



Effects of substrate coarseness and exposure on plant succession in uranium-mining wastes

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Abstract

Species turnover and speed of primary revegetation on uranium-mining spoils are described from the Centre-West part of Spain. Four 21-yr-old successional seres differing in substrate-grain size (broken/unbroken waste) and slope orientation (North/South) are compared. Qualitative and quantitative changes in species composition and the time required for recovery of a terminal stage are analysed, using an undisturbed pasture as reference. Revegetation succession is faster on the broken waste and on the North slope. Moreover, there is a combined effect of both abiotic factors on the pattern and duration of revegetation succession. 195 plant taxa are recorded showing one of four patterns of change: (1) 'pioneer'; (2) 'intermediate'; (3) 'late coloniser'; (4) 'fluctuating'. Multivariate analysis allows us to identify species following each of these patterns on each substrate.

Introduction

Primary succession on new substrates, such as sand dunes, volcanic deposits, and receding glaciers has been a subject of ecological study and debate all along the last century (Olf et al. 1993; Del Moral et al. 1995; Aplet et al. 1998). However, due to man's industrial activity there are also many man-induced primary successions on substrates produced by excavation of sand and gravel, on mine-spoil heaps or on various industrial wastes (Leisman 1957; Down 1975; Anderson 1977; Marrs et al. 1981; Roberts et al. 1981; Johnson et al. 1982; Borgegård 1990; Rebele 1992; Marrs and Bradshaw 1993; Ursic et al. 1997).

One major difficulty with the analysis of primary succession is that this process is slow (Walton 1993; Grishin et al. 1996). In the case of mining spoils, revegetation will occur naturally given time (Bradshaw 1984) but, since mine wastes are invariably poor in plant nutrients, sometimes toxic to plants, and their frequent physical shortcomings hardly suitable for plant growth, natural colonisation can be extremely slow (Ellery and Walker 1986). Studies that

examine primary succession over more than a few years without having permanent plots available must trade space for time. They must piece together a chronosequence by using sites that represent a range of ages following the deposition of new soil (Jenny 1941, 1980), rather than following a single site through time (Pickett 1989). At best, it is impossible to be certain that all of the sites in a chronosequence differ only in age. Often it is clear that other factors besides age contribute to differences among the sites (Drury and Nisbet 1973; Puerto et al. 1984; Grishin et al. 1996; Bakker et al. 1996).

The mine chosen for study offered us an opportunity to analyze, in a small area with the same history and environmental conditions, an unusually straightforward and well-defined set of chronosequences derived from a hybrid approach, where some plots were studied sequentially to fill in gaps. The seres differed systematically and independently in size of the original parent material (waste more or less broken-up) and exposure (North or South), but were very similar in other respects. These circumstances enabled us to evaluate the influence of abiotic factors on the pat-

tern and duration of primary succession on uranium mining spoils.

The aim of the study was to test whether disrupting of the original parent material accelerated natural revegetation, and whether it was affected by slope orientation. We also determined the changes in floristic composition along the seres, i.e. the direction of natural revegetation. Qualitative and quantitative changes in species composition during succession as well as the recovery time were described and compared with an undisturbed pasture (a typical Dehesa) as reference.

Methods

Site description and sampling

The study was carried out at the only Spanish uranium mine presently in operation, situated in the SW of the province of Salamanca (CW Spain) (40° 37' N, 6° 38' W). The climate is semiarid Mediterranean with 499 mm of mean annual rainfall and a pronounced summer drought, with only 12% of annual rainfall and high evapo-transpiration from May to September. The soils are acidic loam, with the predominance of distric cambisols, on slate bedrock (Dorronsoro Fernández 1992). The (natural) vegetation is of "Dehesa" formation, i.e. open *Quercus ilex* subsp. *ballota* woodland with herbaceous layer encroached by matorral dominated by *Cytisus multiflorus*, utilized as a pasture for cattle and sheep, with moderate grazing pressure and extensive land use.

When opencast mining started in 1974, grazing was excluded from the study area. One part of this area formed the uranium mine and the other was still a Dehesa (D) without grazing. The top soil that initially covered 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. Once the top soil was removed, the ore was mined, generating a greater volume of waste material. The bedrock was not used because of its low uranium content (and it), was heaped in to different dumps, with strata of 25 m at an incline of 37°. The waste was extremely coarse, not toxic but low in organic matter. We referred to it as unbroken waste (UBW). However, a little volume of the UBW was broken (BW; particle size <15 mm), through the combined effects of the mining process and machinery

movement, and used as a covering of some parts of the dumps. So we usually found on the same slag heap two well-defined parts, covered or not with BW, that underwent a natural revegetation process. It is quite usual to find small areas of 'natural' vegetation at the bottom of the dumps.

Four 21-yr-old successional seres were derived from a hybrid approach, where 23 plots of similar characteristics, except for the substrate-particle size (BW/UBW) and exposure (North/South), were studied sequentially (from 1994 to 1996) to fill in gaps (Table 1). Thus, for ages with data from several plots, mean value and standard error were calculated. We also sampled two plots (North and South), on both TH and D, in 1996 only, being used as reference types characterised for the floristic composition of the final revegetation stage.

In each plot, eight quadrats of 0.25 m², located at random and marked permanently in the first year, were analysed. The cover of all species present was recorded in June. Previously, suitability of this sampling method for the study area was checked (Martínez Ruiz 2000). The total number of quadrats sampled was about 600. At least 195 vascular plant species of 34 families were encountered and identified using the *Flora Iberica* (Castroviejo et al. 1986–1993) or *Flora Europaea* (Tutin et al. 1964–1980).

Data analysis

The diversity (H'), using the Shannon index (Shannon and Weaver 1949), and its two components, richness (S) and evenness (J') (Pielou 1969), were calculated.

Changes in species composition were estimated using: 1) The qualitative similarity index of Sorensen (1948), $S = 2c/(a + b)$, where a is the number of species in a community A or at time A , b the number of species in a community B or at time B , and c the number of species in common. 2) The quantitative similarity index of Motyka et al. (1950), $M = 2\sum(\min x_i, y_i)/\sum(x_i+y_i)$, where x_i and y_i are the cover values for species i in the communities x_i and y_i , and $\min(x_i, y_i)$ is the lowest cover for each species common to both communities or time points. Three types of comparison were made: 1) between the 1st and subsequent years of revegetation, including TH and D, for each sere; 2) between the oldest revegetation stage of each sere and the reference communities; and 3) between slopes in the different years of revegetation

Table 1. Plots sampled to derive the four successional series.

PLOTS		AGE (years)																					
BW	North	Plot 1 ^a	1	2																			
		Plot 2			3	4	5																
		Plot 3					5	6	7														
		Plot 4						6	7	8													
		Plot 5							7	8	9												
		Plot 6										14	15	16									
		Plot 7																				19	20
	South	Plot 8 ^a	1	2																			
		Plot 9			3	4	5																
		Plot 10				4	5	6															
		Plot 11					5	6	7														
		Plot 12						6	7	8													
		Plot 13									9	10	11										
		Plot 14																				19	20
UBW	North	Plot 15 ^a	1	2																			
		Plot 16			3	4	5																
		Plot 17																					
		Plot 18																					
		Plot 19 ^a	1	2																			
		Plot 20		3	4	5																	
		Plot 21								9	10	11											
	Plot 22																						
	Plot 23													14	15	16					19	20	21

^aSampled for the first time in 1995. The rest from 18194 to 1996.

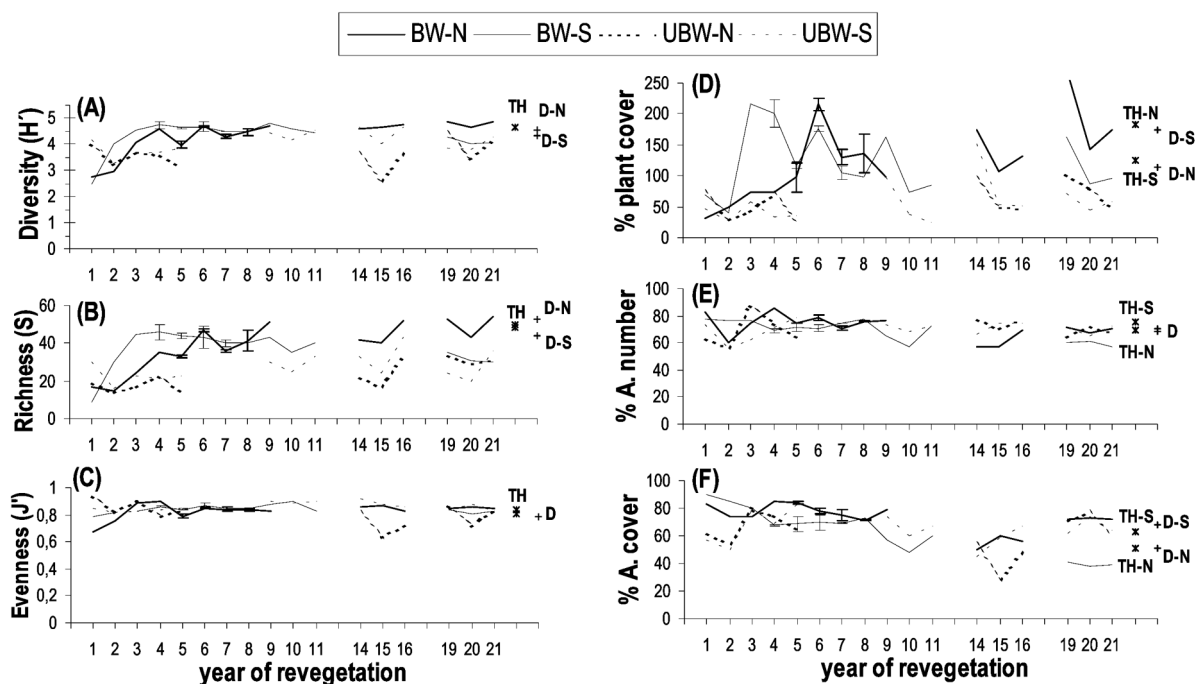


Figure 1. Characteristics of the different stages of revegetation in the four seres (BW = broken waste; UBW = unbroken waste; N = North; S = South) and the later stages of succession (TH = Topsoil Heap and D = Dehesa site); A = annual species.

for each substrate. The second comparison assesses cumulative changes in the floristic composition (S) or cover of all common species (M) with succession age.

In order to gain insight into the direction of change in community composition, a multivariate gradient-analysis technique was applied (Cramer and Hytteborn 1987; Rydin and Borgegård 1988). The plotting technique employed was an HJ-Biplot (Galindo 1985) which is a variant of the biplot graphic display proposed by Gabriel (1971). Samples and species were represented as points on a two dimension scatter diagram (Golub and Reinsch 1970; Galindo 1986) for their later interpretation. It has been shown (Galindo 1985) that the quality of plotting, both for samples and species, is superior to that achieved by similar techniques. To make the equilibrium points of the two clouds (species and samples) coincide, the data were subjected to a double centring. The analysis was conducted in such a way that the discrimination power of the variables would be a function of their relative variability. This ordination method has provided better results than other conventional techniques in several studies (Galindo and Cuadras 1986; Galindo et al. 1996; Pérez-Mellado and Galindo 1986; Rivas-Gonzalo et al. 1993; Santos et al. 1991). One HJ-Biplot refers to the 14 plots on BW (Figure 3A) and the

other to the 9 plots on the UBW (Figure 3B). Before that plots have been grouped according to their age: 1 yr, 2 yr, 3–5 yr, 6–8/9 yr, 9–11 yr, 14–16 yr and 19–21 yr.

Results

Diversity (Figure 1) increased on the BW during the first 4 years of revegetation and stabilised afterwards, albeit with some fluctuation on the North slope. At older revegetation stages (19–21 yr), it decreased but only on the South slope. Diversity values were, in general, higher on the South slope during the first 5 years and on the North one at older revegetation stages. Differences between slopes resulted (primarily) from the richness component (Figure 1). In the case of the UBW, no tendency was observed with age, probably because of the high diversity fluctuations even within a single plot. In general, values were lower than on BW, except for the first year. Diversity values at older revegetation stages on BW-N were similar to those found at TH and D. However, they were lower on the other three seres, particularly on UBW-S. It was mainly due to richness.

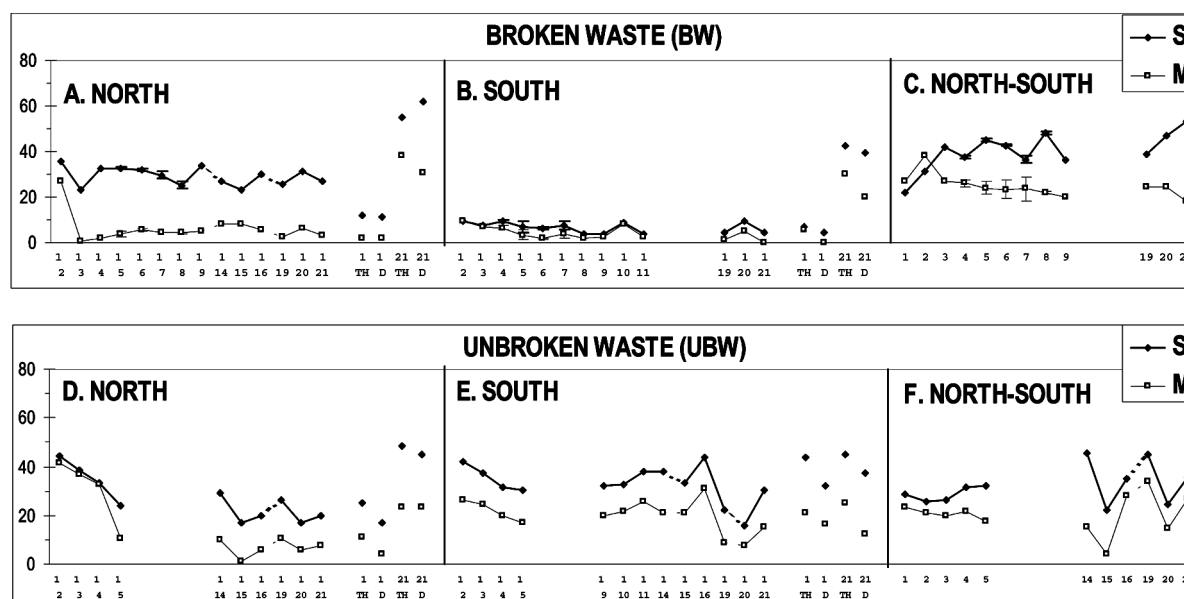


Figure 2. Qualitative (S index) and quantitative (M index) floristic similarity patterns. A: between the 1st and subsequent years, including TH and D, and between year 21 and TH and D, on BW-N; B: As A for the BW-S; C: between slopes in the different years of revegetation on BW; D, E and F: As A, B and C, respectively, for the UBW.

Plant cover (Figure 1) increased on the BW over the earlier years of revegetation. At the 4th yr, cover values were already similar to those on TH or D but, later, fluctuations were very marked. As regards the UBW, no tendency was shown but cover values were, in general, lower than on BW, TH or D. The proportion of annual species (number and cover; Figure 1) was quite high for every age in the four seres. It decreased slowly during succession on BW, but not on the UBW, and tended towards the values of the reference communities.

Floristic similarity between the 1st and subsequent years decreased on BW (Figure 2); the sharpest drop occurred between years 1 and 3 on the North slope, specially with the quantitative index. Qualitative levels were higher on the North slope, where they were also well above quantitative levels. As for the UBW, both similarity patterns were similar for each slope (Figure 2). Floristic similarity decreased during the first 5 years but later no trend was revealed. On both slopes, quantitative levels were equally below the qualitative ones.

The similarity between first and last revegetation stages and the reference communities (TH, D) increased with succession age in the four seres, although more clearly on the BW-N and less so on the UBW-S. On the other hand, the quantitative similarity between the last stage and the reference commu-

nities increased just as much as the qualitative similarity suggesting an absence of dominance in both stages.

Floristic similarity between slopes on BW increased during the first 2 years of revegetation (Figure 2). Afterwards, qualitative similarity increased with succession age, albeit with some fluctuation, whereas quantitatively a gradual decrease occurred. As regards the UBW, both similarity patterns were roughly the same, but no tendency was observed, probably because of the very pronounced fluctuations at older revegetation stages.

The analysis of plots on BW (Figure 3A) opposed on axis 1 the youngest plots (1–2 yr) on the ridge (positive pole) to oldest ones (19–21 yr) (negative pole). The other plots followed a gradient of age along axis 1. Axis 2 clearly opposed North to South plots, but only within the older revegetation stages. In the analysis of plots on the UBW (Figure 3) axis 1 reflected an age gradient and although axis 2 opposed North to South plots, at older revegetation stages, no species could be associated with exposure.

Table 2 showed the most important species associated with different revegetation stages on BW and UBW, respectively. The changes in the cover of each species along the seres allowed us to distinguish four different colonising types: (1) Pioneer (1–2 yr), (2) Intermediate (3–11 yr), (3) Late-colonising (>14 yr)

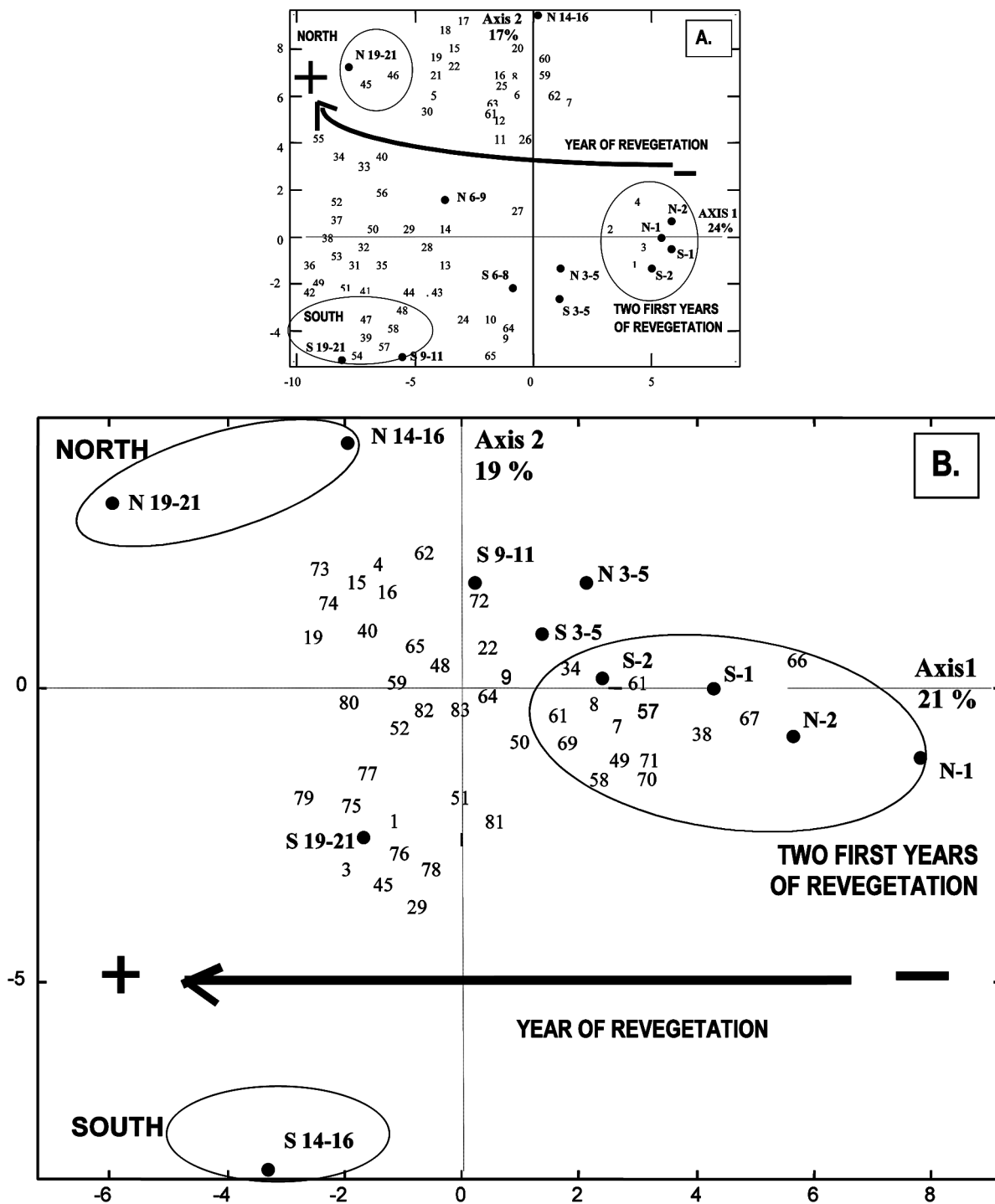


Figure 3. A: Biplot concerning the 12 groups of age established for the BW and the 104 species encountered. B: Biplot concerning the 11 groups of age established for the UBW and the 67 species encountered. Only the more important species have been represented.

and (4) Fluctuating species (without a clear trend along the seres). On BW, only 4 pioneer species, all annuals were recorded. The number of intermediate

species was higher (34), among these, six perennial species acquired importance (*Poa bulbosa*, *Quercus ilex* subsp *ballota*, *Agrostis castellana*, *Rumex indu-*

ratus, *Hypericum perforatum*, *Cytisus multiflorus*). The latter remained at later stages, when other six perennial species increased in cover. Thus, a tendency towards a steady increase in perennial species was revealed. On the UBW, there were a higher number of pioneer species and a lower number of intermediate and late colonising species. No trend was observed in relation to perennial species, and it was impossible to associate species with exposure within the later stages. It was indeed clearly shown that several late-colonising species on UBW were intermediate (*Bromus rigidus*, *B. tectorum*, *Lathyrus angulatus*, *C. multiflorus*) or even pioneer species (*Fumaria reuteri*, *Reseda luteola*, *Senecio lividus*) on BW. All of them were annual except *C. multiflorus* whose presence seemed not to be related with time.

Discussion

Increase in diversity during succession in undisturbed environments, at least up to advanced age, is generally accepted (Monk 1967; Margalef 1968; Odum 1969; Reiners et al. 1970; Puerto et al. 1984). This is confirmed on the BW successional seres. However, the increase is not always gradual as the BW-N suggests. Diversity can temporarily decline, e.g. as a result of changing weather conditions during sampling years. On UBW, the higher diversity fluctuations from year to year may have prevented us from sketching out a trend.

It is noteworthy that such high diversity values are found on both substrates even the first year of revegetation on UBW. In general, it is to be expected that under severe conditions (including new environments) diversity may be low, since only a few species particularly adapted could withstand or thrive above the others (Puerto et al. 1982). Nevertheless, the high diversity values found at the beginning, specially on the UBW, are mainly due to the high evenness component. As they are new environments, there is no space limitation. This fact together with the high spatial heterogeneity registered in the dumps (Martín-Ruiz 2000) make possible the coexistence of species that managed to establish themselves, and provide high diversity values from the beginning. A similar relationship between high heterogeneity and high diversity is also reported by other authors (Grubb 1977; Grime 1985). All species are well represented and therefore there is no dominance effect. The absence of dominance remains at older revegetation

stages, when higher richness values are reached. The highest richness in rather poor areas is related to the lowest relative dominance of competitive species (Grime 1979). Therefore, not only the environmental conditions, but also the main features of the plant species should take into account while interpreting diversity (Whittaker 1965; Puerto et al. 1982). The distance from patches of 'natural' vegetation is an environmental factor in itself determining the colonising species. Among these, annual species are well represented in the study area. It is known their variability in relation to weather conditions (Puerto et al. 1984), what may contribute to diversity and plant cover fluctuations with time and, so, masked their tendencies over succession.

Cumulative changes in floristic similarity with time show a decrease in the speed of species replacement during succession, as it is generally accepted (Whittaker 1975; Grime 1979; Borkman 1981; Burrows 1990; Titlyanova and Nironycheva-Tokareva 1990; Prach et al. 1993). However, the decrease is not the same in the four seres. It depends on site conditions (substrate coarseness and exposure). A sharp decrease in the speed of species turnover between Phase I (1–2 yr) and the rest is revealed on BW-N, and during the first 5 years on the UBW successional seres. So, in these seres, species replacement is very fast at the beginning and slower as succession progresses, just as Puerto et al. (1984) reports in a study of old field successions (nearby). On the BW-S, decrease occurs gradually. There is a lack of data on the relationship between the rate of species turnover and site conditions, and usually only vague statements are presented. Some of them are related to the factors analysed here: original parent material (Tilman 1988) and exposure (Drury and Nisbet 1973). Other factors as availability of nutrients (Drury and Nisbet 1973; Luken 1990; Olson 1958; Piha et al. 1995), climate (Major 1974), artificial fertilisation (Luken 1990; Piha et al. 1995) and seed immigration (Drury and Nisbet 1973) are also reported.

Generally, a slow rate of succession, both in terms of recovery time and species turnover, is typical of extreme habitat conditions, e.g. on dumps from coal mining in Bohemia (Prach et al. 1993). In the Spanish uranium mine the time required for recovery of a terminal stage is even lower than in Siberian coal mines (Titlyanova and Nironycheva-Tokareva 1990). Our results also suggest that there is a combined effect of site conditions (substrate-grain size and exposure) on the speed of revegetation, i.e. the multifac-

Table 2. Patterns of change of plant species according to the substrate-grain size; in brackets: number identifying species in the Biplots and slope preferred (N = North; S = South) if possible.

Pattern of change	Species	
	Broken waste (BW)	Unbroken waste (UBW)
Pioneer (1–2 first years)	<i>Fumaria reuteri</i> (1) <i>Polygonum aviculare</i> (2) <i>Reseda luteola</i> (3) <i>Senecio lividus</i> (4)	Only present at this moment: <i>Linaria saxatile</i> (66), <i>Rumex pulcher</i> (67), <i>T. striatum</i> (38). Also present later: <i>T. arvense</i> (68), <i>Crepis capillaris</i> (8), <i>Chondrila juncea</i> (61), <i>Herniaria glabra</i> (34), <i>Logfia gallica</i> (57), <i>Rapahanus raphanistrum</i> (7), <i>Tolpis barbata</i> (58), <i>Anarrhinum bellidifolium</i> (49), <i>Helichrysum stoechas</i> (69), <i>Lotus subbiflorus</i> (70), <i>Thymus mastichina</i> (71) <i>Holcus setigulumis</i> (72) <i>Hypochoeris radicata</i> (48)
Intermediate (3–11 years)	Only present at this stage: <i>Trifolium campestre</i> (5), <i>Daucus durieua</i> (6), <i>Rapahanus raphanistrum</i> (7), <i>Crepis capillaris</i> (8), <i>Coryza</i> sp. (9), <i>Logfia minima</i> (10), <i>Briza maxima</i> (11), <i>Crucianella angustifolia</i> (12), <i>Bromus horderaceus</i> (13), <i>Vulpia myuros</i> (14) Also present later but with less importance: <i>Bromus rigidus</i> (15), <i>B. tectorum</i> (16), <i>Centranthus calcitrapae</i> (17), <i>Cerastium glomeratum</i> (18), <i>Lathyrus angulatus</i> (19), <i>Poa bulbosa</i> (20), <i>Quercus ilex</i> subsp. <i>ballota</i> (21), <i>Vicia sativa</i> (22), <i>Agrostis castellana</i> (23), <i>Rumex induratus</i> (24), <i>Sherardia arvensis</i> (25), <i>Hypericum perforatum</i> (26), <i>Evax carpetana</i> (27), <i>Coronilla repanda</i> (28), <i>Cytisus multiflorus</i> (29), <i>Trifolium angustifolium</i> (30).	<i>Holcus setigulumis</i> (72) <i>Hypochoeris radicata</i> (48)
Late coloniser (>14 years)	Only present at this stage: <i>Bellardia trixago</i> (31), <i>Centaurea paniculata</i> (32), <i>Daucus carota</i> (33), <i>Herniaria glabra</i> (34), <i>Ornithopus compressus</i> (35), <i>Petrorhagia nanteuilli</i> (36), <i>Plantago lanceolata</i> (37), <i>Trifolium striatum</i> (38), <i>T. cherleri</i> (39S). <i>Bromus rubens</i> (40N), <i>Aegilops triunciales</i> (41), <i>Cynosurus echinatus</i> (42), <i>Lolium rigidum</i> (43), <i>Silene gallica</i> (44), <i>Sanguisorba minor</i> (45N), <i>Taeniatherum caput-medusae</i> (46N), <i>Gaudinia fragilis</i> (47S), <i>Hypochoeris radicata</i> (48S) Present from beginning to end but with the higher cover at the end: <i>Anarrhinum bellidifolium</i> (49), <i>Andryala integrifolia</i> (50), <i>Anthyllis cornicina</i> (51), <i>Leontodon traxacoides</i> (52), <i>Trifolium glomeratum</i> (53), <i>Vulpia bromoides</i> (54S), <i>V. ciliata</i> (55), <i>Ornithopus perpusillis</i> (56), <i>Logfia gallica</i> (57S), <i>Tolpis barbata</i> (58S)	<i>Geranium molle</i> (73), <i>Periballia involucrata</i> (74), <i>Fumaria reuteri</i> (1), <i>Hirschfeldia incana</i> (75), <i>Lavandula stoechas</i> (76), <i>Sanguisorba minor</i> (45), <i>Sonchus oleraceus</i> (77), <i>Teesdalia coronopifolia</i> (78). <i>Bromus rigidus</i> (15), <i>B. rubens</i> (40), <i>Bromus tectorum</i> (16), <i>Holcus lanatus</i> (62), <i>Lathyrus angulatus</i> (19), <i>Cytisus multiflorus</i> (29), <i>Dactylis glomerata</i> (79), <i>Reseda luteola</i> (3), <i>Senecio lividus</i> (4)
Fluctuating	<i>Avena sterilis</i> (59), <i>Campanula lusitanica</i> (60), <i>Chondrila juncea</i> (61), <i>Holcus lanatus</i> (62), <i>Aira caryophyllea</i> (63), <i>Filago pyramidata</i> (64), <i>Spegularia rubra</i> (65).	<i>Andryala integrifolia</i> (50), <i>Avena sterilis</i> (59), <i>Briza maxima</i> (80), <i>Coryza</i> sp. (9), <i>Filago pyramidata</i> (64), <i>Leontodon traxacoides</i> (52), <i>Papaver rhoeas</i> (81), <i>Rumex acetosella</i> (82), <i>Spegularia rubra</i> (65), <i>Vicia sativa</i> (22), <i>Anthemis arvensis</i> (83), <i>Anthyllis cornicina</i> (51).

Species identified according to *Flora Iberica*: 1, 2, 3, 7, 18, 21, 24, 26, 34, 36, 65, 67, 75, 78, 81, 82. The rest according to *Flora Europea*.

torial character of natural revegetation (Glenn-Lewin 1980; Gibson et al. 1985; Dunson and Travis 1991; Prach et al. 1993) is revealed. This may be demonstrated by the equally slow floristic similarity between the 21-yr-old and the reference communities on the BW-S and on the UBW-N seres.

Nevertheless, the influence of slope orientation is not equally evident on both substrates. Since the dynamics of primary succession are strongly influenced by soil dynamics, the slow rate of soil formation probably reduces the importance of a several factors (e.g. exposure) that may influence succession on a more suitable substrate. Hence, the floristic composition hardly differs with exposure during succession on the UBW. So, no species can be assigned to exposure even at later stage (21-yr-old). Conversely, on BW, although the number of species in common to both slopes increases with age, since it may be that there was more time for plant-species establishment (Titlyanova and Nironycheva-Tokareva 1990; Del Moral et al. 1995), their cover values differ more and more, possibly owing to the different competitive capacity of plant species under various conditions (e.g. exposure). This makes possible to associate species with exposure within the later stages on BW, albeit the influence of exposure on the floristic composition is already revealed at intermediate stages (Figures 2 and 3). The best represented species on the North slope are especially *Gramineae*, whereas *Leguminosae* and *Compositae* in rosette preferably colonise the South slope.

The results confirm the influence of abiotic factors on vegetation dynamics. In particular, it is noteworthy that the mere breaking-up of the original parent material accelerates the natural revegetation, strongly on the North slope. This information can be helpful and applied in the management of similar spaces or waste areas.

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