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Full Length Research Paper

Community succession analysis and environmental biological processes of naturally colonized vegetation on abandoned hilly lands and implications for vegetation restoration strategy in Shanxi, China

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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 of natural colonized plants on abandoned hilly lands in Shanxi are below: Assoc. *Potentilla chinensis* + *Setaria viridis* → Assoc. *Artemisia sacrorum* + *S. viridis* + *Oxytropis caoraloa* → Assoc. *A. sacrorum* + *Artemisia capillaries* → Assoc. *A. capillaries* + *Pedivularis shansiensis* + *Echinops pseudosetifer* → Assoc. *Hippophae rhamnoides– A. sacrorum* + *Cleistogenes squarrosa* → Assoc. *H. rhamnoides* + *Ostryopsis davidiana–A. sacrorum* → Assoc. *O. davidiana–A. sacrorum* + *Dendranthema chanetii* → Assoc. *Populus davidiana–Caragana korshinskii–A. sacrorum* → Assoc. *Larix principis-rupprechtii–H. rhamnoides–A. sacrorum*. This established a recovery model of natural vegetation on abandoned hilly lands in Shanxi. The structure, composition and life-forms changed significantly during succession. Four indices of species diversity were used to analyze changes in the heterogeneity, dominance, richness and evenness of species during the succession process. The species richness and heterogeneity of plant communities increased significantly, the dominance decreased obviously and the evenness decreased slightly. The analysis of variance (ANOVA) also proved the significance of these five indices. Pioneer species of *S. viridis*, *A. sacrorum*, *O. caoraloa*, *A. capillaries*, *P. shansiensis*, *E. pseudosetifer*, *C. squarrosa*, *H. rhamnoides*, *O. davidia*, *C. korshinskii*, *P. davidiana* and *L. principis-rupprechtii*, etc. colonize successfully and play important roles on the vegetation restoration of abandoned hilly lands.

Keywords: Abandoned hilly lands, vegetation community succession, environmental biological process, soil quality.

INTRODUCTION

Plant community succession is one of the most important aspects of vegetation ecology (Leendertse, 1997; Luisa et al., 2001; Zhang, 2005). Previous studies on plant community 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, relatively few studies have been conducted in the community succession on abandoned hilly lands towards forestation (Billings, 1938; Grau et al., 2003; Otto et al., 2006), and even fewer have been carried out in Shanxi, China. Hilly lands are the main land

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types on the Loess Plateau and account for 72% of total land in Shanxi. At present, most of them have been abandoned due to the serious soil erosion, low soil fertility and harsh environment, which face the double pressures of improving poor economy and bad environment. According to the Chinese government policy of returning cultivated land to forest and grassland, these areas urgently need revegetation. Based on previous research, the most effective method to improve the bad ecological condition on abandoned hilly lands is the restoration of natural vegetation (Zhang et al., 2000; Ma, 2001) and vegetation technique is strongly proposed in these areas.

Up to now, natural recovery of vegetation is getting increasing attention in various restoration projects, especially in developed countries such as the United States, United Kingdom, the Netherlands, and Germany (Luken, 1990; Rebele and Dettmar, 1996; Bradshaw, 1997; Karel and Petr, 2001). This paper takes the typical abandoned hilly lands, Yuzhuangxiang of Ningwu Country as a case research site, where technocratic approaches do not prevail in the restoration of degraded land. Its aims is to clarify the succession processes of naturally colonized vegetation on abandoned hilly land in Shanxi, to establish a pathway model for vegetation restoration, and to analyze the changes of ecological relationships and species diversity during succession. The ultimate goal is to propose some pioneer species for revegetation and to provide scientific strategy for ecological restoration on abandoned hilly land in the Loess Plateau.

MATERIALS AND METHODS

Study site

The field study was conducted on the abandoned hilly lands of Yuzhuangxiang in Ningwu County, a very typical hilly lands on the Loess Plateau, located in the northwest of Shanxi province (N38°57′23″-39°03′42″, E112°36′18″-112°37′25″), China (Figure 1). The region enjoys a typical semi-arid continental monsoon climate with annual mean temperature of 6-7°C and annual mean precipitation of about 480-770 mm; more than 70% of annual precipitation falls from July to September. The frost-free period varies from 90 to 130 days. In addition, its average annual wind speed is 3.1-5.6 ms^{-1} and prevailing wind direction is southeast. Its dominant landform is loess-covered hills with an average altitude varying from 1,500 to 2, 450 m and most of which are actually over 1,500 m, where serious soil erosion would occur easily in case of unreasonable interruption. The major soil types are hilly cinnamon and brown soil. Based on the system of Chinese national vegetation regionalization, this area is classified in the cold-temperate deciduous broad-leaf forest region with the dominant species of *Artemisia sacrorum*, *Setaria viridis*, *Pedivularis shansiensis*, *Hippophae rhamnoides*, *Ostryopsis davidiana*, *Populus davidiana*, *Larix principis-rupprechtii*. The original vegetation has been drastically destroyed in the area due to the long-term extensive land use mainly in cultivated terraces and coal mining. Nowadays this area surrounded by terraced fields, villages and forest has been abandoned for more than 39 years, where the oldest one has been abandoned since 1970, while the youngest one has only been abandoned since 2007.

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 quadrat method from the bottom to the top of the hilly lands. Quadrats of 10×10, 5×5 and 1×1 m were used respectively for woodland, scrubland and grassland communities. The sizes of the quadrat 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 (15, 12 and 12 for grassland, scrubland and woodland stages, respectively) at each succession stage were determined according to their areas (approximately 180, 250 and 360 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 VENTURE-etrex handheld GPS and compass. A total of 84 species were examined (Table 1). The ages of abandoned hilly lands were obtained through personal interviews with some local aged peoples.

Data analysis

A total of 84 species were identified in the floristic inventories in 39 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:

$$IV_{tree} = (\text{Relative density} + \text{Relative frequency} + \text{Relative dominance})/300 \quad (1)$$

$$IV_{shrub} = (\text{Relative coverage} + \text{Relative height})/200 \quad (2)$$

$$IV_{herb} = (\text{Relative coverage} + \text{Relative height})/200 \quad (3)$$

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 84×39 (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, as well as the relationship among plot groups defined by TWINSPAN. These calculations were carried out by the CANOCO (T. Braak, 1991) and TWINSPAN (Hill, 1979) computer programs. Thirdly, the heterogeneity, dominance, richness and evenness of the species in each quadrant were measured to reveal their variation along the succession gradient. The following four diversity indices (including one heterogeneity, one richness, one dominance and one evenness indices) were used:

Shannon–Wiener heterogeneity index (*H′*)

Figure 1. Study site.

$$H' = -\sum_{i=1}^{S}\left(\frac{N_i}{N}\right)\ln\left(\frac{N_i}{N}\right) \quad (4)$$

The Simpson dominance index (*DS*)

$$DS = \sum N_i^2 \quad (5)$$

The Alatalo evenness index (*EA*)

$$EA = [1/(P_i)^2 - 1/[\exp^{(-\sum P_i \ln P_i)} - 1] \quad (6)$$

The Patrick richness index (Pa)

$$Pa = S \quad (7)$$

Here, *Ni* is the *IV* of the *i-th* species in a quadrat, *N* is the sum of *IV*s of all species in the same quadrat, *Pi* is the proportional *IV* in a quadrat (*Pi=Ni/N*) and *S* is the species number in a quadrat (Greig-Smith, 1983). All the species diversity indices were analyzed using a one-way analysis of variance followed by multiple comparisons (Duncan's) (SPSS 11.5 for Windows V 3.0©; SPSS Corporation, Chicago, IL, USA; P <0.05).

RESULTS

Classification of succession stages

39 samples were classified into 9 groups by using TWINSPAN, representing 9 different types of communities. Based on the principle and method of plant succession stage division (M. Dombois, 1974), these associations belong to three vegetation succession stages; the herbaceous community stage including Assoc. I1, I2, I3 and I4; the shrub community stage including Assoc. II1, II2 and II3; the tree community stage including Assoc. III1 and III2 (Figure 2 and 3). Each succession stage included several different communities, and it was related to the length of time since abandonment and the changes of dominant species. The composition, structural characteristics and the environment of the succession stages are described below.

Grassland community stage

This stage started the year following the abandoned and took 15-20 years to reach the scrubland stage. The communities changed quickly during this stage. The loess soil of the abandoned hilly lands was deep but

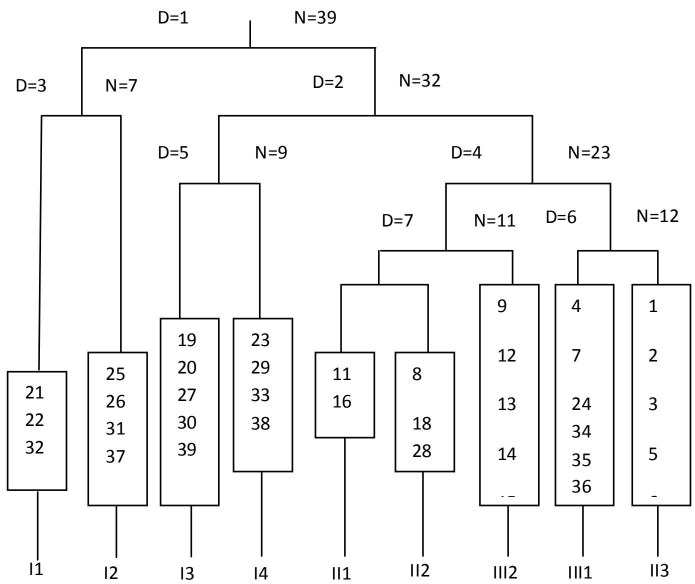

Figure 2. Dendrogram of 39 quadarts by TWINSPAN, *Di* refers to the *i*-th division, *N* to the number of samples in a group.

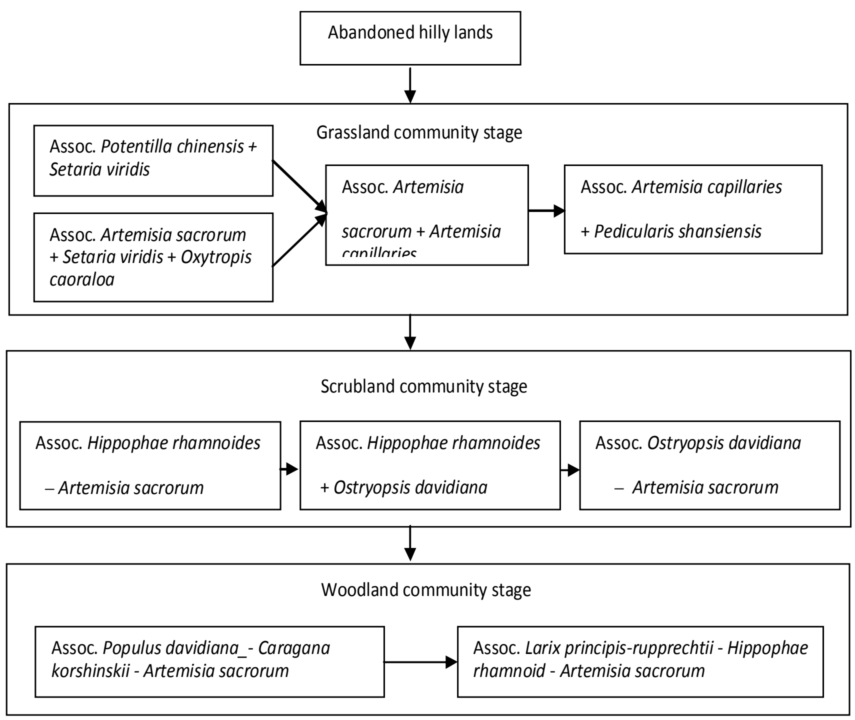

Figure 3. The recovery model of natural plant community on abandoned hilly lands, Shanxi.

poor, with only 0.06% 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, 4 associations could be identified.

I1 Assoc*. Potentilla chinensis* + *S. viridis*. This association included quadrat 21, 22 and 32, which appeared in northeast hills at 1,570 m in altitude for 2-3 years after abandonment. The total coverage of the association was about 60%. It mainly comprised of annual herbage. The dominant species was *P. chinensis* (that its coverage was about 50%) and *S. viridis* (that its coverage was about 15%). There were many species in the community and the most common and important species were *Smilax glauca*, *Poa annua*, *Dendranthema chanetii*, *Potentilla supine*, *Sida scordifolia*, *Polygonum viviparum* and *Chenopodium botrys*. So the composition and structure of this community were highly unstable during the succession process.

I2 Assoc. *A. sacrorum* + *S. viridis* + *Oxytropis caoraloa*. This association included quadrat 19, 20, 27, 30 and 39 and appeared in northwest hill between 1,590 and 1,650 m for 2-5 years after abandonment. The total coverage of the community was about 50%. The dominant species included *A. sacrorum*, *S. viridis* and *O. caoraloa*, whose important value contribution ratio reached 25.7%. The main companion species included *Artemisia capillaries*, *Astragalus membranaceus*, *Ligusticum filisectum, Sonchus oleraceus*, *Larix dahurica*, *Elymus dahuricus*, *Scabiosa tschiliensis*, *P. annua, Thymus mongolicus, Padus asiatia* and *Lacmellea floribunda*.

I3 Assoc. *A. sacrorum* + *A. capillaries*. This association was comprised of quadrat 25, 26, 31 and 37, and occupied the northwest hills between 1,570 and 1,650 m for 3-10 years after abandonment. The coverage of the community was around 55%. The coverage of dominant species of *A. sacrorum* and *A. capillaries* were 35% and 38%, respectively. The main companion species included *S. oleraceus, Saccharina japonica, S. lithospermun* and *E. ciliate*.

I4 Assoc. *A. capillaries* + *P. shansiensis* + *Echinops pseudosetifer*. This association included quadrat 23, 29, 33 and 38, and occupied in northwest hills at the elevation of 1,650-1,700 m for 10-20 years after abandonment. The total coverage of the community was around 70%. The coverage of dominant species of *A. capillaries*, *P. shansiensis* and *E. pseudosetifer* were about 45%, 30% and 20%, respectively. The main companion species included *P. communi*, *T. mongolicum* and *P. chinensis*. Additionally, there were some scrub species in the community, such as *L. daurica*, *H. rhamnoides* and *Caragana korshinskii*. This suggested that Assoc. I4 was developing towards scrubland.

Scrubland community stage

This stage usually started 15 years after abandonment and formed stable scrubland 25–30 years after abandonment. Its soil was deep with relatively rich organic-matter content and better water conditions than the grassland stage, which was due to soil development during the preceding regeneration stages. In the study area, the area of scrubland was not particularly large and the community types were simple. Based on the community composition and structure, 3 associations could be identified.

II1 Assoc. *H. rhamnoides*–*A. sacrorum* + *Cleistogenes serotina*. This association included quadrat 11 and 16, and appeared in east hills at 1,690 m for 10-15 years after abandonment. The total coverage of the community was over 97%. The shrub coverage was around 95% and the dominant species was *H. rhamnoides*. The coverage of herbaceous layer was about 70% and the dominant species was *A. sacrorum* and *C. serotina*. The main companion species composition included *Siegesbeckia pubescens, P. lafruticosa, W. chamaedaphne, Elymus dahuricus*, *Poa sphondylodes* and *S. media*.

II2 Assoc. *H. rhamnoides* + *O. davidiana* – *A. sacrorum*. This association included quadrat 8, 18 and 28, and occupied in northwest hill between 1,630 and 1,670 m for 15-20 years after abandonment. The total coverage of the community was around 90%. The coverage of shrub layer was about 80%. *H. rhamnoides* was absolutely dominant in the community and its coverage was around 70%. The coverage of *O. davidiana* was around 20%. There were many species under the bush canopy. The coverage of herbaceous layer was around 75%, its dominant species absolutely was *A. sacrorum*. The other companion species included *H. odorata*, *S. pubescens*, *Bupleurum chinense*, *Cunnighamia lanceolata*, *Acacia elata*, *Heteropappus altaicus* and *Stipa capillata*. The content of water in soil became better in this community, so it was adapted to grow for shrub plants.

II3 Assoc. *O. davidiana*–*A. sacrorum* + *Dendranthema chanetii*. This association included quadrat 1, 2, 3, 5, 6 and 10, and appeared in northwest slope, 25º gradient, between 1,700-1,810 m for 18-30 years after abandonment. The total coverage of the community was over 95%. The coverage of tree layer was around 10% and the most common species was *L. principis-rupprechtii*. The coverage of shrub layer was over 85%. The constructive species was *O. davidiana*, although *H. rhamnoides* was also found. The coverage of herbaceous layer was around 65%. *A. sacrorum* and *D. chanetii* were its dominant species. The other companion included *W. chamaedaphne, O. caoraloa*, *C. lanceolata*, *A. membranaceus*, *Physalis heterophylla* and *B. chinenes*.

Forest community stage

The forest community was developed from scrubland under natural conditions in the Loess Plateau. This started after 30 years, whereas forestation began 40–50 years after abandonment. 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 vertical zonal vegetation types over 1,200m in this area. There were two main associations of forest communities

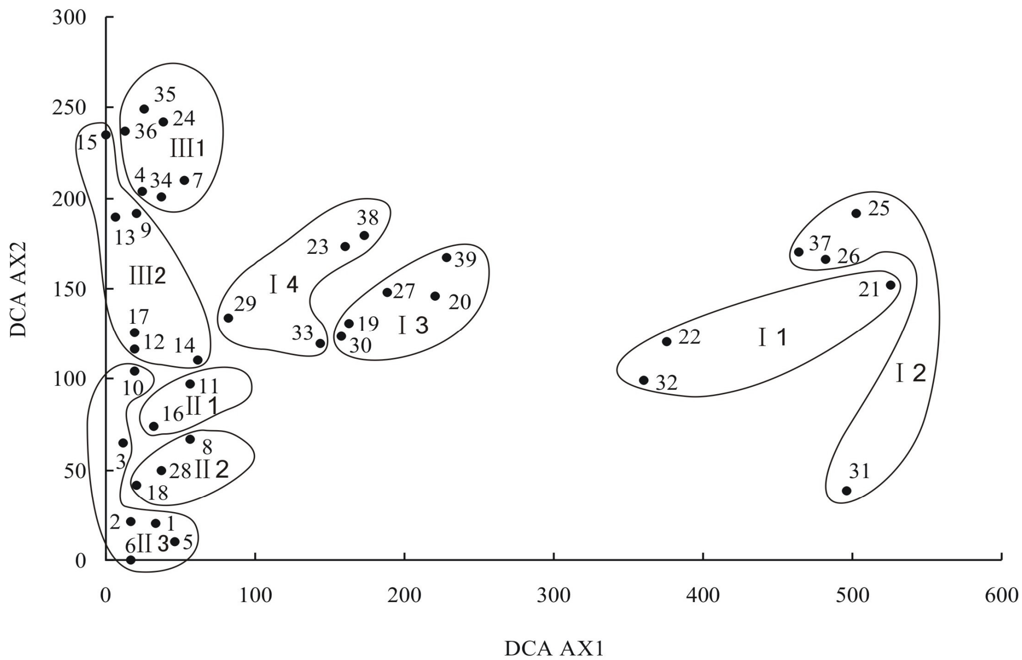

Figure 4. Two dimensional ordination diagram of 39 quadrat by DCA I1,I2,…III2 represent 9 associations of vegetation by Twinspan.

developed from abandoned hilly lands in the northwest of Shanxi.

III1 Assoc. *P. davidiana–C. korshinskii–A. sacrorum*. This association comprised of quadrat 4, 7, 24, 34, 35 and 36, and appeared in northwest hill at 15º slope, between 1,710 and 1,750m for 30-35 years after abandonment. The total coverage of the community was around 80%. The coverage of the tree, shrub and herbaceous layers were 30, 60 and 55%, respectively. The dominant species of this community is *P. davidiana*, *C. korshinskii* and *A. sacrorum*, respectively. The main companion species were *L. principis-rupprechtii*, *H. rhamnoides*, *W. chamaedaphne*, *L. leontopodioides*, *G. verim*, *H. odorata*, *T. prtaloideum*, *P. chinensis*, *P. heterophylla*, *B. chinensis*, *P. asiatia*, *O. caoraloa*, *Bothriochloa parviflora* and *M. officinalis*.

III2 Assoc. *L. principis-rupprechtii–H. rhamnoid–C. lanceolata*. This association comprised of quadrat 2, 9, 13, 14, 15 and17 and appeared in northwest hills between 1,650 and 1,680m for 30-40 years after abandonment. The total coverage of the community was over 90%. The important value contribution ratio of the three dominant species was 31.25%. The tree layer coverage was around 75%. The dominant species was *L. principis-rupprechtii*. The coverage of shrub layer was about 40%. *H. rhamnoides* was absolutely dominant in this layer. The coverage of herbaceous layer was about 65%. The dominant species was *C. lanceolata*. The species diversities of the association increased rapidly. The most common species included *S. divaricata*, *H. odorata*, *P. supine*, *E. pseudosetifer*, *R. cordifolia*, *G. verim*, *Schistura irregularis*, *O. caoraloa*, *B. chinense*, *S. tschiliensis*, *C. serotina*, *A. sensecns*, *W. chamaedaphne*, *T. mongolicus*, *P. davidiana*. This association was a local vertical zonal type of vegetation in Northwest of Shanxi, and could persist for long period of time in natural conditions.

Ordination analysis of succession

DCA ordination eigenvalues (λ) were higher for the first axis (λ=0.783) than for the second (λ=0.541) and third axis (λ=0.492). 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 (Figures 4 and 5). The results reveal the succession sequence of the plant communities.

DCA ordination diagram of quadrats

The ordination of DCA for the quadrat reflects quite good gradient relation among trends, direction and process of succession and environment (Zhang, 1995; 2000). Figure 1, shows a DCA ordination diagram of the 39 quadrats, the Arabic number represent the quadrats, and I1, I2, I3… III2 represent nine associations of vegetation at the three succession stages. The first DCA axis represents a succession gradient of time since abandoned, that is, the succession periods become longer from right to left along

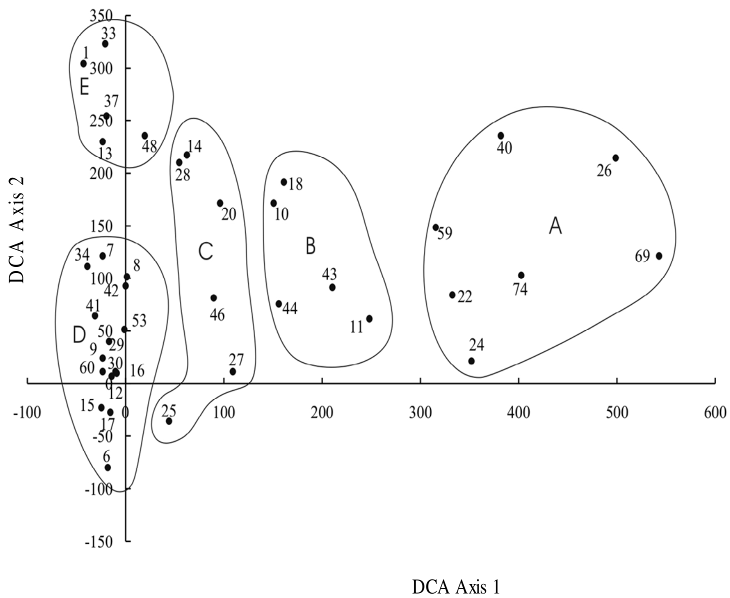

Figure 5. DCA ordination diagram of 38 dominant species at different succession stages of communities on abandoned hilly lands. The number refers to species numbers (Table 1).

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 Figure 4. The first DCA axis also represents an altitude gradient, that is, the altitude is increasing from right to left along the first axis. The second DCA axis represents the gradient of water content in soil and slope orientation, that is, from the bottom up (Figure 4). While its water content in soil increases, the slope orientation shifts from shadow slope to semi-shadow slope, and plant species also changed from herbaceous *A. sacrorum* to trees *L. principis-rupprechtii* from right to left along the second axis. Meanwhile, the style of community shows a tendency from Assoc. I1 to Assoc. II1 to Assoc. III2 while the ecotype of the community varies from xeorphyte herbaceous community to xero-mesophyte shrub community to mesophyte forest community. Moreover, the species diversities of the community gradually increase.

DCA ordination of dominant species

DCA ordination diagram of the 38 dominant species illustrates the changes of dominant species during the succession process (Figure 5). The first DCA axis represents a gradient of succession time from right to left. The 38 dominant species were divided into five ecological species groups, that is, Group A, B, C, D and E. These five 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 dominant species differs. The dominant species in group A, B and C mainly present at the herbaceous community stage, most of them belong to the xerophyte or xero-mesophyte species, including *A. sacrorum, A. capillaries*, *P. annua*, *E. dahuricus*, *A. membranaceus* and so on. At the same time, meso-xerophyte species also present in this stage, including *D. chanetii*, *S. viridis*, *P. chinensis*, *S. scordifolia*, *D. chinensi* and so on. The dominant species in group D mainly present at the scrub community stage and most of them belong to the meso-xerophyte species, including *L. dahurica*, *H. rhamnoides*, *O. davidiana*. The other scrub species also present in this stage, including *S. pubescens*, *P. lafruticosa*, *W. chamaedaphne*, *O. caoraloa* and *C. korshinskii*. The dominant species in group E mainly present at the forest community stage and the typical dominant species are *L. principis-rupprechtii*, *P. davidiana* and *B. platyphylla*, which ecotype belongs to the mesophyte species. Some species (including *S. viridis*, *A. sacrorum*, *D. chanetii*, *P. shansiensis*, etc.) are found at all three succession stage (Table 1). The distribution of dominant species in different communities is also influenced by soil water content and elevation (the second DCA axis).

The number of species increases and the structure of life-form become more complex as succession progresses (Table 1). This is in accordance with the general succession rules of plant communities (Zhang et al., 2006). It is obvious that the succession of plant community on abandoned hilly lands of Yuzhuangxiang in Ningwu County, Shanxi is evidently restricted by the

Table 1. 84 species and their ecotypes of vegetation on abandoned hilly lands in Yuzhuang County of Shanxi.

Species No.	Species name		Ecotype	Growth-form	Life-form	Found in stage associations
1	*Larix principis-rupprechtii* Mayr	Prince Rupprecht's Larch	M	Tr	PH	Ii,iii
2	*Betula platyphylla* Suk.	Asia White Brich	M	Tr	PH	ii
3	*Populus davidiana Dode*	Wild Poplar	M	Tr	PH	Ii,iii
4	*Caragana korshinskii* Koll	Korshinsk Peashrub	X	S	PH	iii
5	*Tilia amurensis* Rupr.	Amur Linden	M	Tr	PH	ii
6	*Ostryopsis davidiana* Decne.	David Ostryopsis	MX	S	PH	ii
7	*Wikstroemia chamaedaphne* Meissn.	Lowdaphne Stringbush	XM	S	PH	Ii,iii
8	*Oxytropis caerulea* (Pall) DC.	Blue Crazyweed	M	S	H	Ii,iii
9	*Carex lanceolata* Boott	Lanceolate Sedge	M	P	C	I,Ii,iii
10	*Poa annua* Linn.	Annual Bluegrass	X	T	T	I,Ii,iii
11	*Dendranthema chanetii* (Lévl.)Shih	Chanet Daisy	MX	T	T	I,Ii,iii
12	*Patrinia heterophylla* Bunge	Diversifolious Patrinia	M	T	T	I,Ii,iii
13	*Bupleurum chinense* DC.	China Thorowax	MX	P	CH	Ii,iii
14	*Scutellaria baicalensis* Georgi	Skullcap	MX	P	H	I,Ii,iii
15	*Spiraea pubescens* Turcz.	Pubescent Spiraea	M	S	PH	Ii,iii
16	*Hippophae rhamnoides* Linn.	Sandthorn	MX	S	PH	I,Ii,iii
17	*Potentilla glabra* Lodd.	Glabrous Cinquefoil	X	S	PH	Ii,iii
18	*Artemisia sacrorum* Ledeb.	Holy Sagebrush	X	S	CH	I,Ii,iii
19	*Elsholtzia ciliata* (Thunb.) Hyland	Elsholtzia	M	T	T	Ii,iii
20	*Elymus dahuricus* Turcz.	Dahuria Lymegrass	X	P	C	I,Ii,iii
21	*Plantago asiatica* Linn.	Asia Plantain	M	P	H	I,Ii,iii
22	*Phlomis umbrosa* Turcz.	Jerusalemsage	M	T	Y	ii
23	*Rosa bella* Rehd. Et Wils.	Solitary Rose	M	S	PH	ii
24	*Potentilla chinensis* Ser.	China Cinquefoil	M	P	H	I,Ii,iii
25	*Dianthus chinensis* Linn.	China Pink	MX	P	C	I,Ii,iii
26	*Lithospermum erythrorhizon* Sieb. et Zacc	Gromwell	X	T	T	I,Ii,iii
27	*Astragalus membranaceus* (Fisch.) Bunge	Milkvetch	XM	P	H	I,Ii,iii
28	*Thalictrum petaloideum* Linn.	Petalformed Meadowrue	M	P	H	Ii,iii
29	*Scabiosa tschiliensis* Grün	N. China Bluebasin	M	P	H	I,Ii,iii
30	*Adenophora stricta* Miq.	Ladybell	M	P	C	Ii,iii
31	*Gakuyn aparine var. Tenerum* Rchb.	Tender Bedstraw	M	T	T	ii
32	*Deutzia parviflora* Bunge	Smallflower Deutzia	MX	S	PH	ii
33	*Saussurea japonica* (Thunb.) DC.	Windhairdaisy	M	T	T	Ii,iii
34	*Saposhnikovia divaricata* (Turcz.) Schischk.	Fangfeng	XM	P	H	Ii,iii
35	*Viburnum schensianum* Maxim.	Shaanxi Arrowwood	M	S	PH	ii
36	*Potentilla discolor* Bunge	Discolor Cinquefoil	X	P	H	iii

environmental factors such as slope direction, water content in soil and altitude, which shows that the results of DCA ordination successfully reveal the characteristics of species distribution and the law of community succession on abandoned hilly lands in Shanxi.

Changes in species diversity

Species heterogeneity, dominance, richness and evenness in each quadrat were measured using the four indices described above. The first DCA axis was used horizontally to represent the succession gradient; that is, the succession periods became longer from right to left along the first DCA axis. The values of the diversity indices were used as the vertical axis to display the changes in species diversity (Figure 6). At the same time, all the four species diversity indices were tested using a one-way analysis of variance followed by multiple comparisons (Duncan's). The results showed that they have significant difference between herbage stage and shrub stage or forest stage ($P<0.01$, $P<0.05$).

Figure 6a shows that the heterogeneity (H) of species clearly increased during the community succession

Table 1. Contd.

Species No.	Species name		Ecotype	Growth-form	Life-form	Found in stage associations
37	*Bidens parviflora* Willd.	Smallflower Beggarticks	X	T	T	Ii,iii
38	*Melilotus officinalis*(Linn.)Pall	Yellow Sweetclover	XM	T	T	iii
39	*Sonchus oleraceus* Linn.	Common Sowthistle	M	T	T	I,ii
40	*Rubia cordifolia* Linn.	India Madder	M	T	T	Ii,iii
41	*Lespedeza floribunda* Bunge	Flowery Bushclover	M	S	PH	I,Ii,iii
42	*Hierochloe odorata*(Linn.)Beauv.	Vanillagrass	MX	T	T	I,Ii,iii
43	*Lespedeza dahurica*(Laxm.)Schindl.	Xing'an Bushclover	X	S	CH	I,Ii,iii
44	*Ligusticum filisectum* (Nakai et Kitag.)Hiroe	Silkleaf Ligusticum	M	P	C	Ⅰ, Ⅱ, Ⅲ
45	*Vicia amoena* Fisch. ex DC.	Wild Vetch	M	P	C	Ⅱ
46	*Pedicularis shansiensis* Tsoong	Shanxi Woodbetony	M	P	C	Ⅰ, Ⅱ, Ⅲ
47	*Potentilla supina* Linn.	Carpet Cinquefoil	MX	T	T	Ⅲ
48	*Echinops pseudosetifer* Kitag.	Pinnatifid Globethistle	X	P	C	Ⅰ, Ⅱ, Ⅲ
49	*Galium verum* Linn.	Yellow Bedstraw	MX	P	C	Ⅲ
50	*Leontopodium leontopodioides* (Wild.) Beauv.	Common Edelweiss	X	P	CH	Ⅰ, Ⅲ
51	*Saussurea irregularis* Y. L. Chen et.	Differsplit Wiindhairdaisy	XM	P	C	Ⅲ
52	*Veratrum nigrum* Linn.	Falsehellebore	M	P	C	Ⅲ
53	*Thymus mongolicus* Ronn.	Mongo Thyme	X	P	CH	Ⅰ, Ⅱ, Ⅲ
54	*Phragmitas communi* Trin.	Reed	X	P	C	Ⅰ,Ⅲ
55	*Stipa capillata* Linn.	Needlegrass	X	P	H	Ⅱ, Ⅲ
56	*Pisum sativum* Linn.	Garden Pea	M	T	T	Ⅲ
57	*Cardamine hirsuta* Linn.	Pennsylvania Bittercress	M	P	C	Ⅱ, Ⅲ
58	*Poa sphondylodes* Trin. ex Bunge	Hard Bluegrass	X	P	H	Ⅱ, Ⅲ
59	*Artemisia capillaris* Thunb.	Diversifolious Patrinia	X	P	H	Ⅰ, Ⅱ, Ⅲ
60	*Cleistogenes squarrosa* (Trin.) Keng	Scabrous Hideseedgrass	X	P	H	Ⅱ, Ⅲ
61	*Stellaria media* (Linn.) Cyr.	Chickweed	M	T	T	Ⅱ, Ⅲ
62	Heteropappus altaicus(Willd.)Novopokr.	Altai Puppyflower	MX	P	H	Ⅰ, Ⅱ
63	*Clematis intricate Bunge*.	Intricate Clematis	M	P	H	Ⅲ
64	*Allium senescens* Linn.	Aging Leek	XM	P	C	Ⅲ
65	*Thalictrum squarrosum* Steph.	Nodding Meadowrue	M	P	C	Ⅱ
66	*Rhamnus parvifolia* Bunge	Littleleaf Buckthorn	XM	S	PH	Ⅱ
67	*Suaeda glauca* (Bunge) Bunge	Common Seepweed	X	T	T	Ⅰ
68	*Chenopodium botrys* Linn.	Feather Geranium	XM	T	T	Ⅰ

process. That is, the longer the time of abandonment, the greater the species heterogeneity. This was mainly due to the increasing number of species and the changes of life-forms (Zhang, 2000). The one-way ANOVA result showed the species heterogeneity (H') was greatly significant.

The dominance index (*DS*) is another type of species heterogeneity, which decreased with the succession process (Figure 6c). This is because the interspecies competition became severe with the species number of the community increasing during the succession process. The dominance role of some species was weakened. The one-way ANOVA result showed it was significant.

Table 1. Contd.

Species No.	Species name		Ecotype	Growth - form	Life-form	Found in stage associations
69	*Setaria viridis* (Linn.) Beauv.	Green Bristlegrass	MX	T	T	Ⅰ, Ⅱ, Ⅲ
70	*Echinochloa crusgalli* (Linn.)Beauv.	Barnyardgrass	M	T	T	Ⅰ
71	*Potentilla reptans* Linn.	Creeping Cinquefoil	M	P	H	Ⅰ
72	*Polygonum viviparum* Linn.	Bulbil Knotweed	MX	P	C	Ⅰ
73	*Mentha hlocalyxap* Briq.	Mint	M	P	C	Ⅰ
74	*Sutellaria scordifoliac* Fisch. ex Schrank	Twinflower Scullcap	MX	P	C	Ⅰ
75	*Taraxacum mongolicum* Hand. – Mazz.	Mongol Dandelion	M	P	H	Ⅰ
76	*Salsola collina* Pall.	Common Russianthistle	X	T	T	Ⅰ
77	*Bothrichloa ischaemum* (Linn.) Keng	Whitesheep grass	XM	P	CH	Ⅰ
78	*Medicago falcata* Linn.	Sickle Alfalfa	M	P	C	Ⅰ
79	*Artemisia lavandulaefolia* DC.	Lavenderleaf Sagebrush	X	P	CH	Ⅰ
80	*Fagopyrum esculentum* Moench	Buckwheat	M	T	T	Ⅰ
81	*Angelica dahurica* (Fish. ex Hoffm.) Benth.	Baizhi Angelica	M	P	C	Ⅰ
82	*Dracocephalum moldavica* Linn.	Fragrant Greenorchid	XM	T	T	Ⅰ
83	*Geranium wilfordii* Maxim.	Wilford Granebill	MX	P	C	Ⅰ
84	*Xanthium sibiricum* Patrin	Siberia Cocklebur	M	T	T	Ⅰ

The change of species richness was more obvious (Figure 6b). The richness increased with succession development, which was significantly correlated with the first DCA axis. The increase in species richness was mainly due to the increase in species number during the succession process. In the primary stage of succession, only a few herbaceous species occurred because of the poor environmental conditions. Scrub and tree species appeared when the community environments had significantly improved, the community structure had become more complex and the layer system was established. At this time, many species of different eco-types could coexist in the community, which caused an increase in species richness. The one-way ANOVA result showed it was greatly significant.

Species evenness (*EA*) showed a different pattern of change compared to species heterogeneity, and clearly decreased during the community succession process (Figure 6d). That is, the longer the time since abandonment, the lower the evenness. During the succession process, the dominant species increased, their roles became more important and the community structure and composition of the life-forms became more complicated with the change of communities from grassland stage to forest stage. All these factors contributed to the decrease of species evenness along the succession gradient. The changes in the environments of the communities also contributed to the reduction in species evenness. The one-way ANOVA result showed it was significant.

DISCUSSIONS

There are many methods for community succession analysis (Lewin et al., 1992; Heshmatti and Squires, 1997; Zhang, 2005; Du et al., 2007). Due to the irreversibility of time, space is often used instead of time-series practice, and the method of multiple plots was used to infer the trends and the succession rate during the succession study of vegetation restoration (Pichett, 1982; Aplet and Vitousek, 1994; Elgersma, 1998). 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

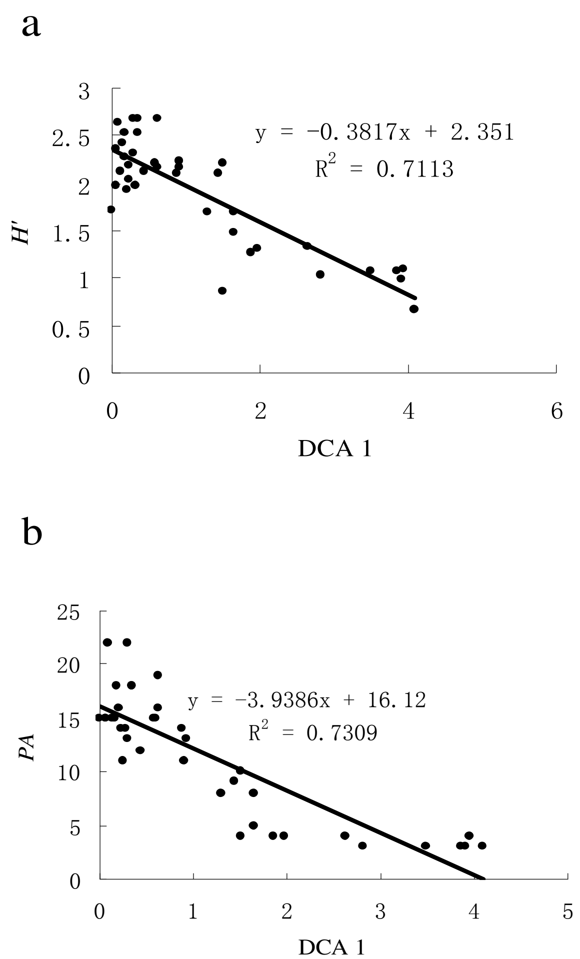

Figure 6. The changes of species heterogeneity, dominance, evenness and richness during the succession process on the abandoned hilly lands in Shanxi. (a) Shannon-Wiener heterogeneity index (H′), (b) Patrick richness index (Pa), (c) Simpson dominance index (DS), (d) Alatalo evenness index (EA).

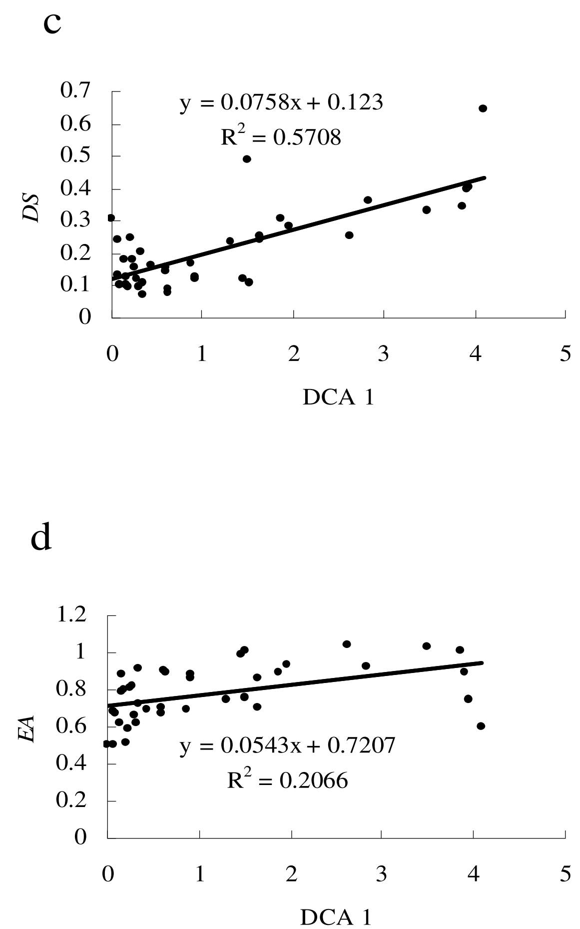

Figure 6. Contd.

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 onthe abandoned hilly lands (Figure 4-6). 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 abandoned hilly lands were as follows: Assoc. *P. chinensis* + *S. viridis* → Assoc. *A. sacrorum* + *S. viridis* + *O. caoraloa* → Assoc. *A. sacrorum* + *A. capillaries* → Assoc. *A. capillaries* + *P. shansiensis* + *E. pseudosetifer* → Assoc. *H. rhamnoides–A. sacrorum* + *C. serotina* → Assoc. *H. rhamnoides* + *O. davidia–A. sacrorum* → Assoc. *O. davidiana–A. sacrorum* + *D. chanetii* → Assoc. *P. davidiana–C. korshinskii–A. sacrorum* → Assoc. *L. principis-rupprechtii–H. rhamnoid–A. sacrorum*. Based on the results, we can establish a general model of community’s natural recovery on abandoned hilly lands in Shanxi (Figure 3).The environment of abandoned hilly lands in Shanxi was wretched with poor available nutrient, low soil water content and harsh weather, thus many species colonization and development have been affected by such terrible environment that the community stay withsimple composition and structure, low resistance ability, and slow speed of natural succession. The forest communities could not be the climax according to Clements’ definition (Clements, 1916), but they have developed into a stable stage. 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 development of forests on abandoned fields takes more than 40-50 years in the Loess Plateau (Zhang, 2005), moreover, the time of it on abandoned hilly lands takes longer.

The composition of communities varied greatly during the

Table 2. The change of species diversity indices and the one-way ANOVA on different succession stages.

Diversity indices	Herbage stage				Shrub stage			Forest stage		F
	I1	I2	I3	I4	II1	II2	II3	III1	III2	
H'	0.975	1.278	1.363	1.785	2.360	2.335	2.316	2.215	2.253	17.805**
Patrick	6	8	11	11	16	17	18	16	15	18.203**
Simpson	0.424	0.293	0.254	0.221	0.116	0.129	0.145	0.152	0.148	7.112*
EA	0.857	0.948	0.921	0.851	0.853	0.806	0.709	0.685	0.729	8.105*

Note: ***p*<0.01; **p*<0.05.

succession process. All of the dominant species present could be classified into five groups, corresponding to the three succession stages (Figure 5; Table 1 and Table 2). The pioneer species in the first stage were *S. viridis, C. serotina, P. asiatia*, *P. annua, A. sacrorum, E. dahuricus*. The typical species in the second stage were *H. rhamnoides*, *H. odorata, E. pseudosetifer*. The most common species in the third were *P. davidiana*, *L. principis-rupprechtii*, *O. davidiana*, *C. korshinskii*, *H. rhamnoides*, *A. sacrorum*, *E. dahuricus*.

The succession processes of plant communities are mainly influenced by time since abandonment. However, it is also affected by the environmental variables. The first DCA axis also represents a gradient of elevation. The second DCA axis represents a soil water content gradient. This shows that elevation of soil water content is the major limiting factors affecting community succession and vegetation restoration on abandoned hilly lands in Shanxi.

The species diversities varied greatly with the development of succession. Species heterogeneity clearly increased during the plant community succession. Species richness also slowly increased as the succession progressed (Zhang, 2005; Xu et al., 2005). Species evenness lightly decreased with succession development. Species dominance significantly decreased with the succession time extending. These results are in agreement with several formal study results (He and Chen, 1997; Zhang, 2005; Li et al., 2008). This result showed that the four indices of species diversity used in this research are efficient (Zhang, 2005; Forman and Godron, 1986). The one-way ANOVA analysis also illuminated the importance of this method (Table 2).

Conclusions

The study shows that the community succession of naturally colonized plants on abandoned hilly lands 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 on abandoned hilly lands. The most important thing is to structure stable and sustainable ecosystem in ecological restoration. A model of the natural recovery vegetation on abandoned hilly lands is established, which is of great benefit for selecting pioneer species for revegetation, and effectively speed up the community succession process in order to develop a self-maintained ecosystem on the areas in Shanxi. The proposed pioneer species are *S. viridis*, *A. sacrorum*, *O. caoraloa*, *A. capillaries*, *P. shansiensi*, *E. pseudosetifer*, *C. serotina*，*H. rhamnoides*, *O. davidia* , *C. korshinskii* , *P. davidiana* and *L. principis-rupprechtii*, etc.

Implications for vegetation restoration strategy

This present study shows that in the hill gully areas of the Loess Plateau, the natural vegetation succession, from the herbaceous stage → shrub stage → tree stage, and final to form the stable local zonal vegetation, usually needs about 60 years. But this region, because the natural environment is bad with serious soil erosion and the semi-arid and arid climate, therefore, only depends upon the natural vegetation succession rule to control soil erosion is not realistic. It must strengthen the construction of artificial vegetation. Through the artificial vegetation construction (planting, cultivation, nursing, etc.), could accelerate the rate of vegetation succession, makes this local the vegetation to restore as soon as possible, this is a very effective way.

In the process of artificial vegetation restoration, the pioneer species selection should be target-oriented and is suitable for the species in the region. According to the results of this study, any these species (*S. viridis*, *A. sacrorum*, *O. caoraloa*, *A. capillaries*, *P. shansiensis*, *E. pseudosetifer*, *C. serotina*，*H. rhamnoides*, *O. davidia*, *C. korshinskii*, *P. davidiana* and *Larix principis-rupprechtii*), can speed up the rate of vegetation succession and achieve a self-sustaining, stable artificial vegetation system as soon as possible.

In the process of artificial vegetation restoration, it is also important to configure the species model; this study shows that the effect of ecological restoration of the mixed-model of tree, bushes and grass is significant. Therefore, in the future artificial vegetation restoration process on the hill gully areas of the Loess Plateau should promote this pattern vigorously in order to accelerate soil erosion control and environmental quality improvement.

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Abbreviations

DBH, Diameter at breast height; **TWINSPAN;** two-way indicator-species analysis. **DCA,** de-trended correspondence analysis; **DS,** dominance index; **EA,** species evenness; **IV,** importance values.

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