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The stability of various community types in sand dune ecosystems of northeastern China

Estabilidad de varios tipos de comunidad en ecosistemas de dunas en el noreste de China

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Abstract

The stability of artificial, sand-binding communities has not yet fully studied. A similarity index was developed to evaluate the stability of artificial communities in shifting and semi-fixed sand dunes. This similarity index consisted of 8 indicators (*i.e.*, vegetation cover, Shannon-Wiener Index, biomass, organic matter, Total N, available P and K, and sand particle ratio). The relative weight of these indicators was obtained using an analytic hierarchy process (AHP) method. Stability was compared on *Artemisia halodendron* Turczaninow ex Besser, Bull communities in shifting and semi-fixed sand dunes, and of *Caragana microphylla* Lam. communities with different planting ages. The similarity indexes of the *A. halodendron* communities were 0.24 and 0.54 in shifting and semi-fixed sand dunes, respectively. The peak stability of *C. microphylla* communities was 0.55, and it was reached when these communities were 20-year-old. It is suggested that *A. halodendron* communities should be planted preferentially in semi-fixed to moving sand dunes. Furthermore, the planting age of artificial communities should be included in planting programs. This study improved the understanding of some mechanisms contributing to maintain community stability, and is critical for guiding the artificial planting in sand dunes.

Keywords

Artemisia halodendron • analytic hierarchy process • *Caragana microphylla* • sand dunes • stability indicators

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Resumen

La estabilidad de comunidades artificiales que contribuyen a la fijación de suelos arenosos no se ha estudiado completamente. Se desarrolló un índice de similitud para evaluar la estabilidad de comunidades artificiales en dunas móviles y fijadas medianamente. Este índice de similitud consistió de 8 indicadores (cobertura vegetal, índice de Shannon-Wiener, biomasa, materia orgánica, N total, P y K disponibles, y relación de partículas de arena). La importancia relativa de estos indicadores se obtuvo utilizando un método de procesamiento jerárquico analítico (AHP). Se comparó la estabilidad de comunidades de *Artemisia halodendron* Turczaninow ex Besser, Bull en dunas móviles y fijadas medianamente, y la de comunidades de *Caragana microphylla* Lam. de diferentes edades de plantación. Los índices de similitud de las comunidades de *A. halodendron* fueron 0,24 y 0,54 en dunas móviles y fijadas medianamente, respectivamente. La estabilidad máxima de las comunidades de *C. microphylla* fue 0,55, la que se obtuvo cuando dichas comunidades alcanzaron 20 años de edad. Se sugiere que las comunidades de *A. halodendron* se deberían plantar preferencialmente en dunas fijadas medianamente a móviles. Además, la edad de plantación de las comunidades artificiales se debería incluir en programas de plantación. Este estudio mejoró el entendimiento de algunos mecanismos que contribuyen a mantener la estabilidad de las comunidades, y es crítico para guiar la plantación artificial en áreas de dunas.

Palabras clave

Artemisia halodendron • proceso analítico jerárquico • *Caragana microphylla* • dunas • indicadores de estabilidad

Introduction

Since the 1950's, desertification has attracted the attention in China. A series of ecological engineering projects were initiated to control desertification in China, especially in Horqin Sandy Land, where desertification is a major constraint to achieve sustainable development (30). Ecological restoration achieved through ecological engineering projects is considered as a major useful way to deal with desertification (15).

Establishment of artificial, sand-binding vegetation is one of the most effective techniques for ecological restoration in sand lands. After years of practice, approximately 1.21 million ha have been established of sand-binding vegetation such as *Artemisia ordosica*, *Caragana intermedia*, *and Caragana microphylla*, in arid and semi-arid desert ecosystems (17).

The effects of artificial, sand-binding communities on ecological restoration have been long studied.

The presence of these communities can gradually (1) alter the spatial distribution of nutrients (2, 27), increase soil fertility (2, 29, 40), and affect water distribution (5, 51), resulting in changes of biodiversity and vegetation cover (57). In addition, artificial, sand-binding vegetation can effectively protect the topsoil from wind erosion and trap wind-blown materials from nearby areas (36).

Although several artificial communities (*e.g.*, of *Artemisia halodendron*, *C. microphylla*, or *Salix gordejevii* Chang) are established for sand-binding in Horqin Sandy Land, they have different spatial distributions in these sand dunes (11).

Artemisia halodendron communities often appear in semi-fixed and shifting sand dunes, and disappear in fixed sand dunes. *Caragana microphylla* communities grow on semi-fixed and fixed sand dunes. *Salix gordejevii* communities mainly distribute in semi-fixed sand dunes (28).

Their different spatial distributions are due to their stabilities, whose core is their resistance and resilience in the sand dune positions. How to compare the stability of artificial communities is not yet clear.

Some empirical studies have documented stability in artificial, sand-binding communities (3). However, most previous studies are far from quantitatively comparing the stability in these artificial, sand-binding communities. This is because of two major reasons: (1) there is diversity in defining the concept of stability, and (2) the quantification of stability is far from reaching an agreement. According to an inventory, 163 definitions and 70 stability concepts have been reported (6).

The existing information of stability in some major communities is based on different definitions of that concept. For example, resilience ability has been used to assess vegetation stability in degraded grasslands in Horqin Sandy Land (49). In contrast to this, stability of *Mongolian pine* communities has been based on the assessment of survival rates, life span, and the ability to resist adverse circumstances (44).

Many variables are used to measure the stability, which represent an inconvenient at the time of comparing the stability of various artificial, sand-binding communities in arid and semiarid desert ecosystems.

Succession theory can provide an effective way to measure and compare the stability of communities.

According to the classical succession theory, communities succeed to a climax community with an increase in stability, even in rangelands, where grazing pressure might disrupt the succession (37, 38). It is suggested that the climax community is the one with the highest stability within a series of successional stages (1).

It is considered that communities are stable when their stability is similar to that of the climax community. Taking the climax community as a reference, the similarity between this and other communities could work as an indicator for measuring stability. This can be achieved by comparing the similarity between artificial and the climax communities, which have the highest stability, to have a measure of the stability of artificial plant communities.

The similarity between artificial and climax communities could be described using a similarity index. The higher the similarity index, the higher the stability of the study plant community. The similarity index should contain indicators representing the structure of communities and the functioning of ecosystems (9).

The structure of plant communities is commonly reported in biodiversity, richness and vegetation cover studies (15, 32). Meanwhile, the functioning of ecosystems is often reported in terms of biomass, nutrient content and cycling, and energy flow (23, 33).

The vegetation succession process is consistent with the sand dune fixing process in Horqin Sandy Land (48). Semi-fixed sand dunes are a subsequent stage from shifting sand dunes. Communities of *A. halodendron* appeared both in shifting and semi-fixed sand dunes (48). This led us to think that *A. halodendron* might have a higher stability in semi-fixed than in shifting sand dunes.

The dynamic of plant communities is an important aspect of the community succession process. Community succession, from a successional stage to the next one, accompanies the development of plant communities. For example, the community of *Artemisia intramongolica* changed in biomass and canopy when shifting sand dunes turned into semi-fixed and fixed sand dunes (20). This led us to think that stability might be greater in older than younger artificial, sand-binding communities.

Sparse elm (*Ulmus pumilia* L.) woodland is an original vegetation type in Horqin Sandy Land, one of the four biggest sand lands in China (31). This woodland, as a climax community, is a reference to evaluate stability of artificial plant communities. It plays a major role in reducing wind erosion, accelerating vegetation restoration, and increasing nutrient accumulation (12).

The results of this study are helpful for (1) elucidating stability-maintaining mechanisms, and (2) guiding artificial planting in sand dunes.

Objectives

- To determine the stability of *A. halodendron* in semi-fixed and shifting sand dunes.
- To evaluate the stability of artificial, sand-binding communities of various ages.
- To develop an integrated index to evaluate the stability of various artificial communities at a given time.

Materials and methods

Study site

The study was mainly conducted in Naiman county (42°15' N, 120°42 ' E, 345 m a. s. l.) and Balinyou Banner (43°12'-44°27' N, 118°12'-120°01' E, 1000 m a. s. l.).

Naiman is located in the hinterland of the Horqin Sandy Land, which has a continental semi-arid monsoon climate, and it is in the temperate zone. The mean annual precipitation is 364 mm, while the mean annual potential evaporation is 1920 mm (53).

Balinyou Banner is located in western Horqin Sand Land. Average annual temperature is 4.9°C. The mean annual precipitation is 358 mm (43).

The landscape in these two regions is characterized by dunes alternating with lowland areas. The original vegetation is sparse elm woodland at the two study sites. The current vegetation is dominated by shrubs and herbs, such as *Salix gordejevii*, *Artemisia halodendron*, *Aristida adscensionis*, *Agriophyllum squarrosum* and *Setaria viridis* (5, 52).

Sampling procedures

The data used for calculation of stability index were obtained from the literature. It was made by searching journal articles and theses published before January 2014 using the Web of Science and www.cnki.net. The selection criteria were as follows: at least one of the study, target communities was measured; all the study, target variables were measured.

Study communities included sparse elm woodland, *A. halodendron, C. microphylla* or *S. gordejevii* communities. Main species in these communities are shown in table 1 (page 109).

Table 1. Major species composition of the *Artemisia halodendron*, *Caragana microphylla*, *Salix gordejevii*, and Sparse elm woodland communities.

Tabla 1. Principales especies de las comunidades de *Artemisia halodendron*, *Caragana microphylla*, *Salix gordejevii* y *Ulmus pumila*.

Communities	Species composition	Reference
A. halodendron	*Bassia dasyphylla, Corispermum elongatum, Cynanchum thesioides, Setaria viridis*	Yin *et al.*, 2006
C. microphylla	*Corispermum elongatum, Eragrostis pilosa, Salsola ruhtenica, Setaria viridis*	He, *et al.*, 2013
S. gordejevii	*Astragalus adsurgens, Corispermum elongatum, Cynanchum thesioides, Inula salsoloides, Pennisetum centrasiaticum, Setaria viridis*	Li *et al.*, 2000
Sparse elm woodland	*Bassia dasyphylla, Chloris virgata, Cleistogenes squarrosa, Corispermum elongatum, Eragrostis pilosa, Lespedeza davurica, Pennisetum centrasiaticum, Salsola collina, Setaria viridis*	Zuo *et al.*, 2005

The study variables were vegetation cover (%), biodiversity (Shannon-Wiener Index), biomass (g m^{-2}), soil organic matter (%) and nutrient contents [Total N (mg kg^{-1}), available P (mg kg^{-1}), available K (mg kg^{-1})], and sand particle ratio [*i.e.*, sand/(sand+silt+clay)*100, %]. The sand dunes types (*i.e.*, fixed dunes, semi-fixed dunes and shifting dunes), where communities were located, were recorded. Time when communities were planted was recorded whenever it was reported. To avoid the effects of spatial heterogeneity in soil nutrient contents (56), we used a relative soil nutrient content as the indicator of soil nutrients in artificial communities (*i.e.*, the ratio of content of soil nutrients in the study communities and their adjacent regions, %). This is, soil nutrient content data were also recorded from the adjacent regions.

The final data included information from 8 theses and papers (4, 10, 16, 34, 41, 42, 45, 46). A data thief software GetData Graph Digitizer was used to extract data from figures of the selected literature (35).

In this study, the calculation process used to obtain the relative weight of the indicator variables followed that of Zhang *et al*. (2013).

The Analytic Hierarchy Process (AHP) methodology is an effective decision-making tool to deal with complex and multi-factor problems (14).

The AHP procedure includes three basic steps: (1) design of the decision hierarchy, (2) pairwise comparison of elements of the hierarchical structure, and (3) construction of an overall priority rating. This AHP was used to estimate the relative weight of indicator variables, which reflected the structure of plant communities and the functioning of ecosystems. Structure indicators were vegetation cover, and the Shannon-Wiener Index. Functioning indicators were biomass, organic matter, Total N, available P, available K, and the sand particle ratio. After establishing the hierarchical structure (*i.e.*, the study structure and functioning aspects), pairwise comparisons of indicators were judged, and its consistency was tested with the consistency ratio (CR). Finally, the relative weight of indicators was calculated.

The Similarity Index (SI) was calculated following equation (1), where W_i represented the relative weight of indicator i with respect to the total number of indicators (n). In this equation, SI_i represented the similarity in the indicators, and it was calculated following equation (2) or (3).

$$SI = \sum_{i=1}^{n} SI_i \times W_i \qquad (1)$$

$$SI_i = \frac{\mathrm{Var}_{ic}}{\mathrm{Var}_{ij}}, \mathrm{Var}_{ij} > \mathrm{Var}_{ic} \qquad (2)$$

$$SI_i = \frac{\mathrm{Var}_{ij}}{\mathrm{Var}_{ic}}, \mathrm{Var}_{ij} \leq \mathrm{Var}_{ic} \qquad (3)$$

In equations (2) and (3), Var_{ic} means the value of an *i* indicator (*i.e.*, variable=Var) on the *c* community (*i.e.*, climax community, which is sparse elm woodland in this paper). Var_{ij} represents the indicator of the current, study communities: it means the value of indicator *i* in community *j* (*j*: communities were of *A. halodendron*, *C. microphylla* or *S. gordejevii*).

In equations (1), (2) and (3) *i* means the *i* change from 1 to n (n=8), as 8 indicators were used here (*i.e.*, vegetation cover, biodiversity, biomass, organic matter, Total N, available P, available K, and the sand particle ratio).

When the value of indicator *i* in community *j* was larger than that in the climax community (*i.e.* sparse elm woodland), we used equation (2). When the value of indicator *i* in community *j* was less than or equal to that in the climax community, we used equation (3).

The SI changes in the range of 0 to 1 in equations (2) and (3). For example, let us assume that the value of the sand particle ratios in the *S. gordejevii*, *C. microphylla*, and sparse elm woodland communities were 95.21%, 90.02%, and 91.55%, respectively. We used equation (2) to calculate the SI of the sand particle ratio in the *S. gordejevii* community (0.9155/0.9521), and equation (3) to calculate the SI of the *C. microphylla* community (0.9002/0.9155).

The SI was compared among seven communities which differed in species composition, age from planting, and stage of sand dune fixation: (1) *A. halodendron* community in shifting sand dunes; (2) *A. halodendron* community in semi-fixed sand dunes; (3) 6-year-old *C. microphylla* community in semi-fixed sand dunes; (4) 14-year-old *C. microphylla* community in semi-fixed sand dunes; (5) 20-year-old *C. microphylla* community in semi-fixed sand dunes; (6) 27-year-old *C. microphylla* community in semi-fixed sand dunes; (7) sparse elm woodland community in fixed sand dunes.

Results

Relative weights of indicator variables

According to the hierarchy for assessment of the stability of artificial communities (figure 1, page 111), three comparison matrixes were developed (CR=0.0000<0.10). Since the obtained CR < 0.10, a reasonable level of consistency was achieved in the pair-wise comparisons made.

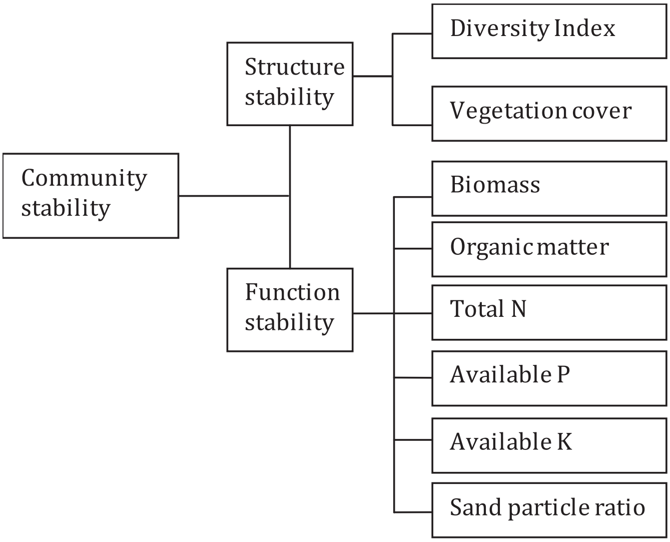

Figure 1. A hierarchy for evaluating the stability of artificial plant communities.

Figura 1. Diagrama de la jerarquía para evaluar la estabilidad de comunidades vegetales artificiales.

Table 2 clearly shows the relative contribution of each indicator variable to the total weight (*i.e.*, 1) of all indicators. It is clear that almost 75% of the contribution to the total weight of all indicators was achieved by plant-related variables.

Table 2. Relative weight of each indicator variable for evaluating stability of artificial plant communities.

Tabla 2. Importancia relativa de cada variable (indicador) para evaluar la estabilidad de comunidades vegetales artificiales.

Indicators	Weight
Diversity index	0.3750
Vegetation Cover	0.1250
Biomass	0.2405
Organic matter	0.1262
Total N	0.0343
Available P	0.0229
Available K	0.0255
Sand particle ratio	0.0506

Because of the lack of agreement between the number of communities (4) and the types of communities (7), species in each community (table 1, page 109), and the lack of mention on where each type of data was obtained from, table 3 (page 112), was included with the information on the sources of the used data.

Similarity Index

Anytime we refer to higher than, lower than, etc. in the following paragraph, it refers in terms of absolute values. This is because the values were obtained from the available literature and as a result they were not exposed to any statistical analysis.

Table 3. Community types and positions with their indicator variables are shown from previous research.

Tabla 3. Tipos y ubicación de diferentes comunidades con sus variables indicadoras se muestran de investigaciones previas.

Reference Number	References	Community types	Community positions	Indicator variables
17	Li, 2003	Sparse elm woodland	fixed-sand dunes	Diversity index, vegetation cover, biomass, sand particle ratio
44	Zhang, 2004	Sparse elm woodland	fixed-sand dunes	Organic matter, total N, available P, available K
41	Yin, 2006	*A. halodendron*	shifting-and semi fixed-sand dunes	Diversity index, vegetation cover, Biomass
33	Wang, 2006	*A. halodendron*	shifting-and semi fixed-sand dunes	Organic matter, total N, available P
4	Cao, 2007	*A. halodendron*	shifting-and semi fixed-sand dunes	Available K
45	Zhang, 2004	*A. halodendron*	shifting-and semi fixed-sand dunes	Sand particle ratio
11	Jiang, 1982	*C. microphylla*	all community ages mentioned in this study	Biomass
40	Yang, 2010	*C. microphylla*	all community ages mentioned in this study	Diversity index, vegetation cover, organic matter, total N, available P, available K, sand particle ratio

The similarity index of the *A. halodendro*n community in semi-fixed sand dunes was 0.54, which was higher than that in shifting sand dunes (figure 2, page 113).

In semi-fixed sand dunes, the 20-year-old *C. microphylla* community showed the highest similarity index (figure 2, page 113).

In general, the older the community, the higher the SI on the *C. micropylla* community located in semi-fixed sand dunes (figure 2, page 113).

The only exception was on the 27-year-old *C. microphylla* community on semi-fixed sand dunes, where the SI was lower than that on 14- and 20-year-old communities of this species on the same sand dune type.

The highest SI among all seven study communities was reached by the sparse elm woodland community on fixed sand dunes (figure 2, page 113).

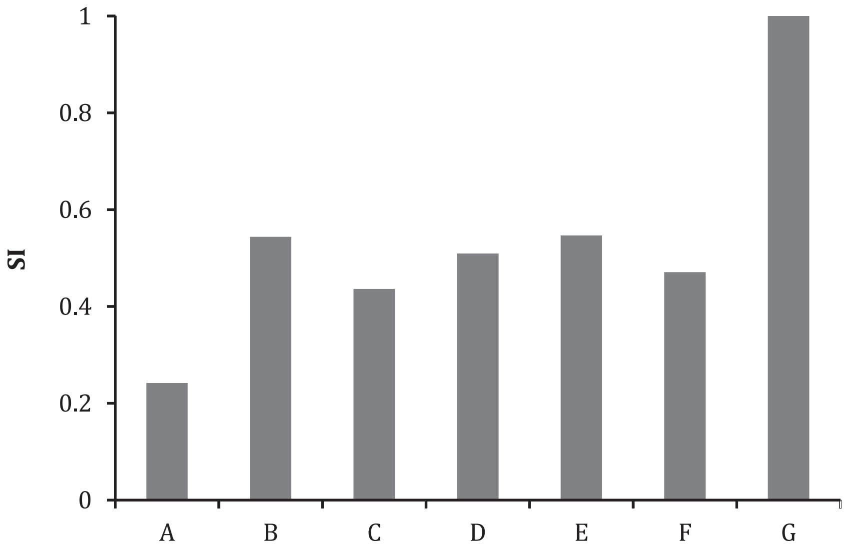

Figure 2. The Similarity Index (SI) of the *A. halodendro*n and *C. microphylla* communities in shifting-, semi-fixed-, and fixed-sand dunes. Communities were: A: *A. halodendron*; B: *A. halodendron*; C: 6-year-old *C. microphylla*; D: 14-year-old *C. microphylla*; E: 20-year-old *C. microphylla*; F: 27-year-old *C. microphylla*; G: Sparse elm woodland. These communities were located in A: shifting sand dunes; B to F: semi-fixed sand dunes; G: fixed sand dunes.

Figura 2. Indice de similitud (SI) en las comunidades de *A. halodendro*n y *C. microphylla* en dunas móviles, o fijadas en forma moderada o total. Las comunidades fueron: A: *A. halodendron*; B. *A. halodendron*; C: *C. microphylla* de 6 años de edad; D*: C. microphylla* de 14 años de edad; E: *C. microphylla* de 20 años de edad; F: *C. microphylla* de 27 años de edad; G: Arbustal de *Ulmus pumila* esparcido. Estas comunidades estaban ubicadas en A = dunas móviles; B a F: dunas fijadas en forma moderada; G: dunas fijadas totalmente.

Discussion

It was found that the weight of plant indicators to the total weight of all variables related with stability was greater than that of soil variables. Other studies have reported that sand dunes become stable when perennial plants colonize them (21).

This results showed that the similarity index of the *A. halodendron* community was greater in the semi-fixed than in shifting sand dunes. This is consistent with previous studies (26), and supports our hypothesis that *A. halodendron* in semi-fixed sand dunes has a higher stability than that community in moving sand dunes.

This findings also agree with those of Li *et al.* (2007) who reported that *A. halodendron* and *Agriophyllum squarrosum* were the dominant species in semi-fixed and shifting sand dunes, respectively.

The diversity index and vegetation cover were among the most important indicators for contributing to explain the stability of the study plant communities. These indicators imply at the same time an increasing need of water supply (23). These results suggest that semi-fixed sand dunes should be more suitable for drought resistant species. Main or fine roots allow water uptake from deep or surface soil layers, respectively, in *A. halodendron* which increases its water use efficiency and resistance to drought (47).

Although some population characteristics of *A. halodendron* might decrease in semi-fixed sand dunes (*i.e.*, single body biomass, canopy and height: 28), community stability increased. This increase might be due to (1): the increases in species diversity and vegetation cover, proportion of clay and silt particles, and soil nutrients, and (2) regulation of the soil pH values (48). Therefore, *A. halodendron* communities are suitable for restoring vegetation and binding sand in moving sand dunes, especially in semi-fixed sand dunes.

The stability of the *C. microphylla* community, as measured by the SI, increased until it was 20-year-old, and decreased afterwards. This partly supports our hypothesis that stability should be higher in older than younger artificial, sand-binding communities. *Caragana microphylla* can decrease wind velocity through its branches, which contributes to improve the accumulation of clay and silt particles in its canopy (7).

Previous studies have reported that the proportion of clay and silt particles is 2.6% before planting *C. microphylla* (30). This proportion, however, reached 14.4% in the canopy of *C. microphylla* after 21 years from planting (29).

The increase in the proportion of clay and silt particles promotes the accumulation of soil organic matter, nutrients and water holding capacity (39).

In addition, herbs in the *C. microphylla* community also promote the cycling of organic matter and soil nutrients (22). Therefore, the stability of the *C. microphylla* community increased with age from its initial establishment.

However, the similarity index was lower on 27- than on 20-year-old *C. microphylla* communities, indicating that the stability of these communities decreased after reaching a peak. Pfisterer and Schmid (2002), reported an inverse relationship between biodiversity and the stability of ecosystem functioning. This suggests that the community of *C. mycrophylla* might have increased in biodiversity after 27-year-old.

Also, Anward Maun (2009) reported that as the plant community develops from open sand dunes to more mature stages in the succession process, there is in general an increase in weathering of soil and an increase in silt and clay, and in the humus content. For example, Holmes (2001) reported that primary succession occurs in essentially lifeless areas - places in which the soil is incapable of sustaining life such as newly formed sand dunes. Secondary succession occurs in areas where an ecosystem that previously existed has been removed. This type of succession is typified by smaller-scale disturbances that do not eliminate all life and nutrients from the environment. Primary and secondary succession both create a continually changing mix of species within communities as disturbances of different intensities, sizes, and frequencies alter the landscape.

The sequential progression of species during succession, however, is not random. At every stage, certain species have evolved life histories to exploit the particular conditions of the community (niches). This situation imposes a partially predictable sequence of change in the species composition of communities during succession.

Figure 2 (page 113), helps identify the process of succession in a sand dune system. Initially only a small number of species from surrounding habitats are capable of thriving in a disturbed habitat and harsh environment.

As new plant species take hold, they modify the habitat by altering such things as the mineral composition of the soil. These changes allow other species that are better suited to this modified habitat to succeed the old species. These newer species are superseded, in turn, by still newer species. As succession is a slow process (and change in soil and vegetation often takes many tens or hundreds of years at any one location), zonation (*i.e.*, the variation of species or communities over a particular area) is often used in sand dune studies to show how successions can work. This assumption is simply based on the fact that the dunes nearest the sea or coast are young and they become progressively older as the distance increases inland (8).

Petersen *et al*. (1968) reported that soil available moisture was negatively correlated with increasing clay content in soils. Then, less water might be available for root uptake in the *C. microphylla* community. Therefore, the stability of the oldest *C. microphylla* community in this study might have decreased because of a lower soil water availability for plant growth.

According to this results, the match between artificial communities and their location in sand dunes should be considered carefully. *Artemisia halodendron* communities should be planted preferentially in semi-fixed to moving sand dunes.

Furthermore, the planting age of artificial communities should be included in a planting program. For example, the greatest stability of *C. microphylla* communities appeared when they were 20-year-old. Additional artificial measures should be imposed to the elder *C. microphylla* community to maintain its stability.

The AHP method has already been used in evaluating the stability of wetland ecosystems, and in assessing the effects of protective systems in desert ecosystems (50, 54). In this study, this method was used to evaluate the stability of artificial communities.

The AHP method is suitable for situations where both quantitative and qualitative analyses are needed.

The accurateness of this method mainly depends on the correction of the weight estimations. We collected and synthesized data from the literature to evaluate the stability of communities in sandy lands.

This study demonstrated the usefulness of collecting and appropriately analyzing and interpreting ecological data from the literature to address answers to ecological issues.

Conclusions

The higher stability of *A. halodendron* communities was reached in semi-fixed than in shifting sand dunes. This was most likely due to increases in species diversity and vegetation cover, and the improvement in physicochemical soil properties.

Communities of *C. microphylla* reached a peak of stability when they were 20-year-old.

It suggests that *A. halodendron* communities should be planted preferentially in semi-fixed to moving sand dunes.

Furthermore, the planting age of artificial communities should be included in planting programs. This study improved the understanding of the mechanisms contributing to maintain stability, and is helpful for guiding the artificial planting in desert ecosystems.

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