A REVIEW OF RESEARCH ON THE DEVELOPMENT AND EVOLUTION OF SCRUB DUNES

BA, Z. D. – DU, H. S.* – WANG, S. H.

Key Lab. of Remote Sensing of Ecological Environment in Jilin Province, Jilin Normal Univ., Siping 136000, China

**Corresponding author*
e-mail: duhs@jlnu.edu.cn; phone: +86-151-4466-1359

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Abstract. Scrub dunes are an important part of the landscape in arid and semi-arid regions, and their occurrence is a sign of land degradation and desertification. The fertile island effect is of great significance to curb the degradation of ecological functions and biodiversity conservation in arid and semi-arid regions. In recent decades, with the continuous development of desert science, a lot of research work has been carried out on the spatial distribution, morphological characteristics, formation conditions, dynamic processes; development patterns and evolution of scrub dunes, and fruitful results have been achieved. In future research, the spatial and temporal scope of the study should be further expanded to achieve a multi-angle, multi-scale and multi-dimensional comprehensive studies, so as to provide a scientific basis for the regional sand prevention and control method.
Keywords: *scrub dune, morphology pattern, dune formation, airflow pattern, dune evolution*

Introduction

Scrub dunes are a type of wind-deposited bio morphology formed by the accumulation of sandy material in and around scrub due to wind and sand flows are blocked by scrubs (Tengberg and Chen, 1998; Khalaf and Al-Awadhi, 2012), and a product of the proximal movement of sandy material under wind action (Khalaf et al., 1995; Langford, 2000). In addition to wind conditions (Bristow and Hill, 2020), sand sources and vegetation, the development of scrub dunes is also influenced by topography, precipitation and groundwater (Wang et al., 2010; Wang, 2003; Tengberg and Chen, 1998). Therefore, scrub dunes contain a wealth of information on regional environmental change. In most regions, scrub dunes with high vegetation cover (e.g., >14%) show little surface erosion even during the season of highest wind-sand activities (Kuriyama et al., 2005; Wiggs et al., 1995; Pye and Tsoar, 1990). Their internal deposition is relatively continuous from embryonic to mature development (Wang et al., 2006, 2008, 2010), and their unique developmental and sedimentary characteristics make it an ideal vehicle for studying wind-sand activities (Chen et al., 2019; Tsoar and Møller, 2020), Dry-Wet conditions, hydrological characteristics, and ecological environments and their evolution in arid and semi-arid regions. In addition, because of the close relationship with the dynamics of the Gobi, dry rivers and dry lake basins, the development process of scrub dune formation in arid and semi-arid regions also records the history of regional geomorphological evolution. In grassland reclamation areas, scrub dunes are the product of wind erosion of agricultural soils (Li et al., 2021), and their occurrence is a main characteristics of the occurrence of regional soil wind erosion and desertification (Li et al., 2014; Quets et al., 2013), and their development process is also related to the grassland reclamation process, which is one of the direct indicators of the degree of land desertification (Tengberg, 1995). Therefore, the study of the

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development of scrub dune formation and its relationship with environmental changes not only helps to improve the theory of aeolian geomorphology (Goudie, 2020; Cong et al., 2020) and desertification science, but also has important significance to enrich the research in the field of global change (Hermas et al., 2019).

Distribution and morphological characteristics of scrub dunes

Distribution of scrub dunes

Scrub dunes are widely developed in most arid semi-arid and sub-humid regions of the world along the leading edge of alluvial fans (dive level depth 1-3 m) (King et al., 2006; Wang et al., 2006; Parsons et al., 2003), degraded grasslands and agricultural lands, desert oasis transition regionals, agro-pastoral interface regions, desert margins and river banks that penetrate into the desert. It is also found in alluvial plains, lake basin depressions, dry deltas, along dry riverbeds (dive level depth 2-5 m) and some sandy coastal regions (Wu et al., 2006a, 2008; Qong et al., 2002; Dong, 2001), it is also found in alpine valleys, plateau basins and other alpine desert areas at altitudes of 4,000 to 5,000 m above sea level (Wu, 2003; Zhu, 1999), and even some arid and semi-arid desert areas where the negative effects of human activities (e.g. over-cultivation, overgrazing) are severe the only wind-deposited landscapes. These areas not only have good moisture and plant growth conditions (Wu et al., 2006a; Dong, 2020), but also have a large amount of erodible material, which provides favorable conditions for scrub dune development (Xia et al., 2005; Khalaf et al., 1995; Hesp, 1981). Scrub dunes are found in the southwestern United States (Seifert et al., 2009; Parsons et al., 2003; Langford, 2000; Rango et al., 2000), Africa (Dougill and Thomas, 2002; Tengberg and Chen, 1998; Tengberg, 1995; Nickling and Wolfe, 1994) and the Middle East (El-Bana et al., 2003; Khalaf et al., 1995; Warren, 1982), all of which are present on a large scale and cover approximately 5% of the global land area (*Fig. 1*) (Thomas et al., 2005).

Figure 1. *The top view of shrub dunes in Songnen Sandy Land, Jilin Province, China*

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Morphological characteristics of scrub dunes

Scrub dunes can be isolated and scattered, or clustered in groups, probably related to the type of scrub, for example, *Tamarisk chinensi* is more isolated (Kang et al., 2019; Du et al., 2007), while Nitraria retusa is mostly clustered in groups (Zhang et al., 2018). The typical form of scrub dune is a raised sandbag with a rounded top and gentle slope (Yeh et al., 2020; Cowling et al., 2019), which can be broadly classified into conical, hemispherical and dome-shaped except for the early shield-shaped and late irregular forms. The draped, less branched and densely planted thickets often form taller cone-like dunes, while the prostrate, less branched and less densely planted ones often form relatively short hemispherical or dome-like dunes (Hesp, 1981). For example, on the southern coast of South Africa, Gazania rigens and Arctotheca populifolia form conical and hemispherical scrub dunes respectively (Hesp and Mclachlan, 2000); on the northern coast of Kuwait, Scrub dunes such as Nitraria retusa and Suaeda vermiculata are commonly dome shaped morphologically (Khalaf et al., 2014, 1995); in the Tarim Basin, Tamarisk chinensis scrub dunes are hemispherical in morphology, while reed and camel thorn scrub dunes are semi-ellipsoidal (Wu et al., 2008). In addition, scrub dunes have different morphologies at different developmental stages. For example, Zhu Zhenda and Chen Guangting (1994) showed that under a single wind direction, the morphology of scrub dunes undergoes four stages: Straight sand bars — isosceles triangular sand spout — the profile is a streamlined, ovoid mound of sand — nearly circular or oval mound of sand. The height of scrub dunes is mainly influenced by the evolutionary stage, vegetation type, sand source abundance and water supply and demand balance (Wang et al., 2010; Tengberg and Chen, 1998; Rhodes and Pownall, 1994), such as 0.4-1.8 m for scrub dunes formed by Caragana microphylla, 0.13-4.5 m for those formed by Nitraria retusa, and Tamarisk chinensis forms 1 to 15 m (Du et al., 2010; Hermas et al., 2019), mainly related to its clump canopy height (*Fig. 2*) (Khalaf et al., 1995).

Figure 2. *Nitraria shrub dunes*

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Conditions and dynamical processes in the formation of scrub dunes

Conditions for the formation of scrub dunes

Vegetation, wind conditions and sand sources are key factors in the development and morphological evolution of scrub dunes (Taminskas et al., 2020; Molina et al., 2020), scrub vegetation is the primary condition for their formation, the presence of upwind sand sources is the physical condition for their formation, and strong winds are the dynamic condition for their formation (Hesp, 1981; Zhao et al., 2020). However, it should be noted that if wind strength and frequency are both sufficient (Fitoka, 2020; Li, 2009), the area of scrub dune formation must have both good moisture conditions for scrub development and a dry surface to ensure the supply of sand (Feng et al., 2021),which obviously constitute a contradiction between these two conditions, resulting in many areas of vigorous scrub growth not being able to form scrub dunes due to lack of sand sources, while areas with sufficient sand sources cannot grow scrub due to moisture limitation (Hilgendorf et al., 2021; Pan et al., 2019). The ability of a region to form scrub dunes depends on the dynamic balance between moisture conditions and sand source availability in the region (Dougill and Thomas, 2002; Hesp and Smyth, 2017). Therefore, scrub dunes in semi-arid areas only form in areas where moisture conditions and sand supply can easily reach a dynamic equilibrium (Li et al., 2020), such as desert oasis transition regions, desert margins, river banks, floodplains, Lake Basin depressions, dry riverbed shores, and degraded grasslands. In addition, a variety of scrubs in arid and semi-arid areas can trap sand material to form scrub dunes, such as Caragana microphylla (Ding et al., 2019), Nitraria retusa, Tamarisk chinensis, Artemisia ordosica and Achnatherum splendens, etc. However, there are significant differences in their height, canopy morphology and scale, and these factors also play a key role in controlling the development of scrub dunes formed around them (Yao et al., 2021), and the morphology of dunes varies among different scrubs (Ma and Lu, 2019). The flexibility and density of scrub branches are closely related to the morphology of scrub dunes (Zhao et al., 2019), for example, scrub with upright branches and high branch density tends to form conical dunes, while scrub with soft branches and low density tends to form hemispherical dunes (Gunn, 2021; Wu et al., 2009).

Dynamical processes of scrub dune formation

Regional wind-sand activities are the driving force behind the formation of scrub dunes. On the one hand, wind-sand activities enable material to be transported and deposited on the surface of scrub dunes; on the other hand, under the influence of micro-geomorphology, the near-surface air flow accelerates, the ability of air flow to carry sand material increases, and the surface erosion intensifies. It causes local activation of scrub dunes (Acosta et al., 2021; Wang et al., 2021). A combination of domestic and international wind tunnel and field experiments (Pakari and Ghani, 2019; Zhong et al., 2021), the dynamics mechanism of scrub dune formation can be briefly described as follows: after the development of scrub in the field, the wind speed is still high in a certain range in front and on both sides of it (Miri et al., 2021; Pei and Pang, 2020), although it is a deceleration regional of airflow, which shows slight wind erosion, and a certain range above it is an acceleration regional of airflow, and a certain range behind it is a weak vortex regional and an obvious deceleration regional of airflow (Gillies et al., 2014; Cornelis and Gabriels, 2005); the wind-sand flow over and through the scrub rapidly shifts from unsaturated to saturated, and sand material begins

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to be deposited, gradually forming a fledgling wind-shadowed dune trailing a long tail; as the amount of sand material deposited increases, the fully permeable scrub changes to a lower impermeable scrub dune (Zhang et al., 2013; Abbate et al., 2019; Gong et al., 2021), and the scrub increases the roughness of the dune surface (Wang et al., 2020). The top of the exposed dune eliminates the area of strong wind erosion that is common on top of the dune, and its dense bottom and sparse top structure also reduces the extent of the airflow deceleration zone on the leeward slope and significantly decelerates the airflow on the windward slope and sides, resulting in a shortening of the length of the dune in the windward direction and an increase in height and width on both sides, which eventually evolves into a vertical projection with an elliptical or sub-circular shape (*Table 1*) (Zhang et al., 2013; Marzialetti et al., 2019).

Table 1. *Morphology, soil and vegetation status of the scrub dunes at different stages of development*

Developmental stage	Morphology	Soil	Vegetation status
Increases	Conical or hemispherical, with good correlation of morphological parameters	The surface is predominantly fluvial, with no crust or a small distribution	Higher vegetation cover and better growth on scrub dunes, less scrub dieback on dunes; lower vegetation cover and poorer growth on interdune sites
Stabilise	Conical or hemispherical, with good correlation of morphological parameters	The surface is predominantly clean skinned, without or with a small distribution of fluvial sand	High vegetation cover and good growth on both scrub dunes and interdunes, with less scrub dieback on dunes
Degeneration	Hemispherical or with wind erosion collapse, morphological parameters poorly correlated	The surface is predominantly fluvial, with no crust or a small distribution	Low vegetation cover and poor growth on both scrub dunes and interdunes, with more dead scrub on the dunes

Patterns of scrub dune development and succession processes

Patterns of scrub development

Under dry and windy conditions, the sand flow is blocked by shrubs and sand material is deposited in the shrubs and scrub downwind (Yang et al., 2019), forming sand bars, and with continued wind action and continued deposition of sandy material, the length of the sand bars shortens and the tails merge, forming a dawn scrub dune, or wind shadow dune (Xia et al., 2004a). When the height of dune increases, low scrub is formed downwind and around the dune, which increases the vegetation cover and is more conducive to reducing wind erosion and intercepting wind and sand flow. When the dune height increases excessively, the scrub roots die because they cannot reach the water table (Miao et al., 2022; Mahmoud et al., 2020; Wang et al., 2010), the plant stems break due to wind action, the root system loses adhesion, the dune starts to activate, the windward slope blows and the leeward slope piles up, and with the continuous action of wind, the scrub dune all blows and turns into drifting sand land, and the scrub dune dies out (Qong et al., 2002; Du et al., 2007). Therefore, scholars

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mostly summarize the process into three stages: growth, stabilization and decline. In addition, scrub dunes can also be in a stable state when the wind is weakened and dust cannot be raised, but scrub dunes in a stable state may grow again after changes in sand sources and wind (Conery et al., 2020; Wang et al., 2015); when sand sources are reduced or even depleted, the water table drops or the scrub dies, scrub dunes suffer strong erosion, the height gradually decreases, the horizontal scale continues to increase, and the whole dune gradually tends to die out (Wang et al., 2010; Molina et al., 2020). The process of scrub dune erosion is a kind of ecological geomorphological process, and its various aspects are intertwined with a series of ecological processes of plant growth, death and dune morph dynamic processes, as well as the dynamic response and feedback between them (Tang et al., 2008).

Scrub succession process

Arid and semi-arid scrub is divided into primary scrub and secondary scrub. Primary scrub has developed a complete mechanism to adapt to local habitats during long-term evolution (Huang et al., 2010), it is mainly distributed in typical grassland and mixed agro-pastoral areas with low water table and relatively poor moisture conditions, and in arid desert areas with high water table and relatively good moisture conditions (Provoost and Declerck, 2020). There are two opposite processes of succession in secondary scrub. The first is due to deterioration of regional moisture conditions, where herbaceous growth is stunted while shrubs win in competition due to deeper root systems, called grassland scrubification (Harte et al., 2015; Sulub-Tun et al., 2020), and is a common phenomenon in arid and semi-arid grasslands. The process involves scrub developing mainly in degraded areas of grasslands with low water tables and relatively poor moisture conditions, and will decline when moisture conditions deteriorate to the point where the minimum requirements needed for shrub growth cannot be met. The second is that in some severely degraded vegetation areas, when moisture conditions improve, scrub develops before herbaceous plants due to better adaptation (Zhao et al., 2009a). In this process, scrub is mainly located in regionals with high water table and relatively good moisture conditions. When moisture conditions continue to improve, herbaceous plants recover and scrub declines due to competition with herbaceous plants (*Fig. 3*) (Zhao et al., 2009b; Rafi et al., 2019).

Construction of the scrub dune chronological sequence and dating of formation

Construction of a chronological sequence of scrub dunes

The chronological sequence of scrub dunes can be determined from the chronology of their vertical profiles (Yang et al., 2019), which is a prerequisite for revealing the developmental process of their formation. Currently, the chronology of scrub dunes is mainly based on grain layer counting (Zhao et al., 2011; Xia et al., 2004b), Accelerator Mass Spectrometric (AMS).14C (Weems and Monger, 2012) and Optically Stimulated Luminescence (OSL). Stimulated Luminescence (OSL) (Forman and Pierson, 2003), dating methods, with varying applicability and advantages and disadvantages (*Table 1*). Although scrub dunes are of relatively short age (1-3 years), the use of OSL dating can enable the establishment of chronological sequences under certain conditions (Ballarini et al., 2003; Bailey et al., 2001). OSL dating is inevitably inaccurate in some areas because scrub dune sediments originate mainly from adjacent areas, are transported over short

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distances (Khalaf et al., 1995; Farrell and Connolly, 2021), do not necessarily receive sufficient light recession, and quartz brightness varies from place to place (Hanson et al., 2009; Rhodes and Pownall, 1994). However, for most scrub dunes, the buried annual leaf litter within the sediment provides excellent material for AMS14C dating, and the chronological sequences thus established are relatively accurate (Weems and Monger, 2012; Wang et al., 2008, 2010). However, on some occasions, due to factors such as species differences or poor preservation, material ideal for AMS14C dating does not exist in some dunes (Sun et al., 2019, 2020). Therefore, a more appropriate dating method, or a combination of different methods, should be used to establish a credible chronological sequence, depending on regional realities (*Table 2*) (Barsanti et al., 2020).

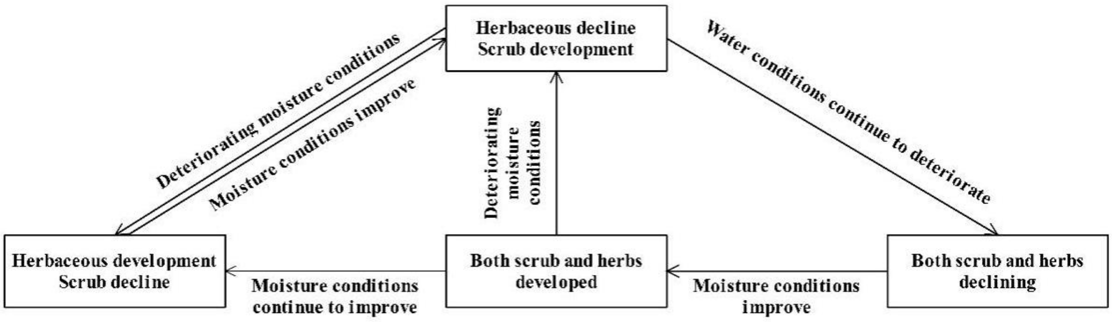

Figure 3. *Scrub succession in arid and semi-arid zones*

Table 2. *Comparison of different dating methods for scrub dunes*

Evaluation	**Method**		
	Layer count	**AMS^{14}C**	**OSL**
Strengths	Simple and relatively accurate dating method	Smaller error, suitable for short timescale dating	Applicable to the dating of wind-formed deposits
Deficiencies	Blurred boundaries or missing layers affect the dating accuracy, and layers are rare	Organic residue burial has limitations	Large errors in some samples and relatively low dating accuracy

In the scrub dunes, wind-generated sand accumulates in spring and dead leaves in autumn, and there is a theoretical wind-generated sand-dead leaves interaction layer in the dunes with an accuracy of up to years (Chojnacki et al., 2020). These clear chronological layers are similar to tree chronologies, lake sediment layers, etc., allowing chronological sequences to be accurate to the year (Wu et al., 2019; Kiani et al., 2021). However, the presence of striated layers has only been found in tamarisk scrub sands in the Taklamakan Desert and Lop nor in China (Wang et al., 2015; Xia et al., 2005; Jiang and Yang, 2019), and has not been reported in other regions of the world or in other types of scrub sands. The exact conditions for the existence of this layer need further study.

Dating the formation of scrub dunes

In addition to dating methods such as grain layer counts, AMS^{14}C and OSL, recent studies have found that in polar, alpine and desert areas lacking tree distribution, some shrub species and even perennial herbs have recognizable annual rings and formation

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patterns that can be used to determine population age structure and reconstruct regional high-resolution climate and environmental evolution histories (Lan et al., 2021; Xiao et al., 2014; Liang and Eckstein, 2009; Yeh et al., 2020). The age of scrub dune formation varies considerably between regions (*Table 2*), which may be due to the different sensitivity of environmental evolution to global climate change in different regions on the one hand, and to regional factors influencing environmental evolution on the other. It was found that several red willow scrub dunes in the Lop Nor region in the growth phase were formed more than 100 years ago (Zhao et al., 2011; Xia et al., 2005, 2004b), However, the two tamarisk scrub dunes on the Alashan Plateau (Hu et al., 2019; Xie and Steinberger, 2005), which are in a growth phase and 800 m apart, are about 200 years apart in age (Wang et al., 2010, 2008), and the relict scrub dunes in the south-central United States are 2400-700 years old (Gillies et al., 2014; Seifert et al., 2009), suggesting that clusters of scrub dunes in the same area may have formed simultaneously or slowly and gradually (*Table 3*).

Table 3. *Age and environment of scrub sand dune formation in arid and semi-arid zones*

Study area	Formative era	Method of fixing the year	Forming the environment	Number of sand dunes	References
South Central USA	2400-700 years	OSL	Climate drought	4	Gillies et al., 2014; Seifert et al., 2009
Chihuahuan Desert, USA	About 1100 years ago	AMSC	Climate drought	1	Weems and Monger, 2012
Southern Taklamakan Desert	200 to 450 years	AMSC	—	3	Zhao et al., 2016
Lop Nor on the south-eastern edge of the Mongolian Plateau	700 to 60 years	OSL	Deteriorating water conditions	4	Wang et al., 2006
	About 100 years ago	layer count	—	1	Xia et al., 2004a, 2005
Mopti region West Africa	—	—	Farming, grazing, Climate drought	—	Nickling and Wolfe, 1994
Western Sahel region	About 50 years ago	Satellite images, field surveys	Climate drought	—	Tengberg, 1995

Environmental significance of sediment indications from scrub dunes

Environmental significance of sediment grain size characteristics indications

Some progress has been made in research on the particle size characteristics of sediments from scrub dunes (*Table 3*). A number of studies have indicated that particle size variations effectively document the evolution of regional physical sources and/or the wind-sand environment. For example, in the northern foothills of the Yinshan Mountains, changes in the content of particle size fractions larger than 500 μm reveal the evolutionary history of the regional wind and sand environment (Wang et al., 2006). On the Alashan Plateau, when the scrub dunes develop to a certain height, the particle size fraction of the material source stabilises and the change in particle size reveals the evolution of the regional surface from arable land and dry riverbed to the Gobi (Wang et al., 2008; Qin et

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al., 2015). In general, changes in the content of the fine-grained fraction (<10 μm) of the sediment record changes in the source, while changes in the content of the coarse-grained fraction (>100 μm) are indicative of changes in the intensity of regional wind and sand activity (Wang et al., 2010; Liu et al., 2009). In the Lop nor region, given the similarity of sediment grain size frequency curves and probabilistic accumulation curves between sediment layers within the dunes, some scholars have suggested that there is relative consistency in the regional depositional environment over time, but that changes in coarse sand content and median grain size reflect changes in the strength of depositional dynamics (Zhao et al., 2009a; Zhang et al., 2011). In the south-central USA, the grain size characteristics of sediment from different orientations of scrub dunes are indicative of regional palaeowind changes (Seifert et al., 2009; Zhang et al., 2008). Grain size is sometimes used as a secondary indicator in characterizing regional climatic dry or wet variability, and chalky clay layers in wind-deposited profiles rich in organic residues of tamarisk in the Lobos' region can help to reveal relatively wet regional climatic conditions during the Little Ice Age (*Table 4*) (Liu et al., 2011).

Table 4. *Indication of grain size and δ13C of organic residues in sediments from different areas of scrub dunes*

Research area	Particle size targets	Indicative meaning	$\delta^{13}C$ Indicator Signification	Country
Tarim Basin[a] (Xia et al., 2005)	—	—	Atmospheric CO_2 concentration and changes in climate cold/warm, dry/wet	China, Xinjiang Uygur Autonomous Region
Tarim Basin[a] (Zhao et al., 2009)	Coarser sand content and median grain size	Variation in the strength of sedimentation dynamics	—	China, Xinjiang Uygur Autonomous Region
Tarim Basin[a] (Liu et al., 2011)	Silt layer clay layer	Combining $\delta^{13}C$ indicators of climate change	Changes in dry/wet climate	China, Xinjiang Uygur Autonomous Region
Alaska Plateau[a] (Wang et al., 2008)	Content of fine particles less than 16 μm and coarse particles greater than 200 μm	Wind power changes	—	USA, State of Alaska
Alaska Plateau[a] (Wang et al., 2008)	Less than 10 μm fine particles Greater than 100 μm coarse particle fraction content	Variation in physical sources and intensity of wind and sand activity	Changes in regional moisture conditions	USA, State of Alaska
Yinshan Mountains[b] (Wang et al., 2008)	Content of particle fractions larger than 500 μm	Wind power changes	—	China, Inner Mongolia Autonomous Region
Arkansas, USA[c] (Seifert et al., 2009)	Greater than 63 μm less than 2000 μm sand fraction content	Ancient wind direction change	—	USA, Arkansas

[a]*Tamarix chinesis*
[b]*Caragana microphylla*
[c]Indeterminate scrub dune

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In general, grain size characteristics are a valid proxy in the use of scrub dune sediments as indicators of environmental change, but also in the context of the regional environment and the specific evolution of the dunes. For example, during the development of the dunes, there is some change in the physical source during wind and sand activity as well as environmental changes (e.g. changes in water table and vegetation cover), and this should be fully taken into account in inversion studies of regional environmental evolution. In addition, as scrub dunes continue to develop and increase in height, the ability of coarse-grained fractions to be transported to the top of the dunes by leapfrogging, etc., gradually decreases (Dong et al., 2005; Lancaster, 1995; Anderson, 1991; White et al., 1976; Bagnold, 1941), which leads to a decrease in the amount of coarse-grained fraction transported to the top of the dunes from the This has resulted in a gradual reduction in sediment grain size from the early stages of formation to the mature stages of development, although regional wind and sand activity has not diminished, or even intensified.

Environmental significance of sediment total organic carbon content, total nitrogen content and carbon to nitrogen ratio value indications

The plant communities in arid and semi-arid zones are relatively simple and have low productivity, while the vegetation that builds scrub dunes and their well-developed root systems provide good conditions for organic matter and Nitrogen (N) storage (Zhang et al., 2011; Cakan and Cigdem, 2006; Day and Ludeke, 1993) and can be used to reflect regional vegetation development history through changes in Total Organic Carbon (TOC) and Total Nitrogen (TN) content in wind-sand accumulations (Zuo et al., 2010; Li et al., 2008). For example, in the northern Sinai Peninsula (Zuo et al., 2010; Li et al., 2008), the TOC and TN contents of the wind and sand accumulation can be used to invert the vegetation development history of the region. For example, in the northern Sinai Peninsula (Egypt), the high organic matter content in the wind-sand layer reflects good regional vegetation development, favorable moisture conditions and low temperatures (El-Bana et al., 2003; Zhang, 2019). In the northern foothills of the Yin Mountains, a comparison of TOC, TN, P_2O_5 and K_2O contents in scrub dune sediments, undisturbed soils and cultivated land was used to invert the history of regional land degradation and scrub dune development (Wang et al., 2006; Liu et al., 2008). In the northern Negev Desert (Israel), the nitrogen content of the surface 0-10 cm sediment of different scrub dunes reveals changes in soil moisture conditions (Zhang et al., 2015), while dissolved organic carbon reveals changes in temperature and shows that the total organic matter content of the scrub dune sediment is relatively stable under different temperature and moisture conditions (Xie and Steinberger, 2005; Foth, 1990). Some scholars have also pointed out that changes in TOC content, TN content and Carbon to nitrogen ratio (C/N) values of tamarisk scrub dunes in the Lop nor region are mainly controlled by changes in atmospheric CO_2 concentration, but also reflect regional climate changes in cold/warm, dry/wet (Zhao et al., 2011; Xia et al., 2005). In fact, although the Chrono sequence of the scrub dunes in this region is relatively accurate, changes in TOC content, TN content and C/N values are not in good agreement with the instrumental temperature and precipitation measured by neighboring weather stations (Zhao et al., 2016). For example, changes in TOC content and temperature are opposite to each other, and changes in TN content and precipitation are opposite to each other, which have not been adequately and reasonably explained. Therefore, the

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environmental significance of the TOC content, TN content and C/N values of the scrub dunes needs to be further explored.

The interrelation of influencing factors of shrub dune development

Reciprocal feedbacks of scrub dunes and vegetation

The interaction between wind-sand activities and vegetation is mainly reflected in two aspects: firstly, the modification and control of near-surface wind-sand activities by vegetation, which is manifested in the construction of landscape formation and the control of its morphological evolution in plant-based wind and sand landscape types (Telfer et al., 2020); secondly, the response process of vegetation to wind-sand activities, which is mainly manifested in the distribution pattern of vegetation and the response of vegetation succession to it (Wu et al., 2006a, b). The sand-blocking ability of plants is the result of the joint action of the above-ground part of plants (height, canopy, stems and leaves, etc.) and the below-ground part (root system), which can increase the surface roughness and change the structure of the near-ground airflow field, thus playing a key role in the sand-blocking of plants (Gao et al., 2015); the below-ground part of plants keeps water and soil, accumulates nutrients, and changes soil physical and chemical properties through the long-term interaction with soil and soil microorganisms, which contributes to plant growth and evolution (Zhang et al, 2021). The subsurface part of plants, through long-term interaction with soil and soil microorganisms, retains water and soil, accumulates nutrients, and changes soil physical and chemical properties (Doniger et al., 2020), providing good conditions for plant growth and succession and sand retention (Zhang, 2019; Lopez et al., 2020), while the improvement of soil properties in sand dunes also affects plant growth and distribution patterns (Tengberg, 1995; Leenders et al., 2007). Under certain environmental conditions, sand material continues to be deposited with the developmental succession of vegetation, and wind shadow dunes gradually evolve into scrub dunes (Conery et al., 2020). Dune morphology and depositional structure are influenced by vegetation type and morphology, while wind speed, blowing time, plant height and crown width, and sidelight area also influence the dune development process (Zuo et al., 2018; Zhao et al., 2021).

Reciprocal feedbacks of scrub dunes with vegetation and soils

There is a positive feedback between shrubs and soil heterogeneity (He et al., 2021; Hou et al., 2019), which is related to shrubs changing soil physicochemical properties through their own physiological activities, decomposition of decaying dead branches and leaves, and root activities (Wang et al., 2020); scrub canopy width is positively correlated with fine, very fine, and chalky sand in the soil, but canopy height has little effect on the percent content of sand grain size; the soil particle composition of scrub dunes is dominated by fine sand content, and The trend of soil water content changes in different parts was consistent; the nutrient content of the scrub soil was significantly higher than that of the inter dune site, thus verifying that scrub affects soil water, redistribution of nutrients and enhances soil heterogeneity (Wang et al., 2015). On the other hand, changes in soil properties of sand dunes also affect the survival, growth and distribution patterns of vegetation (El-Bana et al., 2003). Therefore, scrub dune is a dynamic bio morphology that changes over time, and the plant growth, soil

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physicochemical properties and biodiversity of scrub dune and inter dune sites change accordingly with their formation (He and Zhao, 2004), development and decline processes, and when extended to the regional spatial scale, the regional landscape and ecosystem change with the development and morphological evolution of scrub dune (Marrero-Rodríguez et al., 2020).

The role of scrub dune development on the ecology

Scrub is divided into primary scrub and secondary scrub. Primary scrub has developed a well-developed mechanism to adapt to local habitats over a long period of evolution, and it is mainly distributed in typical grassland and agro-pastoral areas where the water table is low and moisture conditions are relatively poor (El-Sheikn et al., 2010). Secondary scrub, on the other hand, is mainly distributed in arid desert areas where the water table is high and moisture conditions are relatively good (Qiu et al., 2015; Tyler et al., 2021). There are two opposing processes of succession in secondary scrub with important ecological impacts (Yan et al., 2019). The first is caused by the deterioration of regional moisture conditions, where herbaceous growth is stunted while shrubs win in competition due to deeper root systems, and is called grassland scrubbing, and a common phenomenon in arid and semi-arid grasslands (Cai et al., 2020). In this process, scrub mainly develops in degraded grassland areas with low water table and relatively poor moisture conditions, and will decline when moisture conditions deteriorate to the point where the minimum requirements for shrub growth cannot be met; the second is in some severely degraded vegetation areas, and when moisture conditions improve, scrub develops before herbaceous plants because it is more adaptable. In this process, scrub is mainly located in areas with high water tables and relatively good moisture conditions, and when moisture conditions continue to improve, herbaceous plants recover and scrub declines due to competition with herbaceous plants (Jia and Li, 2008; Kinast et al., 2013). In any case, when the dominance of scrub declines, herbaceous plants increase species diversity (Sperandii et al., 2019), especially during the decline of scrub, herbaceous plants lack shelter and community diversity declines, and scrub communities tend to decline; soils show an increase in the average particle size of sediment, a trend of decreasing clay and powder particles, an increase and then decrease in the specific gravity of fine sand, and a continuous increase in the content of coarse sand particles; soil capacity increases, water content, soil respiration decreases The organic matter, total N, and pH increased and then decreased (Bo and Zheng, 2015). In general, due to the large amount of wind and sand materials stored in the cluster scrub dunes, they play a protective role for the stability of the surface they are on, especially for the oasis on the downwind side from drifting sand invasion, and are of great importance for the protection of deserts and oases and the enhancement of desert ecosystem services (Mou, 2019).

Conclusion

The development or retention of well-adapted scrub in arid and semi-arid areas is the primary condition for the formation of scrub dunes, the presence of upwind sand sources is the physical condition for their formation, and strong wind is the dynamic condition for their formation, where the role of wind is to connect the sand sources to the scrub.

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When regional moisture conditions deteriorate, herbaceous plants decline and scrub develops, and when moisture conditions deteriorate to a certain extent, regional moisture conditions and sand supply reach a dynamic equilibrium, and wind strength and frequency are sufficient, scrub dunes gradually form. In the early stage of scrub development, when the regional moisture conditions and sand supply are in dynamic equilibrium, scrub and scrub dunes may appear simultaneously, and if they are not in dynamic equilibrium, the time of scrub dune development depends on the time of formation of this dynamic equilibrium.

At present, scholars mostly focus on static research on scrub dunes, but in fact scrub dunes are dynamic bio morphological features that change with time. The plant growth, soil physical and chemical properties and biodiversity of scrub dunes change with the process of their formation, development and decline, and when extended to the regional spatial scale, the regional landscape and ecosystem change with the development and morphological evolution of scrub dunes. Therefore, there is an urgent need for a multidisciplinary and comprehensive study to reveal the mechanism of the geomorphological process of scrub dune development.

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