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Soil and vegetation conditions changes following the different sand dune restoration measures on the Zoige Plateau

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Abstract

Restoration of alpine sand dunes has been increasingly attracting the attention of ecologists due to their difficulty and importance among the mountain-river-forest-farmland-lake-grass system (referred as meta-ecosystem) restoration. Alpine sand dunes are suffered from unstable soil and lack of plants. Efficient restoration measures are vital to guide the sand dune restoration. Whether the engineering materials co-applied with seeding could achieve considerable restoration in such areas? Here, sandbag and wicker as environmental friendly materials combined with *Elymus nutans* seeding were implemented on the Zoige Plateau sand dune, comparing with the 'control' treatment that only seeding. We assessed the topsoil conditions by sampled the surface soil and measured the water capacity and nutrients. We also utilized interspecific relationship and population niche to analyse the plant community structure variances among different restoration measures. Results showed that the soil conditions got clearly improved in sandbag area than that in wicker area when compared with that in control area. The community in control area was the least structured, while the species showed the closest related in sandbag area. In addition, average population niche overlap showed a control (0.26) < wicker (0.32) < sandbag (0.39) ranking. Thus, we suggested that sandbag or wicker co-applied with indigenous grass seeding is a practical and quick restoration approach in alpine sand dunes, and the sandbag may surpasses the wicker. Moreover, soil amending measures including nutrient improvement, and microbial fertilizer addition may further accelerate sand dune restoration.

Keywords: interspecific relationship; niche; *Elymus nutans*; sand barrier; restoration

1. Introduction

The terrestrial ecosystem has experienced increasingly severe land degradation and desertification [1]. Desertification threatens the ecological safety and its restoration is one of the vital elements in the mountain-river-forest-farmland-lake-grass system (referred as meta-ecosystem) restoration [2, 3]. The long-termed complex causes (e.g., overgrazing, climate change) accelerate desertification process and the sand dunes are expanding continuously on the Zoige Plateau [4-6]. Sand dunes are generally covered by nutrient devoid sandy soil that lacks favourable properties for plant growth and is prone to wind erosion [7]. The expanded sand dunes destroy fertile land and welfare of local populations. For example, they threaten livestock productivity, society development, ecological civilization, household income or human beings health [8-10]. Hence, sand dunes restoration is crucial in ensuring the conservation and sustainable development of the Zoige Plateau and meeting aspiration for better living standards in local people.

Decades worth of works have been conducted on sand dunes restoration [11, 12]. Mechanical sand barriers as the classical and simplest measure have been shown to contribute to reduce sand dunes mobility [13]. Stone or straw checkerboard barriers have been utilized to fix active sand dunes along the railway in alpine sandy land, such as Baotou-Lanzhou Railway and the eastern shore of the Qinghai Lake [14]. However, the single use of types of barriers is non-optimal choice in alpine sand dune restoration. They were often buried by sand sediments due to lack of vegetation cover eventually, in addition, traditional mechanical materials were much expensive and hard to operate [13].

Vegetation restoration is an important objective during sand dune restoration [15, 16]. It has been proved to be practical in decreasing wind velocity and increasing soil nutrients in sand dune to accelerate vegetation restoration [17-19]. Given the poor seed bank in active sand dunes, natural vegetation restoration is almost not feasible [20, 21], so that of indigenous seeds application is an inevitable method to improve seed bank [22, 23]. For example, marram grass (*Ammophila arenaria*) was one of an optimal species for sand dune restoration in Ille et Vilaine, France [11]. 'Tree-screens' and 'shelter-belt' plantations of the Thar Desert in India were launched and achieved great ecological benefits in vegetation cover [17]. Sahara mustard (*Brassica tournefortii*) usually occupied dominated status in the drier sand dune region, and the flourishing weed also could control sand dune in the semi-arid regions of Inner Mongolia [24, 25]. In addition, Farmland constructed in the Mu Us Sandy Land has changed the barren desert to fertile farmland over ten-year restoration, providing compelling evidence of biotic approaches advantages in sand dune restoration [26]. Also, shrub-planting is an effective restoration measure to fix the sand dune in the semiarid Mu Us desert [27].

Although there were plenty of successful project cases of sand dunes restoration around the world previously, few of them were suitable for sand dune restoration on the alpine area. Here, we focus on two environmental friendly barrier materials (i.e., Poly Lactic Acid sandbag and *Salix paraplesia* wicker) that are easily reproducible and durable in harsh conditions. Poly Lactic Acid is hydrophilic, ultraviolet radiation resistance, and easy transportation [28], making them as optimal barrier materials in sand dune restoration on the Zoige Plateau. Meanwhile, *S. paraplesia* is widely cultivated in alpine area which makes it convenient to acquire wicker materials. These two materials combined with indigenous grass (*Elymus nutans*) were used with expectation to fix the active sand dune on the alpine sand dunes. Our objectives were compare the different restoration approaches' effects on the alpine sand dunes and expect to provide a suitable strategy for alpine sand dune restoration.

2. Materials and Methods

2.1. Study area

The study area is located in Xiaman, Assi Township, on the Zoige Plateau (3,486 m asl.), which is characterized by an alpine continental monsoon climate with a pronounced winter season. The annual average temperature is 2.5°C and the average annual rainfall is 520 mm. The maximum wind speed is up to 36 m/s, with northwest prevailing winds [9]. The soil is dominated by alpine or subalpine meadow soil, with marshlands distributed throughout. Over the years, the land degradation process has increased greatly. Thus it led to types of degraded landscapes, form a large area of active sand dune. The active sand dune has caused serious threatens to ecological safety.

2.2. Field investigation design and sampling

We established a restoration demonstration zone in a 10 ha degraded land in which active sand land occupied more than 55%. This area is a typical degraded alpine land on the Zoige Plateau. We employ sandbag and wicker as sand barrier materials combined with *Elymus nutans* (60 kg hm^{-2}) sowing in the study area (referred as “sandbag” and “wicker”). The sand dune that only implemented sowing was set as ‘control’. Thus, three restoration measures areas consist of control, wicker, and sandbag area were organized in a randomized block design in the restoration demonstration zone. The barrier checkerboard was 2.0 m × 2.0 m × 0.3 m. (Fig 1)

108 quadrats were randomly investigated in three restoration areas at the third growth season after the restoration measures were implemented. Parameters of plant taxa, natural plant height, species cover and stem number were recorded. Surface soil in each quadrat was sampled by soil core, sieved (<

2 mm) to filter out gravel or plant roots and divided into three subsamples. One was saved in a refrigerator (4°C) for microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) determination by the chloroform fumigation-incubation method co-applied with an N/C Analyser (multi N/C® 3100 TOC, analytikjena, Germany); one was air-dried to measure total soil organic carbon (thereafter SOC) by titrimetry, total soil nitrogen (TN), total soil phosphorus (TP), soil ammonium nitrogen (AN), soil nitric nitrogen (NN), soil available phosphorus (AP) by Smartchem Discrete Auto Analyzer (Smartchem 200, AMS/Westco, Italy); and one was used for soil moisture determination using the gravimetrical method by drying at 105°C.

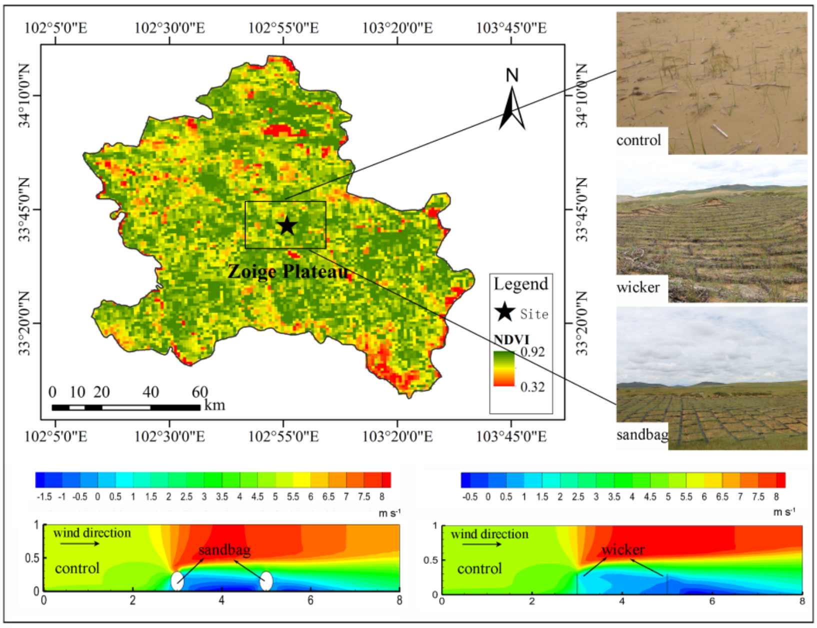

Fig 1. Demonstration area and speed flow distribution characteristics of different restoration measure on the Zoige Plateau

2.3 Data analysis

The species importance value (*IV*) was calculated using the following equation:

$$IV = \frac{relative\ cover + relative\ height + relative\ density}{3}$$

The Jaccard interspecific association (*JI*) test was conducted based on the 2 × 2 contingency tables by the plant investigation data (Table 1).

Table 1. Illustration of the 2×2 contingency tables.

	Quadrats number of species j appeared	Quadrats number of species j absented
Quadrats number of species i appeared	a	b
Quadrats number of species i absented	c	-

$$JI = \frac{a}{a+b+c}$$

The *JI* value was classified into 4 grades: none association, $0 \leqq JI \leqq 0.25$; weak association, $0.25 < JI \leqq 0.5$; middle association, $0.5 < JI \leqq 0.75$; and song association, $0.75 < JI \leqq 1.0$ [29].

Furthermore, the Spearman rank correlation ($r(i,\ k)$) was tested to assess the interspecific correlation degree.

$$r(i,k) = 1 - \frac{6\sum_{j=1}^{N}(x_{ij} - x_{kj})^2}{N^3 - N}$$

Here, $r(i,\ k)$ is the correlation coefficient between species i and k, x_{ij} and x_{kj} are the importance values of species i and k in quadrat j.

Additionally, niche theory has been widely used in the study of plant community ecology [30]. Niche breadth and overlap are important indices to further quantify the resource utilization efficiency and competition/coexistence of different populations [31-33]. Shannon-Wiener niche breadth (B_i) was calculated following Colwell & Futuyma [34] and The Pianka niche overlap (O_{ik}) was calculated using the following equation [35]:

$$B_i = -\sum_{j=1}^{r}(P_{ij} \ln P_{ij})$$

$$P_{ij} = {n_{ij}}/{N_{ij}}$$

$$O_{ik} = \frac{\sum_{j=1}^{r} P_{ij}P_{kj}}{\sqrt{(\sum_{j=1}^{r} P_{ij})^2 (\sum_{j=1}^{r} P_{kj})^2}}$$

Here, P_{ij} and P_{kj} are a proportion of quadrat *j* among the total quadrats occupied by species *i* and *k*; *r* is the total number of quadrats. The n_{ij} is the importance values of species *i* in quadrat *j* and $N_{ij} = \sum n_{ij}$.

The soil metric and species richness data were calculated using MS Excel 2010, and statistical analyses were performed using SPSS Statistics 20.0 (P<0.05) (SPSS Inc., Chicago, IL, US). The soil condition graphs were run with OriginPro 2016 (OriginLab Corporation, Northampton, MA, US). The map was created with ArcGIS v10.2. The speed flow distribution characteristics were simulated by Gambit 2.4, Fluent 16.0, and Tecplot 360. The niche overlap matrix diagram was run with the 'Lattice' package in R. The Jaccard interspecific association graphs, niche overlap matrix diagrams, and field experimental site pictures were merged by Adobe Photoshop CS6 v6.0.335.0.

3. Results

3.1. Plant composition and soil conditions in different restoration area

We recorded 9, 12, and 10 plant species in the sandbag, wicker and control area, respectively. The vegetation cover increased by 161.99% in wicker area and 331.67% in sandbag area compared with that in control (P<0.05). The same species importance values varied among the different restoration area. The *E. nutans* occupied the dominant position in all restoration area, especially in the sandbag area in which its importance value was up to 52.89. (Table 2)

Table 2. Plant composition, importance value (*IV*), niche breadth (*Bi*), and vegetation cover (VC) in different restoration area.

Sandbag				Wicker				Control			
Species	*IV*	*Bi*	VC	Species	*IV*	*Bi*	VC	Species	*IV*	*Bi*	VC
En.	52.89	1.55		*En.*	32.03	1.54		*En.*	39.57	1.55	
Cm.	17.04	1.54		*Ls.*	19.43	1.48		*Cm.*	19.64	1.42	
Ls.	10.86	1.50		*Hb.*	12.21	1.50		*Kr.*	17.77	1.46	
Hb.	8.19	1.41		*Of.*	10.98	1.40		*Ls.*	7.48	1.17	
Of.	7.78	1.39	19.08	*Hl.*	7.61	1.40	11.58	*Pb.*	4.38	0.91	4.42
Fo.	1.43	0.69	±0.77c	*Cm.*	7.48	1.11	±0.70b	*Hb.*	4.20	1.07	±0.16a
Dh.	1.27	0.82		*Kr.*	5.52	1.24		*Hl.*	2.28	0.76	
Ms.	0.31	0.48		*Am.*	1.27	0.58		*Of.*	2.03	0.48	
Od.	0.23	0.30		*Ps.*	1.24	0.38		*Dh.*	1.82	0.69	
				Ms.	0.87	0.77		*Ms.*	0.82	0.48	
				Sc.	0.84	0.48					
				Ap.	0.54	0.48					

Note: *En., Elymus nutans; Cm., Carex moorcroftii; Kr., Kobresia robusta; Ls., Ligusticum scapiforme; Pb., Potentilla bifurca; Hb., Heteropappus bowerii; Hl., Hypecoum leptocarpum; Of., Oxytropis falcate; Dh., Dracocephalum heterophyllum; Ms., Microula sikkimensis; Am., Artemisia macrocephala; Ps., Polygonum sibiricum; Sc., Salsola collina; Ap., Axyris prostrata; Fo., Festuca ovina; Od., Oxytropis densa.*

The soil water capacity and nutrient metrics increased greatly in the area where the sand barriers were implemented (P<0.05). The atomic ratios of SOC: TN, SOC: TP, TN: TP, and MBC: MBN varied in different restoration area. Comparing with the control, MBC: MBN ratios decreased a lot in sandbag area and wicker area, while the SOC: TP and TN: TP ratios increased. In more detail, the SOC: TN and MBC: MBN were only 11.67± 1.46 and 10.57± 0.21 in sandbag area, which was lower than that in wicker and control areas; the MBC: MBN in sandbag area was less than one-half of that in control area. The TN: TP and the SOC: TP ratios also were the highest in sandbag area while lowest in control area. (Table 3; Fig 2)

Table 3. The soil conditions variances in different restoration area ($P < 0.05$).

	Moisture/ %	TN / g kg^{-1}	TP/ g kg^{-1}	AN/ mg kg^{-1}	NN/ mg kg^{-1}	AP/ mg kg^{-1}	SOC/ g kg^{-1}	MBC/ mg kg^{-1}	MBN/ mg kg^{-1}
Sandbag	4.11 a ±0.02	0.19 a ±0.02	0.30 a ±0.00	24.93 a ±2.04	7.68 a ±0.24	84.05 a ±0.24	2.19 a ±0.10	65.83 a ±0.31	6.23 a ±0.14
Wicker	3.60 b ±0.02	0.10 b ±0.01	0.33 a ±0.01	22.19 a ±1.24	5.78 b ±0.50	73.37 b ±0.34	1.66 b ±0.09	52.37 b ±0.17	3.53 b ±0.14
Control	2.81 c ±0.08	0.06 b ±0.00	0.22 b ±0.02	13.39 b ±0.55	3.07 c ±0.74	43.80 c ±0.71	0.95 c ±0.03	15.27 c ±0.60	0.67 c ±0.07

Note: The different lowercase letters means significant difference in a certain soil condition ($P < 0.05$).

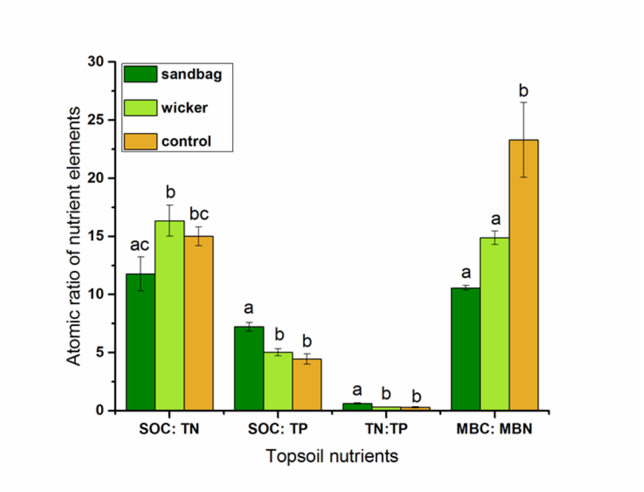

Fig 2. The soil nutrients atomic ratios in different restoration area. The different lowercase letters means significant difference in a certain pair-wise ($P < 0.05$).

3.2. Interspecific relationship in different restoration area

The summed ratio of none and weak associations were 93.33%, 83.33%, and 75.00% in control, wicker, and sandbag areas, respectively. Both of strong and middle association ratios rank was control < wicker < sandbag. The plant community was the simplest structured in the control area, and less structured in wicker area compared with that in sandbag area where the species association degree was stronger. It indicated that the community stability and community development status got better in sand barriers areas (Fig 3).

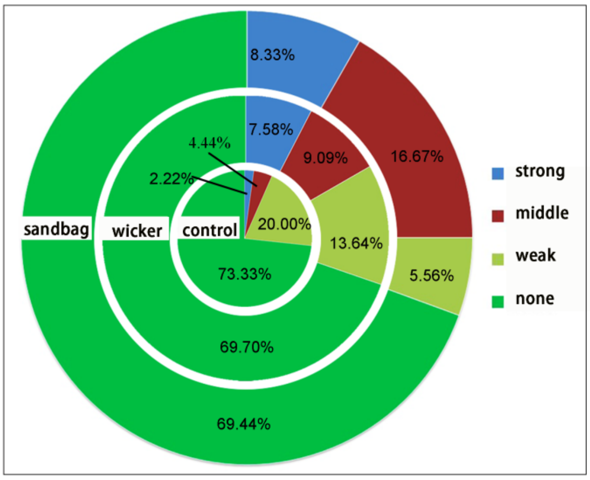

Fig 3. The Jaccard interspecific association (*JI*) ratios in different restoration area.

The species Spearman rank correlation indices were mostly negative in all restoration areas. *E. nutans* was negatively correlated with most of plants. The positive correlation ratio was the lowest in sandbag area. In addition, the same species pair interspecific correlation changed when the sand barriers were implemented to fix the active sand land. For example, the interspecific correlation of *E. nutans-C. moorcroftii* changed from greatly negative correlation to positive correlation (-0.47 ($P< 0.01$) in control, -0.18 in wicker, and 0.10 in sandbag area); and the negative correlation degree of *E. nutans-H. bowerii* was enhanced in wicker and sandbag area (-0.08 in control, -0.34 ($P< 0.05$) in wicker, and -0.47 ($P< 0.01$) in sandbag area) (Tables 4-6).

Table 4. Spearman rank correlation between species-pair in sandbag area.

	En	*Cm*	*Ls*	*Hb*	*Of*	*Fo*	*Dh*	*Ms*
Cm	0.096							
Ls	-0.217	-0.149						
Hb	-0.466**	-0.050	-0.266					
Of	-0.006	-0.489**	-0.318	-0.189				

Fo	-0.055	0.113	-0.528**	0.148	-0.081			
Dh	-0.339*	-0.363*	0.629**	-0.071	-0.246	-0.195		
Ms	-0.470**	-0.254	-0.442**	0.393*	0.395*	0.508**	-0.147	
Od	-0.108	0.203	-0.265	0.190	-0.084	-0.097	-0.118	-0.073

Table 5. Spearman rank correlation between species-pair in wicker area.

	En	*Ls*	*Hb*	*Of*	*Hl*	*Cm*	*Kr*	*Am*	*Ps*	*Ms*	*Sc*
Ls	-0.128										
Hb	-0.336*	-0.345*									
Of	-0.150	0.225	-0.237								
Hl	-0.269	-0.196	0.005	-0.275							
Cm	-0.179	-0.689**	0.526**	-0.214	0.053						
Kr	0.337*	0.395*	-0.488**	-0.162	-0.047	-0.747**					
Am	-0.416*	-0.145	0.195	-0.151	0.304	-0.054	-0.147				
Ps	-0.359*	-0.344*	0.180	-0.075	0.242	0.175	-0.279	0.585**			
Ms	-0.511**	0.022	0.143	0.218	0.153	0.099	-0.119	-0.157	-0.134		
Sc	0.202	-0.478**	0.339*	-0.394*	-0.394*	0.533**	-0.279	-0.106	-0.091	-0.134	
Ap	0.363*	-0.172	-0.479**	0.196	0.060	-0.243	0.348*	-0.106	-0.091	-0.134	-0.091

Table 6. Spearman rank correlation between species-pair in control area.

	En	*Cm*	*Kr*	*Ls*	*Pb*	*Hb*	*Hl*	*Of*	*Dh*
Cm	-0.465**								
Kr	0.102	-0.614**							
Ls	-0.314	-0.277	0.068						
Pb	-0.019	-0.181	0.405*	-0.241					
Hb	-0.085	0.405*	-0.487**	-0.380*	-0.392*				
Hl	0.118	0.101	-0.455**	-0.359*	-0.253	0.701**			
Of	0.278	0.312	-0.436**	-0.243	-0.172	-0.207	-0.134		
Dh	-0.207	-0.326	0.246	0.596**	-0.228	-0.275	-0.178	-0.121	
Ms	-0.376*	0.082	0.027	0.224	-0.172	-0.207	-0.134	-0.091	-0.121

Note: *, $P < 0.05$; **, $P < 0.01$.

3.3. Niche breadth and overlap in different restoration area

Population niche breadth and niche overlap analyses could effectively assess the resources utilization and interspecific competition. The niche breadth ranged from 0.48 to 1.55 in control area, 0.38 to 1.54 in wicker area, and 0.29 to 1.55 in sandbag area. *E. nutans* had the widest niche breadth in all restoration areas. And the drought resistance plants, such as *H. bowerii*, and *C. moorcroftii* also occupied a relative wide niche breadth in all restoration areas. Furthermore, sand barriers provided a possibility for some other species' dispersal and settle down, such as *P. sibiricum*, *S. collina*, and *F. ovina* (Table 2).

The average population niche overlap indices in sandbag, wicker, and control areas were 0.39, 0.32, and 0.26, respectively. Furthermore, the niche overlap indices species pair number ratio that higher than 0.50 were 33.33%, 25.76%, and 20.00% in sandbag, wicker, and control areas, respectively. The increased niche overlap indicated that the competition was stronger after the sand barriers were implemented. Moreover, there was a stronger effect of sandbag sand barriers on plant community (Figure 4).

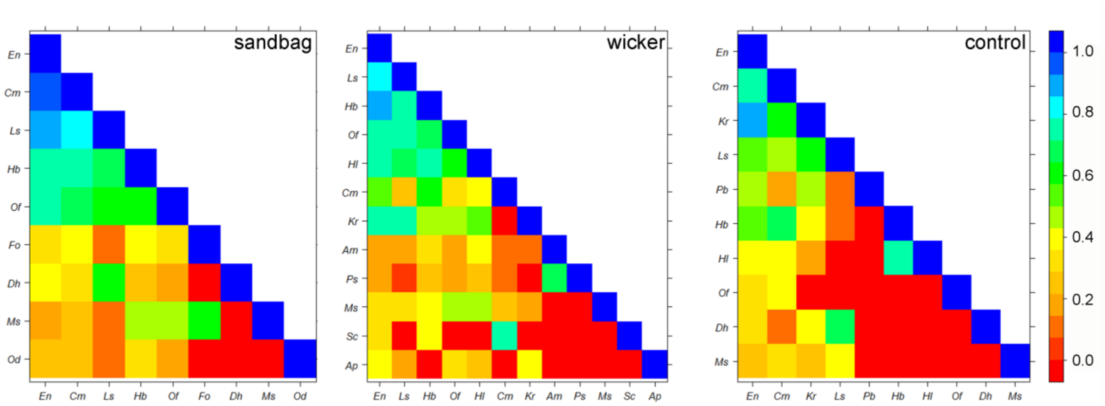

Figure 4 Niche overlap of all plant pairs in different restoration area

4. Discussion

The sandbag and wicker sand barriers co-applied with seeding amendment were both practical approaches and were better than that only seeding during alpine sand dunes restoration. The vegetation and soil conditions were the best in the sandbag area and also were improved greatly in the wicker area compared with the control. In the control area, the soil was extremely droughty and poor, and the vegetation cover was also the lowest. The soil moisture and nutrients conditions are the preconditions that regulate the plant growth on the sand dune [36]. The soil moisture and nutrient conditions were improved greatly in the sandbag area. The sandbag is airtight whereas the wicker has a higher porosity and there was no protection in the control area. This difference leads to different near-surface wind velocities that pass by the restoration area [37, 38] (Fig 1). The strong wind would take away the soil water and destabilize the surface soil which makes it difficult for plant to sprout and grow. In addition, although the soil nutrients were was lower than the wetland where the TN was 4.9-12.0 g kg^{-1} on the Zoige Plateau [39], they were promoted greatly under wicker or sandbag amendments. The greatly increased microbial mass indicated higher microbe richness. Hence, it accelerated the litter decomposition in the soil and fed back a nutrients increasing which promoted the nitrogen content and led a lower MBC: MBN ratios [40]. The SOC: TN ratio in sandbag area also decreased to close to the level of the meadow on the Zoige Plateau (SOC: TN=11.8) [41]. Nonetheless, the SOC: TP and TN: TP ratios were far less than the ratios reported in the meadow which indicated a clear phosphorus inhibition [42]. These changes suggested that the nutrients inhibition degree was reduced, such as nitrogen inhibition was reduced, when the sand barriers were implemented. And the amendment effect of sandbag sand barrier on soil conditions was stronger than that of wicker. Moreover, soil amendments may also provide indispensable assistance during the sand dunes restoration. Except for soil nutrients regulation, bioactive fertilizer amendment may also be an effective and environmentally friendly measure to promote the microbial biomass and accelerate restoration in alpine areas [43, 44].

Plant interspecific association is important for revealing how species interact with each other and adapt with the environment, and hence have important implications for optimal restoration in degraded ecosystems [45]. Species interspecific relationships or niches play a critical role in stabilizing community [30, 46]. The tighter interspecific correlation and higher niche overlap reflected a stronger plants competitive relationship when the sand barriers were conducted [47]. The population space occupancy and correlation degree was the lowest in control while highest in sandbag area. Hence, the sandbag barrier may lead to the best plant community development in sand dune restoration [37]. The interspecific association degree was enhanced when the community was improved by wicker or sandbag barriers. However, some previous studies stated that interspecific competition/association intensity reduced gradually with the plant community development [48, 49]. The plant community that developed in alpine sand dunes area was still with limited structure and minimal resource acquisition ability, thus the independence between vascular plants was strong in such barren habitat [50].

Plant communities in sand dunes area are sensitive and vulnerable to environment changes, indicating the orientation of plant community development as well [51], allowing for revealing quantitatively community assembly mechanism or community stability [49, 52]. Plant species survived and reproduced within different restoration areas, and the population niche and interspecific relationships changed along this abiotic gradient [53]. These changes stimulated the development of the sand dune community [49, 54, 55]. Resource variations cause populations to adopt different ecological strategies to intersect with other populations [50, 56, 57]. The *E. nutans* importance value improved in the sand barrier area, especially in the sandbag area. And it occupied the wider niche to compete for the soil and light resource with the similar strategies species and coexist with the different niche requirement species. For example, *E. nutans-C. moorcroftii* changed from greatly negative correlation to positive correlation while the negative correlation degree of *E. nutans-H. bowerii* was enhanced in wicker and sandbag area. Thus, it suggested that the seeded grass regulated the relationship with other species with similar or different strategies to adapt the changed habitat and thus increase the vegetation cover. Accordingly, we also suggested that it is important to restore sand dunes by preliminarily developing a community with different ecological strategies.

5. Conclusions

The alpine sand dunes restoration by implementing the sand barriers and indigenous grass enhances community structure and improves the soil conditions. Using sandbag or wicker sand barriers to fix the active sand dunes would gain a better restoration effect than that only seeding. Moreover, sandbag sand barrier allowed for a better restoration of harsh soil conditions and plant community. We suggest that species interspecific relationships and niche breadth could assess the sand dune restoration efficiency well. And the soil amending measures including nutrient improvement, and microbial fertilizer addition may further accelerate sand dune restoration.

Author Contributions

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Formal analysis: Jiufu Luo.

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Methodology: Jiufu Luo, Dongzhou Deng, Jinxing Zhou.

Project administration: Li Zhang, Dechao Chen.

Resources: Dongzhou Deng, Li Zhang, Dechao Chen, Xinwei Zhu.

Software: Jiufu Luo.

Supervision: Jinxing Zhou, Dongzhou Deng.

Validation: Jinxing Zhou, Dongzhou Deng.

Visualization: Jiufu Luo, Dechao Chen.

Writing ± original draft: Jiufu Luo.

Writing ± review & editing: Jinxing Zhou

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References

1. Zhao JZ, Wu G, Zhao YM, Shao GF, Kong HM, Lu Q. Strategies to combat desertification for the twenty-first century in China. International Journal of Sustainable Development & World Ecology 2002; 9(3):292-297. DOI: 10.1080/13504500209470124
2. El-Salam MMA, Elhakem AH. Desertification and its effect on the erosion of vegetation in the south-western region of Saudi Arabia. Environmental Monitoring Assessment 2016; 188: 164. DOI: 10.1007/s10661-016-5164-z

3. Zou CX， Wang Y， Wang WL, Xu DL, Lin NF, Li WJ． Theory of mountain-river-forest-farmland-lake-grass system and ecological protection and restoration research. Journal of Ecology and Rural Environment 2018; 34(11): 961-967.

4. Dong ZB, Hu GY, Yan CZ, Wang WL, Lu JF. Aeolian desertification and its causes in the Zoige Plateau of China's Qinghai-Tibetan Plateau. Environmental Earth Sciences 2010; 59: 1731-1740. DOI: 10.1007/s12665-009-0155-9

5. Gao JQ, Zhang XW, Lei GC, Wang GX. Soil organic carbon and its fractions in relation to degradation and restoration of wetlands on the Zoige Plateau, China. Wetlands 2014; 34: 235-241. DOI: 10.1007/s13157-013-0487-9

6. Yu KF, Lehmkuhl F, Falk D. Quantifying land degradation in the Zoige Basin, NE Tibetan Plateau using satellite remote sensing data. Journal of Mountain Science 2017; 14: 77-93. DOI: 10.1007/s11629-016-3929-z

7. Breckle SW, Yair A, Vest M. Arid Dune Ecosystems. Ecological Studies Springer, Berlin, Heidelberg, New York. 2008; pp. 79-89.

8. Qing Y, Sun FD, Li Y, Chen WY, Li X. Analysis of soil carbon, nitrogen and phosphorus in degraded alpine wetland, Zoige, southwest China. Acta Prataculturae Sinica 2015; 24: 38-47.

9. Shui W, Bai JP, Jian XM, Qi XH, Su ZA, Chen Y, et al. Changes in water conservation and soil physicochemical properties during the recovery of desertified grassland in Zoige, China. Acta Ecologica Sinica 2017; 37: 277-285.

10. Shen ST, Zhang SJ, Fan L, Wang Q. Classification of plant functional types based on the nutrition traits: a case study on alpine meadow community in the Zoige Plateau. Journal of Mountain Science 2017; 14: 2003-2012. DOI: 10.1007/s11629-016-4133-x

11. Roze´ F, Lemauviel S. Sand dune restoration in North Brittany, France: a 10-year monitoring study. Restoration Ecology 2004; 12: 29-35. DOI: 10.1111/j.1061-2971.2004.00264.x

12. Ohsowski BM, Dunfield K, Klironomos JN, Hart M. Plant response to biochar, compost, and mycorrhizal fungal amendments in post-mine sandpits. Restoration Ecology 2018; 26: 63-72. DOI: 10.1111/rec.12528

13. Xie SB, Qu JJ, Liu B, Xu XT. Advances in research on the sand hazards and its controls along the Qinghai-Tibet Railway. Journal of Desert Research 2014; 34: 42-48.

14. Tian LH, Wu WY, Zhang DS, Lu RJ, Wang XQ. Characteristics of erosion and deposition of straw checkerboard barriers in alpine sandy land. Environmental Earth Sciences 2015; 74(1):573-574. DOI: 10.1007/s12665-015-4059-6

15. Hu YF, Peng JJ, Yuan S, Shu XY, Jiang SL, Pu Q, et al. Influence of ecological restoration on vegetation and soil microbiological properties in Alpine-cold semi-humid desertified land. Ecological Engineering 2016; 94: 88-94. DOI: 10.1016/j.ecoleng.2016.05.061

16. Lian J, Zhao XY, Li X, Zhang TH, Wang SK, Luo YQ, et al. Detecting sustainability of desertification reversion: vegetation trend analysis in part of the agro-pastoral transitional zone in Inner Mongolia, China. Sustainability 2017; 9: 211. DOI: 10.3390/su9020211

17. Chauhan SS. Desertification control and management of land degradation in the Thar desert of India. Environmentalist 2003; 23: 219-227. DOI: 10.1023/b:envr.0000017366.67642.79

18. Raji BA, Uyovbisere EO, Momodu AB. Impact of sand dune stabilization structures on soil and yield of millet in the semi-arid region of NW Nigeria. Environmental Monitoring and Assessment 2004; 99: 181-196. DOI: 10.1007/s10661-004-4018-2

19. Li YQ, Chen YP, Wang XY, Niu YY, Lian J. Improvements in soil carbon and nitrogen capacities

after shrub planting to stabilize sand dunes in China's Horqin sandy land. Sustainability 2017; 9: 662. DOI: 10.3390/su9040662

20. Lichter J. Colonization constratints during primary succession on costal Lake Michigan sand dunes. Journal of Ecology 2000; 88: 825-839. DOI: 10.1046/j.1365-2745.2000.00503.x
21. Yan QL, Liu ZM, Zhu JJ, Luo YM, Wang HM, Jiang DM. Structure, pattern and mechanisms of formation of seed banks in sand dune system in northeastern Inner Mongolia, China. Plant and Soil 2005; 277: 175-184. DOI: 10.1007/s11104-005-6836-6
22. Fan B, Zhang A, Yang Y, Ma Q, Li X, Zhao C. Long-Term Effects of Xerophytic Shrub Haloxylon ammodendron Plantations on Soil Properties and Vegetation Dynamics in Northwest China. PLoS ONE 2016; 11(12): e0168000. DOI: 10.1371/journal.pone.0168000
23. Dietterich LH, Casper BB. Initial soil amendments still affect plant community composition after nine years in succession on a heavy metal contaminated mountainside. Restoration Ecology 2017; 25: 201-210. DOI: 10.1111/rec.12423
24. Barrows CW, Allen EB, Brooks ML, Allen MF. Effects of an invasive plant on a desert sand dune landscape. Biological Invasions 2009; 11: 673-686. DOI: 10.1007/s10530-008-92826
25. Masayuki N, Toshiya O, Xu B. The role of weed invasion in controlling sand dune reactivation in abandoned fields in semi-arid Inner Mongolia, China. Ecological Research 1997; 12: 325-336. DOI: 10.1007/BF02529462
26. Wang T, Zhu Z, Wu W. Sandy desertification in the north of China. Science of China (Series D) 2002; 45: 23-34.
27. Fan DQ, Zhang YQ, Qin SG, Wu B. Relationships between Artemisia ordosica communities and environmental factors following sand-dune stabilization in the Mu Us desert, northwest China.

Journal of Forestry Research 2017; 28(1):115-124. DOI: 10.1007/s11676-016-0289-z

28. Wei YJ, Zuo XF, Wang J, Dang XH, Liu XJ. Summarization of application of mechanical sand barrier in desertification control. Journal of Inner Mongolia Agricultural University (Natural Science Edition) 2017; 6: 86-93.

29. Kong YY, Yu YW, Hou FJ. Interspecific associations in plant communities under yak dung depositions in an alpine meadow. Acta Prataculturae Sinica 2017; 26: 44-52.

30. Levine JM, HilleRisLambers J. The importance of niches for the maintenance of species diversity. Nature 2009; 461: 08251. DOI: 10.1038/nature08251

31. Anthwal S, Bhatt AB, Nautiyal BP, Anthwal A. Vegetation structure, niche width, niche overlap and types of competition in temperate grazingland of Garhwal Himalaya, India. Environmentalist 2008; 28: 261-273. DOI: 10.1007/s10669-007-9137-1

32. Pontes LDS, Maire V, Schellberg J, Louault F. Grass strategies and grassland community responses to environmental drivers: a review. Agronomy for Sustainable Development 2015; 35: 1297-1318. DOI: 10.1007/s13593-015-0314-1

33. Kuster TM, Wikinson A, Hill PW, Jones D, Bardgett RD. Warming alters competition for organic and inorganic nitrogen between co-existing grassland plant species. Plant and Soil 2016; 406:117-129. DOI: 10.1007/s11104-016-2856-7

34. Colwell RK, Futuyma DJ. On the measurement of niche breadth and overlap. Ecology 1971; 52: 567-576. DOI: 10.2307/1934144

35. Pianka ER. The structure of lizard communities. Annual Review of Ecology and Systematics 1973; 4: 53-74. DOI: 10.1146/annurev.es.04.110173.000413

36. Yang TT, Ala M, Zhang YS, Wu JB, Wang AZ, Guan DX. Characteristics of soil moisture under

different vegetation coverage in Horqin Sandy Land, northern China. PLoS ONE, 2018; 13(6): e0198805. DOI: 10.1371/journal.pone.0198805

37. Yuan LM, Gao Y, Wang J, Yan DR, Hu SR, Zhang XY, et al. Impacts of sandbag barrier on sand flow and vegetation restoration on mobile dunes. Bulletin of Soil and Water Conservation 2014; 34: 46-50.

38. Yu Y, Jia ZQ, Zhu YJ, Zhao SL, Liu HT, Li QX, et al. Root distribution of Salix chelophila along a chronosequence in high-cold sandland. Journal of Desert Research 2014; 34(1): 67-74. DOI: 10.7522/j.issn.1000-694X.2013.00188

39. Ma K, Zhang Y, Tang SX, Liu JG. Characteristics of spatial distribution of soil total nitrogen in Zoige alpine wetland. Chinese Journal of Ecology 2016; 35: 1988-1995. DOI: 10.13292/j.1000-4890.201608.010

40. Aponte C, Marañón T, García L. Microbial C, N, and P in soils of Mediterranean oak forests: influence of season, canopy cover and soil depth. Biogeochemistry 2010; 101: 77-92. DOI: 10.1007/s10533-010-9418-5

41. Lin L, Zhang FW, Li YK, Han DR, Guo XW, Cao GM. The soil carbon and nitrogen storage and C/N metrological characteristics of chemistry in *Kobresia humilis* meadow in degradation succession stage. Chinese Journal of Grassland 2012; 34: 42-47.

42. Manzoni S, Trofymow JA, Jackson RB, Porporato A. Stoichiometric controls on carbon, nitrogen, and phosphorus dynamics in decomposing litter. Ecological Monographs 2010; 80: 89-106. DOI: 10.1890/09-0179.1

43. Wu F, Liu CW, Chen HK, Diao ZF, Zhao S, Xie H. Use of nutrient medium technique for vegetation restoration in Karst region of Southwest China. Journal of Integrative Environmental

Sciences 2018; 15(1):135-155. DOI: 10.1080/1943815X.2018.1471725

44. de Santiago A, Recena R, Perea-Torres F, Moreno MT, Carmona E, Delgado A. Relationship of soil fertility with biochemical properties under agricultural practices aimed at controlling land degradation. Land Degradation & Development, 2019; DOI: 10.1002/ldr.3298
45. Zhang ZH, Hu G, Zhu JD, Luo DH, Ni J. Spatial patterns and interspecific associations of dominant tree species in two old-growth karst forests, SW China. Ecological Research 2010; 25:1151-1160. DOI: 10.1007/s11284-010-0740-0
46. Díaz S, Cabido M. Plant functional types and ecosystem function in relation to global change. Journal of Vegetation Science 1997; 8: 463-474. DOI: 10.2307/3237198
47. Odriozola I, García-Baquero G, Etxeberria A, Aldezabal A. Patterns of species relatedness created by competitive exclusion depend on species niche differences: Evidence from Iberian Atlantic grasslands. Perspectives in Plant Ecology, Evolution and Systematics. 2017; 28:36-46. DOI: 10.1016/j.ppees.2017.07.002
48. Lou YJ, Zhao KY. Analysis of interspecific association of Carex lasiocarpa community in recent 30-year succession in Sanjiang Plain. Chinese Journal of Ecology 2008; 27: 509-513.
49. Gong R, Gao Q, Wang YL. Effects of exclosure on community inter-specific relationships in a typical temperate grassland. Journal of Plant Ecology 2016; 40: 554-563.
50. Harpole WS, Suding KN. A test of the niche dimension hypothesis in an arid annual grassland. Oecologia 2011; 166: 197-205. DOI: 10.1007/s00442-010-1808-9
51. Nathan R. Long-distance dispersal of plants. Science 2006; 313: 786-788. DOI: 10.1126/science.1124975
52. Álvarez-Yépiz JC, Dovčiak M. Ontogenetic shifts in plant-plant interactions in a rare cycad within

angiosperm communities. Oecologia 2014; 175: 725-735. DOI: 10.1007/s00442-014-2929-3

53. Cornwell WK, Ackerly DD. Community assembly and shifts in plant trait distributions across an environmental gradient in coastal California. Ecological Monographs, 2009; 79(1), 109-126. DOI: 10.1890/07-1134.1

54. Callaway RM. Competition and facilitation: Contrasting effects of Artemisia tridentata on desert vs montane pines. Ecology 1996; 77: 2130-2141. DOI: 10.2307/2265707

55. Callaway RM, Brooker RW, Choler P, Kikvidze Z, Lortie CJ, Michalet R, et al. Positive interactions among alpine plants increase with stress. Nature 2002; 417: 844-848. DOI: 10.1038/nature00812

56. Chen YR, Yin LK. Community composition and niche change characteristics of dominant species in the wind-breaking and sand-fixing forest, Xinjiang, China. Journal of Plant Ecology 2008; 32: 1126-1133.

57. Bewick S, Chisholm RA, Akcay E, Godsoe W. A stochastic biodiversity model with overlapping niche structure. Theoretical Ecology 2015; 8: 81-109. DOI: 10.1007/s12080-014-0227-7