Ecological effects of establishing a 40-year oasis protection system in a northwestern China desert

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https://doi.org/10.1016/j.catena.2019.104374
Received 31 August 2019; Received in revised form 30 October 2019; Accepted 15 November 2019

1. Introduction

Land degradation due to poor land management and climate change is one of the most prominent global environmental problems (Zhu et al., 1988; Duan et al., 2019). In arid and semi-arid regions, land degradation is often referred to as “desertification”, which may result in a persistent loss of ecosystem services and pose a serious threat to sustainable livelihoods in already ecologically fragile areas (Millennium Ecosystem Assessment, 2005). Over the past several decades, the amount of desertified land has grown globally due to intensified land-use activities (i.e., over-cultivation, over-grazing, and fuelwood collection) and shifts in climate (Feng and Fu, 2013). This trend is expected to continue, particularly in arid regions in northwestern China, where there are increasing human population pressures and warming and drought due to climate change (Xue, 2006; Feng et al., 2015). An oasis is a human settlement located in arid regions in China and throughout the world, which has developed agriculture and animal husbandry in a fragile ecological environment (Ingram, 1987). The establishment of an oasis protection system can reverse desertification using multiple measures, including re-vegetation through shrub or tree plantations, protection from livestock grazing, and the creation of a sand-binding vegetation system, has been widely implemented in many semi-arid and arid regions (Redman, 1999; Reynolds et al., 2007; Cao et al., 2011).

The effects of establishing oasis-protection systems on soil and vegetation properties are highly variable, depending on the treatments applied, the plant species selected, and the methodologies used in the evaluation of ecosystem recovery (Tongway et al., 2003; Bhattachan et al., 2014). For example, Su et al. (2007) reported that the large scale plantation of Caragana microphylla improved the physical, chemical, and microbial properties of soil, and increased vegetation biomass in the Horqin Sandy Land. Similarly, Chen et al. (2007) found that soil...
erosion was reduced following land protection and restoration in heavily cultivated areas in the hilly region of the semi-arid Loess Plateau. However, Jackson et al. (2005) showed that afforestation across eight sites in the Pampas of Argentina significantly increased soil salinization. At the same time, Zhou et al. (2011) and Yuan et al. (2015) also found that oasis protection systems substantially increased soil acidification and planted vegetation started to degrade after 20 years. Thus, understanding the long-term effects of oasis protection efforts could be critical for sustainable ecosystem management in water-limited environments.

Desert ecosystems cover about 20% of China’s land surface, and many oases with different sizes and shapes intersperse in the vast desert area. These natural or artificial oases represent only 4% of the land surface, but support the life of about 95% of the human population (He et al., 2007; Han et al., 2015). Increased demand for food and fiber due to the rapidly growing population has led to extensive cultivation, intensive grazing, and over-fuel-wood collection, causing severe destruction of vegetation and the encroachment of shifting sand into the transition zone between the oasis and desert over the past century (He et al., 2005). Establishing a rain-fed oasis-protection system has been a principal strategy to maintain or recover the ecological integrity of fragile ecosystems in China and throughout the world. The effects of establishing oasis-protection systems on soil and vegetation properties may take several decades, as desert ecosystems are slow to recover and short-term changes in vegetation and soil properties could be a transient state (Jones and Schmitz, 2009; Bagchi et al., 2012). The evaluation of long-term effects of establishing oasis protection systems on soil and vegetation recovery can avoid misleading trends detected with short-term data (Fukami and Nakajima, 2011; Hughes et al., 2013) and reveal urgently needed strategies to reduce land degradation (Millennium Ecosystem Assessment, 2005).

This study evaluates the long-term ecological effects of establishing an oasis protection system on vegetation and soil properties along a protection gradient in a typical desert-oasis ecotone located along the southern fringes of the Badain Jaran Desert in northwestern China. We expected vegetation and soil properties to be increasingly affected along the gradient in land protection from shifting dunes (unprotected), to prohibited grazing shrubland (fuelwood collection permitted), to fenced shrubland (no fuelwood collection permitted), to shrub- and tree plantations. We hypothesized that (1) the oasis-protection system can effectively prevent wind erosion and increase vegetation cover and soil stability and fertility; (2) the shrub and tree plantations contribute to soil desiccation in deep layers and increase soil salinity and soil sodicity; (3) plant species introduced to the protection system will not regenerate if they experience these negative soil effects, which may affect the success of restoration efforts in the long-term.

2. Material and methods
2.1. Study site

The study was carried out along a typical desert-oasis ecotone located along the southern fringes of the Badain Jaran Desert in northwestern China (Fig. 1). This region has a continental temperate climate, with windy and dry springs and very hot summers followed by cool autumns and cold winters. The mean annual air temperature is about 7.6 °C, varying from −27 °C in January to 39.1 °C in July. The mean annual precipitation is about 117 mm with over 70% occurring between June and September. The potential evaporation is 2390 mm year−1, which is 20 fold more than mean annual precipitation. The mean annual wind velocity is 3.2 m s−1 and the prevailing wind direction is northwest. Gales with wind velocity ≥ 17 m s−1 mainly occur in the spring for 15 or more days per year. Sand- and dust-transport by wind is characteristic of this vast desert landscape. The dominant vegetation at the desert-oasis ecotone is composed of natural growing species such as Calligonum mongolicum Turcz., Nitaria sphaerocarpa Maxim., Hedysarum scoparium Fisch. et Mey., and planted species Haloxylon ammodendron (C.A. Mey.) Bge., Caragana korshinskii Kom. and Elaeagnus angustifolia Linn. The main crops are maize (Zea mays L.) and cotton (Gossypium hirsutum L.) in the farmlands of the oasis.

2.2. The oasis-protection system

Farmland occurs in the oasis, and is surrounded by shifting dunes with sparse vegetation cover. Unsuccessful reclamation of land, over grazing and fuel collection have led to natural vegetation loss and encroachment of shifting sand dunes, which threatens the stability of oasis ecosystems. To prevent desertification of the oasis and promote ecosystem recovery, a succession of protection measures was implemented in different areas, and an oasis-protection system composed of four distinctive areas (subsequently referred to as “belts”) has gradually established at increasing distances from the unprotected desert without irrigation (Table 1 and Fig. 2).

2.3. Experimental design and sampling

This system provides a protection spatial gradient on sites with similar soils, parent materials, climatic conditions, and land-use history prior to the creation of the oasis. The shifting dunes were selected as an unprotected reference site. Long-term impacts of different measurements on soil properties and vegetation community can be evaluated by investigating soil and vegetation conditions in sites of different belts.

A nested sampling design was used to investigate vegetation and soil properties in each of the five belts in August 2013. Three replicated sites of 300 × 500 m (200–300 m apart) were chosen at random in each belt. At each of the three sites, three replicate plots (25 × 25 m, 50–80 m apart) were randomly selected to investigate vegetation. The statuses of dominant species were investigated by measuring plant height and canopy width at the sites of five different belts (Table S1). The roots of the dominant species of five different belts were excavated to investigate their vertical distribution (20, 40, 60, 80, 100, 120, 140, 160, 180 and 200 cm depth). Meanwhile, the regeneration traits (density, cover and height) of dominant species along the spatial gradient were also investigated. Within each plot, five replicates of subplots (1 × 1 m, 5 m apart) were chosen at random. In each sub-plot, the density, species number, and cover of herbaceous plants were measured. To measure plant biomass, the grasses were collected by clipping at ground level, oven-dried at 80 °C for 48 h, and weighed.

For each belt, three replicate sites used for vegetation survey were selected to collect soil samples, and three soil samples were collected under the plant canopy and in the inter-canopy area (i.e., half way between two adjacent canopies) in August 2013. At each site, a composite soil was sampled at 0–10 and 10–20 cm from three random sampling locations. Soil samples were air-dried and passed through a 2-mm sieve before soil physical and chemical analyses. Soil texture was measured by pipette method (ISSCAS, 1978). Soil pH and electrical conductivity (EC) were measured by using a combination pH electrode (Multiline F/SET-3, Germany). Soil organic C was determined by dichromate oxidation of Walkley-Black (Nelson and Sommers, 1982), total N by the Kjeldhal procedure (UDK140 Automatic Steam Distilling Unit, Automatic Titroline 96, Italy), and total P by UV-1601 Spectrophotometer (Japan) (ISSCAS, 1978). Soil ions (i.e., SO42−, Cl−, HCO3−, CO32−, Ca2+, Mg2+, K+, Na+) were measured using the methods summarized in Table S2. Soil sodicity was characterized using pH and exchangeable sodium percentage (ESP). Sodium adsorption ratio (SAR) and ESP in 0–10 and 10–20 cm were calculated:

\[
SAR = Na^+ A_0 \times (Ca^{2+} + Mg^{2+})
\]
Soil moisture content was measured gravimetrically and calculated as the ratio of the mass of water to dry soil after drying the samples at 105 °C for 72 hr. Soil moisture under the dominant species canopy was monitored continuously during the growing season (in mid-April – September) from 2002 to 2013 in each of the five belts. According to the soil moisture level and distribution of root systems of dominant species, the soil profile divided into three layers: top active layers (20, 40 and 60 cm), shallow sub-active layers (80, 100 and 120 cm) and deep layers (140, 160 and 180 cm). Soils at these depths were sampled using a stainless steel auger (5 cm in diameter), except during rain events when samples were taken 1 week after the rainfall.

Wind erosion was monitored by measuring aeolian sand transport rates in each of the five belts during storm events on 23 April 2004 and 12 May 2005. The aeolian sand transport rate was measured by using modified Wilson and Cooke (MWAC) samplers. The samplers comprise a vertical mast carrying a set of six sediment traps, which are constructed from MWAC bottles (5.4 cm long and 3.2 cm in diameter) with glass inlet and outlet tubes (each 1.0 cm in inner diameter). The MWACs were installed at 10, 15, 20, 30, 50, and 100 cm above the sand surface, and the sand fraction caught by every MWAC was weighed on a balance after the sandstorms.

2.4. Statistical analysis

One-way analyses of variance (ANOVAs) were performed to test for significant differences in soil physical and chemical parameters among different-belt sites with post hoc Duncan tests (alpha = 0.05). All data were analyzed in SPSS 16.0. Linear regressions were used to investigate the relationship between soil texture (content of silt and clay) at 0–20 cm soil depth and soil nutrients; the relationship between different belts and response variables, including herbaceous plant density, cover, total above ground biomass, species number; and soil water content and year of measurement. All regression trend lines shown in the results are significant (alpha = 0.05).

3. Results

3.1. Wind velocity and wind erosion

Compared with shifting dunes, the mean wind velocity and wind erosion (i.e., sand transport rate) decreased gradually along the oasis-protection gradient, with the lowest levels at shrub and tree plantation belts. For example, on 23 April 2004, the mean wind velocity (at 50 cm height) decreased by 7, 44, 56 and 72%, and the sand transport rate (at 10 cm) decreased by 49, 91, 96 and 97% at the prohibited grazing shrubland, fenced shrubland, shrub and tree plantation belts, respectively (Fig. 3a, c); On 12 May 2005, mean wind velocity decreased by 25, 63, 66, and 75%, and the mean sand transport rates decreased by 49, 91, 96, and 97% at the prohibited grazing shrubland, fenced shrubland, shrub and tree plantation belts, respectively (Fig. 3b, d).

3.2. Soil texture

The contents of silt and clay increased along the oasis-protection gradient, from shifting dunes to the tree plantation belt (Fig. 4). At 0–10 cm depth, the mean contents of silt and clay increased from 6.5% in the shifting dunes to 10.2, 13.0, 21.2 and 64.1% under the dominant species canopy (Fig. 4a), and from 5.9% to 7.2, 8.6, 17.3 and 52.6% in the inter-canopy (Fig. 4b) at the prohibited grazing shrubland, fenced shrubland, shrub- and tree plantation belts, respectively. At 10–20 cm depth, the increasing trend was less pronounced than the surface 0–10 cm depth: the mean silt and clay contents increased from 5.1% in shifting dunes to 8.4, 8.3, 18.0 and 6.7% under the canopy (Fig. 4c), and to 7.8, 8.4, 15.8 and 6.3% in the inter-canopy at the prohibited grazing shrubland, fenced shrubland, shrub- and tree plantation belts, respectively (Fig. 4d).
<table>
<thead>
<tr>
<th>Belt Type</th>
<th>Dominant Plants Species</th>
<th>Site Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shifting dunes</td>
<td>Calligonum mongolicum</td>
<td>Natural desert, 3000 m², shifting dunes, no practice</td>
</tr>
<tr>
<td>Livestock exclusion zone</td>
<td>Nitraria sphaerocarpa</td>
<td>Natural recovery zone, 2500 m², prohibited grazing, restoration of native vegetation</td>
</tr>
<tr>
<td>Fenced shrubland belt</td>
<td>Haloxylon ammodendron</td>
<td>1000 m², planted 1 × 1 m, irrigated 1 × 3 times at the first 3 years, then no irrigation</td>
</tr>
<tr>
<td>Fenced shrubland belt</td>
<td>Elaeagnus angustifolia</td>
<td>20 m², planted 3 × 3 m, irrigated 3 – 5 times, then no irrigation every year, seedlings survived after 3–5 years</td>
</tr>
</tbody>
</table>

Note: NOB refers to the number of oasis-protection belts, shifting dunes were selected as an unprotected reference site; FTB refers to functional types of the belts; RM refers to restoration methods; IT refers to intervention type; DF refers to distance from farmland.

3.3. Soil nutrients

Soil organic carbon (SOC), total nitrogen (TN) and total phosphorus (TP) also increased along the oasis-protection system. At the surface layer (0–10 cm), SOC increased from 1.1 g kg⁻¹ in the shifting sand dunes to 2.4, 3.4, 4.2 and 9.9 g kg⁻¹ under the canopy (Fig. 5a), and from 0.8 g kg⁻¹ to 0.9, 0.9, 2.7 and 7.9 g kg⁻¹ in the inter-canopy at the prohibited grazing shrubland, fenced shrubland, shrub- and tree plantation belts, respectively (Fig. 5b). At 10–20 cm depth, SOC increased from 0.7 g kg⁻¹ to 0.9, 1.5, 2.1 and 1.1 g kg⁻¹ under the canopy at the prohibited grazing shrubland, fenced shrubland, shrub and tree plantation belts, respectively (Fig. 5a). Total N followed the same spatial increase pattern as SOC, increased from 0.2 in the shifting dunes to 1.3 g kg⁻¹ in the 0–10 cm soil layer, and from 0.1 to 0.8 g kg⁻¹ in the inter-canopy at the tree plantation belt (Fig. 5c, d), while the increase trend in the inter-canopy was not significant. Total P at 0–10 cm depth increased from 0.5 g kg⁻¹ in the shifting sand dunes to 0.6, 0.8, 0.8 and 1.1 g kg⁻¹ under the canopy, and to 0.6, 0.6, 0.7 and 1.0 g kg⁻¹ in the inter-canopy at the prohibited grazing shrubland, fenced shrubland, shrub- and tree plantation belts, respectively (Fig. 5e, f). At 10–20 cm depth, total P increased from 0.5 g kg⁻¹ to 1.1 g kg⁻¹ under the canopy and to 0.6 g kg⁻¹ in the inter-canopy at the tree plantation belt. The increase in soil nutrients at 0–10 cm was greater than that at 10–20 cm depth.

3.4. Herbaceous plants

An herbaceous plant community gradually developed, with increases in plant density, cover, biomass and species richness along the oasis-protection gradient. In the shifting dunes, only a few herbaceous plants occurred and the density and cover was very low due to the frequent disturbance of sand burial and wind erosion (Fig. 6a, c). At prohibited grazing shrubland and fenced shrubland belts, the herbaceous plant community developed very slowly, with only some pioneer annual species, such as Bassia dasyphylla and Agriophyllum squarrosum, colonizing. At shrub- and tree plantation belts, herbaceous plant density, biomass, and cover continued to increase and reached their highest levels: the density increased from 12 to 300 plants/m², biomass from 3 to 60 g/m² and species richness from 4 to 12 species (Fig. 6a, c, d). However, the herbaceous plant community consisted mostly of short-lived annual grasses and forbs (Table S3).

3.5. Soil moisture in deep layers

The soil moisture at deep layers (i.e., 160 and 180 cm) decreased sharply at the tree plantation belt through time (Fig. 7). The mean soil water content decreased from an initial 20–24% to 3–5% (Fig. 7b-i). At the deep soil layers (160 and 180 cm) of the tree plantation belt, the decline of the soil water content could be well described by a linear function with a decrease of 0.1% every year.

3.6. Soil ions

The concentration of soil ions under the canopy, including SO₄²⁻, Ca²⁺, Mg²⁺, K⁺ and Na⁺, significantly increased along the oasis-protection gradient, and reached their highest levels at tree plantation (0–10 cm) (Fig. 8) and shrub plantation belts (10–20 cm) (Fig. 9). At 0–10 cm depth, the total ions increased 7-fold under the canopy of the tree plantation belt: SO₄²⁻ increased 39-fold, Ca²⁺ 19-fold, Mg²⁺ 15-fold, K⁺ 22-fold and Na⁺ 18-fold compared with shifting dunes; likewise, in the inter-canopy SO₄²⁻ increased 9-fold and Na⁺ 9-fold. At 10–20 cm depth of the shrub plantation belt, the total ions under the canopy increased 6-fold: SO₄²⁻ increased 24-fold, K⁺ 29-fold, and Na⁺ 15-fold. But in the inter-canopy the increase of soil ions was not significant. In general, the concentrations of soil ions under the shrub
canopy were markedly higher than in the inter-canopy.

3.7. Soil sodicity

Soil sodicity (i.e., soil pH $\geq 8.0$ and exchangeable sodium percentage $\geq 20\%$) occurred under the canopy in the tree plantation and shrub plantation belts. At 0–10 cm depth, pH increased from 7.7 in shifting dunes to 8.6 under the canopy at tree plantation belt (Fig. 10a), and from 7.6 to 7.7 in the inter-canopy at shrub plantation belt (Fig. 10b). At 10–20 cm depth, pH showed no significant difference. At 0–10 cm depth, exchangeable sodium percentage (ESP) increased from 1% to 22% under the canopy at shrub plantation belt (Fig. 10c), and to 12% in the inter-canopy (Fig. 10d). At 10–20 cm depth, ESP increased from 7% to 53% under the canopy at shrub plantation belt, and from 4 to 16% in the inter-canopy.

3.8. Regeneration traits of the dominant species

At the shrub- and tree plantation belt, the introduced species were unable to effectively establish new individuals directly underneath...
adults of the same species: for planted \textit{H. ammodendron}, the regenerated plant cover, density and height were 7\%, 80 stems/ha and 60 cm, respectively; for \textit{E. angustifolia}, no seedling was found to have germinated and established naturally at the tree plantation belt (Fig. 11).

4. Discussion

4.1. Positive effects of the oasis-protection system

4.1.1. Decrease in wind velocity and erosion

We found that the mean wind velocity (at 50 cm height above ground) and wind erosion (aeolian sediment transport at 10 cm height above ground) decreased by 75 and 97\% when storms passed through the most protected shrub- and tree plantation belts of the oasis system, respectively, compared to unprotected sand dunes. Consistent with our study, in the same study area, planting \textit{Haloxylon ammodendron} can reduce wind velocity and wind erosion, but only by 13\% and 70\%, respectively (He et al., 2005). These results suggest that the oasis-protection system composed of multiple protection measures is more effective than a single measure (i.e., planting shrubs) in halting the spread of sand and dust storms and mitigating wind erosion. Moreover, we also found mean wind velocity (at 50 cm) and the sand transport rate decreased gradually along the oasis protection gradient. These reductions are because the wind momentum and moving sand particles were gradually absorbed by increasing amounts and heights of vegetation (Xue, 2006) along the four sand binding belts.

4.1.2. Accumulation of fine soil particles

We found a significant increase in silt and clay content along the gradient of the oasis-protection system. Soil particle size distribution is an important indicator that reflects the extent of soil erosion by wind in desert ecosystems (Lobe et al., 2001). Due to long-term wind erosion in the study area that preferentially eroded fine particles, only coarse sand was left on the surface of shifting dunes. The establishment of the oasis-protection system functioned as a barrier for reducing wind velocity and protected fine particles from being eroded at the initial dune...
surface. Meanwhile, large amounts of suspended dust were deposited on dense vegetation patches when wind velocity sharply decreased at the shrub- and tree-plantation belts. Therefore, the fine particle contents at the sand surface under canopies increased by 10-fold at the tree plantation belt compared to unprotected sand dunes. This increase of silt and clay altered the original soil substrate and associated physical properties of the soil.

4.1.3. Increase in soil nutrients

We found a significant increase in SOC, TN and TP along the gradient of the oasis-protection system. These results are consistent with other observations from the Negev in Israel (Zaady and Ofer, 2009), the Horqin Sandy Land (Zhao et al., 2011) and the Tengger Desert (Li et al., 2007) in northeastern China. In this study, the contents of SOC, TN, and TP were positively correlated with the contents of silt and clay, which accounted for 87, 79, and 85% of the increase in SOC, TN and TP, respectively (Fig. S1). Similarly, Su et al. (2004) showed that when the silt and clay content decreased by 1%, the SOC decreased by 0.17 g kg\(^{-1}\) in semi-arid Horqin Sandy Land. Collectively, these findings demonstrate that soil carbon and nutrients are mainly stored in fine soil particles within desert ecosystems. Moreover, the increase in primary productivity provides a large reservoir for carbon and nutrients (Lal, 2004). This increase has a positive feedback on generating higher litterfall and rhizosphere inputs into soil carbon and nutrient pools (Wang et al., 2015). We observed a significant increase in carbon and nutrients in the inter-canopy, but much less than under canopies. This difference between microsites leads to an increase of soil resource heterogeneity, forming a mosaic of nutrient rich soil patches under the canopies, which are known as ‘islands of fertility’ (Schlesinger et al., 1990; Ma et al., 2017).

Fig. 5. Soil organic carbon (SOC, g kg\(^{-1}\)) (a, b), total nitrogen (TN, g kg\(^{-1}\)) (c, d), total phosphorus (TP, g kg\(^{-1}\)) (e, f) at 0–10 cm and 10–20 cm depths under the canopy (a, c, e) and in the inter-canopy (b, d, f) at the five oasis-protection belts. Refer to Fig. 3 for 1–5 oasis-protection belt definitions. Note: different lowercase letters indicate significant differences among the different belts at p < 0.05.
4.1.4. Herbaceous plant development

We found that herbaceous plants increased along the protection gradient, and the development of herbaceous plant cover transformed a single over-story woody plant community to a multi-layer, ecological system. The development of shallow rooted herbaceous plants was facilitated by a variety of factors including an increase in nutrient content (Kawada et al., 2011; Liu et al., 2012), decreased wind erosion associated with a positive feedback generated by colonizing grasses (Yu et al., 2016) and increased seed availability (Zhao et al., 2007). Pan et al. (2008) indicated that shallow-rooted perennial herbaceous plants could replace deep-rooted shrubs to become the dominant in an artificial community after 20 years following vegetation restoration in the Tengger Desert, Northern China. In this study, throughout the oasis-protection system, most of the plants in the herbaceous community were short-lived annual grasses and forbs (Fig. 5a, c, d). Without perennial herbaceous plants, the annual plant dominated community has high inter-annual variability in cover, and the growth of the annual herbaceous layer is unstable due to low and variable annual and seasonal precipitation. This instability provides limited potential for recovery of soil and other ecosystem properties, suggesting that this state may be transient and longer-term recovery may be needed for the ecosystem to return to a stable state.

4.1.5. Negative effects of the oasis-protection system

4.1.5.1. Desiccation of deep soil layer. In drylands, soil moisture is the principal limiting factor for revegetation efforts (Porporato et al., 2002). In this study, we found a significant decrease in soil water content in deep soil layers (160 and 180 cm) in the tree plantation belt. Consistent with this study, Li et al. (2007) and Yuan et al. (2015) also found significant reduction in soil water content in deep soil depths after the creation of shrub plantations in the fringe of Tengger Desert and in the hilly region of the Loess Plateau. Generally, soil moisture conditions depend on the input of precipitation, the losses of soil evaporation and plant transpiration, and soil properties that influence water retention and movement (D’Odorico et al., 2013). In this study, the increased soil sodicity that occurred in shrub- and tree plantation belts can alter soil physical properties, destroy soil structure, and reduce soil porosity and soil permeability (Rengasamy et al., 2003). Due to low hydraulic conductivity of the saline-sodic soil, soil water in the deep layers may not recharge after a series of precipitation events, thereby diminishing water content after decades of shrub or tree plantations. On the other hand, the outputs of soil water content increased due to the high transpiration of planted trees. The annual transpiration loss of E. angustifolia is about 350 mm in this study area (Shen et al., 2014, 2015), which is more than 2–3 fold of annual precipitation. We found that the capillary roots of E. angustifolia were mainly distributed in the deep soil layers of 160–180 cm (Fig. S2), and thus soil desiccation likely occurred in these layers.

4.1.5.2. Soil salinity. We found that shrub and tree plantations without freshwater irrigation could induce soil salinization. Consistent with our study, soil salinization was also observed after the creation of large-scale plantations in other arid and semi-arid regions such as southern Australia (Heuperman, 1999), the Caspian steppes of Russia (Sapanov, 2003), and the Pampas of Argentina (Jackson et al., 2005). The rate and area of salinization are expected to continue to increase under a predicted future drier and warming climate (Charles and Dukes, 2009; Dai, 2010), which may negatively affect future revegetation following restoration (van Dijk et al., 2007).

There are three major mechanisms for soil salinity in arid and semi-arid regions: groundwater associated salinity, non-groundwater associated salinity, and irrigation associated salinity (D’Odorico et al., 2013). In this study, the soil salinity at shrub and tree plantation belts is groundwater associated salinity. Due to the limited annual precipitation of 110 mm, the planted trees and shrubs mainly consumed water from the deep soil layer (Fig. S2). As these plants aged, soil desiccation in deep soil layers occurred, and water usage of planted trees likely switched from the deep soil layer (Fig. S3) to the groundwater in this study area where there is a shallow groundwater table (Zhou et al., 2017). A large amount of ions dissolved in the groundwater could be

Fig. 6. Herbaceous plant density (a) and cover (b), total above ground biomass (c), and species number (d) at the five oasis-protection belts. Linear regression results show whether the slope of the regression line differed significantly from zero. Refer to Fig. 3 for 1–5 oasis-protection belt definitions.
brought up to the rooting-zone via hydraulic lift or capillary action, leading to eventual accumulation at the soil surface where there is high evaporation (Rengasamy, 2006).

4.1.5.3. Soil sodicity. We found that soil sodicity (soil pH $\geq 8.0$ and exchangeable sodium percentage $\geq 20\%$) occurred at the shrub and tree plantation belts. As halophytes, *H. ammodendron* and *E. angustifolia* - the dominant species of these plantation belts - can contain Na$^+$ within different tissues, such as leaves and roots, to maintain low root water potential and take up water from a saline soil (Kang et al., 2013). However, when the salt concentrations exceed a threshold level, they exclude the excessive salt (i.e., Na$^+$) to prevent salt damage to plant tissue (Wang and Guo, 1998). These excluded salts then rise to the shallow soil layers via capillary action (i.e., exfiltration) and at last accumulate at the soil surface.

4.1.5.4. Regeneration traits of the dominant species. We found that the planted *H. ammodendron* and *E. angustifolia* in the shrub- and tree plantation belts could not effectively regenerate after 40 years. This may be associated with high salinity and sodicity. Seedlings tolerate only low concentrations of salt in plant tissues, and their productivities are adversely affected by soil salinity and sodicity due to osmotic related effects (Larcher, 1995; Rawat and Banerjee, 1998). Sodicity also affects plant regeneration due to eliciting soil compaction, which may inhibit seedling emergence and establishment. Therefore, only when the stresses of high soil salinity and sodicity are gradually eliminated, do seedlings have a probability to establish naturally.

In this study, we examined the effects of the 40-year oasis protection system composed of four belts (prohibited grazing shrubland, fenced shrubland, shrub- and tree plantation). We found that the most protected belt, tree plantation, decreased wind erosion, increased fractions of silt and clay, associated soil carbon and nutrients, and herbaceous plant cover. Despite these changes, tree plantations decreased deep soil moisture from groundwater use, which led to increased soil salinity and sodicity. Although plantations improved several ecosystem properties, they may negatively affect the future sustainability of the oasis protection system over the long-term under forecasts of a future drier and warming climate.

A potential limitation of this study is that we did not directly measure soil evaporation and transpiration of the dominant species across different belts across the protection gradient. Although we considered complementary studies on evapotranspiration in the same study.

![Changes of soil moisture during the growing season, 12 years after the oasis protection system was established, under the canopy of the dominant plant species at the five oasis-protection belts.](image)
area, this research may be not able to represent the water balance of the entire system. Further studies are needed to compare the hydrological dynamics in different belts of the protection system with the help of isotope tracers and model simulations. Nevertheless, this study provides new knowledge on the degree to which oasis protection systems can reverse land degradation in dryland ecosystems. In a warming climate, with potential increased soil evaporation and soil salinity, crop residues (i.e., corn stalks) could be used as mulch to reduce soil evaporation, and inter-plantings of cover crops (such as *Melilotus suaveolens*, *Medicago sativa* and *Astragalus adsurgens*) could be considered as a biological measure to absorb salts and eliminate salinization in the tree- and shrub plantation belts.

5. Conclusions

This study improved understanding of the long-term effects of establishing an oasis-protection system on soil and vegetation properties in a desert ecosystem. We demonstrated that 40 years after establishing an oasis-protection system, there can be both positive and negative ecosystem effects. The oasis-protection system reduced wind erosion, improved soil fertility and favored the development of an herbaceous plant understory community. However, the tree- and shrub-plantation belts in this system increased soil salinity, sodicity, and desiccation in deep soil layers, which may diminish the long-term stability of the oasis-protection system. *H. ammodendron* and *E. angustifolia* plantations can facilitate the establishment and growth of herbaceous species, while these species themselves could not effectively regenerate. Shrub
or tree dominance in planted belts may be a transient state, even with apparently thriving vegetation for years or decades. We suggest that future research is conducted to understand the inter-relationships between woody overstory, herbaceous understory, soil water and nutrients, particularly over the long-term, could improve future protection measures against desertification.

**Declaration of Competing Interest**

We declare that we have no conflict of interest. Any use of trade, product, or firm names in this paper is for descriptive purposes only and does not imply endorsement by the U.S. Government.

**Acknowledgements**

We are grateful for the guidance of Dr. Wenzhi Zhao. We also appreciate the help in data collection by Gefei Zhang, Fang Li and Qiyue Yang. The editor Adrian L. Collins and two anonymous reviewers are thanked for their constructive comments. This research was funded by National Natural Science Foundation of China (41701045), Shanxi Provincial Natural Science Foundation of China (201801D221336) and Key Laboratory of Ecohydrology of Inland River Basin, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences (KLEIRB-ZS-16-05). Seth Munson was supported by the U.S. Geological Survey Ecosystem Mission Area. Any use of trade, product,
or firm names in this paper is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2019.104374.

References
