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Assessment of Vegetation Establishment on Tailings Dam at an Iron Ore Mining Site of Suburban Beijing, China, 7 Years After Reclamation with Contrasting Site Treatment Methods

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Abstract Strip-mining operations greatly disturb soil, vegetation and landscape elements, causing many ecological and environmental problems. Establishment of vegetation is a critical step in achieving the goal of ecosystem restoration in mining areas. At the Shouyun Iron Ore Mine in suburban Beijing, China, we investigated selective vegetation and soil traits on a tailings dam 7 years after site treatments with three contrasting approaches: (1) soil covering (designated as SC), (2) application of a straw mat, known as "vegetation carpet", which contains prescribed plant seed mix and water retaining agent (designated as VC), on top of sand piles, and (3) combination of soil covering and application of vegetation carpet (designated as SC+VC). We found that after 7 years of reclamation, the SC+VC site had twice the number of plant species and greater biomass than the SC and VC sites, and that the VC site had a comparable plant abundance with the SC+VC site but much less biodiversity and plant coverage. The VC site did not differ with the SC site in the vegetation traits, albeit low soil fertility. It is suggested that application of vegetation carpet can be an alternative to introduction of topsoil for treatment of tailings dam with fine-structured substrate of ore sands. However, combination of topsoil treatment and application of vegetation carpet greatly increases vegetation coverage and plant biodiversity, and is therefore a much better approach for assisting vegetation establishment on the tailings dam of strip-mining operations. While application of vegetation carpet helps to stabilize the loose surface of fine-structured mine wastes and to introduce seed bank, introduction of fertile soil is necessary for supplying nutrients to plant growth in the efforts of ecosystem restoration of mining areas.

Keywords Biodiversity · Iron ore mine · Reclamation · Tailings dam · Vegetation carpet

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Introduction

Ever since the Industrial Revolution beginning in the mid-18th century, the global socio-economic development has depended heavily on mining industry for provision of mineral resources. Mining activities impose various degrees of impacts on ecosystems and landscape connectivity through land clearance and transport, and by generating a vast amount of mine wastes on top of existing vegetation. This is causing a series of environmental and ecological consequences and health problems (Cooke and Johnson 2002; Li 2006). The direct effects of mining activities may include losses of arable lands, forests and pastures, and the overall reduction of land productivity; whereas the indirect effects may include soil erosion, air and water pollution, toxicity, geo-environmental disasters, loss of biodiversity, and ultimately loss of economic wealth (Xia and Cai 2002; Wong 2003).

In China, rapid growth in population and urbanization, coupled with widespread mining activities nationwide, has put a great pressure on lands for agricultural and forestry development. By the end of 2004, only 14 % of land was cultivatable in China, with arable land per capita merely at

0.106 ha, far below the world's average of 0.236 ha; whilst the derelict mining lands have markedly increased from 2 to 3.2 Mha in less than 20 years (Guo and others 1989; Li 2006). Reclamation of derelict mined lands has been estimated at 10–12 % of the disturbed area with that of metal ore mining possibly even lower in China (Lin and Ho 2003). Ecosystem restoration on mining sites is of particular importance for environmental protection and ecological construction. Establishment of vegetation is a cost-effective and environmentally sustainable method of stabilizing and reclaiming derelict land in mining areas (Tordoff and others 2000).

On severely disturbed mining sites, e.g. open-pit, tailings dam or waste rock stockpiles, establishment of vegetation can be extremely difficult and the natural process of vegetation may resemble primary succession due to exposure of base rock or covering of solid wastes. The succession on such derelict land can take decades or centuries to complete by natural processes (Dobson and others 1997; Bradshaw 2000; Foley and others 2005). For example, the study of Kimmerer (1984) demonstrates that on calcareous lead and zinc mines in SW Wisconsin, USA, very little plant colonization occurs during the first 20 years. Difficulty in establishment of plants on derelict lands of metal mines is mainly due to scarce organic matter, heavy metal toxicity, and extreme soil pH, etc. (Shu and others 2001; Roy and others 2002; Pandey and Maiti 2008; Kullu and Behera 2011). Reclamation effort making use of engineering techniques may facilitate the vegetation development on the derelict land (Bradshaw 2000). Stabilization of loss materials on land surface through engineering techniques is especially critical at beginning of site treatment in mining area with potential danger to surrounding residents and environments (Allen and others 1997; Hodačová and Prach 2003). Previous research has established that, with proper engineering and ecological measures, most damaged ecosystem can recover from very major perturbations on timescales of decades to half-centuries (Cullen and others 1998; Jones and Schmitz 2009). In the reclamation process of damaged systems, soil and seed pool are the two major limiting factors (Bakker and Berendse 1999; Burke 2007), with the issues of restoring biodiversity and productivity being the central tasks in restoration ecology (Bradshaw and Huttl 2001; Perrow and Davy 2002; Ruiz-Jaen and Aide 2005).

Over the past two decades, many different approaches have been tested for treating mining areas with different types of substrate (Hobbs and Norton 1996; Tordoff and others 2000; Xia and Cai 2002). The techniques commonly involve substrate amelioration with soil amendment (Xia and Cai 2002; Wong 2003) and selection of plant species (Cullen and others 1998; Miao and Marrs 2000; Tordoff and others 2000; Holmes 2001). However, few studies have investigated the long-term effects of site treatment on plant community development by natural processes in mining areas (Cullen and others 1998; Melanie and others 2006; Alday and others 2011c). Knowledge on natural vegetation dynamics of the restored derelict lands is essential for guiding the conservation efforts in restoring biodiversity and site productivity of mined lands. The concept of adaptive management and the notion that a restored site be regarded as a long-term experiment is a sensible perspective. In practice, however, the lack of post-restoration monitoring and research has meant few opportunities to improve the theory and practice of ecological restoration in mining areas (Cooke and Johnson 2002; Alday and others 2011a).

Three types of derelict lands typically occur in areas of mining operations: exposed base rock stripped off top soils, disposed mine wastes at the tailings dam, and waste rock stockpiles. The exposed base rock and waste rock stockpiles are difficult to rehabilitate without deployment of engineering mechanism, but it is often restricted in size with careful production operations and imposes little immediate environmental problems because of the solid structure. The tailings dam, on other hand, is prone to water and wind erosion because it is made up finely fragmented ore sand with poor structures; the high stockpiles of loose sand are potential sources of pollutants and airborne dusts. Quick establishment of vegetation on tailings dam is therefore necessary for controlling water and wind erosion during and after mining operations. Establishment of self-sustaining plant communities is key to successful reclamation of mined sites.

The commonly applied technique in reclamation of derelict mined lands in China involves reconstruction of topsoil and planting. In many of the mined sites, however, availability of sufficient soil can be a constraint for such operations. Over the past decade, a new technique aiming for fast establishment of vegetation on disturbed sites was developed, i.e. application of a straw mat, known as "vegetation carpet", which contains prescribed plant seed mix and water retaining agent, on surface of the wastelands. The new technique was applied on a trial basis at the Shouyun Iron Ore Mine in suburban Beijing in 2004, along with the conventional site treatment method of topsoil reconstruction (Zhao and others 2009). This provided us with the opportunity to assess and identify practical approaches in restoring soil productivity and plant community on derelict mined lands, specifically the tailings dam, by studying selective vegetation and soil traits after 7 years of reclamation. In this study, we measured plant species composition and biomass, and soil physicochemical properties on sites of three contrasting site treatment approaches: (1) soil covering (SC), i.e., topsoil application, (2) application of vegetation carpet (VC), and (3) combination of soil covering and application of vegetation carpet (SC+VC), at the Shouyun Iron Ore Mine. We anticipated greatly improved vegetation establishment and facilitation of plant community development by using the vegetation carpet as a mechanism of introducing plant seed source and stabilizing the loose materials on the slope of tailings dam.

Methods

Study Area

The study was conducted in the Shouyun Iron Ore Mine, located in Miyun county of Beijing (40°19′–40°27′N, 116°52′–117°04′E, elevation 126–330 m). It is a medium-sized strip-mining operation venture founded in 1969 for iron ore production. Since 2006, opencast and underground mining have been carried out simultaneously. The climate of the study area is semi-humid and continental, with cold dry winters and hot summers. The long-term mean annual, minimum and maximum air temperatures for this area are 9.6, −6.5, and 25.7 °C, respectively. Mean annual precipitation is 760 mm, of which nearly 75 % occur during the growing season (July–September). The soil type is a brown earth (calcaric cambisols) typical in the hilly lands of the region (FAO-UNESCO 1988). Vegetation in this region is made up predominantly herbs and shrubs, with plant coverage at about 47 %. The major herbaceous plants include *Kalimeris indica* (L.) Sch-Bip, *Themeda japonica* (Willd) Tanaka, *Arthraxon hispidus* Thunb, *Artemisia scoparia* Waldst, and the dominant woody species consists of *Vitex negundo* L. var., *Ziziphus jujuba* var. *spinosa*, *Lespedeza bicolor* Turcz, *Periploca sepium* Bunge, *Ulmus pumila* L.

Site Treatment and Monitoring

The mining area consists of a mining open pit, spoil heaps, a tailings dam, and ore production site. The tailings dam, which was initiated in 1985 and completed in 2004, consists of three levels of terraced ore sand piles. Each sand pile has a slope surface of 20 ∼ 30 m in width (up and down) with an average slope of 20 % facing the south. The adjacent sand piles were separated by a 5 m flat buffer strip with a ditch constructed of bricks and cements for draining storm-water along the contour line. The entire tailings dam measured 2.4 km in length along an East–West orientation. The sand piles were compacted with soil compacting machinery prior to three contrasting site reclamation treatments, one for each sand pile in an ascending order: (1) soil covering (designated as SC), in which the surface of ore sand was overlaid, without plowing, with a 10–20 cm layer of soil, (2) application of vegetation carpet (designated as VC), and (3) combination of soil covering and application of vegetation carpet (designated as SC+VC). The soil was collected fresh from the sub-layer at the foot of a nearby hill with a mechanical excavator and transported strait to the site of treatments. They were dumped onto the site from top of each sand pile by transport truck and leveled with a motorized grader. The vegetation carpet (Chinese patent No. 200420116280.4), about 2 cm in thickness, consists of a central layer containing plant seed mix (*Astragalus adsurgens* Pall., *Cosmos bipinnata* Cav., and *Lolium perenne* L. in this study) and water retaining agent, two sub-layers of wheat straw, and two outer layers of bio-degradable fabric netting. Each set of vegetation carpet measures 3 m in width and cut to variable length as required, and placed along contour lines of the treatment sites.

All sites were treated in March 2004 after reshaping and addition of soil cover, and left for natural plant colonization except those introduced through the use of vegetation carpet.

The assessment of vegetation establishment and soil physiochemical properties was made by establishing three replicated plots on each treatment site.

In August 2011, 7 years after the initial site treatments of the tailings dam, we set up three 10 × 10 m plots at each treatment site along an East–West transect taking into account of the topography and spatial coverage of the given treatment type. The three plots within the same treatment site were well separated in space, with a distance >500 m between two adjacent plots. Each plot was further divided into four 5 × 5 m subplots; within each subplot five 1 × 1 m quadrates were set up as sampling units for investigation of plant communities.

Measurements

Within each 1 × 1 m quadrate, we visually assessed coverage of all species, recorded the number of species counted, and measured the average height by species. The aboveground biomass, root biomass, and litter mass were also measured by harvesting using the 1 × 1 m quadrates following the sampling protocol of Fang and others (2009). The plant species were categorized into five plant functional groups (PFGs) on the basis of life form, including annual and biennials (AB), nitrogen-fixing plants (NF), shrubs and semi-shrubs (SS), perennial grass (PG, including both rhizome grass and bunchgrass), and perennial forbs (PF) (Bai and others 2004; García-Palacios and others 2011).

Importance Value Index (IVI) for individual plant species was determined as the sum of their relative height, relative abundance, and relative coverage (Curtis 1959).

The biodiversity traits of plant communities were described by plant abundance, diversity (species richness), evenness (Pielou index, Pielou 1975), and Shannon–Wiener Index (Shannon and Weiner 1949).

As there were mostly herbaceous plants, we selected height, coverage, biomass, and life form for comparing the plant communities among sites of different treatments. Plant biomass (including both above- and belowground) and litter mass were measured at peak growth season (mid-Aug).

Soil samples were collected to a depth of 40 cm with a cylindrical soil core sampler (10 cm in diameter) at three random locations on each plot. Those samples were subdivided into different portions and placed in cloth bags for air-drying in a ventilation room. Soil bulk density was determined from the dry soil mass and the corresponding volume of the soil core.

After manual removal of litter and pebbles, the air-dried soil samples were ground to pass through a 2-mm sieve. Analysis was made on soil organic matter content, total N, nitrate-N, available P, available K, and soil pH. The soil pH was measured with an acidity meter (Sartorius PT-21, Shanghai, China) in a 1:5 soil–water mixture. Organic matter content was determined with dichromate oxidation method (Nelson and Sommers 1982). Soil total N was measured with titration of distillates after Kjeldahl sample preparation and analysis, and nitrate-N was measured with ultraviolet spectrophotometry (Jackson 1958). Available P was measured with method of molybdenum blue colorimetry and available K was measured using atomic absorption spectrophotometry (Bao 2000).

Statistical Analyses

ANOVA and LSD's multi-range test at $P = 0.05$ were used to evaluate the effects of site treatments on average height, coverage, aboveground and root biomass, litter mass, and selective soil variables. These statistical analyses were performed using SPSS (ver.15.0) software. Species abundance was calculated from random sites and was compared between different treatments using a mixed model ANOVA (Proc MIXED, SAS Institute 2004) and others with a nested design. Treatments (including SC, VC and SC+VC) were considered as a fixed effect and sites as the random effect. Other diversity measures, including species richness, Shannon–Wiener Index and Pielou index, were analyzed separately, using a mixed model ANOVA with the same design as described above.

We used redundancy analysis (RDA) in the CANOCO package to examine the relationship between plant community and site variables (Ter Braak and Šmilauer 1998). RDA is an ordination method that links the arrangement of sample sites to environmental parameters. The IVI was used to characterize the plant communities of each plot. The site variables included: (a) soil acidity, (b) soil bulk density, (c) soil organic carbon, (d) soil total nitrogen, (e) available phosphorus, and (f) available potassium. We tested the statistical significance of the correlation between the plots and environment matrices with a Monte Carlo permutation tests. The IVI matrix was used by CANOCA version 4.5 for this analysis and graphical outputs were elaborated by CANODRAW.

Results

Differences in Soil Properties Among Sites of Contrasting Reclamation Methods

Examination of selective soil physicochemical properties show that the VC site had lower fertility than the other two sites as indicated by significantly lower ($P < 0.05$) values of TN (df $= 2$, $F = 48.40$), nitrate-N (df $= 2$, $F = 3.62$), available P (df $= 2$, $F = 5.05$), available K (df $= 2$, $F = 3.64$), and organic matter content (df $= 2$, $F = 12.79$) (Table 1). The SC and SC+VC sites significantly differed ($P < 0.05$) only in available P (df $= 2$, $F = 5.05$) and organic matter content (df $= 2$, $F = 12.79$) (Table 1).

Differences in Vegetational Traits Among Sites of Contrasting Reclamation Methods

The average height and coverage of plants, the above- and belowground biomass, and the litter mass were all significantly greater ($P < 0.05$) on the SC+VC site than on the SC and VC sites (Table 2). The SC and VC sites did not differ in all the growth variables except the litter mass, which was lowest on the VC site among the three site types. On both SC and VC sites, there were proportionally more mesophytes than xerophytes; whereas on the SC+VC site, the xerophytes outweighed the mesophytes (Table 2).

The plant abundance significantly differed between sites with and without vegetation carpet (df $= 2$, $F = 14.93$, $P = 0.0047$; Fig. 1a). The VC site ranked the same as the SC+VC site in plant abundance ($P = 0.40$); both sites were significantly higher than that of SC site ($P < 0.005$; Fig. 1a). There was no significant difference in species richness between the SC and VC sites ($P = 0.1880$), which both had significantly lower species richness than the SC+VC site (df $= 2$, $F = 12.22$, $P = 0.0077$; Fig. 1b). Values of Shannon–Wiener Index differed significantly among the three site treatments, similar to the trend of species richness (df $= 2$, $F = 10.39$, $P = 0.0113$; Fig. 1c). The values of Pielou index were only marginally affected by site treatments (df $= 2$, $F = 3.84$, $P = 0.0843$; Fig. 1d).

Table 1 Selective soil physicochemical properties (mean ± SE, $n = 3$) on tailings dam at Shouyun Iron Ore Mine in suburban Beijing, China, 7 years after reclamation with three contrasting site treatment methods

Site treatment	Bulk density (g/cm^3)	TN (g/kg)	Nitrate-N (mg/kg)	Available-P (mg/kg)	Available-K (mg/kg)	Organic matter (g/kg)	pH
SC	1.39 ± 0.02 a	4.61 ± 0.51 b	46.3 ± 17.3 b	20.0 ± 8.0 a	145 ± 37 b	13.5 ± 2.4 a	7.54 ± 0.19 a
VC	1.70 ± 0.07 b	1.86 ± 0.40 a	35.9 ± 16.4 a	13.8 ± 5.6 a	94 ± 9 a	6.5 ± 0.7 a	7.30 ± 0.06 a
SC+VC	1.34 ± 0.05 a	5.08 ± 0.38 b	53.8 ± 7.5 b	57.6 ± 30.3 b	173 ± 5 b	19.1 ± 1.1 b	7.31 ± 0.15 a

Values designated by the same letter within each variable are not significantly different at $P = 0.05$

SC soil covering, *VC* application of vegetation carpet, *SC+VC* combination of soil covering and application of vegetation carpet

Table 2 Selective vegetation traits and litter mass (mean ± SE, $n = 3$) on tailings dam at Shouyun Iron Ore Mine in suburban Beijing, China, 7 years after reclamation with three contrasting site treatment methods

Site treatment	Average height (cm)	Coverage (%)	Aboveground biomass (g/m^2)	Belowground biomass (g/m^2)	Litter mass (g/m^2)	Life form	
						Mesophyte (%)	Xerophyte (%)
SC	55 ± 3 a	71 ± 3 a	204 ± 8 a	179 ± 14 a	158 ± 8 a	58.6	41.4
VC	51 ± 3 a	76 ± 3 a	234 ± 7 a	198 ± 14 a	100 ± 8 b	53.9	46.1
SC+VC	64 ± 5 b	88 ± 2 b	363 ± 9 b	268 ± 5 b	185 ± 6 a	41.5	58.5

Values designated by the same letter within each variable are not significantly different at $P = 0.05$

SC soil covering, *VC* application of vegetation carpet, *SC+VC* combination of soil covering and application of vegetation carpet

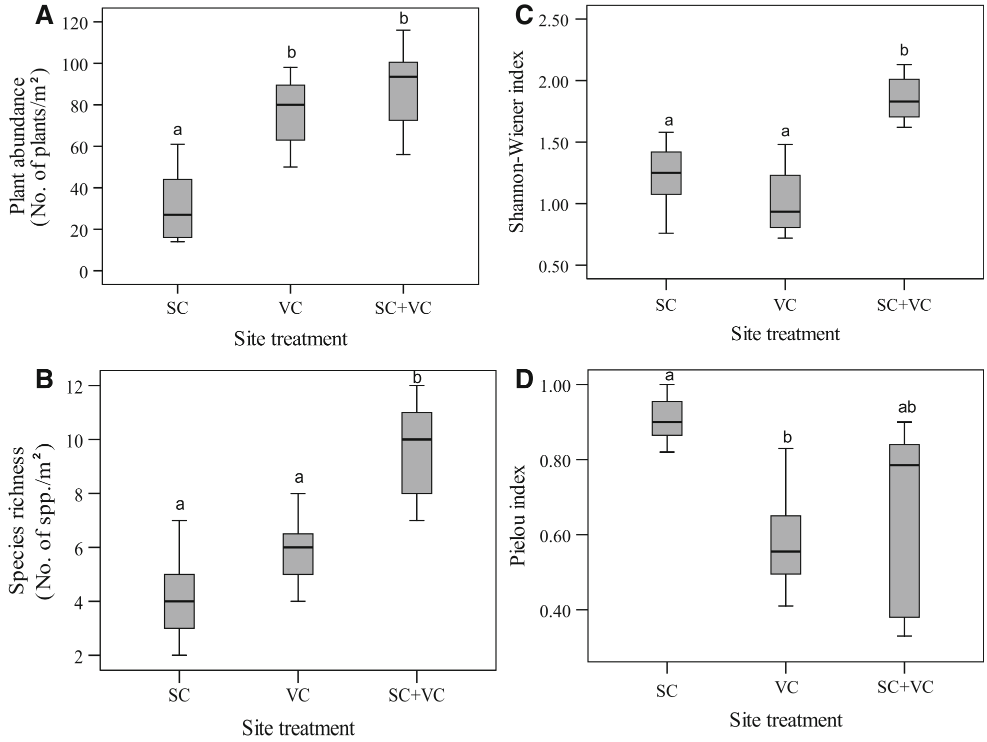

Fig. 1 Plant abundance (**a**), species richness (**b**), Shannon–Wiener Index (**c**) and Pielou index (**d**) on tailings dam at Shouyun Iron Ore Mine in suburban Beijing, China, 7 years after reclamation with three contrasting site treatment methods. *Box-plots* with upper and lower quartiles; the *horizontal line within the box* shows the median value, and the *vertical lines outside the box* indicate the value range of the variable

Differences in Plant Community Structure Among Sites of Contrasting Reclamation Methods

A total of 28 plant species, belonging to 12 families, were found across the three site types (Table 3); half of the plant species came from only three families: Leguminosae (5 species), Compositae (5 species), and Gramineae (4 species). The pattern of species occurrence differed greatly among the three site types (Table 3). The SC+VC site was found to be most species rich, containing all but *Tribulus* *terrestris* (AB; Zygophyllaceae) and *Digitalis purpurea* (PF; Scrophulariaceae) of the 28 plant species, and covering all five PFGs. *Tribulus terrestris* was found as only a minor species on the VC site; whereas *D. purpurea* occurred exclusively on the SC site. The number of plant species on the SC and VC sites were only about half of that on the SC+VC site, occurring predominantly as the species of the AB category (Table 3). The VC site was co-dominated by *Digitaria sanguinalis* (AB; Gramineae) and *Astragalus adsurgens* (NF; Leguminosae); whilst *A. scoparia* (AB; Compositae), *Setaria viridis* and *D. sanguinalis* (AB; Gramineae), and *Salsola collina* (AB; Chenopodiaceae) prevailed on the SC site. Plants in the NF group were completely absent on the SC site. *Astragalus adsurgens* (NF; Leguminosae) was an introduced plant species with the use of vegetation carpet, and found to dominate the plant communities on both the VC and SC+VC sites but absent on the SC site.

The RDA joint plot illustrated the interrelationship between community structure and site factors studied and separated the plots of contrasting site reclamation methods based on the IVI matrix (Fig. 2). The first axis clearly reflected the soil fertility, including total nitrogen (TN), soil organic carbon (SOC), available-K, etc., which explained 41.7 % the variance in the difference among the three site treatments. The second axis reflected the influence of soil pH (Table 4). The biplot of the first and second axis, which accounted for 54.3 % of the variance, showed the influence of soil properties on species distribution. The RDA analysis indicated that the plant community on the VC site was separated from the other two sites by soil fertility and that of SC from the other two sites by soil acidity (Fig. 2).

The plants of AB group were most dominant in the aboveground biomass regardless of the site types, but their relative contribution differed markedly among the three sites (Fig. 3). The aboveground biomass on the SC site was predominantly made up of the AB plants; whereas the NF plants and a combination of SS and PF plants each contributed about a quarter of the total aboveground biomass on the VC and SC+VC sites.

Discussion

Vegetation establishment on derelict wastelands in mining area can be extremely slow by natural processes. Soil condition and soil seed bank are the key limiting factors (Bryan and others 2007; García-Palacios and others 2011). Introducing or restoring topsoil has been a conventional approach in rehabilitation of abandoned mines (Kundu and Ghosh 1994; Bradshaw and Hǘttl 2001). In this study, introduction of topsoil on the fine-structured substrate of iron ore sands resulted in spontaneous vegetation development over a 7 years period following site treatments, in consistency with the findings in other similar studies (e.g. Prach and Pysek 2001; Alday and others 2011b; Kullu and Behera 2011). The study of Alday and others (2011b) also shows that topsoil treatment facilitates restoration of coal mines under Mediterranean climate. Being the source of nutrients and organic matter, topsoil acts as buffer, negating the adversities of the wasteland and ameliorating soil physicochemical properties and hydrological processes in favor of vegetation establishment (Bradshaw and Chadwick 1980). Topsoil also serves as seed back for initial floristic development. However, we found that the plant communities on the site of topsoil treatment were mainly annuals or biennials and had relatively low biodiversity after 7 years of site treatment. Moreover, topsoil treatment often involves disturbance or severe damage to the soil-donor sites. Its application is especially constraint in areas with poor soil resources. For this concern, application of surface covering bio-materials can be an alternative approach for facilitating vegetation establishment on mining sites with fine-structured substrate.

On loose slopes, such as on the tailings dam, surface stabilization or quick establishment of vegetation is required for controlling soil erosion by water and/or gravity (Ruiz-Jaen and Aide 2005; Tordoff and others 2000; Alday and others 2011b). Use of vegetation carpet, especially in combination with topsoil application, has been demonstrated in this study as an effective approach for treatment of tailings dam with fine-structured substrate of iron ore sands. We found that application of vegetation carpet alone is comparable to topsoil treatment in facilitating vegetation establishment; whilst combination of topsoil treatment and application of vegetation carpet greatly improved plant community structure and site productivity.

In this study, 7 years after the site treatments, plant communities were mostly annuals or biennials in the families of Leguminosae, Compositae and Gramineae. This is consistent with findings by other similar studies in the region (Guo and others 2005; Zhou and others 2009) and other part of the world (Kullu and Behera 2011). The use of vegetation carpet resulted in the dominance of an introduced NF plant *A. adsurgens*. It is intriguing to note that, a combination of topsoil treatment and application of vegetation carpet resulted in a large number of plant species absent on the sites with either topsoil treatment or application of vegetation carpet alone. We also found that different site treatment approaches led to establishment of different plant communities. On the site with only topsoil treatment, *A. scoparia* (AB; Compositae), *S. viridis* and *D. sanguinalis* (AB; Gramineae), and *S. collina* (AB; Chenopodiaceae) were the dominant species; whereas *D. sanguinalis* (AB; Compositae) and *A. adsurgens*

Table 3 Importance values (mean ± SE, $n = 3$), computed as function of relative height, coverage and abundance, of plant species on tailings dam at Shouyun Iron Ore Mine in suburban Beijing, China, 7 years after site treatments

Functional group	Family	Species	Site treatment		
			SC	VC	SC+VC
Annual and biennial (AB)	Compositae	*Cosmos bipinnatus* Cav.	0.0109 ± 0.0072		0.0504 ± 0.0312
		Artemisia scoparia Waldst.	0.2028 ± 0.0488	0.0624 ± 0.0081	0.0415 ± 0.0088
		Xanthium sibiricum Patrin.		0.0021 ± 0.0012	0.0024 ± 0.0016
		Bidens parviflora Willd.		0.0201 ± 0.0103	0.0586 ± 0.0223
		Artemisia annua L.			0.0036 ± 0.0025
	Gramineae	*Setaria viridis* (L.) Beauv	0.2278 ± 0.0562	0.0237 ± 0.0178	0.0617 ± 0.0269
		Arthraxon hispidus Thunb.	0.0389 ± 0.0123		0.0033 ± 0.0011
		Digitaria sanguinalis L.	0.271 ± 0.0565	0.4651 ± 0.0296	0.0548 ± 0.0265
	Convolvulaceae	*Pharbitis nil* L.		0.0013 ± 0.0007	0.0288 ± 0.0133
		Pharbitis purpurea L.			0.0014 ± 0.0009
	Chenopodiaceae	*Chenopodium album* L.	0.0231 ± 0.0034	0.0064 ± 0.0019	0.0187 ± 0.0105
		Salsola collina Pall.	0.1771 ± 0.0323	0.0702 ± 0.0103	0.1168 ± 0.0161
	Zygophyllaceae	*Tribulus terrestris* L.		0.0016 ± 0.0005	
	Amaranthaceae	*Amaranthus tricolor* L.		0.0135 ± 0.0032	0.0462 ± 0.0338
Nitrogen-fixing plants (NF)	Leguminosae	*Melilotus alba* Medic.			0.0037 ± 0.0016
		Melilotus officinalis L			0.0287 ± 0.0082
		Vigna radiata L.			0.0135 ± 0.0080
		Astragalus adsurgens Pall.		0.3212 ± 0.0144	0.291 ± 0.0155
		Cassia pumila			0.0239 ± 0.0211
Perennial grass (PG)	Violaceae	*Viola verecunda* A.			0.001 ± 0.0007
	Rubiaceae	*Rubia cordifolia* L.			0.0025 ± 0.0008
	Gramineae	*Themeda japonica* (Willd) Tanaka.	0.0139 ± 0.0058		0.0046 ± 0.0008
Perennial forb (PF)	Scrophulariaceae	*Rehmannia glutinosa* (Libosch) Libosch.			0.0197 ± 0.0129
		Digitalis purpurea L.	0.0267 ± 0.0138		
	Asclepiadaceae	*Cynanchum chinense* R. Br.			0.0013 ± 0.0005
		Metaplexis japonica (Thunb) Makino.		0.0062 ± 0.0019	0.0051 ± 0.0025
	Moraceae	*Humulus scandens* (Lour) Merr.			0.0186 ± 0.0025
Shrub and semi-shrub (SS)	Asclepiadaceae	*Cynanchum thesioides* (Freyn) K. Schun.	0.0078 ± 0.0075	0.0062 ± 0.0031	0.0982 ± 0.0369

Site treatment: *SC* soil covering, *VC* application of vegetation carpet, *SC + VC* combination of soil covering and application of vegetation carpet

(NF/introduced; Leguminosae) co-dominated the site with application of vegetation carpet. On the site with combined treatments of topsoil and vegetation carpet, *A. adsurgens* and *S. collina* prevailed in the plant community.

Lolium perenne completely disappeared from VC and SC+VC sites and *C. bipinnatus* only appear on SC+VC site. The selection of seed in vegetation carpet was initially based on commercial availability. After 7 years of natural development, *L. perenne* gave way to other local plants possibly due to poor competition for light when plant community has established (Hofmann and others 2001; Correll and others 2003). This finding is supported by the studies of Marriott and Bolton (1998), Marriott and others (2003), and Pavlu and others (2005). *Cosmos bipinnatus* was not able to persist long under poor soil fertility in the VC site. The topsoil seed bank might partly explain the occurrence of other plant species on the treatment sites. However, a more probable explanation is colonization through wind dispersal, which could easily occur with short-lived plants in open-ground. This is demonstrated by greater number of plant species on sites where vegetation carpets were applied despite that they only contained three species. The study of Kirmer and others (2008) shows that the abundance of species up to as far as 17 km could influence colonization processes following large-scale destruction of ecosystems and that an accumulation of plant species can be expected on nutrient-deficient open sites with time because the sites act as seed traps in the

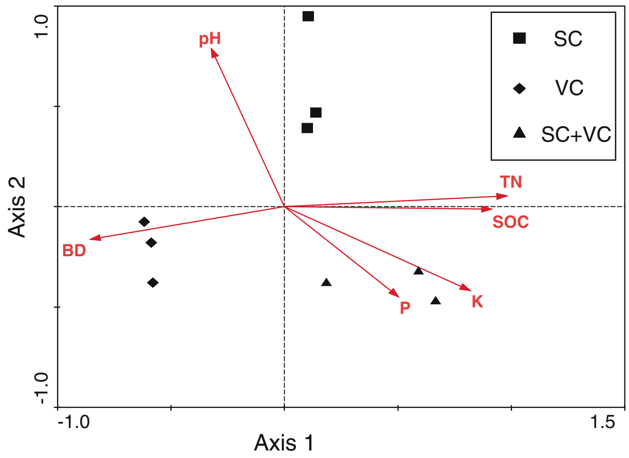

Fig. 2 Joint plot of redundancy analysis (RDA) of vegetation on the tailings dam at Shouyun Iron Ore Mine in suburban Beijing, China, 7 years after reclamation with three contrasting site treatment methods. All data were pooled across sub-plots and quadrates within the same plot. Site variables introduced in the analysis include: *pH* soil acidity, *BD* soil bulk density, *SOC* soil organic carbon, *TN* soil total nitrogen, *P* available phosphorus, *K* available potassium. *SC*, *VC* and *SC+VC* represents three site treatment methods of soil covering, application of vegetation carpet, and combination of soil covering and application of vegetation carpet, respectively

Table 4 The results of redundancy analysis (RDA) and Monte Carlo permutation test of vegetation on the tailings dam at Shouyun Iron Ore Mine in suburban Beijing, China, 7 years after reclamation with three contrasting site treatment methods

Variable	Correlations	
	Axis1	Axis2
pH	−0.32	0.79**
P	0.50**	−0.45
K	0.82**	−0.42
TN	0.98**	0.05
SOC	0.91**	−0.01
BD	−0.85	−0.16
Eigenvalues	0.417	0.126
P value	0.002	0.002
F value	20.77	6.57

All data were pooled across sub-plots and quadrates within the same plot

Site variables introduced in the analysis include: *pH* soil acidity, *BD* soil bulk density, *SOC* soil organic carbon, *TN* soil total nitrogen, *P* available phosphorus, *K* available potassium

** Significant at $P < 0.01$

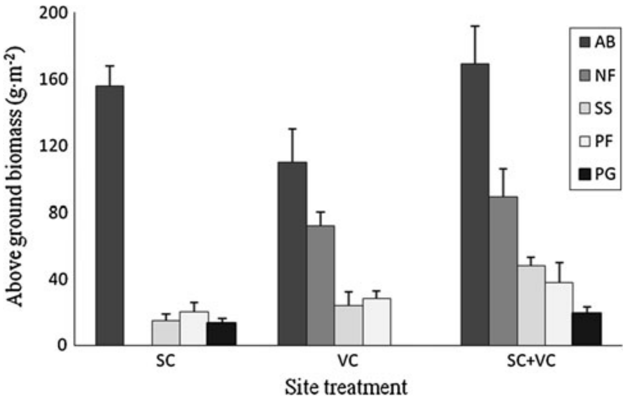

Fig. 3 Histogram of aboveground biomass by plant functional groups (PFGs) on tailings dam at Shouyun Iron Ore Mine in suburban Beijing, China, 7 years after reclamation with three contrasting site treatment methods. *Vertical bars* indicate 1× standard errors of means ($n = 3$). Site treatment: *SC* soil covering, *VC* application of vegetation carpet, *SC+VC* combination of soil covering and application of vegetation carpet. Plant functional group: *AB* annual and biennial, *NF* nitrogen-fixing plant, *SS* Shrub and semi-shrub, *PF* Perennial forb, *PG* Perennial grass

landscape. There are also findings that the initial floristic composition and the order of species arrivals are important for long-term vegetation development in the restoration of surface-mined land (Baasch and others 2012). Therefore, the differences in plant communities among the sites of contrasting reclamation methods are clearly the result of site conditions for plant establishment rather than seed sources. The significantly increased legume species richness in the combination of topsoil application and vegetation carpet is intriguing. Further experimental studies are needed to elucidate the mechanism of this phenomenon.

Success of vegetation establishment and achieving the goal of ecosystem restoration is often judged with a set of criteria such as plant abundance, species richness, plant coverage and colonization by target species (Zedler 2007; Alday and others 2011c). In this study, we assessed the effects of site treatments on vegetation development on the tailings dam with selective vegetation and soil traits. Our findings suggest that topsoil treatment is mainly effective in facilitating colonization of annuals and biennials. For achieving the ultimate goal of ecosystem restoration, i.e., improved site productivity and biodiversity, engineering efforts incorporating ecological approaches are needed. Use of bio-materials, such as vegetation carpet used in this study, both as surface coverage of the loose slopes and seed bank, can greatly facilitate the restoration of derelict mining lands. While application of vegetation carpet helps to stabilize the loose surface of fine-structured mine sands, introduction of fertile soil is necessary for supplying nutrients to plant growth in the efforts of ecosystem restoration of mined lands.

In this study, the vegetation carpet contained mainly short-lived and early successional plants. For effectively achieving the long-term goal of reclamation of mined sites, incorporation of local seed species and intermediate-successional species and diversification of the seed mix may facilitate the establishment of plant community structures of native feature and greater stability.

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