the natural revegetation.

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