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Community Succession Analysis of Naturally Colonized Plants on Coal Gob Piles in Shanxi Mining Areas, China

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Abstract Data were collected simultaneously at different succession stages using a space-for-time substitution, and were analyzed using the quantitative classification method (Twinspan) and the ordination technique (DCA). The community succession analysis of naturally colonized plants on coal gob piles in Shanxi mining areas was as followings: Assoc. *Setaria viridis* + *Amaranthus retroflexus* → Assoc. *Tribulus terrester* + *Setaria viridis* → Assoc. *Setaria viridis* + *Artemisia annua* → Assoc. *Bothriochloa ischaemum* + *Artemisia capillaries* → Assoc. *Bothriochloa ischaemum* + *Artemisia scoparia* → Assoc. *Periploca sepium* − *Artemisia gmelinii* → Assoc. *Periploca sepium* + *Lespedeza daurica* − *Artemisia gmelinii* → Assoc. *Periploca sepium* + *Vitex negundo* var. *heterophylla* − *Bothriochloa ischaemum* → Assoc. *Ailanthus altissima* − *Lespedeza daurica* − *Artemisia gmelinii* → Assoc. *Robinia pseudoacacia* − *Vitex negundo* var. *heterophylla* − *Bothriochloa ischaemum*. This established a model of the recovery of natural vegetation on coal gob piles in Shanxi mining areas. The structure, composition and life-forms changed significantly during succession. Six indices of species diversity were used to analyze changes in the richness, evenness and heterogeneity of species during the succession process. As the succession progressed, the richness of plant communities increased significantly, the evenness increased slightly and the heterogeneity increased obviously. The plant development could obviously increase the organic content in the surface layer of coal gob piles. Pioneer species of *Setaria viridis, Amaranthus retroflexus*, *Tribulus terreste*, *Artemisia gmelinii*, *Bothriochloa ischaemum, Periploca sepium*, *Lespedeza daurica*, *Vitex negundo* var. *heterophylla*, *Ailanthus altissima* and *Robinia pseudoacacia*, etc. could colonize successfully and play important roles on the vegetation restoration of coal gob piles.

Keywords Coal gob piles · Community succession · Mining areas · Naturally colonized plants · Shanxi

1 Introduction

Plant community succession is one of the most important aspects of vegetation ecology (Leendertse 1997; Luisa et al. 2001; Zhang 2005). Many previous studies on community plant succession have focused on the restoration of forests after felling (Avis 1995; Begon et al. 1990; der Marrel 1996; der Veen and Grootjans 1997; Sarmiento et al. 2003). However,

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relatively few studies have been conducted in the community succession on coal gob piles in mining areas towards forestation (Billings 1938; Grau et al. 2003; Ottoa et al. 2006), and even fewer have been carried out in Shanxi, China. Up to now, natural recovery of vegetation is getting increasing attention in various restoration projects, especially in developed countries such as the USA, UK, The Netherlands, and Germany (Luken 1990; Rebele and Dettmar 1996; Bradshaw 1997; Karel and Petr 2001). This paper is based on field vegetation investigation in Shanxi mining areas where technocratic approaches do not prevail in the restoration of degraded land.

Coal gob, the discarded coal waste and fractured rock, takes the largest proportion of industrial solid wastes in China. Usually, coal gob is dumped in adjacent gullies and gradually accumulates to coal gob piles. Up to now, the total accumulative amount of coal gob is nearly 4 billion tons in China, which occupied 13,340 ha land. There are around one billion tons of coal gob and more than 380 coal gob piles in Shanxi, the largest coal mining industry base in China. Also, the annual production of coal gob in Shanxi is still growing at a speed of 25 million tons (Zhang 2006).

The accumulation of coal gob has not only occupied precious land resources but also caused various environmental problems such as dump failures, gully erosion and underground water deterioration. Meanwhile, unreasonably piled coal gob easily causes spontaneous combustion and releases poisonous and deleterious wastes (Yang et al. 2004). The mineral component of coal gob mostly consists of kaolinite, charcoal, quartz, illite and calcite. Besides carbon, hydrogen and oxygen, its chemical elements are mostly silicon, iron, aluminum and a few other heavy metals that can cause health risks (Cao et al. 2004). In Shanxi, coal gob easily gets weathered and turns into loose porous materials, releases nutrition elements and gradually forms soil structure due to the semi-arid climate. Usually, the weathered crust about 10 cm in thickness on the surface of coal gob piles would form in a few months or several years as soon as the dump ends (Zhao 1993). In the coal industry today, the conventional utilization of coal gob is an issue of low efficiency, like brick production. Filling is very costly and challenging. Therefore, the most effective method to improve the bad ecological condition on coal gob piles in Shanxi mining areas is to recover vegetation (Zhang et al. 2000; Ma 2001) and vegetation technique is strongly proposed for the coal gob disposal. The community succession study is the starting point in developing vegetation restoration and management strategies. This paper aims to clarify the succession processes of naturally colonized plants on coal gob piles in Shanxi mining areas, to establish a pathway model for primary succession and to analyze the changes of ecological relationships and species diversity during succession. The ultimate goal is to select pioneer species for revegetation and to provide scientific suggestions for ecological restoration on coal gob piles in Shanxi mining areas.

2 Study Site

The field study was conducted on coal gob piles in Yangquan mining areas, a very famous old underground coal mine in China, located in the east of Shanxi province (37°05′ N–37°58′ N, 112°49′ E–113° 41′ E; Fig. 1). The region enjoys a typical semi-arid continental monsoon climate with annual mean temperature of 10.9°C and annual mean precipitation about 590 mm; more than 70% of annual precipitation falls from July to September. The frost-free period varies from 114 to 180 days. In addition, its average annual wind speed is 2.3–4.7 ms^{-1} and prevailing wind direction is northwest.

Its dominant landform is loess-covered hills with an average altitude varying from 600 to 1,400 m and most of which are actually over 1,000 m, where

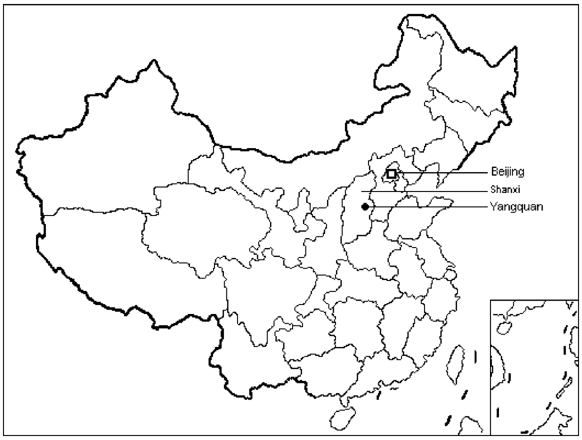


Fig. 1 The geographic location of Yangquan mining areas, Shanxi province, China

severe water and soil erosion would occur easily in case of unreasonable interruption. The major soil types are cinnamon soil, fluvo-aquic soil, skeletal soil and lithosol soil. Based on the system of Chinese national vegetation regionalization, this area is classified in the warm temperate deciduous broad-leaved forest region with the dominant species of *Quercus liaodungensis, Pinus tabulaeformis*, *Vitex negundo* var. *heterophylla, Bothriochloa ischaemum* and *Artemisia gmelinii*, etc. (Wu 1982; Ma 2001; Yan et al. 2002). The original vegetation has been drastically destroyed in the area and surrounding area because of the intensive underground coal mining since 1950 and the long-term extensive land use mainly in planting cereals (in cultivated terraces). Nowadays there are more than 14 coal gob piles with the height from 750 to 900 m in Yangquan (Chaulya et al. 1999), among them, the oldest one has been heaped since 1953, whereas the most recent one has only been heaped since 1993 and continue to pile for 2–3 years. The coal gob piles are surrounded by the coal mines, terraced fields, villages and miners' residence.

3 Methods

3.1 Sampling

In order to study the characteristics of the various plant communities, samples were collected simultaneously at different succession stages using a space-for-time substitution (Carolina and Belén 2005). The vegetation was sampled randomly using quadrate method from the bottom to the top of the coal gob piles, each altitude was then sampled with three quadrats whose location was selected at random and geobotanical data were recorded in each quadrat during 2006. Quadrats of 10×10 m, 5×5 m and 1×1 m were used respectively for woodland, scrubland and grassland communities. The sizes of the quadrats were determined in consideration of the minimum community areas of each vegetation type (Zhang 2005). Based on the species-area curve (Song 2001), the numbers of samples (58, 18 and eight for grassland, scrubland and woodland stages, respectively) at each succession stage were determined according to their areas (approximately 97.14, 8.40 and 3.10 ha for grassland, scrubland and woodland stages, respectively, in the study area).

In each quadrat, the cover percentage of all plant species was estimated, the average height of all plant species and the diameter at breast height (DBH) at 1.3 m height of each arboreal species were respectively measured with a ruler. Then environmental factors of elevation, latitude, longitude, slope and slope direction, etc. were also measured with GARMIN-eTrex handheld GPS and compass. A total of 84 quadrats were examined (Table 1). The ages of coal gob piles were obtained with reference to the coal cutting and gob dumping records of Yangquan Coal Group, through personal interviews with some retired miners and judgment by tree growth rings. Ten living representative trees of *Ailanthus altissima* and *Robinia pseudoacacia* were chosen respectively, each of them was drilled two core samples using tree increment borer and a total of 40 core samples were collected to read their ages (Naurzbaev et al. 2004). Meanwhile, three typical topsoil samples (each approximately 500 g) were collected from each quadrat at 0–10 cm depth using soil drill at each stage of coal gob piles for further analysis. In each quadrat the topsoil was collected from five random points, and mixed into one sample.

3.2 Data Analysis

A total of 71 species were identified in the floristic inventories in 84 quadrats, their species names, arabic numbers and ecological characteristics are also listed in Table 1. The species importance values (*IV*) for each sample were calculated using the following formula:

$$IV_{tree} = (\text{Relative density} + \text{Relative frequency} + \text{Relative dominance})/300,$$
$$IV_{shrub} = (\text{Relative coverage} + \text{Relative height})/200,$$
$$IV_{herb} = (\text{Relative coverage})/200.$$

Table 1 71 species and their ecotypes of vegetation on coal gob piles in Yangquan mining areas, Shanxi

Species number	Species name		Ecotype	Growth-form	Life-form	Found in stage associations
1	*Artemisia gmelinii* Web. ex Stechm.	Gmelin Sagebrush	MX	P	Ch	I, II, III
2	*Cynanchum chinense* R. Br.	China Mosquito trap	X	P	H	I, II, III
3	*Setaria viridis* (Linn.) Beauv.	Green bristlegrass	M	T	T	I, II, III
4	*Digitaria sanguinalis* (Linn.) Scop.	Common Crabgrass	M	T	T	I, II, III
5	*Agrimonia pilosa* Ledeb.	Cocklebur	M	P	H	II
6	*Erodium stephanianum* Willd.	Heronbill	MX	T	T	II
7	*Bothriochloa ischaemum* (Linn.) Keng	Whitesheep grass	MX	P	H	II, III
8	*Bidens parciflora* Willd.	Smallflower Beggarticks	M	T	T	II, III
9	*Artemisia dracunculus Linn.*	Tarragon	MX	P	H	II
10	*Erigeron acer* Linn.	Bitter Fleabane	M	B	Ch	I, II
11	*Salsola collina* Pall.	Common Russianthistle	XM	T	T	I, II
12	*Stipa capillata* Linn.	Needlegrass	X	P	H	II, III
13	*Eleusine indica* (Linn.) Gaertn.	Goosegrass	M	T	T	I, II, III
14	*Heteropappus altaicus* (Willd.) Novopokr.	Altai Puppyflower	X	P	H	I, II
15	*Datura stramonium* Linn.	Jimsonweed	M	T	T	I
16	*Chenopodium glaucum* Linn.	Oakleaf Goosefoot	M	T	T	I
17	*Amaranthus retroflexus* Linn.	Redroot Amaranth	M	T	T	I
18	*Cynodon dactylon* (Linn.) Pars.	Dogtoothgrass	M	P	H	I, II
19	*Agropyron cristatum* (Linn.) Gaertn.	Wheatgrass	X	P	H	III
20	*Artemisia argyi* Lévl. et Vant.	Argy Sagebrush	XM	P	H	II, III
21	*Humulus scandens* (Lour.) Merr.	Japan Hop	M	T	T	I, II
22	*Viola prionantha* Bunge	Serrare Violet	XM	P	H	I, II
23	*Ixeris chinensis* (Thunb.) Nakai	china Ixeris	MX	P	G	I, II
24	*Echinochloa crusgalli* (Linn.) Beauv.	Barnyardgrass	M	T	T	I
25	*Phragmites communis* Trin.	Reed	Hy	P	G	I, II
26	*Poa annua* Linn.	Annual Bluegrass	M	T	T	II
27	*Xanthium sibiricum* Patrin	Siberia Cocklebur	M	T	T	I, II
28	*Hibiscus trionum* Linn.	Flower of an hour	XM	T	T	I
29	*Solanum nigrum* Linn.	Dragon Mallow	M	T	T	I
30	*Cuscuta chinensis* Lam.	China Dodder	A	T	T	I
31	*Dendranthema zawadskii* (Herb.) Tzvel.	Zawadsk Daisy	M	P	H	II
32	*Ixeris sonchifolia* Hance	Sowthistle-laef Ixeris	M	P	H	II, III
33	*Artemisia hedinii* Ostenf.	Hedin Sagebrush	M	T	T	I
34	*Eragrostis pilosa* (Linn.) Beauv.	India Lovegrass	M	T	T	I, II
35	*Portulaca oleracea* Linn.	Purslane	M	T	T	I
36	*Tribulus terrester* Linn.	Caltrop	M	T	T	I, II
37	*Artemisia annua* Linn.	Sweet Sagebrush	XM	T	T	II
38	*Bromus inermis* Leyss.	Awnless Bromegrass	M	P	H	II, III
39	*Festuca ovina* Linn.	Sheep Fescue	MX	P	H	II, III
40	*Artemisia scoparia* Waldst.et Kitag.	Virgate Sagebrush	XM	T	T	I, II
41	*Incarvillea sinensis* Lam.	China Hornsage	M	T	T	I
42	*Bidens bipinnate* Linn.	Beggarticks	M	T	T	I, II
43	*Kochia scoparia* (Linn.) Schrad.	Broomsedge	M	T	T	I
44	*Plantago asiatica* Linn.	Asia Plantain	M	P	H	I
45	*Fagopyrum tataricum* (Linn.) Gaertn.	Bitter Buckwheat	M	T	T	III
46	*Rubia cordifolia* Linn.	India Madder	M	T	T	I
47	*Vicia amoena* Fisch. ex DC.	Wild Vetch	XM	P	H	I
48	*Agriophyllum squarrosum* (Linn.) Moq.	Squarrose Agriophyllum	X	T	T	I, II, III
49	*Saussurea japonica* (Thunb.) DC.	Windhairdaisy	M	B	H	I
50	*Chloris virgata* Swartz	Fingergrass	M	T	T	II
51	*Inula japonica* Thunb.	Inula	M	P	H	II

Table 1 (continued)

Species number	Species name		Ecotype	Growth-form	Life-form	Found in stage associations
52	*Calystegia hederacea* Wall.	Ivy Glorybind	XM	T	T	II
53	*Dendranthema chanetii* (Lévl.) Shih	Chanet Daisy	M	P	H	II
54	*Polygonum aviculare* Linn.	Knotgrass	M	T	T	I
55	*Carex lanceolata* Boott	Lanceolata Sedge	M	P	H	III
56	*Cleistogenes squarrosa* (Trin.) Keng	Scabrous Hideseedgrass	MX	P	H	III
57	*Themeda japonica* (Willd.) Tanaka	Yellowback grass	MX	P	H	I, II
58	*Pharbitis nil* (Linn.) Choisy	Morning glory	M	T	T	I, II
59	*Artemisia capillaris* Thunb.	Capillary Sagebrush	MX	P	H	I
60	*Patrinia heterophylla* Bunge	Diversifolious Patrinia	MX	P	H	III
61	*Cephalanoplos segetum* (Bunge) Kitam.	Common Cephalanoplos	XM	P	H	I
62	*Periploca sepium* Bunge	China Silkvine	XM	S	Ph	II, III
63	*Lespedeza daurica* (Laxm.) Schindl.	Xing'an Bushclover	XM	S	Ph	II, III
64	*Ziziphus jujuba var.spinosa* (Bunge) Hu	Sour Jujube	XM	S	Ph	II, III
65	*Vitex negundo* var. *heterophylla* (Franch.) Rehd.	Heterophyllous Chastetree	M	S	Ph	II, III
66	*Amygdalus persica* Linn.	Peach	M	Tr	Ph	III
67	*Ailanthus altissima* (Mill.) Swingle	Ailanthus	M	Tr	Ph	III
68	*Ulmus pumila* Linn.	Elm, Sibiria Elm	M	Tr	Ph	III
69	*Salix babylonica* Linn.	Babylon Weeping Willow	M	Tr	Ph	III
70	*Robinia pseudoacacia* Linn.	Black Locust	M	Tr	Ph	III
71	*Populus simonii* Carr.	Simon Poplar	M	Tr	Ph	III

M mesophyte, *XM* xero-mesophyte, *MX* meso-xerophyte, *X* xerophyte, *Hy* Hygrophyte, *A* autoeciousness, *T* therophytes, *B* biennial, *H* hemicryptophytes, *Ch* chamaephytes, *Ph* phanerophytes, *G* geophytes, *P* perennial herbs, *S* scrubs, *Tr* trees

Frequency refers to the percentage of the quadrat number containing a tree species over the total quadrat number at the woodland stage, and dominance refers to the sum of the basal areas for a tree species within a quadrat. Matrix of IVs of 71×84 (species × quadrats) was developed as the basis of the succession analysis. Firstly, two-way indicator-species analysis (Twinspan) was used to classify the succession stages of the communities. Secondly, the relationships between the succession stages were analyzed using de-trended correspondence analysis (DCA). By way of a DCA, a graphic ordination of the plots was obtained on the basis of its floristic composition, allowing the relationship between the vegetation and soil types to be studied as well as the relationship among plot groups defined by Twinspan. These calculations were carried out by the CANOCO (Ter Braak 1991) and Twinspan (Hill 1979) computer programs. Thirdly, the heterogeneity, richness and evenness of the species in each quadrant were measured to reveal their variation along the succession gradient. The following six diversity indices (including two heterogeneity, two richness and two evenness indices) were used:

Shannon–Wiener heterogeneity index (*H*′)

$$H' = -\sum_{i=1}^{s} (P_i 1\mathrm{n} P_i) \tag{1}$$

The Simpson heterogeneity index (*DS*)

$$DS = 1 - \sum (N_i/N)^2 \tag{2}$$

The Pielou evenness index (*JP*)

$$JP = -\sum P_i \ln P_i / \ln S \tag{3}$$

The Alatalo evenness index (*EA*)

$$EA = \left[1 \Big/ (P_i)^2 - 1\right] \Big/ \left[\exp^{\left(-\sum P_i \ln P_i\right)} - 1\right] \tag{4}$$

The Margalef richness index (*Ma*)

$$Ma = (S-1)/\ln N \tag{5}$$

The Patrick richness index (*Pa*)

$$Pa = S \qquad (6)$$

Here, N_i is the *IV* of the *i*th species in a quadrat, N is the sum of *IVs* of all species in the same quadrat, P_i is the proportional *IV* in a quadrat ($P_i = N_i/N$) and S is the species number in a quadrat (Greig-Smith 1983).

3.3 Chemical Analysis

The chemical analysis of three typical topsoil samples were conducted according to the procedures Allen et al. (1974) and Sparks (1996) in order to study whether the nutrient has been accumulated or the content of trace elements have been changed in the topsoil (0–10 cm) of coal gob piles. Samples of topsoil were analyzed after they had been ground in a stainless steel mill to pass through a 20-mesh (0.84 mm) sieve. Concentrations of heavy metals and trace elements were determined by an atomic absorption spectroscopy (AAS); the Hg was determined by cold vapor atomic absorption spectroscopy (CVAAS). Total organic carbon, organic nitrogen and saline salinity were measured by routine method. Chemical properties of un-spontaneous combustion weathered particles were listed in Table 2, which shows that the content of heavy metals (Pb, Cr, Cd, Ni and Hg) of un-spontaneous combustion weathered particles in the uncovered surface layer (0–10 cm) of

Table 2 Chemical properties of un-spontaneous combustion weathered particles in the uncovered surface layer (0–10 cm) of coal gob piles in Yangquan mining areas and the background value of element in soil, Shanxi

Properties	Un-spontaneous combustion weathered particles	The background value of element in soil in Shanxi
pH[a]	7.3	6.3–9.0
Total organic mater (‰)[b]	81.687	2.3–100.21
Total organic nitrogen (‰)[c]	3.15	–
Carbon: nitrogen ratio	15.2	–
Total saline salinity (%)[d]	0.0773	–
Extractable analysis (mg/kg)		–
Available nitrogen[e]	40.19	
Available phosphorus[f]	1.60	–
Available potassium[g]	81.0	–
Available copper[h]	0.58	–
Available manganese[h]	10.79	–
Available iron[h]	29.1	–
Available zinc[h]	6.16	–
Lead[i]	17.51	4.3–29.0
Chromium[i]	15.90	30.2–455.9
Cadmium[i]	0.23	0.031–0.358
Nickel[i]	10.7	8.4–55.6
Hydrargyrum[i]	0.209	0.03–0.261

Source: State Bureau of Environment Protection. (1990). The background value of element in soil in China (pp. 259–486). Beijing: China Environmental Science Press.

[a] Soil/water ratio 1:1

[b] $K_2Cr_2O_7$–H_2SO_4 method

[c] Semimicro Kjeldahl method

[d] Hydrometer method

[e] 1M NaOH–H_3BO_3 method

[f] Olsen (0.5 M $NaHCO_3$) extracts, analyzed colorimetrically

[g] 1 M NH_4OAc (pH 7) extracts, analyzed AAS

[h] DTPA extracts, analyzed AAS

[i] 1M HNO_3 extracts, analyzed AAS

coal gob piles in Yangquan mining areas was lower than that of local cropland.

4 Results

4.1 Vegetation Composition and Structure Characteristics

Vascular plant classification and nomenclature respectively follows the Engler classification system and the Linnaean binomial system of nomenclature (Liu 1992–2004). There were 71 species of naturally colonized plants belonging to 26 families and 62 genera on coal gob piles (Table 1). The main families were Compositae (19 species), Gramineae (16 species), Chenopodiaceae (six species) and Leguminosae (three species), which accounted for 61.97% of total species. It indicates that these four families occupy important position in flora and play an important role in natural vegetation recovery on coal gob piles in Shanxi mining areas. In addition, there were Convollvula (three species), Solanaceae (two species), Rosaceae (two species), Salicaceae (two species), Asclepiadaceae (two species), Valerianaceae (one species), Plantaginaceae (one species), Zygophyllaceae (one species), Violaceae (one species), Malvaceae (one species), Simarubaceae (one species), Verbenaceae (one species), Portulacaceae (one species), Geraniaceae (one species), Rubiaceae (one species), Moraceae (one species), Cypeaceae (one species), Rhamnaceae (one species), Amaranthaceae (one species), Ulmaceae (one species), Bignoniaceae (one species). From the life-form (Raunkiaer 1934), the main vegetation composition was the herbaceous species which took 61 species and 85.92% in total. Among all plant species, annual and biennial accounted for 33 species; perennial plants accounted for 38 species including 10 woody plants, and they accounted for 46.48% and 53.52% of the total, respectively. The statistics showed that the vegetation types of the coal gob piles were composed of herbaceous, shrubby and arboreal communities. Herbaceous communities took the dominant status, which had the obvious tendency to succession toward the shrubby and arboreal communities.

Plant species and their coverage increased obviously along with coal gob dump age, which showed that the physical and chemical structure of coal gob piles were improved with gob dump age, and its habitat became gradually steady, which allowed plants to grow flourishing on it and the community structure became more complicated. But the new coal gob piles were unstable, extremely arid and with high temperature, which left few plants to grow on it. The associations of *Setaria viridis* + *Amaranthus retroflexus*, *Tribulus terrester* + *Setaria viridis*, *Setaria viridis* + *Artemisia annua*, *Bothriochloa ischaemum* + *Artemisia capillaries*, *Bothriochloa ischaemum* + *Artemisia scoparia*, *Periploca sepium* − *Artemisia gmelinii* and *Periploca sepium* + *Lespedeza daurica* − *Artemisia gmelinii* had relatively larger distribution areas, but the associations of *Periploca sepium* + *Vitex negundo* var. *heterophylla* − *Bothriochloa ischaemum*, *Ailanthus altissima* − *Lespedeza daurica* − *Artemisia gmelini* and *Robinia pseudoacacia* − *Vitex negundo* var. *heterophylla* − *Bothriochloa ischaemum* scattered on the coal gob piles with species gathering in smaller distribution areas. Compared with the local zonal vegetation of Yangquan city, all the diversity indices of those small communities were low, which reflected that coal gob seriously influenced the vegetation formation and decreased its diversity. *Setaria viridis, Amaranthus retroflexus*, *Tribulus terreste*, *Artemisia gmelinii*, *Bothriochloa ischaemum, Periploca sepium*, *Lespedeza daurica*, *Vitex negundo* var. *heterophylla*, *Ailanthus altissima* and *Robinia pseudoacacia*, etc. could colonize successfully and were dominant species in the vegetation that could be used for vegetation restoration on the coal gob piles.

The field sample investigation showed that the vegetation on the coal gob piles was distributed on patches and scattered with simple structure and low species diversity, but the coverage extended to 80–90% in some plant-gathering places. According to the species composition and their dominance, the vegetation on the coal gob piles could be divided into several relatively steady small communities with subdominant or co-dominant species and patches with mono-dominant species. The main patches of single plant were *Portulaca oleracea* pitch, *Tribulus terrester* pitch and *Bidens bipinnate* pitch, etc. The species numbers of wind-dispersed species increased with the increase of coal gob dump ages. The data of field sample investigation also showed that the dominant species of different coal gob dump age mainly consisted of the wind-dispersed species, which indicated that the pioneer species on coal gob piles were mainly propagated by wind-dispersion (Toshiyuke 1999).

4.2 Classification of Succession Stages

Using Twinspan analysis, 84 samples were classified into 10 groups, representing 10 different types of communities belonging to three vegetation succession stages: grassland, scrubland and woodland (Tables 1 and 3; Fig. 2). Each succession stage could be divided into different community stages. This was related to the age of gob dump and the changes in dominant species. The composition, structural characteristics and the environment of the succession stages are described below.

4.2.1 Grassland Community Stage

This stage started the year following the dump and took 25–30 years to reach the scrubland stage. The communities changed quickly during this stage. Most of the coal gob particles were coarse-grain with low weathered degree and the surface temperature on weathered particles of coal gob was high that the available nutrients in the topsoil were poor (Akers and Muter 1974; Singh et al. 1996; Raman and Madhoolika 2003; Li et al. 2005) with only 47.90‰–124.04‰ organic matter. This stage was the primary period of the restoration progress, so the community turnover was high and community types varied considerably. Based on the community composition and structure, five associations could be identified.

I1 Assoc. *Setaria viridis* + *Amaranthus retroflexus*. This association included sample 6, 14–17, 36, 38, 39, 44, 53, 54, 56 and 75, and appeared on coal gob piles 1–10 years after dump between 790 and 900 m in altitude. The topsoil was coarse-grain weathered particles 10 cm in thickness. The coverage of the community varied from 10% to 40% and in some areas over 60%. There were many species in the community, which mainly comprised annual herbs 68.42%, accounting for the 62.50% of the total. The most common and important species were *Chenopodium glaucum*, *Datura stramonium*, *Xanthium sibiricum*, *Solanum nigrum*, *Hibiscus trionum*, *Salsola collina* and *Incarvillea sinensis*. The composition and structure of this community were highly unstable during the succession process. Specially, the species increased obvious-

Table 3 Characteristics of the 10 associations in this study

Number of association	Latitude/longitude	Elevation (m)	Slope (degree)	Slope direction	Dump age (a)	Thickness of topsoil (cm)	Include number of sample
I1	37°38′ N–37°41′ N; 113°39′ E–113°4′ E	790–900	0–35	SE, S	1–10	10	6, 14–17, 36, 38, 39, 44, 53, 54, 56, 75
I2	37°45′ N–37°58′ N; 113°19′ E–113°3′ E	770–826	10–35	SW, W	10–20	10	10, 45, 59, 60, 65, 77
I3	37°39′ N–37°41′ N; 113°19′ E–113°4′ E	755–840	5–30	SE, S	20–30	10	25, 61, 63, 64, 66–68, 70, 73, 76, 81
I4	37°46′ N–37°58′ N; 113°19′ E–113°3′ E	800–845	0–10	SW	30–40	10	24, 26–29, 31, 33, 37, 40, 41, 43, 47, 48, 55, 58, 62, 69
I5	37°39′ N–37°41′ N; 113°19′ E–113°4′ E	750–850	0–30	SE	30–40	10	19, 21, 42, 46, 78–80, 82, 83, 32, 35
II1	37°38′ N–37°41′ N; 113°39′ E–113°4′ E	850–890	5–30	N	30–40	>10	3, 11, 13, 18
II2	37°38′ N–37°41′ N; 113°19′ E–113°4′ E	800–890	0–30	NE, N	40–45	>10	1, 2, 5, 20, 22, 23, 30, 34, 52, 57, 71
II3	37°45′ N–37°46′ N; 113°39′ E–113°4′ E	750–800	0–30	NE, N	40–50	>10	72, 74, 84
III1	37°39′ N–37°41′ N; 113°19′ E–113°41′ E	870–890	30–35	NE, WN	>50	>10	4, 8, 9, 12
III2	37°46′ N–37°58′ N; 113°19′ E–113°3′ E	760–849	0–30	NE, N	>50	>10	7, 49–51

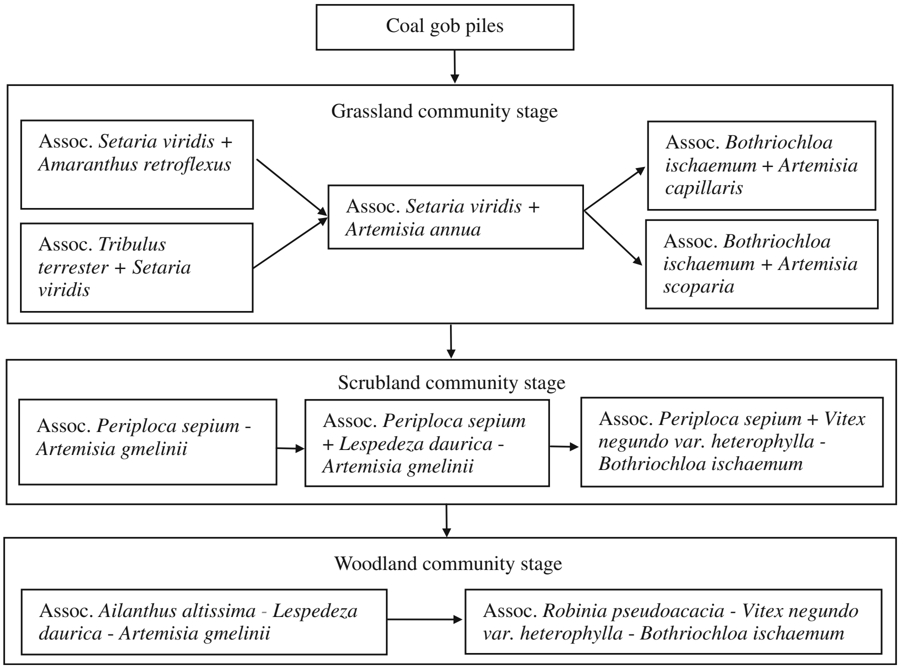


Fig. 2 The recovery model of natural plant community on coal gob piles in Yangquan mining areas, Shanxi

ly in some areas where living rubbish dumped on the coal gob piles.

I2 Assoc. *Tribulus terrester* + *Setaria viridis*. This association included sample 10, 45, 59, 60, 65 and 77, and occupied the coal gob piles between 770 and 826 m in altitude, 10–20 years after dump. The topsoil was coarse-grain and medium-grain weathered particles 10 cm in thickness. The coverage of the community varied from 30% to 50%. The dominant species included *Tribulus terrester* and *Setaria viridis*, whose important value contribution ratio reached 52.05%. The main companion species included *Amaranthus retroflexus*, *Chenopodium glaucum*, *Artemisia gmelinii*, *Artemisia dracunculus*, *Kochia scoparia* and *Plantago asiatica*. There was low species diversity in this community, which mainly comprised annual herbs accounting for the 62.50% of the total. With the increasing of coal gob dump age, the perennial herbage of *Artemisia gmelinii*, *Cephalanoplos segetum*, *Heteropappus altaicus*, *Artemisia dracunculus*, etc. invaded and caused gradually increase in the species diversity of the community.

I3 Assoc. *Setaria viridis* + *Artemisia annua*. This association included sample 25, 61, 63, 64, 66–68, 70, 73, 76 and 81, and occupied the coal gob piles between 755 and 840 m in altitude, 20–30 years after dump. The topsoil was medium-grain and fine-grain weathered particles 10 cm in thickness. The total coverage of the community varied from 40% to 60%. It was rich in composition. The common species included *Bidens bipinnate*, *Artemisia hedinii*, *Tribulus terreste*, *Agriophyllum squarrosum*, *Artemisia scoparia*, *Echinochloa crusgalli*, *Phragmites communis* and *Themeda japonica*.

I4 Assoc. *Bothriochloa ischaemum* + *Artemisia capillaris*. This association included sample 24, 26–29, 31, 33, 37, 40, 41, 43, 47, 48, 55, 58, 62 and 69, and appeared on the coal gob piles between 800 and 845 m in altitude, 30–40 years after dump. The topsoil was medium-grain and fine-grain weathered particles 10 cm in thickness. The total coverage of the community varied from 40% to 70%. There were several dominant species and they were rich in composition. The main species were *Setaria viridis*, *Tribulus terreste*, *Cynanchum chinense*, *Saussurea japonica*, *Bromus inermis*, *Phragmites communis*, *Cynodon dactylon*, *Heteropappus altaicus*, *Eleusine indica* and *Carex lanceolata*. Additionally, there were some scrub species in the community, such as *Lespedeza daurica* and *Periploca sepium*.

I5 Assoc. *Bothriochloa ischaemum* + *Artemisia scoparia*. This association included sample 19, 21, 42, 46, 78–80, 82, 83, 32 and 35, and appeared on the coal gob piles between 750 and 850 m in altitude, 30–40 years after dump. The topsoil was medium-grain and fine-grain weathered particles 10 cm in thickness. The total coverage of the community varied from 45% to 70%. There were also several dominant species and they were rich in composition. The main species were *Bothriochloa ischaemum*, *Artemisia scoparia*, *Setaria viridis*, *Agriophyllum squarrosum*, *Artemisia capillaris*, *Poa annua* and *Cleistogenes squarrosa*. Additionally, there were some scrub species in the community, such as *Lespedeza daurica*, *Periploca sepium* and *Ziziphus jujuba var.spinosa*. This suggested that Assoc. I4 and Assoc. I5 were developing towards scrubland.

4.2.2 Scrubland Community Stage

This stage usually started 30 years after dump. Scrubland formed 30–40 years after dump and stable scrubland formed 40–50 years after dump. Most of the coal gob particles were medium-grain and fine-grain in high weathered degree that its topsoil was more than 10 cm in thickness with relatively richer organic-matter content and better water conditions than the grassland stage due to soil development during the preceding regeneration periods. In the study area, the scrubland area was not particularly large and the community types were simple and dull. Based on the community composition and structure, three associations could be identified.

II1 Assoc. *Periploca sepium* - *Artemisia gmelinii*. This association included sample 3, 11, 13 and 18, and appeared on the coal gob piles between 850 and 890 m in altitude, 30–40 years after dump. The topsoil was medium-grain and fine-grain weathered particles over 10 cm in thickness. The total coverage of the community varied from 50% to 75%. There were two dominant species and their important value contribution ratio was 37.07%. The main companion species were *Artemisia argyi*, *Artemisia scoparia*, *Bothriochloa ischaemum*, *Lespedeza daurica*.

II2 Assoc. *Periploca sepium* + *Lespedeza daurica* - *Artemisia gmelinii*. This association included sample 1, 2, 5, 20, 2, 23, 30, 34, 52, 57 and 71, and appeared on the coal gob piles between 800 and 890 m in altitude, 40–45 years after dump. The topsoil was medium-grain and fine-grain weathered particles over 10 cm in thickness. The total coverage of the community varied from 45% to 75%. There were three dominant species and their important value contribution ratio was 56.73%. The main companion species were *Heteropappus altaicus*, *Cynanchum chinense*, *Bothriochloa ischaemum* and *Ixeris sonchifolia*. With the increase of coal gob dump age, drought tolerance species of shrub and arboreal such as *Ziziphus jujuba* var. *spinosa*, *Vitex negundo* var. *heterophylla*, *Ailanthus altissima*, *Ulmus pumila*, *Salix babylonica* and *Populus simonii* gradually invaded and the invaded species and its quantity increased obviously especially on the sites covered by rubbish.

II3 Assoc. *Periploca sepium* + *Vitex negundo* var. *heterophylla* - *Bothriochloa ischaemum*. This association included sample 72, 74 and 84, and appeared on the coal gob piles between 750 and 800 m in altitude, 40–50 years after dump. The topsoil was medium-grain and fine-grain weathered particles over 10 cm in thickness. The total coverage of the community varied from 45% to 75%. The important value contribution ratio of the three dominant species was 56.73%. The main companion species were *Artemisia gmelinii*, *Phragmites communis*, *Dendranthema chanetii*, *Cynanchum chinense* and *Lespedeza daurica*. With the increase of coal gob dump age, drought-tolerant arboreal species, such as *Ailanthus altissima*, *Ulmus pumila*, *Salix babylonica*, *Populus simonii* and *Robinia pseudoacacia*, invaded gradually. The species diversities of the association were obviously high largely due to the wind blown weed seeds and soil from the surrounding farmland falling down on the surface of coal gob piles.

4.2.3 Woodland Community Stage

The woodland community developed from scrubland in natural conditions on coal gob piles in Shanxi. This stage started more than 40–50 years after dump and formed stable forestland 50–100 years after dump. This period might be shortened through planting trees in scrubland and grassland. However, this hypothesis requires further empirical study (Bradshaw 1989 and 1997).

The forests were local zonal vegetation types in Yangquan city, Shanxi. In natural conditions, the broadleaf such as *Ailanthus altissima*, *Robinia pseudoacacia*, *Ulmus pumila*, *Populus simonii* could grow well and turn into forest in the area, but there were only the drought, barren and salt tolerated species of *Ailanthus altissima* and *Robinia pseudoacacia* could grow and develop into scattered forest because of the bad environment of coal gob piles. There were two main associations of forest communities that developed on coal gob piles in Yangquan mining areas.

III1 Assoc. *Ailanthus altissima* − *Lespedeza daurica* − *Artemisia gmelinii*. This association included sample 4, 8, 9 and 12, and appeared on the coal gob piles between 750 and 800 m in altitude, 40–50 years after dump. The topsoil was medium-grain and fine-grain weathered particles over 10 cm in thickness. The total coverage of the community varied from 45% to 80%. The important value contribution ratio of the three dominant species was 33.26%. *Ailanthus altissima* was absolutely dominant in the tree layer of the community, although *Ulmus pumila*, *Salix babylonica* and others were also present. There was only a kind of bush species of *Lespedeza daurica* under the forest canopy, but herbaceous species were richer than bush species in the association. The main companion species were *Bidens parciflora*, *Bothriochloa ischaemum*, *Cynanchum chinense*, *Fagopyrum tataricum*, *Artemisia argyi*, *Digitaria sanguinalis* and *Phragmites communis*. The species diversities of the association increased slowly because of the spontaneous combustion of coal gob piles in this section.

III2 Assoc. *Robinia pseudoacacia* − *Vitex negundo* var. *heterophylla* − *Bothriochloa ischaemum*. This association included sample 7, 49–51, and appeared on the coal gob piles between 760 and 849 m in altitude, over 50 years after dump. The topsoil was also a mixture of fine-grain and medium-grain weathered particles over 10 cm in thickness. The total coverage of the community varied from 50% to 90%. The important value contribution ratio of the three dominant species was 31.25%. *Robinia pseudoacacia* was absolutely dominant species in the tree layer of the community, although *Ulmus pumila*, *Salix babylonica*, *Populus simonii* and others were also present. A few scrub species, such as *Vitex negundo* var. *heterophylla*, *Lespedeza daurica* and *Periploca sepium*, formed the scrub layer, but herbaceous species were richer than bush species in the association. The main companion species were *Bidens parciflora*, *Bothriochloa ischaemum*, *Cynanchum chinense*, *Fagopyrum tataricum*, *Artemisia argyi*, *Digitaria sanguinalis* and *Phragmites communis*. The coverage of the herbaceous plant layer was less than 40%. The most common herbaceous species included *Bothriochloa ischaemum*, *Artemisia gmelini*, *Cynanchum chinense*, *Fagopyrum tataricum* and *Stipa capillata*. This association was a zonal type of vegetation in Yangquan city of Shanxi, and could persist for long period of time in natural conditions.

4.3 Ordination Analysis of Succession

DCA ordination eigenvalues (λ) were higher for the first axis (λ=0.726) than for the second (λ=0.576) and third axis (λ=0.487). Because eigenvalue of the first axis (AX1) is the largest and the second axis (AX2) is the second, which contain more ecological information, the first and the second DCA axis are used to draw a two-dimensional scatter diagram (Figs. 3 and 4). The results reveal the successional sequence of the plant communities.

Figure 3 shows a DCA ordination diagram of the 84 quadrats, the Arabic numbers represent the quadrats, and I1, I2, I3, …, III2 represent ten associations of vegetation at the three succession stages. The first DCA axis represents a succession gradient of time since dump; that is, the succession periods become longer from right to left along the first axis. Correspondingly, the types of vegetation vary greatly from right to left. This represents the direction of succession and its process. The relationships between plant communities in the succession process are clearly illustrated in Fig. 3. This is consistent with the results of the Twinspan analysis presented above.

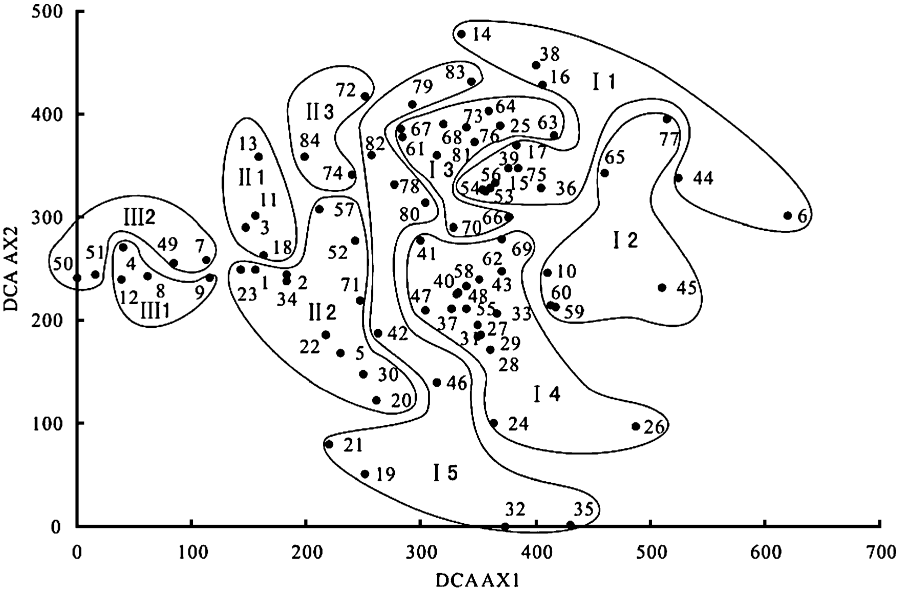


Fig. 3 DCA ordination diagram of 84 quadrats at different succession stages of communities on coal gob piles of Yangquan mining areas, Shanxi. I1, I2, I3, …, III2 represent 10 associations of vegetation at the three succession stages produced by Twinspan

The first DCA axis also represents a gradient of slope orientation; that is, the slope orientation shifts from sunny slope and semi-sunny slope to semi-shadow slope and shadow slope from right to left along the first axis.

The second DCA axis represents a temperature gradient of the weathered surface layer and a gradient of community ecotype; that is, the temperature increases from the bottom up while its water content decreases. The style of community shows a tendency from Assoc. III2 to Assoc. II1 to Assoc.I1 while the ecotype of the community varies from mesophyte forest community to xero-mesophyte scrub community to xerophyte herb community, meanwhile, the species diversities of the community gradually decreases. Assoc. III2 was composed of *Robinia pseudoacacia*, distributing on shadow slope and semi-shadow slope (north slope and northeast slope), over 50 years after dump. Having experienced long-term wind blowing, rain drenching and insolating, the surface layer of coal gob has became 10 cm weathered layer. The weathered particles were fine-grain ones with low temperature and high soil moisture content, thus the invaded wild species were rich, but

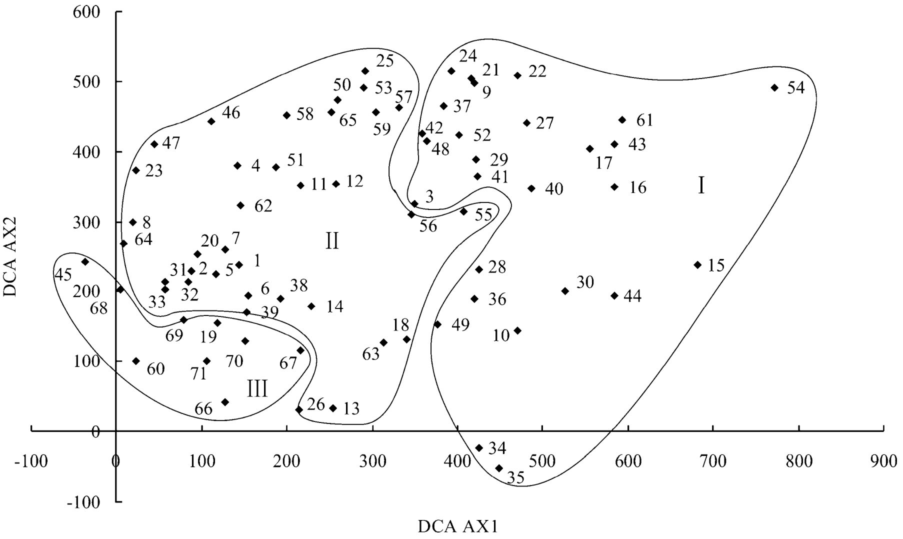


Fig. 4 DCA ordination diagram of 71 species at different succession stages of communities on coal gob piles of Yangquan mining areas, Shanxi. The number refers to species numbers (Table 1)

Assoc. II1 and Assoc. I1 were composed of *Periploca sepium* and *Setaria viridis*, separately, distributing on sunny slope and semi-sunny slope (Southeast Slope, South Slope and East Slope), from 40 to 1 year after dump. The surface layer of coal gob has also formed 10 cm weathered layer while its weathered particles were coarse-grained with high temperature, low soil moisture content and nutrient resulting in poor invading wild species. This shows that slope orientation, high temperature and poor soil nutrient were the major limit factors affecting community succession and vegetation restoration on coal gob piles (Li et al. 2005; Bradshaw 1989 and 1997; Fan et al. 2003).

Figure 4 shows a DCA ordination diagram of the 71 plant species, illustrating the changes in species during the succession of communities. The variation in species along the first DCA axis from right to left represents the species the succession gradient. All 71 species can be clustered into three groups in the ordination space (Table 1; Fig. 4). These groups represent the species appearing at the three succession stages. The environments of the communities show significant changes from one succession stage to the next, therefore, the composition of their species differs. The species in group I on the right are mainly present at the herbaceous community stage, the species in group II in the middle are mainly present at the scrub community stage, and the species in group III on the left are mainly present at the forest community stage. Some species (including *Artemisia gmelinii*, *Setaria viridis*, *Digitaria sanguinalis*, *Cynanchum chinense* and *Bothriochloa ischaemum*) are found at all three stages (Table 1). The distribution of species in different communities is also influenced by soil nutrient (the first DCA axis) and slope direction (the second DCA axis).

The number of species increases and the structure of life-forms becomes more complex as succession progresses (Table 4). One exception is the association of *Ailanthus altissima*, *Lespedeza daurica* and *Artemisia gmelinii*. The topsoil has poor nutrient due to the spontaneous combustion of coal gob piles in the section, which leads to decrease in the numbers of scrubs and herbs. The therophytes gradually decrease, while the perennial plants and woody species gradually increase as the succession progresses. This is in accordance with the general succession rules of plant communities (Zhang et al. 2006).

Based on Figs. 3 and 4 and Tables 1, 2, 3 and 4, it is obvious that the succession of plant community on coal gob piles in Yangquan mining areas is evidently restricted by the environmental factors such as slope direction, temperature and soil nutrient, which shows that the results of DCA ordination successfully reveal the characteristics of species distribution and the law of community succession on coal gob piles in Yangquan mining areas.

4.4 Changes in Species Diversity

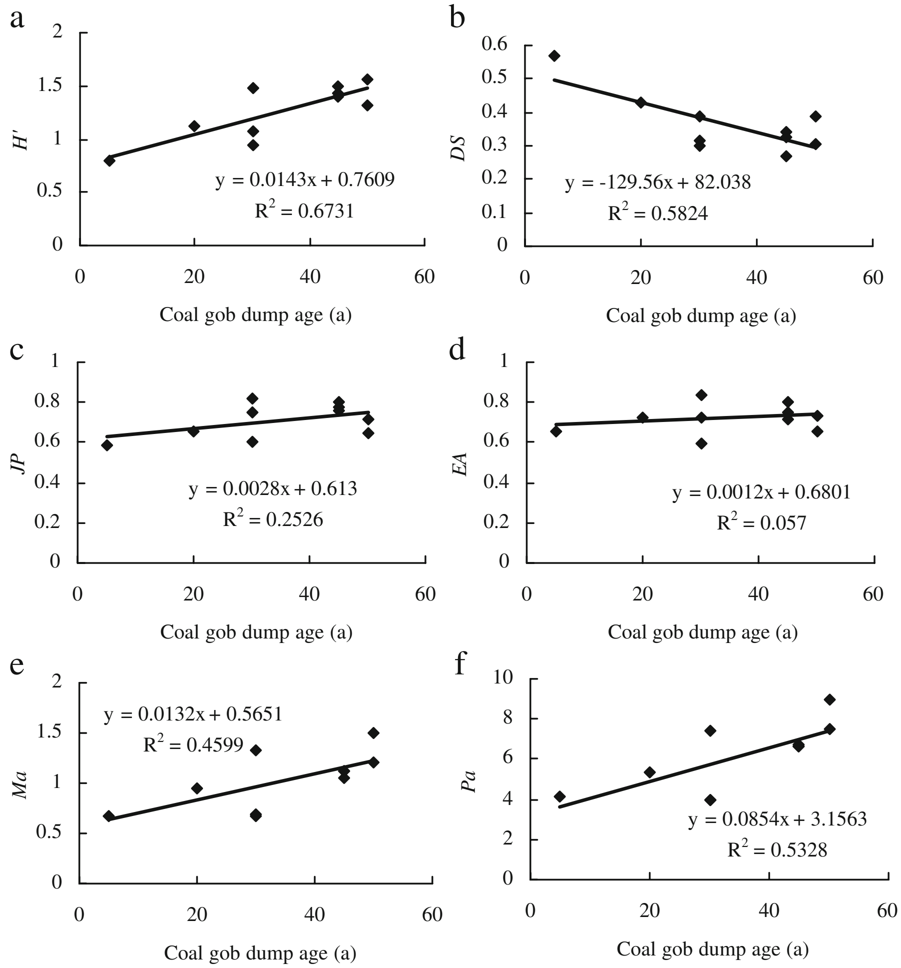
Species heterogeneity, richness and evenness in each quadrat were calculated using the six indices described above. The species diversities of 10 associations were measured by counting the average species diversities of all the corresponding quadrats in each association. The coal gob dump ages were used as horizontal axis to represent the succession gradient. The values of the diversity indices were used as the vertical axis to display the changes in species diversity (Fig. 5a–f).

Figure 5a and b show that the heterogeneity of species clearly increased during the community

Table 4 The changes of species and life-forms during the succession process on coal gob piles of Yangquan mining areas

Species life-from	Species number in different succession stages									
	I1	I2	I3	I4	I5	II1	II2	II3	III1	III2
Total species	19	16	25	19	17	16	28	18	14	27
Therophytes	15	10	15	7	6	6	9	5	5	5
Biennial	0	0	0	1	1	0	0	0	0	0
Perennial herbs	4	6	8	9	8	6	14	8	5	14
Scrubs	0	0	2	2	2	3	3	2	2	4
Trees	0	0	0	0	0	0	2	3	2	4

Fig. 5 The correlation analysis between species diversity of 10 associates and the coal gob dump time on coal gob piles in Yangquan mining areas, Shanxi. **a** Shannon–Wiener heterogeneity index (*H′*), **b** Simpson heterogeneity index (*DS*), **c** Pielou evenness index (*JP*), **d** Alatalo evenness index (*EA*), **e** Margalef richness index (*Ma*), **f** Patrick richness index (*Pa*)



succession process; both the *H′* and the *DS* produced similar results. That is, the longer the time since dump, the greater the species heterogeneity. This was mainly due to the increasing number of species and the changes of life-forms (Zhang et al. 2000).

Figure 5c and d show that species evenness presented a similar pattern of change compared to species heterogeneity, and appeared to increase slowly with succession development, because the vegetation on coal gob piles was at the primary stages of natural succession, the effects of its dominant species gradually increased (Zhang 2005; Xu et al. 2005). That is, the longer the time since dump, the higher the evenness. Both the *JP* and the *EA* revealed the same trend. During the succession process, the dominant species increased, their roles became more significant, and the community structure and composition of the life-forms became more complicated with the change of communities from grass stage to wood stage. All these factors contributed to the increase of species evenness along the succession gradient. The environmental changes of the communities also contributed to the increase in species evenness. The *JP* showed an obvious trend compared with the *EA* in this study.

Figure 5e and f show that the changes in species richness were more obvious. The richness increased with succession development, which was significantly correlated with the first (horizontal) axis. The increase in species richness was mainly due to the increase in species numbers during the succession process (Table 4). At the primary stage of succession, only a few herbaceous species were present because of the poor environmental conditions on coal gob piles. Scrub and tree species appeared when the community environment had significantly been improved with the weathering of topsoil on coal gob piles, the community structure had become more complex and the layer system appeared. At this time, many species of different eco-types could coexist in the community, which caused an increase in species richness.

Thus it can be seen that the species diversity of association has close relationship with coal gob dump age, which successfully shows that the species diversity of the community is affected by slope direction, temperature and nutrient content of the topsoil on coal gob piles in Yangquan mining areas.

4.5 Nutrient Accumulation and Content of Trace Elements in the Surface Layer of Coal Gob Piles at Different Succession Stages

Organic mater is an important symbol of soil fertility. The investigation and analysis showed that the plant development could obviously increase the organic content in the surface layer of coal gob piles, but the elevated degree varied along with the plant species and succession time (Table 5). Table 5 shows that the organic contents of Assoc. *Bothriochloa ischaemum* + *Artemisia scoparia*, Assoc. *Periploca sepium* + *Lespedeza daurica* − *Artemisia gmelinii* and Assoc. *Robinia pseudoacacia* − *Vitex negundo* var. *heterophylla* − *Bothriochloa ischaemum* in the surface layer of coal gob piles (0–10 cm) were respectively 1.52, 1.95 and 3.20 times more than that of bare un-spontaneous combustion weathered coal gob surface layer, which indicated that the nutrition of weathered topsoil was enhanced with the time increase of community succession. Besides, the total nitrogen, available phosphorus and available potassium in the topsoil of Assoc. *Robinia pseudoacacia* − *Vitex negundo* var. *heterophylla* were respectively 37.5%, 37.75% and 87.14% more than that of bare coal gob piles, which showed that *Robinia pseudoacacia* could increase the total nitrogen content, and promoted the nutrient availability of nitrogen and phosphorus, but the nutrient content of available phosphorus, available iron, available manganese and available copper decreased due to the imbibing of silver chain growth.

5 Discussion

There are many methods for community succession analysis (Glenn-Lewin et al. 1992; Heshmatti and Squires 1997; Zhang 2005; Du et al. 2007). Here, succession data were collected simultaneously from different succession stages using synchronic methods (space for time substitution) and were analyzed using the quantitative classification method (Twinspan) and the ordination technique (DCA). This approach is known as ‘static succession analysis’, which was presented in this paper and clearly described the development trends, direction and process of vegetation natural recovery on coal gob piles (Figs. 2, 3 and 4). The first DCA axis represented the succession gradient. The results of the Twinspan classification showed a series of vegetation type changes in the succession process, which was similar to the succession gradient of the DCA results. The succession series of plant communities on coal gob piles in Yangquan mining areas was as followings: Assoc.

Table 5 Chemical properties of weathered particles in the surface layer (0–10 cm) of coal gob piles at different succession stages in Yangquan mining areas, Shanxi

Properties	Topsoil of assoc. I5	Topsoil of assoc. II2	Topsoil of assoc. III2
pH	7.66	7.66	7.68
Total organic mater (‰)	124.04	159.32	261.2
Total organic nitrogen (‰)	2.0169	2.7914	3.3
Carbon: nitrogen ratio	35.61	33.05	45.84
Total saline salinity (%)	0.1447	0.0571	0.0419
Extractable analysis (mg/kg)			
Available nitrogen	26.62	44.39	52.95
Available phosphorus	8.3	20.91	2.55
Available potassium	60.8	68.4	90.2
Available copper	1.756	2.488	5.254
Available manganese	4.532	4.3	7.37
Available iron	9.138	22.412	13.456
Available zinc	1.2444	0.6998	1.4034

Setaria viridis + *Amaranthus retroflexus*, Assoc. *Tribulus terrester* + *Setaria viridis*, Assoc. *Setaria viridis* + *Artemisia annua*, Assoc. *Bothriochloa ischaemum* + *Artemisia gmelinii*, Assoc. *Bothriochloa ischaemum* + *Artemisia scoparia*, Assoc. *Periploca sepium-Artemisia gmelinii*, Assoc. *Periploca sepium* + *Lespedeza daurica* − *Artemisia gmelinii*, Assoc. *Periploca sepium* + *Vitex negundo* var. *heterophylla* − *Bothriochloa ischaemum*, Assoc. *Ailanthus altissima* − *Lespedeza daurica* − *Artemisia gmelinii*, Assoc. *Robinia pseudoacacia* − *Vitex negundo* var. *heterophylla* − *Bothriochloa ischaemum*. Based on the results, we can establish a general model of community's natural recovery on coal gob piles in Yuanquan mining areas (Fig. 2).

The vegetation types of the coal gob piles were composed of herbaceous, shrubby and arboreal communities. The development of herbage community on coal gob piles took 25–30 years to reach the scrubland stage, while shrubbery community took 30–40 years to woodland. The development of woodland community on coal gob piles took more than 40–50 years. In Yangquan mining areas, most of the coal gob piles were dumped after 1980s, only a few were dumped in 1950s. Therefore, herbaceous communities take the dominant status, which have the obviously tendency to succession toward the shrubby and arboreal communities on the coal gob piles here. Additionally, the coal gob piles are surrounded by the villages and miners' residence, local people enjoy planting *Ailanthus altissima* and *Robinia pseudoacacia* in their yards, so that the seeds easily invade and form woody communities on the coal gob piles.

According to Bradshaw's study, the environment of coal gob piles was wretched with the extremely high temperature and poor available nutrient, which were the major limiting factors to restrict the formation and the succession of plant community. Many species colonization and development have been affected by such terrible environment that the community stay with simple composition and structure, low resistance capability, and slow speed of natural succession. The forest communities could be the climax according to Clements' definition (Clements 1916), usually it needed more than 50–100 years to develop into a self-maintained arboreal community in the process of natural succession (Bradshaw 1997), but it could be shortened by human interruption (Zhang 2005; Fan et al. 2006).

The composition of communities varied greatly during the succession process. All of the 71 species present could be classified into three groups, corresponding to the three succession stages (Fig. 4; Table 1). The volunteer pioneer species at the first stage were *Amaranthus retroflexus*, *Cynanchum chinense*, *Tribulus terrester*, *Salsola collina*, *Bidens bipinnate*, *Setaria viridis*, *Artemisia annua*, *Artemisia capillaries* and *Agropyron cristatum*. The typical species at the second stage were *Phragmites communis*, *Bothriochloa ischaemum*, *Carex lanceolata*, *Periploca sepium*, *Lespedeza daurica*, *Ziziphus jujuba var.spinosa* and *Vitex negundo* var. *heterophyll*. The most common species at the third stage were *Bothriochloa ischaemum*, *Carex lanceolata*, *Ailanthus altissima*, *Ulmus pumila*, *Salix babylonica*, *Robinia pseudoacacia* and *Populus simonii*. These species have played an important role in natural vegetation recovery on coal gob piles. Thus it is the first choice to plant local grass and bush species, *Setaria viridis*, *Artemisia gmelinii*, *Lespedeza daurica*, *Periploca sepium*, etc., which are able to tolerate drought, infertility and high temperature as the chief species and to match some drought-enduring arboreal species of *Ailanthus altissima, Ulmus pumila*, *Robinia pseudoacacia, Salix babylonica, Populus simonii*, etc. on the vegetation restoration of coal gob piles.

The succession processes of plant communities are mainly influenced with time duration since dump. However, it is also affected by the environmental variables. The first DCA axis also represents a gradient of slope orientation. The second DCA axis represents a temperature gradient of the weathered surface layer and a gradient of community ecotype. This shows that slope orientation, high temperature and poor soil nutrient are the major limit factors affecting community succession and vegetation restoration on coal gob piles (Li et al. 2005; Bradshaw 1989 and 1997; Fan et al. 2003).

The species diversities varied greatly with the development of succession. Species heterogeneities clearly increased as the succession progressed, species evenness also gradually increased along with the succession gradient, and species richness increased significantly with succession development (Zhang 2005; Xu et al. 2005). These results are in agreement with several formal study outcomes (He and Chen 1997). Species heterogeneity is related to species richness and evenness. This shows that the indices of species diversity used in this research are all efficient (Zhang 2005; Forman and Godron 1986). Combining and comparing several indices within one study is a common method in species diversity research (Markus and Franz 2001).

The process of community succession is not only affected by the surrounding environment (Lavoiel et al. 2003; Dave et al. 2007), but it can also change its surrounding environment. This study shows that the plant development could obviously increase the organic content in the surface layer of coal gob piles, but the elevated degree vary with the plant species and succession time (Table 5). Leguminous plant of *Robinia pseudoacacia* could increase the total nitrogen content, and promote the nutrient availability of nitrogen and phosphorus, but the nutrient content of available phosphorus, available iron, available manganese and available copper decreased due to the imbibing of *Robinia pseudoacacia* growth.

6 Conclusion

The study shows that the community succession of naturally colonized plants on coal gob piles could take long periods of time, several decades or hundred years to reach the climax, so it is a significant way to use engineering and biologic techniques to restore artificial vegetation in mining areas. The most important thing is to structure stable and sustainable ecosystem in ecological restoration. A model of the natural recovery vegetation on coal gob piles is established, which is of great benefit for us to select pioneer species for the revegetation and effectively speed up the community succession process in order to develop a self-maintained ecosystem on coal gob piles in Shanxi mining areas. And the proposed pioneer species are *Setaria viridis, Amaranthus retroflexus*, *Tribulus terreste*, *Artemisia gmelinii*, *Bothriochloa ischaemum, Periploca sepium*, *Lespedeza daurica*, *Vitex negundo* var. *heterophylla*, *Ailanthus altissima* and *Robinia pseudoacacia*, etc.

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