Heliyon 5 (2019) e02243

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.heliyon.com

The increase in ecosystem services values of the sand dune succession in northeastern China

Jiawei Yang, Yi Tang *

School of Life Science, Liaoning University, Shenyang, 110036, China

A R T I C L E I N F O

Keywords:
Environmental science
Ecology
Environmental assessment
Environmental economics
Environmental management
Carbon stock
Horqin Sandy Land
Sparse elm woodlands
Vegetation restoration
Desertification

A B S T R A C T

Ecosystem services values play a vital role in evaluating the economic benefits of ecosystems and for drawing up the vegetation restoration policy. The change of ecosystem services values in sand dune succession, especially in China, is little reported. This study was conducted in the Wulanaodu region, southeastern of the Horqin Sandy Land, one of the largest sandy lands in China. Here, we used quantitative methods including marketing value method, the alternative market method, the carbon tax method, the industrial oxygen method, the opportunity cost method, the water balance method, and the shadow engineering method. We evaluated ecosystem services values in fixed sand dunes, semi-fixed sand dunes, and mobile sand dunes. These sand dunes constitute a sand dune succession. The results showed that ecosystem services values in mobile sand dunes, semi-fixed sand dunes, and fixed sand dunes were 6206.58 CNY·hm^{-2}·a^{-1}, 9986.28 CNY·hm^{-2}·a^{-1}, and 31466.56 CNY·hm^{-2}·a^{-1} separately. The ecosystem services values in fixed sand dunes were five times to these in mobile sand dunes. It suggests that ecosystem services values increase along with the sand dune succession. Moreover, in fixed sand dunes, the main categories contributing to ecosystem services values were gas regulation (17748.11 CNY·hm^{-2}·a^{-1}), and soil formation and retention (6461.80 CNY·hm^{-2}·a^{-1}). Meanwhile, gas regulation (3696.61 CNY·hm^{-2}·a^{-1}), and soil formation and retention (3124.74 CNY·hm^{-2}·a^{-1}) were also the main categories contributing to ecosystem services values in semi-fixed sand dunes. The main categories contributing to ecosystem services values were gas regulation (2760.10 CNY·hm^{-2}·a^{-1}) and water regulation (2278.00 CNY·hm^{-2}·a^{-1}) in mobile sand dunes. This study provides evidence that an increase in ecosystem services values in sandy lands is consistent with the aim of the combat of desertification.

1. Introduction

Desertification, defined as a kind of land degradation occurred in arid, semi-arid and sub-humid arid areas, was confirmed in 1992 (Le Houérou, 1996). Desertification widely appears in one of the three of the land area in the world and influences the lives of 1.5 billion people (Rossi et al., 2015). China, the country with most people, is also suffered from desertification in the area of 2.61 million km^2 (Feng et al., 2016).

Desertification, caused by various factors including climate changes and human activities, leads to the degradation in arid and semi-arid areas (Jiang et al., 2002). To prevent degradation in sandy lands, a series of measures have adopted since the 1950s in China. After decades of combating desertification, some mobile sand dunes were fixed and changed into semi-fixed and fixed sand dunes. The mobile sand dunes, semi-fixed sand dunes, and fixed sand dunes constitute a sand dune succession. The difference in these types of sand dunes includes the species diversity, vegetation dynamic, soil seed bank, soil moisture, and soil physical and chemical characteristics. For instance, species diversity, and richness gradually increase along with the sand dune succession (Zhang et al., 2005a). Moreover, the sand dune succession affects the distribution of microbial species (Poosakkannu et al., 2017). However, it is not well known that changes in ecosystem services values in the sand dune succession.

Calculating ecosystem services values is a method to evaluate ecosystems in a comparable way (Costanza et al., 1997). The ecosystem services values are mainly reported in forests, farmlands, and wetlands (Guo et al., 2001; Barbier et al., 2011; Sutcliffe et al., 2015). Recently, the ecosystem services values in sandy lands have received increasing attention, especially in coastal sand dunes. For example, the values of ecosystem services and their improvement are estimated with system dynamical models in coastal sand dunes in South Korea (You et al., 2018). Meanwhile, ecosystem services values in touristic infrastructure

* Corresponding author.
E-mail address: tangyi@lnu.edu.cn (Y. Tang).

https://doi.org/10.1016/j.heliyon.2019.e02243
Received 25 March 2019; Received in revised form 2 May 2019; Accepted 2 August 2019

are measured using the cost of hotel rooms in coastal sand dunes in Mexico (Mendoza-González et al., 2018). Besides, ecosystem services values in stages in coastal sand dune succession are monetized and compared in Belgium (Van der Biest et al., 2017). However, it is little reported the change of ecosystem services values along the inland sand dune succession.

Although the long-term investigation on a located sand dune is little in reality, the sand dune succession could be observed with the space-for-time substitution method (Miao et al., 2018). According to this method, mobile sand dunes, semi-fixed sand dunes, and fixed sand dunes exsiting simultaneously, could be considered as a sand dune succession. In order to explore the changes in ecosystem services values in sand dune succession, typical communities should be selected, as plant communities found in mobile sand dunes, semi-fixed sand dunes and fixed sand dunes are different from each other. In the Horqin Sandy Land, one of the largest sandy lands in China, mobile sand dunes, semi-fixed sand dunes, and fixed sand dunes distribute widely. In mobile sand dunes, *Caragana microphylla Lam.* is commonly used to prevent the movement of sand dunes. In semi-fixed sand dunes, *Artemisia halodendron* is a dominant species. It declines along with the fixing of the sand dunes. In fixed sand dunes, sparse elm woodland is the climax community and original vegetation. Thus, we selected *C. microphylla* community, *A. halodendron* community, and sparse elm woodland as typical communities representing mobile sand dunes, semi-fixed sand dunes, and fixed sand dunes separately.

Sand dune succession goes along with an increase in plant community stability, higher soil quality, and more abundant biodiversity. Thus, we hypothesized that ecosystem services values increased along with the sand dune succession, i.e., the change from mobile sand dunes to semi-fixed sand dunes and fixed sand dunes. This study aims to test our hypothesis mentioned above and to reveal changes in ecosystem services in sand dune succession. This study could help us know the ecosystem services values of vegetation types in sandy lands exactly and make a decision to decide which vegetation type should be prior protected.

2. Methods

2.1. Study area

The study area is located in the Wulanaodu region, southeastern of the Horqin Sandy Land (42°29′–43°06′N, 119°39′–120 °02′E, 480 m) (Fig. 1). The region is a temperate continental semi-arid monsoon climate with the mean annual temperature of 6.3 °C. The average daily temperatures of the coldest month (January) and the warmest month (July) are -14 °C and 23 °C. The average annual precipitation is 340mm, 70% of which concentrates from June to August. The main wind direction is the northwesterly wind from March to May, followed by the southwesterly wind from June to September (Tang et al., 2014). The primary soil types are prodic arenosols and humic nitosols. Typical plants are *C. microphylla, Setaria viridis*, *Bassia dasyphylla*, *Chenopodium glaucum*, *Chenopodium aristatum*, *Lespedeza daurica, Pennisetum centrasiaticum* (Zhang et al., 2016a).

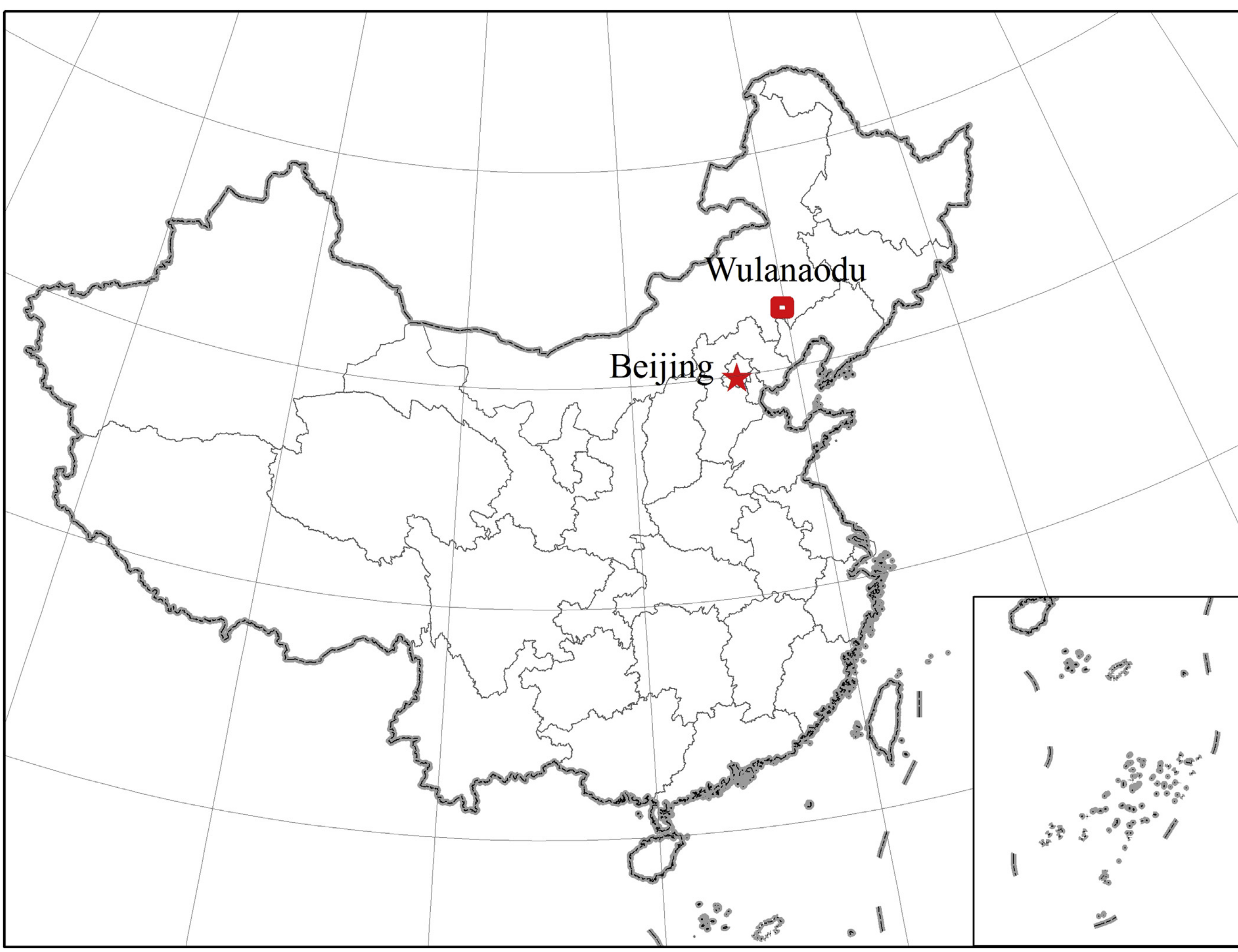

Fig. 1. The location of study area (cited from Zhang et al., (2016a)).

2.2. The estimation of ecosystem services values

In this study region, *C. microphylla* is a typical species in mobile sand dunes, as it is widely planted to fix the movement of sand dunes. Along with fixing of sand dunes, *A. halodendron* becomes a dominant species, especially in semi-fixed sand dunes. Then, *A. halodendron* declines along with the process of sand dune succession. In the last stage of the sand dune succession, i.e., fixed sand dunes, the sparse elm woodland come to be the climax community. Therefore, we selected *C. microphylla* community, *A. halodendron* community, and sparse elm woodland as typical communities representing mobile sand dunes, semi-fixed sand dunes, and fixed sand dunes separately.

The ecosystem services values in this study include five categories, including biodiversity protection, soil formation and retention, nutrient cycling, gas regulation, and water regulation.

2.2.1. Biodiversity protection

Net primary productivity (NPP) is an essential indicator of biodiversity protection. Here, we measured biodiversity protection following previous studies (He et al., 2005; Wen et al., 2013). We used the marketing value method to measure the value of biodiversity protection (Chaikumbung et al., 2016; Saarikoski et al., 2015).

$$V_B = NPP \times Pt_1$$

where V_B is the value of biodiversity protection ($CNY \cdot hm^{-2} \cdot a^{-1}$); Pt_1 is the mass value of organic matter per ton of carbon ($CNY \cdot t^{-1}$ C).

We calculated the NPP following formulations in Li's study (Li, 2006).

$$NPP_{se} = \Delta B = \frac{B_2 - B_1}{t_2 - t_1} + L + G$$

$$NPP_{cm} = \frac{\Delta B}{\Delta t} \times 100 = \frac{B_2 - B_1}{t_2 - t_1} \times 100$$

$$NPP_{ah} = (BM_1 - BM_2) \times 10^{-2}$$

where ΔB is the biomass increment ($g \cdot cm^{-2}$); B_2 or B_1 is the biomass corresponding to the time t_2 or t_1; L is the litter amount from t_1 to t_2 ($t \cdot hm^{-2} \cdot a^{-1}$); G: is the animal feed intake from t_1 to t_2; Δt is the time interval between investigations (a^{-1}); BM_1 is the maximum biomass of *A. halodendron* ($g \cdot cm^{-2}$); BM_2 is the minimum biomass of *A. halodendron.*

The NPP_{se}, NPP_{cm} and NPP_{ah} represent *NPP* in sparse elm woodland, *C. microphylla* community and *A. halodendron* community.

2.2.2. Soil formation and retention

Plant communities play critical roles in reducing soil loss and wind erosion, and in protecting soil fertility (Ouyang et al., 1999; Sutton et al., 2016). In this study, we evaluated ecosystem services values of soil retention considering soil fertility protection and soil erosion reduction. We calculated the value of the soil formation and retention following the equation.

$$V_S = V_1 + V_2$$

$$V_1 = \frac{(C_N + C_P + C_K) \times 10^{-4} \times At}{s} \times Pt_2$$

$$V_2 = \frac{At \times \rho}{H} \times 100 \times Pt_3$$

$$At = Ap - Ar = (\varepsilon_2 - \varepsilon_1) \times s$$

where V_S is the value of soil formation and retention ($CNY \cdot hm^{-2} \cdot a^{-1}$); V_1 is the value of soil fertility protection ($CNY \cdot hm^{-2} \cdot a^{-1}$); V_2 is the value of soil erosion reduction ($CNY \cdot hm^{-2} \cdot a^{-1}$); At is the soil retention ($t \cdot a^{-1}$); Ap is the potential soil erosion in the test site ($t \cdot a^{-1}$); Ar is the actual soil erosion in the test site ($t \cdot a^{-1}$); ε_2 is the soil erosion modulus without forest ($t \cdot hm^{-2} \cdot a^{-1}$); ε_1 is the soil erosion modulus after covering vegetation ($t \cdot hm^{-2} \cdot a^{-1}$); s is the test area (hm^2); C_N is the contents of total N in soil (%); C_P is the contents of available P in soil (%); C_K is the contents of available K in soil (%); Pt_2 is the soil fertility gain per ton mass loss ($CNY \cdot t^{-1}$); H is the test ground layer thickness (cm); P is the soil bulk density ($g \cdot cm^{-3}$); Pt_3 is the biggest benefit from sand per hectare ($CNY \cdot hm^{-2} \cdot a^{-1}$).

2.2.3. Nutrient cycling

Nutrients in ecosystems work as a carrier for storing chemical energy and a material basis for life-sustaining activities (Shi et al., 2007; Tolessa et al., 2017). We calculated the number of nutrients stored in sand dunes ecosystems according to the alternative market method, which could estimate the economic value created by the sand dunes ecosystems in nutrient cycling (Escobedo et al., 2015). The formulation was below.

$$V_N = (C_N + C_P + C_K) \times 10^{-4} \times NPP \times Pt_2$$

where V_N is the value of nutrient cycling ($CNY \cdot hm^{-2} \cdot a^{-1}$); C_N is the contents of total N in soil (%); C_P is the contents of available P in soil (%); C_K is the contents of available K in soil (%); *NPP* is the net primary productivity of the vegetation ($t \cdot hm^{-2} \cdot a^{-1}$); Pt_2 is the soil fertility gain per ton mass loss ($CNY \cdot t^{-1}$).

2.2.4. Gas regulation

The vegetation regulates the atmosphere mainly through the exchange of CO_2 and O_2 with the atmosphere through photosynthesis and respiration (Xu et al., 2013; Chaikumbung et al., 2016). We calculated the value of the adjustment of atmospheric balance using the opportunity cost method, the carbon tax method and industrial oxygen method. The formulation is below.

$$V_G = V_1' + V_2'$$

$$V_1' = Q_1 \times Pt_4 = NPP \times Wt_1 \times Pt_4$$

$$V_2' = Q_2 \times Pt_5 = NPP \times Wt_2 \times Pt_5$$

where V_G is the value of gas regulation ($CNY \cdot hm^{-2} \cdot a^{-1}$); V_1' is the value of carbon storage ($CNY \cdot hm^{-2} \cdot a^{-1}$); V_2' is the value of releasing oxygen ($CNY \cdot hm^{-2} \cdot a^{-1}$); Q_1 is the annual CO_2 fixed amount ($t \cdot hm^{-2} \cdot a^{-1}$); Wt_1 is the carbon sequestration coefficient; Pt_4 is the carbon fixation cost ($CNY \cdot t^{-1}$); Q_2 is the annual O_2 release ($t \cdot hm^{-2} \cdot a^{-1}$); Wt_2 is the oxygen release coefficient; Pt_5 is the oxygen release cost ($CNY \cdot t^{-1}$).

2.2.5. Water regulation

The provision of water is one of the most critical categories of ecosystem services that directly link growing human populations to ecosystems (Sajedipour et al., 2017). We calculated values of water regulation with the water balance method and shadow engineering method. The formulation was below (Xu et al., 2015).

$$V_W = W \times Pt_6 = (1 - \theta) \times R \times Pt_6$$

where V_W is the water regulation value ($CNY \cdot hm^{-2} \cdot a^{-1}$); W is the water source ($mm \cdot a^{-1}$); θ is the runoff coefficient (%); R is the annual average rainfall ($mm \cdot a^{-1}$); Pt_6 is the water storage cost ($CNY \cdot m^{-3}$).

Some data were collected from previous studies to calculate ecosystem services values with the equations mentioned above (Table1).

3. Results

3.1. Ecosystem services values in sand dunes

The ecosystem services values in mobile sand dunes, semi-fixed sand dunes, and fixed sand dunes were 6206.58 $CNY \cdot hm^{-2} \cdot a^{-1}$, 9986.28

Table 1
The variables and values to calculate ecosystem service values.

Vegetation	Variables	Values	Units	References
Sparse elm woodland	ΔB	213	$g{\cdot}cm^{-2}$	Zhang (2004)
	C_P	0.95	$mg{\cdot}kg^{-1}$	Zhang (2004)
	C_N	0.1	$mg{\cdot}kg^{-1}$	Zhang (2004)
	C_K	206.25	$mg{\cdot}kg^{-1}$	Zhang (2004)
	NPP_{se}	11.06	$t{\cdot}hm^{-2}{\cdot}a^{-1}$	Li (2006)
	ρ	1.44	$g{\cdot}cm^{-3}$	Jiang et al., (2008)
	ε_1	31.25	$t{\cdot}hm^{-2}{\cdot}a^{-1}$	Zhang et al., (2016b)
	ε_2	88.04	$t{\cdot}hm^{-2}{\cdot}a^{-1}$	Zhang et al., (2002)
C. microphylla	ΔB	416	$g{\cdot}cm^{-2}$	Jiang et al., (2008)
	C_P	3.81	$mg{\cdot}kg^{-1}$	Zhang et al., (2005b)
	C_N	0.043	$mg{\cdot}kg^{-1}$	Zhang et al., (2005b)
	C_K	40.67	$mg{\cdot}kg^{-1}$	Zhang et al., (2005b)
	NPP_{cm}	1.72	$t{\cdot}hm^{-2}{\cdot}a^{-1}$	Jiang et al., (2008)
	ρ	1.54	$g{\cdot}cm^{-3}$	Cao et al., (2004)
	ε_1	75.2	$t{\cdot}hm^{-2}{\cdot}a^{-1}$	Zhang et al., (2016b)
	ε_2	88.04	$t{\cdot}hm^{-2}{\cdot}a^{-1}$	Zhang et al., (2002)
A. halodendron	ΔB	49.75	$g{\cdot}cm^{-2}$	Yin et al., (2006)
	C_P	0.005	$mg{\cdot}kg^{-1}$	Zhang et al., (2005b)
	C_N	0.007	$mg{\cdot}kg^{-1}$	Zhang et al., (2005b)
	NPP_{ah}	2.30	$t{\cdot}hm^{-2}{\cdot}a^{-1}$	Yuan (2017)
	ρ	1.51	$g{\cdot}cm^{-3}$	Jiang et al., (2008)
	ε_1	25	$t{\cdot}hm^{-2}{\cdot}a^{-1}$	Zhang et al., (2016b)
	ε_2	88.04	$t{\cdot}hm^{-2}{\cdot}a^{-1}$	Zhang et al., (2002)

CNY·hm^{-2}·a^{-1}, and 31466.56 CNY·hm^{-2}·a^{-1}. The values were the highest in fixed sand dunes and were the lowest in mobile sand dunes. More importantly, the ecosystem services value in fixed sand dunes was five times to that in mobile sand dunes (Fig. 2).

3.2. Categories of ecosystem services values

The value of biodiversity protection was 608.88 CNY·hm^{-2}·a^{-1} in mobile sand dunes and increased to 815.47 CNY·hm^{-2}·a^{-1} and 3915.24 CNY·hm^{-2}·a^{-1} in the semi-fixed sand dunes and fixed sand dunes. The value of gas regulation was 2760.10 CNY·hm^{-2}·a^{-1} in mobile sand dunes and increased to 3696.61 CNY·hm^{-2}·a^{-1} and 17748.11 CNY·hm^{-2}·a^{-1} in the semi-fixed sand dunes and fixed sand dunes. The value of nutrient cycling was 37.46 CNY·hm^{-2}·a^{-1} in mobile sand dunes and increased to 71.46 CNY·hm^{-2}·a^{-1} and 1063.41 CNY·hm^{-2}·a^{-1} in the semi-fixed sand dunes and fixed sand dunes. The value of soil formation and retention was 522.16 CNY·hm^{-2}·a^{-1} in mobile sand dunes and increased to 3124.74 CNY·hm^{-2}·a^{-1} and 6461.80 CNY·hm^{-2}·a^{-1} in the semi-fixed sand dunes and fixed sand dunes. The value of water regulation was 2760.10 CNY·hm^{-2}·a^{-1} in three types of sand dunes (Table 2).

3.3. Contributions to ecosystem services

In the mobile sand dunes, the ascending order of proportions in contributing ecosystem services was nutrient cycling (0.60%), soil formation and retention (8.41%), biodiversity protection (9.81%), water source conservation (36.70%), and gas regulation (44.47%). Meanwhile, in semi-fixed sand dunes, the ascending order of proportions in contributing ecosystem services was nutrient cycling (0.71%), soil formation and retention (8.17%), biodiversity protection (22.81%), water source conservation (31.29%), and gas regulation (37.02%). In fixed sand dunes, the ascending order of proportions in contributing ecosystem services was nutrient cycling (3.38%), water regulation (7.24%), biodiversity protection (12.44%), soil formation and retention (20.54%), and gas regulation (56.40%) (Fig. 3).

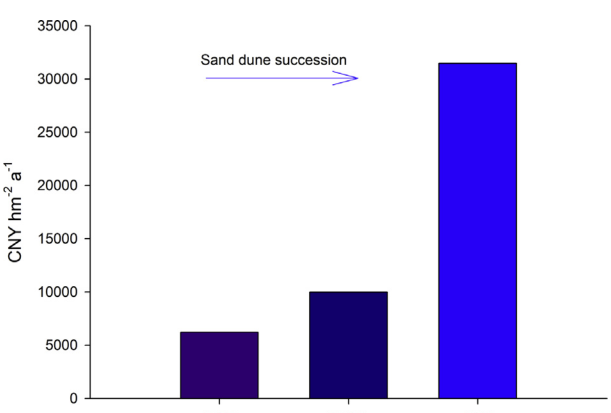

Fig. 2. The ecosystem service values increase along with the sand dune succession.

4. Discussion

This result obtained in this work showed that ecosystem services values were the highest in fixed sand dunes and were the lowest in mobile sand dunes, indicating the ecosystem services values increased along with the sand dune succession. In this study region, the two categories, i.e., gas regulation, and soil formation and retention, contributed most of the ecosystem services values in fixed and semi-fixed sand dunes (76.94% and 68.31%). Meanwhile, the two categories, i.e., gas regulation, and water regulation contributed most of the ecosystem services values in mobile sand dunes (81.17%). The performance in aspects of gas regulation and soil formation and retention was better in fixed sand dunes (Li et al., 2004; Zhang et al., 2015). That might explain why the ecosystem services values are higher in fixed sand dunes.

The ecosystem services values in the Horqin Sandy Land are reported in a previous study. Yuan et al. (2018) reported ecosystem services value in the sparse elm woodlands in the Horqin Sandy Land was 5941.34 CNY·hm^{-2}·a^{-1}, which is much lower than this study. In this study, ecosystem services value was 31466.56 CNY·hm^{-2}·a^{-1} in sparse elm woodlands. The reasons might be due to the values of O_2 regulation and water regulation are not considered in Yuan's study. The lack of values of O_2 regulation and water regulation might partly explain the difference in ecosystem services values in the sparse elm woodlands.

The ecosystem services values in deserts are also reported. For example, Taylor et al. (2017) evaluated the ecosystem services values in the Chihuahuan desert and found the ecosystem services value was 3907.71 CNY·hm^{-2}·a^{-1} (1USD = 7.75CNY). Besides, Richardson (2005) reported the ecosystem services value was 331.43 CNY·hm^{-2}·a^{-1} (1USD = 7.75CNY) in California desert in the USA. It seems that ecological services values in deserts are lower than that in this study. It might be partly explained by lower vegetation cover and poor soil in deserts (Hu et al., 2015b; Yue et al., 2016).

The ecosystem services values in coastal sand dunes are also reported. For instance, Brenner et al. (2010) studied the ecosystem services values of Catalan coastal sand dunes in Spain and claimed the ecosystem services values were 807.13 CNY·hm^{-2}·a^{-1} (1USD = 7.75CNY). In Brenner's study, the ecosystem services values consisted of disturbance regulation, aesthetic values, recreation and cultural and spiritual values. You et al. (2018) reported the ecosystem services value was 232.35 CNY·hm^{-2}·a^{-1} (1USD = 7.75CNY) in Shinduri coastal sand dunes in South Korea (You et al., 2018). In You's study, tourism infrastructure, thinning, coastal sand dune restoration, afforestation, and weeding constituted ecosystem services values. It seems that cultural values such as recreation and tourism

Table 2
The categories of ecosystem services in sand dunes (CNY·hm^{-2}·a^{-1}).

Categories	Mobile sand dunes	Semi-fixed sand dunes	Fixed sand dunes
Biodiversity protection	608.88	815.47	3915.24
Gas regulation	2760.10	3696.61	17748.11
Nutrient cycling	37.46	71.46	1063.41
Soil formation and retention	522.16	3124.74	6461.80
Water regulation	2278.00	2278.00	2278.00

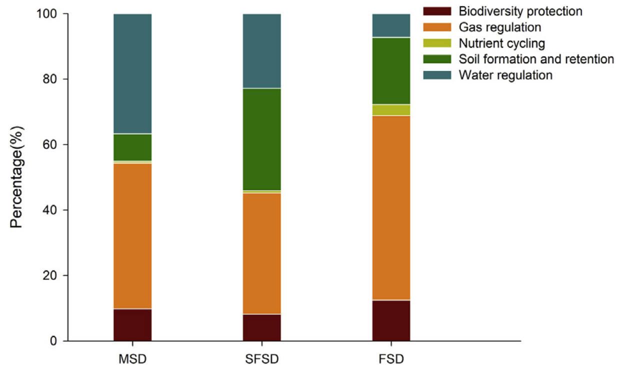

Fig. 3. The percentage of the proportion contributing to ecosystem services in sand dunes. MSD: mobile sand dunes, SFSD: semi-fixed sand dunes; FSD: fixed sand dunes.

are more considered in coastal sand dunes (Katz-Gerro and Orenstein, 2015). However, tourism and recreation are little considered in sand dunes in arid and semi-arid areas.

It is widely reported the ecosystem services values in forests and grasslands (Xie et al., 2010; Wen et al., 2013; Wang et al., 2006; Li et al., 2010; Costanza et al., 2014). According to these studies, ecosystem services values in sand dunes are relatively lower than that in forests and grasslands. It might be due to three reasons. Firstly, the forests and grasslands ecosystems have higher biomass, higher net primary productivity, and better ecosystem services functions occur in forests and grasslands (Wang et al., 2013; Cong et al., 2017). Secondly, soil bulk density, soil water capacity, and soil acidity are the most important factors (Duan et al., 2008). Compared with that in forests and grasslands, the lower vegetation coverage and poor soil cause lower ecosystem services values in sand dunes. Thirdly, land use patterns led by human beings have changed the supply of ecosystem services (Lawler et al., 2014). Human's behaviors tend to transform sand dunes ecosystems with less human benefits into forests and grasslands ecosystems that have greater benefits for humans to gain high economic returns and meet maximum available markets (Sawut et al., 2013).

This results reported the values of carbon storages in mobile, semi-fixed and fixed sand dunes were 1983.08 CNY·hm^{-2}·a^{-1}, 2655.94 CNY·hm^{-2}·a^{-1}, 12751.67 CNY·hm^{-2}·a^{-1}, claiming sand dunes were a vital source of carbon stocks. It is known that the global terrestrial system stores more than 80% of carbon and most of the carbon stored in forests and grasslands ecosystems (Sun et al., 2006). Recently, some studies claim that sand dunes are a potential carbon sink (Hu et al., 2015a; Gao et al., 2017). This result supported the evidence that sand dunes play a vital role in carbon stocks. Moreover, as the capacity of carbon sequestration is larger in fixed sand dunes, it suggests that fixed sand dunes are more critical for carbon stocks than mobile and semi-fixed sand dunes.

5. Conclusion

Here, ecological services values in sand dunes along the sand dune succession in the Horqin Sandy Land were evaluated and compared. The results showed that the ecosystem services values of mobile, semi-fixed, and fixed sand dunes were 6206.58 CNY·hm^{-2}·a^{-1}, 9986.28 CNY·hm^{-2}·a^{-1}, and 31466.56 CNY·hm^{-2}·a^{-1} respectively. The two categories, i.e., gas regulation, and soil formation and retention were the main categories contributing to ecosystem services values in fixed and semi-fixed sand dunes. Their contributions were 76.94 % and 68.31% of ecosystem services values in fixed sand dunes and semi-fixed sand dunes. Meanwhile, gas regulation and water regulation were the main categories contributing to ecosystem services values in mobile sand dunes and they accounted for 81.17% of the ecosystem services values.

First of all, these results support our hypothesis that ecosystem services values increased along with the sand dune succession. The benefits of sand dune succession are mainly related to keeping biodiversity and promoting plant restoration. These findings enlarge the benefits of sand dune succession and provide evidence that the increase in ecosystem services values is consistent with the combat of desertification. Moreover, compared with *A. halodendron* community *and C. microphylla* community, the ecosystem services values are relatively high in sparse elm woodlands It suggests that sparse elm woodland should be under the priority protection for providing ecosystem services values.

Declarations

Author contribution statement

Jiawei Yang: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Yi Tang: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

This work was supported by the National Natural Science Foundation of China (31870709).

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

Acknowledgements

Thanks so much to Prof. Paulo Pereira, the Associate Editor of Heliyon and two anonymous reviewers for the constructive comments on our manuscript.

References

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, S.B.R., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monogr. 81, 169–193.
Brenner, J., Jiménez, J.A., Sardá, R., Garola, A., 2010. An assessment of the non-market value of the ecosystem services provided by the Catalan coastal zone, Spain. Ocean Coast Manag. 53, 27–38.
Cao, C., Jiang, D., Quan, G., Geng, L., Cui, Z., Luo, Y., 2004. Changes of soil physical and chemical properties in artificial sand-fixing area of *Caragana microphylla* in Horqin Sandy Land. J. Soil Water Conserv. 6, 108–111+131.
Chaikumbung, M., Doucouliagos, H., Scarborough, H., 2016. The economic value of wetlands in developing countries: a meta-regression analysis. Ecol. Econ. 124, 164–174.
Cong, R., Wang, B., Gu, J., Niu, X., Hu, T., 2017. Evaluation of forest ecosystem service value in helan mountain national nature reserve in ningxia. J. Arid Land Resour. Environ. 31, 136–140.
Costanza, R., Arge, R., Groot, R., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253–260.
Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S.J., Kubiszewski, I., Farber, S., Turner, R.K., 2014. Changes in the global value of ecosystem services. Glob. Environ. Chang. 26, 152–158.
Duan, W.J., Ren, H., Fu, S.L., Guo, Q.F., Wang, J., 2008. Pathways and determinants of early spontaneous vegetation succession in degraded lowland of South China. J. Integr. Plant Biol. 50, 147–156.
Escobedo, F.J., Adams, D.C., Timilsina, N., 2015. Urban forest structure effects on property value. Ecosyst. Serv. 12, 209–217.
Feng, L., Jia, Z., Li, Q., 2016. The dynamic monitoring of aeolian desertification land distribution and its response to climate change in northern China. Sci. Rep. 6, 39563.
Gao, Y., Dang, P., Zhao, Q., Liu, J., Liu, J., 2017. Effects of vegetation rehabilitation on soil organic and inorganic carbon stocks in the Mu Us Desert, northwest China. Land Degrad. Dev. 29, 1031–1040.
Guo, Z., Xiao, X., Gan, Y., Zheng, Y., 2001. Ecosystem functions, services and their values – a case study in Xingshan County of China. Ecol. Econ. 38, 141–154.

He, H., Pan, Y., Zhu, W., Liu, X., Zhang, Q., Zhu, X., 2005. China's terrestrial ecosystem service value measurement. J. Appl. Ecol. 06, 1122–1127.

Hu, F., Shou, W., Liu, B., Liu, Z., Busso, C.A., 2015a. Species composition and diversity, and carbon stock in a dune ecosystem in the Horqin Sandy Land of northern China. J. Arid. Land. 7, 82–93.

Hu, G., Liu, H., Yin, Y., Song, Z., 2015b. The role of legumes in plant community succession of degraded grasslands in northern China. Land Degrad. Dev. 27, 366–372.

Jiang, D., Liu, Z., Kou, Z., 2002. Prospects for desertification and ecological restoration in Horqin sandy land. J. Appl. Ecol. 12, 1695–1698.

Jiang, D., Cao, C., Akita, A., Musa, A., Li, M., 2008. Study on the characteristics of vegetation and soil degradation during desertification in Horqin sandy land. J. Arid Land Resour. Environ. 10, 156–161.

Katz-Gerro, T., Orenstein, D.E., 2015. Environmental tastes, opinions and behaviors: social sciences in the service of cultural ecosystem service assessment. Ecol. Soc. 20, 28.

Lawler, J.J., Lewis, D.J., Nelson, E., Plantinga, A.J., Polasky, S., Withey, J.C., Helmers, D.P., Martinuzzi, S., Pennington, D., Radeloff, V.C., 2014. Projected land-use change impacts on ecosystem services in the United States. Proc. Natl. Acad. Sci. U.S.A. 111, 7492–7497.

Le Houérou, H.N., 1996. Climate change, drought and desertification. J. Arid Environ. 34, 133–185.

Li, G., 2006. Study on the Ecosystem of Sparse forest and Grassland in Hunshandake Sandland: Biomass, Productivity and Ecological Restoration Approach. Thesis. Graduate School of the Chinese Academy of Sciences (Plant Research Institute).

Li, T., Li, W., Qian, Z., 2010. Variations in ecosystem service value in response to land use changes in Shenzhen. Ecol. Econ. 69, 1427–1435.

Li, X., Xiao, H., Zhang, J., Wang, X., 2004. Long-term ecosystem effects of sand-binding vegetation in the Tengger Desert, northern China. Restor. Ecol. 12, 376–390.

Mendoza-González, G., Martínez, M.L., Guevara, R., Pérez-Maqueo, O., Garza-Lagler, M.C., Howard, A., 2018. Towards a sustainable sun, sea, and sand tourism: the value of ocean view and proximity to the coast. Sustainability 10, 1012.

Miao, R., Qiu, X., Guo, M., Musa, A., Jiang, D., 2018. Accuracy of space for-time substitution for vegetation state prediction following shrub restoration. J. Plant Ecol. 11, 208–217.

Ouyang, Z., Wang, X., Miao, H., 1999. A primary study on Chinese terrestrial ecosystem services and their ecological-economic values. Acta Ecol. Sin. 19, 607–613.

Poosakkannu, A., Nissinen, R., Männistö, M., Kytöviita, M.M., 2017. Microbial community composition but not diversity changes along succession in arctic sand dunes. Environ. Microbiol. 19, 698–709.

Richardson, R.B., 2005. The Economic Benefits of California Desert Wildlands: 10 Years since the California Desert Protection Act of 1994. Island Press, The Wilderness D C.

Rossi, F., Olguín, E.J., Diels, L., De Philippis, R., 2015. Microbial fixation of CO_2 in water bodies and in drylands to combat climate change, soil loss and desertification. N. Biotech. 32, 109–120.

Saarikoski, H., Jax, K., Harrison, P.A., Primmer, E., Barton, D.N., Mononen, L., Vihervaara, P., Furman, E., 2015. Exploring operational ecosystem service definitions: the case of boreal forests. Ecosyst. Serv. 14, 144–157.

Sajedipour, S., Zarei, H., Oryan, S., 2017. Estimation of environmental water requirements via an ecological approach: a case study of Bakhtegan Lake, Iran. Ecol. Eng. 100, 246–255.

Sawut, M., Eziz, M., Tiyip, T., 2013. The effects of land-use change on ecosystem service value of desert oasis: a case study in Ugan-Kuqa River Delta Oasis, China. Can. J. Soil Sci. 93, 99–108.

Shi, Y., Li, Y., Yang, D., Liu, H., Hu, Y., 2007. Value evaluation of Hulunbeier grassland ecosystem service function. J. Agri. Environ. Sci. 6, 2099–2103.

Sun, Y., Ji, H., Luo, J., Li, T., Jiang, Y., 2006. Research progress on climate-driven carbon cycle in terrestrial ecosystems in China. J. Cap. Normal Univ. 5, 90–95.

Sutcliffe, L.M., Batáry, P., Kormann, U., Báldi, A., Dicks, L.V., Herzon, I., Kleijn, D., Tryjanowski, P., Apostolova, I., Arlettaz, R., Aunins, A., 2015. Harnessing the biodiversity value of central and eastern european farmland. Divers. Distrib. 21, 722–730.

Sutton, P.C., Anderson, S.J., Costanza, R., Kubiszewski, I., 2016. The ecological economics of land degradation: impacts on ecosystem service values. Ecol. Econ. 129, 182–192.

Tang, Y., Jiang, D., Lv, X., 2014. Effects of exclosure management on elm (*Ulmus pumila*) recruitment in Horqin sandy land, northeastern China. Arid Land Res. Manag. 28, 109–117.

Taylor, N.T., Davis, K.M., Abad, H., McClung, M.R., Moran, M.D., 2017. Ecosystem services of the big bend region of the Chihuahuan desert. Ecosyst. Serv. 27, 48–57.

Tolessa, T., Senbeta, F., Kidane, M., 2017. The impact of land use/land cover change on ecosystem services in the central highlands of Ethiopia. Ecosyst. Serv. 23, 47–54.

Van der Biest, K., De Nocker, L., Provoost, S., Boerema, A., Staes, J., Meire, P., 2017. Dune dynamics safeguard ecosystem services. Ocean Coast Manag. 149, 148–158.

Wang, Y., Guo, S., Wang, J., Yuan, H., Xu, B., Wang, D., 2013. Evaluation of forest ecosystem service value in qilian mountain national nature reserve of gansu province. J. Desert Res. 33, 1905–1911.

Wang, Z., Zhang, B., Zhang, S., Li, X., Liu, D., Song, K., Li, J., Li, F., Duan, H., 2006. Changes of land use and of ecosystem service values in sanjiang plain, northeast China. Environ. Monit. Assess. 112, 69–91.

Wen, L., Dong, S., Li, Y., Li, X., Shi, J., Wang, Y., Liu, D., Ma, Y., 2013. Effect of degradation intensity on grassland ecosystem services in the alpine region of qinghai-Tibetan plateau, China. PLoS One 8, e58432.

Xie, G., Li, W., Xiao, Y., Zhang, B., Lu, C., An, K., Wang, J., Xu, K., Wang, J., 2010. Forest ecosystem services and their values in Beijing. Chin. Geogr. Sci. 20, 51–58.

Xu, X., Yan, A., Zhu, P., Zhou, Z., 2013. Evaluation of ecosystem service value based on multi-source remote sensing data——taking Hebei Province as an example. Remot. Sens. Land Resour. 25, 180–186.

Xu, X., Xu, L., Yan, L., Ma, L., Lu, Y., 2015. Integrated regional ecological risk assessment of multi-ecosystems under multi-disasters: a case study of China. Environ. Earth Sci. 74, 747–758.

Yin, H., Piao, S., Wang, Z., Yan, X., Zhang, B., Zhai, J., Ding, Y., 2006. Ecological characteristics of *Artemisia halodendron* community and population on Horqin sandy land. J. Appl. Ecol. 17, 1169–1173.

You, S., Kim, M., Lee, J., Chon, J., 2018. Coastal landscape planning for improving the value of ecosystem services in coastal areas: using system dynamics model. Environ. Pollut. 242, 2040–2050.

Yuan, Z., 2017. Temporal and Spatial Variation of Vegetation Productivity and Driving Factors in Hunshandake Sandy Land from 2000 to 2013. Thesis. Inner Mongolia Normal University.

Yuan, J., Duan, C., Ouyang, Z., Zheng, H., Xu, W., 2018. Estimation of economic value of ecosystem services under different ecological restoration modes in the southeastern margin of Horqin Sandy Land. Acta Ecol. Sin. 27, 55–61.

Yue, Y., Ye, X., Zou, X., Wang, J., Gao, L., 2016. Research on land use optimization for reducing wind erosion in sandy desertified area: a case study of Yuyang County in Mu Us Desert, China. Stoch. Environ. Res. Risk Assess. 31, 1371–1387.

Zhang, J., Zhao, H., Zhang, T., Zhao, X., Drake, S., 2005a. Community succession along a chronosequence of vegetation restoration on sand dunes in Horqin Sandy Land. J. Arid Environ. 62, 555–566.

Zhang, M., Wu, J., Tang, Y., 2016a. The effects of grazing on the spatial pattern of elm (*Ulmus pumila* L.) in the sparse woodland steppe of Horqin Sandy Land in northeastern China. Solid Earth 7, 631–637.

Zhang, H., 2004. Discussion on ecological benefits of *Ulmus pumila L.* Woodland in hunshandake sandy land. *Thesis.* Inner Mongolia Agricultural University.

Zhang, Y., Li, Z., Zhang, X., Niu, W., Tang, S., 2016b. Spatial distribution characteristics of soil erosion in wind-water erosion interlocked area of inner Mongolia. J. Inn. Mong. Agric. Univ. (Nat. Sci. Ed.) 37, 50–58.

Zhang, H., He, H., Li, F., Zhang, H., 2005b. Study on ecological effects of several shrubs on sandy soils in Horqin Sandy Land. Geogr. Res. 24, 708–716.

Zhang, H., Li, F., Zhang, T., Li, Y., Su, Y., 2002. Dynamics and variation characteristics of wind erosion in bare sandy farmland in spring. J. Soil Water Conserv. 1, 29–32+79.

Zhang, Z., Chen, Y., Xu, B., Huang, L., Tan, H., Dong, X., 2015. Topographic differentiations of biological soil crusts and hydraulic properties in fixed sand dunes, Tengger Desert. J. Arid. Land 7, 205–215.