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RESEARCH

Analysis of changes in plant species and diversity after planting trees into the semi-arid desert of Hulunbuir, Inner Mongolia

Eui-Joo Kim[1], Seung-Hyuk Lee[2], Sung-Bae Joo[3] and Young-Han You[1]*

[1]Department of Biological Sciences, Kongju National University, Gongju 32588, Republic of Korea
[2]Garden Promotion Department, Korea Arboreta and Gardens Institute, Sejong 30129, Republic of Korea
[3]Ecological Observation Team, National Institute of Ecology, Seocheon 33657, Republic of Korea

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***Corresponding author**
Young-Han You
E-mail youeco21@kongju.ac.kr

Background: Inner Mongolia, desertification is happening due to climate change and land use alterations. In order to evaluate desert restoration effectiveness, this study compares number of species and species diversity in restored (with planted trees), unrestored area, and the reference ecosystem (Ref-E, typical steppe and woody steppe).
Results: The Ref-E had the most plant species (64 taxa), while the unrestored area had the fewest (5 taxa). Among restored areas (restored in 2012, 2008, 2005), older restoration sites had more species (18–42). Similarly, species richness (3.93–0.41) and diversity (1.99–0.40) were highest in the Ref-E and lowest in unrestored areas, with older restored sites having higher values.
Conclusions: More plant species and diversity in older restoration areas suggest progress toward ecosystem stabilization, approaching the Ref-E. Therefore, tree planting in Inner Mongolia's Hulunbuir semi-arid desert is a successful restoration effort.

Keywords: desert plant, plantation, restoration, steppe, vascular plant

Introduction

In 1994, the United Nations launched the Convention to Combat Desertification (UNCCD) through the agreement of many countries around the world, and UNCCD is the only legally binding international agreement linking environment and development for sustainable land management (United Nations General Assembly 1994). The areas referred to in the definition of desertification can be collectively referred to as dryland, and UNCCD refers to a dryland as an area where the ratio of potential evaporation to annual precipitation is in the range of 5 to 65% (Mcsweeney 2019).

According to the Intergovernmental Panel on Climate Change (IPCC), since 3 billion people live in drylands, which account for 46.2% of the entire world's land area (Mirzabaev et al. 2019), about 9.2% of the drylands were expanded by desertification due to indiscreet use of lands by humans during 1980s–2000s, and the desertification affected about 500 million people in 2015 (Mirzabaev et al. 2019). The unsustainable management of lands caused devastation and eventually led to dust storms and eolian dust, which are directly linked to human death (Goldewijk et al. 2017; Montanarella et al. 2018).

The territory of China comprises about 20% forest, about 27% deserts, and about 42% steppes, which occupy the largest area (Xue et al. 2017). The dry lands, of which the area is 332 million km^2 accounting for 34.6% of the total area of China, may be desertified. Although some forests increased by almost 20%, many habitats are continuously threatened, and it is said that nearly 90% of steppes have experienced desertification (UNCCD 2019; Wu et al. 2015).

However, in addition to recent changes in precipitation patterns due to climate change, the land is severely damaged due to the conversion of land use from grasslands to farmlands or from woodland steppe to farms, and rapid increases in the number of livestock (Jun Li et al. 2007). Consequently, the area of grasslands is rapidly decreasing (Akiyama and Kawamura 2007) and desertification is progressing due to land degradation (Kang et al. 2007).

Hulunbuir, which has the steppes of the largest area among the steppes in Inner Mongolia, has experienced reduction in the area ratio of steppes as steppes were devastated and changed into sandy dunes after converting forests into farms (Akiyama and Kawamura 2007; Kim et al. 2021). Since the area ratio of desertification has been increasing to 18.48% in the 2020s, it is predicted that Hulunbuir will become a desert in 40–50 years (XinShi et al. 2009).

The desertification of land is known to be the main culprit that secondarily causes sandstorms and eolian dust, and as damage to neighboring countries due to eolian dust has been increasing, the problem of desertification was recognized as an international environmental problem (Goldewijk et al. 2017; Mcsweeney 2019). In recent years, many sand movements have been observed in Hulunbuir, and the Chinese government is making great efforts to restore this region, which was steppes in the past, from desertification (XinShi et al. 2009). To prevent desertification, the Chinese government, in cooperation with Working Group 2 of the Korea-China-Japan Yellow Sand Joint Research Group, is conducting a monitoring survey at a restoration site where trees were planted in the Ganzuer Hulunbuir, Inner Mongolia (Ministry of Environment 2020).

By understanding the changes in flora caused by planting trees on damaged grasslands, the restoration effect can be known through the number of plant species. Therefore, we sought to investigate changes in the flora of damaged areas due to annual tree planting in the Hulunbuir, Inner Mongolia. Therefore, this study aims to assess the effects and extent of restoration by comparing and analyzing the plant species in restored and unrecovered vegetation areas, as well as in the reference ecosystems (Ref-Es), where woody plants have been introduced in the semi-arid desertified regions in Hulunbuir, Inner Mongolia.

Materials and Methods

Overview of investigation sites

This study site is a site to be jointly investigated by the WG (II) of the South Korea-China-Japan Yellow Dust Joint Research Group and is called Ganzhuer. This site is Xīnbā'ěrhǔ Zuǒ Qí among the 14 administrative districts in Hūlúnbèi'ěr Shì, in the northeastern area of Inner Mongolia Autonomous Region, and is located at N 48°04′13″–48°27′11″, E 119°18′37″–118°17′18″ (Fig. 1). In this site, forestry and livestock farming in steppes have been prosperous from the past and there are diverse ecosystems such as temperate monsoon coniferous forests and steppes. The topography here is sandy dunes thrist form the shape of honeycombs with fixed, semi-fixed, semi-floating, and floating sandy dunes that were already desertified or restored (Angerer et al. 2008).

The climate here belongs to the northern temperate climate, and the annual average precipitation is about 130–330 mm (275 mm) and has been increasing every year since 2014 but has been functioning greatly and not even with large yearly variations. In particular, the annual average rainfall in summer (June–August) is about 74–207 mm, accounting for 59% of the annual rainfall. The rainfall is highly concentrated on the growing season (May–

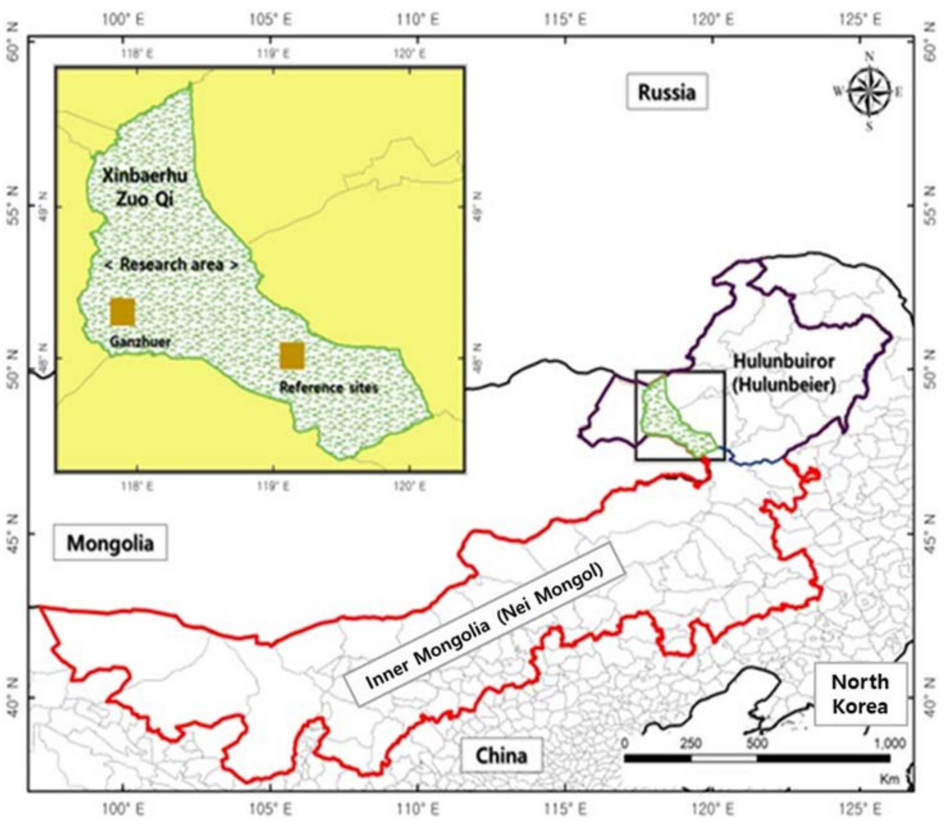

Fig. 1 Map showing the location of the study restoration sites in Ganzhuer of Hulunbuir, Inner Mongolia (Nei Mongol).

September) at 116–282 mm (83%), and the annual average rainfall in other seasons is about 17–48 mm (17%). The relative humidity is 62%–72% (68%), and the annual potential evapotranspiration is 1,400–1,900 mm, which is considerably higher compared to the precipitation. The annual average temperature is −0.4°C to 0.58°C (0.3°C), the minimum temperature is −42° and the maximum temperature is 39°. Climate data used from the China Meteorological Observation Network (http://data.cma.cn/, 2023) measured by the National Meteorological Observatory of Inner Mongolia.

In this study site, restoration projects were carried out in devastated and desertified steppes from 2005 to 2012. Since the topography was in its original state, the vegetation was restored in most cases using seed sowing and tree planting methods. In order to investigate the flora of the regions restored from desertification, the regions restored in 2005 (R-2005yr), 2008 (R-2008yr), and 2012 (R-2012yr), the desertified sandy dune regions, which were not restored (NR), were selected as investigation sites, and the typical steppe area, which is about 80 km in a straight line from the investigation site, and the woody (*Pinus sylvestris* L. var. *mongolica* Litv.) steppe were selected as Ref-Es (Fig. 2).

The trees selected for vegetation restoration were *P. sylvestris var. mongolica* and *Populus canadensis* (native plants), and *Caragana microphylla* and *Corethrodeneron fruticosum* (pioneer species) in Hulunbuir. In R-2012yr, the seed sowing method and shrub planting method were applied simultaneously, and in R-2008yr, and R-2005yr, trees and shrubs were planted simultaneously. The dominant species was *C. fruticosum* in NR, R-2005yr and R-2012yr, and *P. sylvestris* and *C. microphylla* was dominant in R-2008yr. In the Ref-E, *P. sylvestris* var. *mongolica* was dominant.

Flora survey

In order to identify the distribution of all vascular plants appearing in the investigation target site in of Hulunbuir, the regions R-2005yr, R-2008yr, R-2012yr, the NR and Ref-E investigated while walking around the regions in late summer and early fall. Plant species were identified referring to the Flora of China (2020), the Color Atlas of plants of northern China's grasslands (Gu and Wang 2009; Li 2012), the Colored Atlas Book of Chinese Desert Plants (Lu 2012) and the Korean Pictorial Book of Plants (Lee 2003). The scientific names were adopted, and the taxa were arranged according to the Flora of China, and the arrangements below the genus were organized in alphabetical order. The Korean names were given according to the Flora of Korea editorial committee (2007) of those taxa that had no Korean name because they are not distributed in Korea were newly made considering Chinese names, scientific names, and the taxonomic features of the plants.

The research sites for plant species analysis consisted of a total of three restoration areas, one unrecovered area, and one combined site representing the Ref-Es of steppe grassland and woody steppe. In each study area, changes in taxa that appeared over a five-year period from 2014 to 2018 were confirmed and differences in the average number of species were compared. Normal distribution was tested using the Shapiro–Wilk test, and due to the lack of normal distribution ($p < 0.05$), non-parametric analysis was performed on the difference in the number of taxa that appeared in each research site. The significance of these differences across study sites was tested using the Kruskal–Wallis test the Statistica 8 statistical package (StatSoft Inc., Tulsa, OK, USA) was used for the statistical analyses.

Species diversity index

The richness index (RI) was calculated by measuring the number of species per square meter (1 m^2) and applying it to the formula RI = (S − 1) / ln (N) (Margalef 1958), where S represents the total number of species within the community, and N denotes the total number of individuals present within the community. The Diversity Index (H') was calculated by substituting it into the formula H' = −Σ

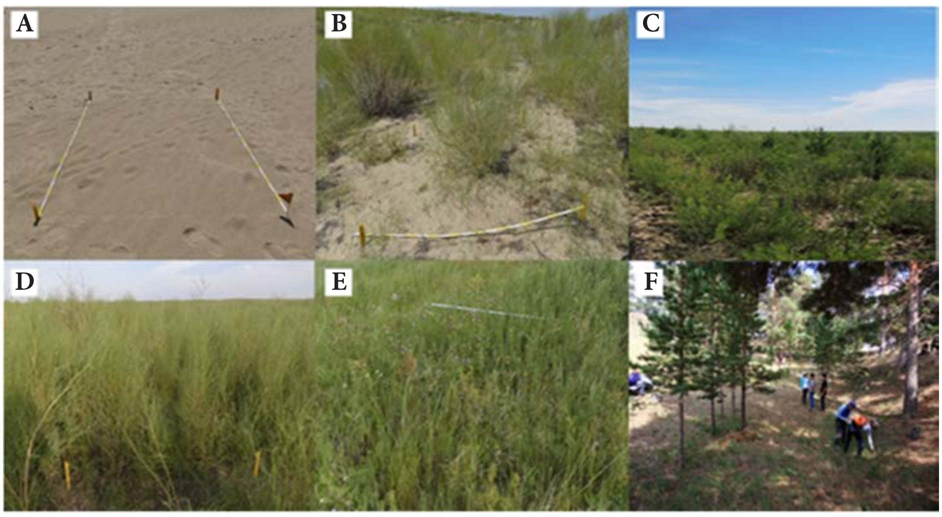

Fig. 2 Overall photographs of the study sites in Ganzhuer of Hulunbuir, Inner Mongolia; Non-restoration site (A), restored in 2012 (B), restored in 2008 (C), restored in 2005 (D), referenced-steppe grassland ecosystem (E), and refereced-woody forest ecosystem (F).

(Pn lnPn) (Shannon and Weaver 1949), where Pn represents the proportion of the nth species within the community, calculated by dividing the number of individuals in each taxonomic group by the total number of individuals. The analysis of species diversity involved determining the total number of species and individuals occurring in each research site (R-2005yr, R-2008yr, R-2012, NR, and Ref-E) to assess the richness and diversity of species distribution.

Results

Flora in each study site

Total study site

A total of 105 taxa comprising 34 families, 87 genera, 98 species and 7 varieties were identified. Among them, only 1 taxon was a gymnosperm, and the remaining 104 taxa were angiosperms comprising 78 dicotyledonous plants and 26 mono-cotyledonous plants corresponding to 75% and 25%, respectively. No Pteridophyta were found (Table 1). As for the ratios of distribution by family, the ratio of distribution of Asteraceae was the highest at 17% (18 species) followed by Poaceae at 12% (12 species), Chenopodiaceae and Fabaceae at 8% (8 species), and 16 families including Pinaceae, Ulmaceae, and Brassicaceae at the lowest ratio of distribution with 1 species each (Fig. 3).

Among the species growing in the study sites, the species with the highest frequency of appearance was *Caragana microphylla* Lam. and among the top five species including it, *Corethrodendron fruticostun* (Pallas) B.H. Choi & H. Ohashi appeared next most frequent followed by *Corispermum hyssopifolium* L. and *Echinops gmelini* Turcz. in order of precedence. These species can be regarded as major core species in this region because they are distributed in almost all study sites, are identified at each investigation period, and the ratios of distribution of them coincide with the ratios of distribution by family (Table S1).

Table 1 The number of vascular plants distributed in study sites

Study site name	Phylum/Class	Family	Genus	Species	Variety	Taxa
Total site	Gymnospermae	1	1		1	1
	Angiospermae	33	86	98	6	104
	Dicotyledons	28	65	74	4	78
	Monocotyledons	5	21	24	2	26
	Total	34	87	98	7	105
Non-restoration	Gymnospermae	-	-	-	-	-
	Angiospermae	5	10	11	-	11
	Dicotyledons	4	9	10	-	10
	Monocotyledons	1	1	1	-	1
	Total	5	10	11	-	11
Restored in 2012	Gymnospermae	1	1	-	1	1
	Angiospermae	8	16	17	-	17
	Dicotyledons	7	12	13	-	13
	Monocotyledons	1	4	4	-	4
	Total	9	17	17	1	18
Restored in 2008	Gymnospermae	1	1	-	1	1
	Angiospermae	16	32	36	1	37
	Dicotyledons	12	22	25	1	26
	Monocotyledons	4	10	11	-	11
	Total	17	33	36	2	38
Restored in 2005	Gymnospermae	-	-	-	-	-
	Angiospermae	15	34	41	1	42
	Dicotyledons	11	24	30	-	30
	Monocotyledons	4	10	11	1	12
	Total	15	34	41	1	42
Reference ecosystems	Gymnospermae	1	1	-	1	1
	Angiospermae	25	54	59	4	63
	Dicotyledons	21	43	47	3	50
	Monocotyledons	4	11	12	1	13
	Total	26	55	59	5	64

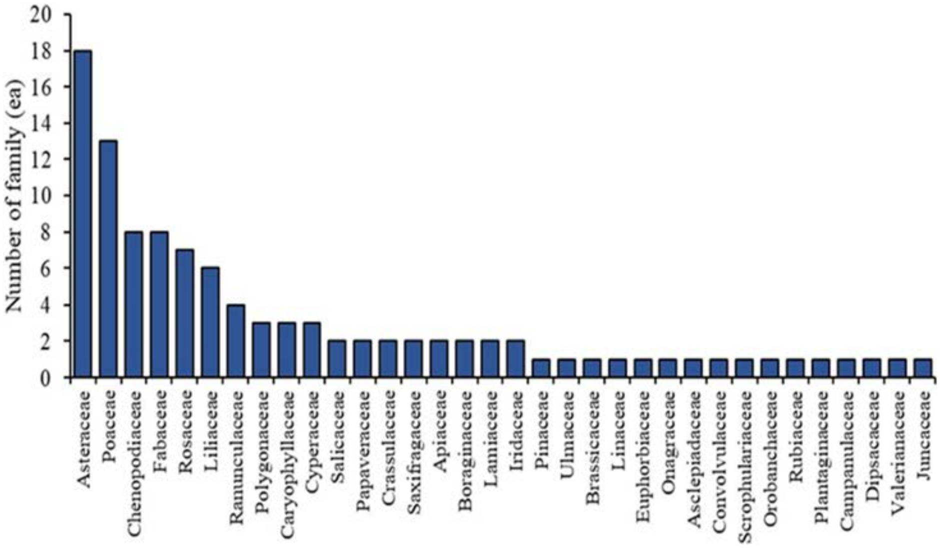

Fig. 3 Family composition of vascular plants for the five years in the study sites, Ganzhuer of Hulunbuir, Inner Mongolia.

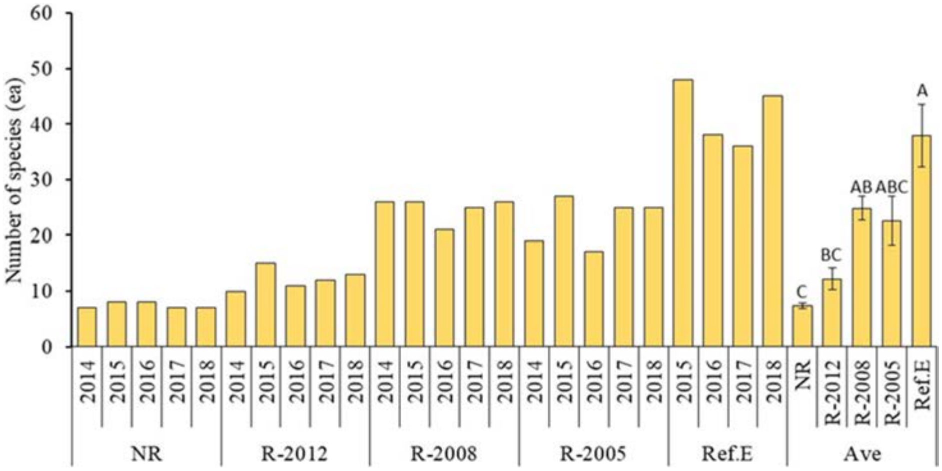

Fig. 4 Total and average (Ave) number of species of vascular plants over 5 years in the study sites, Ganzhuer of Hulunbuir, Inner Mongolia. The vertical bars above graphs indicate the standard deviation and the alphabets above the bars represent the statistical difference among the sites. NR: not restored; R: restored; Ref-E: reference ecosystem.

Non restoration

A total of 5 families, 10 genera, and 11 taxa were identified (Table 1). The ratio of the Fabaceae was the highest among the entire taxa, and the ratio of Orobanchaceae and that of Gramineae were the lowest with one species each (Table S1). Those species whose distribution has been continuously identified for 5 years are four species in total including *Caragana microphylla* Lam., *Orobanche coerulescens* Stephan ex Willd., and *Corispermum hyssopifolium* L., and they do not form community but are scattered individually. The unrestored areas were in the form of a desert, which is not suitable for plant growth. Therefore, not many species, that is, about 11 species were distributed there. Whereas *Corispermum hyssopifolium* L., of which the plant body is about 3–8 cm high, appeared as clusters in some cases or as many individuals, while other tree species were rarely found as one individual at a time and the condition of the plant found was either withered to death or not good. Some species were found with roots exposed or covered with sand due to the movement of sand. As a result of the five-year investigation, 7–8 taxa were identified every year, and there were only differences in some species out of the 7 species found on average in each investigation year and no large change appeared (Fig. 4).

Restored in 2012

A total of 18 taxa comprising 9 families, 17 genera, 17 species and 1 variety was identified (Table 1). Among the entire taxa, the ratios of Fabaceae and Gramineae were the highest, and the ratios of Pinaceae, Ulmaceae, Borraginaceae, and Orobanchaceae were the lowest with one species each (Table S1). The species of which the distribution was continuously identified for 5 years are 7 species in total: *Corispermum squarrosum* (L.) Moq., *Corispermum hyssopifolium* L., *Corethrodendron fruticostun* (Pallas) B.H. Choi & H. Ohashi, *Caragana microphylla* Lam., *Orobanche coerulescens* Stephan ex Willd., *Echinops gmelini* Turcz., and *Artemisia desertorum* Spreng. According to the result of the five-year investigation from 2014, the average number of species was 12, and when seen generally, plant diversity decreased in 2016 to the 2014 level and then gradually increased, but there seems to be no significant change (Fig. 4). Species such as *Cleistogenes squarrosa* (Trin.) Keng, *Cynanchum thesioides* (Freyn) K. Schumann, *Lindernia crustacea* (L.) F. Muell. *Oxytropis racemosa* Turcz., *Astragalus adsurgens* Pall. were not found during the investigation in 2016, and *Cynanchum thesioides* (Freyn) K. Schumann reappeared in 2017, and the redistribution of *Cleistogenes squarrosa* (Trin.) Keng could be identified in 2018 (Fig. 4).

Restored in 2008

A total of 38 taxa comprising 17 families, 33 genera, 36 species, and 2 varieties was identified (Table 1). Among the entire taxa, the ratio of the Asteracese was the highest, followed by Gramineae and Fabaceae, in order of precedence. This is similar to the plant distribution ratios in the entire Hulunbuir. Species of which the growth was identified during the investigation in every year are a total of 12 species; *Pinus sylvestris* L. var. *mongolica* Litv, *Salix cheilophila* C.K. Schneid., *Populus euramericana* Guinier, *Ulmus pumila*, *Corispermum hyssopifolium* L., *Oxytropis racemosa* Turcz., *Corethrodendron fruticostun* (Pallas) B.H. Choi & H. Ohashi, *Caragana microphylla* Lam., *Taraxacum asiaticum* Dahlst., *Plantago depressa* Willd., *Sonchus arvensis* L., and Inula britanica L. (Table S1).

The average number of plant species during the entire investigation period was 25, and during the five years of investigation, the plant diversity decreased during the period of investigation in 2016 and increased thereafter (Fig. 4).

Restored in 2005

A total of 42 taxa comprising 15 families, 34 genera, 41 species, and 1 variety was identified (Table 1). Among the entire taxa, the ratio of the Asteracese was quite high at 24% followed by Gramineae and Chenopodiaceae, in order of precedence. Whereas only *Corispermum squarrosum* (L.) Moq. and *Corispermum hyssopifolium* L. in Chenopodiaceae were found in all other areas among the entire areas restored, four additional species such as *Suaeda asparagoides* Makino and *Chenopodium acuminatum* Willd. were found in these areas thereby showing a different aspect. Species of which the growth was identified during every investigation were a total of six species; *Corethrodendron fruticostun* (Pallas) B.H. Choi & H. Ohashi, *Caragana microphylla* Lam., *Olgaea leucophylla* (Turcz.) Iijin., *Calamagrostis epigeios* (L.) Roth, *Agropyron cristatum* (L.) Gaertn., and (Trin.) Keng (Table S1).

The average number of plant species during the entire investigation period was 23, and during the investigation period, plant diversity was the highest in 2015, and rapidly decreased thereafter so that it was the lowest in 2016 (Fig. 4).

Reference ecosystems

A total of 64 taxa comprising 26 families, 55 genera, 59 species, and 5 variety was identified (Table 1). Among the entire taxa, the ratio of the Asteracese was the highest and the ratios of other families were about equal. The taxa of which the growth was identified during every investigation were 26 species such as *Pinus sylvestris* L. var. *mongolica* Litv, *Ribes diacanthum* Pall, *Potentilla egedei* var. *groenlandica* Polunin, *Rosa davurica* Pall., *Caragana microphylla* Lam., *Thymus mongolicus* Ronn., *Galium verum* var. *asiaticum* Nakai, *Saussurea japonica* DC., *Artemisia capillaris* Thunb., *Leymus chinensis* Tzvelev, and *Agropyron cristatum* Gaertn., and among them those species that were widely distributed the Ref-Es were *Pinus sylvestris* L. var. *mongolica* Litv, *Caragana microphylla* Lam., *Potentilla bifurca* L, *Saussurea japonica* DC., *Artemisia capillaris* Thunb., *Leymus chinensis* Tzvelev, and *Agropyron cristatum* Gaertn (Table S1).

During the entire investigation period, the average number of plant species was 41, and plant diversity was the highest in 2015 and the lowest in 2017. The Ref-Es were sandy dune areas, where *Pinus sylvestris* L. var. *mongolica* Litv. distributed in communities and other woody plants, *Ribes diacanthum* Pall, *Rosa davurica* Pall. and *Prunus padus* L. for. *padus*, which were 1–2 m high, were growing in the woody steeps. The taxa of herbaceous plants appearing every year changed diversely (Fig. 4).

Comparison of species diversity index

The Richness Index (RI) was highest in Ref-E at 3.93, followed by R-2005yr (1.49), R-2008yr (1.16), R-2012yr (0.70), and NR (0.41) (Fig. 5). The Shannon–Wiener diversity index (H') was highest in Ref-E at 1.99, followed by R-2005yr (1.62), R-2008yr (0.99), R-2012yr (0.81), and NR

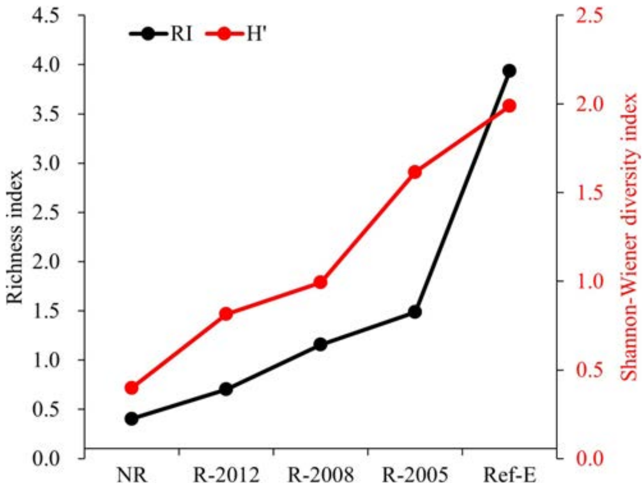

Fig. 5 Species richness and species diversity index by study area Ganzhuer of Hulunbuir, Inner Mongolia. The black line represents the richness index (RI), and the yellow dot on the line represents the corresponding point. The red line represents the Shannon–Wiener diversity index (H'), and the light blue dot on the line represents the corresponding point. NR: not restored; R: restored; Ref-E: reference ecosystem.

(0.40) (Fig. 5). Both species richness and diversity indices were highest in the Ref-E, and they increased with longer restoration years (Fig. 5).

Discussion

Flora

As a result of the investigation of flora in Hulunbuir, China, 105 taxa comprising a total of 34 families, 87 genera, 98 species and 7 varieties were identified (Table 1). In previous studies, the plant species identified as growing in the Sandy Land in Inner Mongolia were a total of 428 taxa comprising 48 families, 177 genera, 378 species, and 50 varieties, and among them, 39 families, 122 genera and 213 species were distributed in the desert, and 46 families, 174 genera, and 370 species were distributed in the temperate steppe areas (Wang et al. 2007). The difference between the number of plants at the research site and previous studies is believed to be due to differences in time and space (area, region, etc.). However, it is unfortunate that the flora survey in this study was conducted only in specific seasons, not all seasons. Nevertheless, the results of this study are meaningful in that they provide basic data for determining the number of plant species over time after planting trees in damaged grasslands.

The finding that the ratios of Asteracese, Gramineae, Chenopodiaceae, and Fabaceae were the highest among the entire plant taxa is identical to the announcement that a total of four plant families were dominant in the sandy areas in Inner Mongolia (Wang et al. 2007), As for genera, whereas Artemisia, Corispermum, Oxytropis, and Astragalus were dominant in the sandy areas in Inner Mongolia (Wang et al. 2007). The dominant genera in our research sites were Artemisia, Potentilla, Chenopodium, and Allium, and only Artemisia was consistent with the existing literature. In the arid-steppes of northern China, plants of the genera Stipa, Aster, and Artemisia are known to be major species and generalist with wide habitat (Tang et al. 2020). All the genera mentioned above appeared in our survey site, and among them, Artemisia was observed to be widely distributed.

Those species that had wide distribution arreas in the Ganzhuer sandy dune area so that they were identified in all study sites were a total of five species comprising *Caragana microphylla* Lam., *Corethrodendron fruticostun* (Pallas) B.H. Choi & H. Ohashi, *Corispermum hyssopifolium* L., *Artemisia desertorum* Spreng., *Echinops gmelini* Turcz., and species that highly frequently appeared were a total of 10 species, including *Orobanche coerulescens* Stephan ex Willd., *Astragalus adsurgens* Pall., *Artesrisia halodendrom* Turcz ex Bess, *Calamagrostis epigeios* (L.) Roth, *Oxytropis racemosa* Turcz. (Table S1). These species are judged to be major species in the Ganzhuer sandy dune area.

In the dry-temperate steppes in the north of China, plants in the genera Stipa, Aster, and Artemisia are known to be major species (Tang et al. 2020). Therefore, some of the species in the study sites correspond to the relevant genera, and it could be observed that the plants in the three genera are widely distributed in the surrounding areas not desertified other the investigation target areas in this study. Considering the characteristics of pioneer species, in the deserts, *Lindernia crustacea* (L.) F.Muell. and *Corispermum hyssopifolium* L. mainly judged as pioneer tree species (Tang et al. 2020). In this study too, *Corispermum hyssopifolium* L. was growing in areas NR and the distribution of both species could be identified in indiviodual restored areas indicating that they play the role of pioneer tree species (Table S1).

Pioneer species refer indigenous species in the initial transition period that come and grow in areas where most plants can hardly grow and live while overcoming unfavorable conditions for growth in terms of nutrients, dryness, wetness, and light (Barbour et al. 2015). Among the major indigenous species that naturally occur and grow like pioneer tree species in the Ganzhuer desertified area, *Corispermum hyssopifolium* L., *Corispermum squarrosum* (L.) Moq., *Oxytropis racemosa* Turcz., *Echinops gmelini* Turcz., *Astragalus adsurgens* Pall., and *Orobanche coerulescens* Stephan ex Willd. are representative.

The fact that the same distributed species as those in Korea exist in Hulunbuir, China found through the investigation of the flora in China is phytogeographically very important. Among the entire 105 taxa, 64 taxa accounting for 61% are identical to species distributed in Korea (Table S1). Although Hulunbuir is 1,580 km away from the South Korea in a straight line, and there is no desert ecosystem per se in South Korea, the same species may be investigated according to the characteristics and distributed areas and the results may be used as basic data for plant classification and ecology.

In the flora of Hulunbuir, 13 species, which are *Bupleurum scorzonerifolium* Willd., *Artemisia capillaris* Thunb., *Artemisia scoparia* Waldst. & Kit., *Belamcanda chinensis* (L.) DC., *Cuscuta australis* R. Br., *Dianthus chinensis* L., *Euphorbia humifusa* Willd., *Lilium pumilum* DC., *Orobanche coerulescens* Stephan ex Willd., *Orostachys fimbriata* A. Berger, *Sanguisorba officinalis* L., *Sanguisorba officinalis* L., *Stipa sareptana* var. *krylovii* (Roshev.) P.C. Kuo. were identified as medicinal plants (Flora of China 2020).

Five species of plants that can be used as food sources for animals were identified as *Agropyron cristatum* (L.) Gaertn., *Calamagrostis epigeios* (L.) Roth, *Cleistogenes squarrosa* (Trin.) Keng., *Corethrodendron fruticostun* (Pallas) B.H. Choi & H. Ohashi, *Stipa tenuissima* Trin. (Flora of China 2020). Since plants that can be used as medicinal plants or animal food sources in terms of plant resources are also distributed in areas where the ecosystem was restored in Hulunbuir as such, an appropriate point of agreement between use and restoration is required, and measures for protection against secondary destruction that may occur due to improper management should be prepared. However, over-cultivation due to increased demand for useful medicinal plant resources can lead to excessive development and environmental destruction, which can have a negative impact on the ecosystem (Volenzo and Odiyo 2020). Therefore, in order to use plants safely and successfully, a clear understanding of the value of plants by local residents must be taken into consideration. Also, as the plants can be used as food sources for animals, it can be regarded that the area is becoming an environment in which wild animals can inhabit, and since plants are gradually diversified, it can be predicted that the diversity of the fauna will increase (White 1978).

There was a trend of increasing plant diversity with the passage of restoration years on an annual basis. However, the plant diversity in all restoration sites experienced a sharp decline in 2016, followed by a gradual recovery and increase (Fig. 4). In the case of the reference sites, the diversity was the lowest in 2017. Plant species with low distribution ratios in individual areas could not be found at all as of 2016 or rediscovered a few years later in many cases. In general, it can be estimated that there were negative factors in the growth environments, such as the death of most of trees and shrubs between 2016 and 2017 by only looking at the surrounding plant conditions. By investigation target area, the plant diversity of the areas that were restored more than 10 years earlier was more two times higher than areas that were restored 6 to 7 years earlier, and it seems that the outcomes of restoration will appear such as increased in the appearance of major native species of Hulunbuir.

Investigations of flora should be conducted in all seasons except for winter, when most plants wither to death for faithful data to be secured (Lee et al. 2016). In the study sites in Hulunbuir, Inner Mongolia too, investigations should be conducted in other seasons too by promoting smooth cooperation of the Chinese side, and it will greatly contribute to improving the reliability of data on changes in the plant diversity of the areas restored, hereafter.

Species diversity index

When species diversity is low, it indicates short-term effects of vegetation restoration, while high diversity suggests long-term effects (Yeochon Association for Ecological Research 2005). High diversity implies the influx of plant species through mechanisms like seed dispersal, leading to an increase in species composition. This increase in species composition can be confirmed through species richness indices. In our study, a comparison of the entire annual restoration sites revealed that sites with longer restoration periods had higher species richness and diversity indices (Fig. 5). This trend aligns with the findings of a study on nearby desertified areas in Hulunbuir (Lv et al. 2008).

However, it's essential to understand that species richness measures how rich the number of species is within a cluster. In our case, restoration sites had more than twice the richness compared to unrecovered sites but lower than the Ref-Es. Additionally, higher diversity indices indicate ecosystem stabilization, as clusters with higher values suggest maturity. These indices can be used as a measure of cluster structure and functional capacity (Yeochon Association for Ecological Research 2005). Therefore, while the vegetation cover in our annual restoration sites showed some signs of recovery, the restoration site with the lowest diversity index (R-2012yr) suggests that the ecosystem's structure and function have not fully recovered to late-stage or pre-restoration levels. This indicates the need for long-term planning and management.

Comparing species richness and diversity indices among the restoration sites, it can be concluded that the vegetation cover in the 2005 and 2008 restoration sites is like or exceeds that of similar or Ref-Es, confirming the effectiveness of vegetation restoration. However, cluster analysis reveals significant differences in species richness, diversity, and evenness, indicating a need for further internal growth within the ecosystem. R-2012yr appears to have only partially recovered in terms of vegetation cover, with indices significantly lower than those of similar grassland ecosystems. This suggests that the ecosystem's structure and function are still in the early stages of restoration, highlighting the need for long-term planning and management.

Conclusions

To prevent desertification, trees were planted in the semiarid desert, and the restoration effects of these areas were assessed. A comparison of plant species and diversity among the restored areas, unrecovered areas, and Ref-Es was conducted. The results showed that as time passed since restoration, the number of plant species, species richness, and species diversity indices increased among the restored areas. Conversely, the most recently restored areas had lower values. The increase in plant species and species diversity indices in older restoration areas indicates progress towards ecosystem stabilization, approaching the Ref-E. Therefore, the planting of trees in the semiarid desert of Inner Mongolia's Hulunbeir is considered a successful restoration effort to combat desertification. This suggests that the ecosystem's structure and function are still in the early stages of restoration, highlighting the need for long-term planning and management.

Supplementary Information

Supplementary information accompanies this paper at https://doi.org/10.5141/jee.23.058.

Table S1 The list of plants in study sites, Ganzhuer of Hulunbuir, Inner Mongolia.

Abbreviations

Ref-E: Reference ecosystem

UNCCD: United Nations launched the Convention to Combat Desertification

IPCC: Intergovernmental Panel on Climate Change

NR: Not restored

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Authors' contributions

KEJ collected, analyzed, and visualized the data, wrote the original draft, and reviewed the finished version. LSH planned the article, collected, and analyzed the data and wrote the original draft. JSB collected, and created the manuscript and reviewed the finished version. YYH planned and supervised the article, conceived the paper, conducted experiments, collected, and analyzed data, visualized the data, and reviewed the completed version and received research funding.

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Competing interests

The authors declare that they have no competing interests.

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