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The relationship between nebkha formation and development and desert environmental changes

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ABSTRACT

Because of the absence of natural records with high resolution, the study of environmental changes in arid and semi-arid desert regions, an important component of the global system, lags behind studies in other regions. In this paper, we summarize the literature on the evolution, forms, and profile features of nebkhas (coppice dunes), and discuss the environmental implications of their formation and development. Based on this review, we argue that future research should focus on the quantitative conversion of environmental proxies revealed by nebkha evolution into the corresponding environmental factors: quantitative definition of the stages of nebkha evolution, enhancing the precision of age-dating, strengthening of cross-disciplinary research, and the comparison of nebkha results with other natural records to provide stronger, more reliable conclusions.

1. Introduction

Research on ancient and recent global climate change has mainly been based on natural records, such as those preserved in ice cores, loess deposits, tree rings, corals, stalagmites, and deep-sea and lake sediments. These records have been used to reconstruct the Earth's past climate, environment, and ecological history, which is an important part of the global change research [1]. In recent decades, researchers have made significant progress in understanding these natural records, interpreting ancient climatic change, and revealing the mechanisms responsible for this climate change [2–4]. However, in the arid and semi-arid desert regions that are an important part of Earth's system, the difficulty in finding high-resolution natural records has made research on environmental changes in these regions lag behind research in other areas [5].

Nebkhas (also called coppice dunes, shrub-coppice dunes, nebkha dunes, nabkhas, vegetation dunes, and vegetated dunes) are a kind of aeolian landform that results from sand accumulation in and around shrubs when the shrubs block the flow of aeolian sand [6–8]. This results in the *in situ* redistribution of sandy material [9,10]. In addition to the wind regime, sand sources, and vegetation condition, other natural factors affect the formation and development of nebkhas; these include topography, precipitation, and groundwater depth [10,11]. Most of the existing nebkhas formed during the late Holocene, and their deposition process forms a relatively continuous sequence from the dune's progenitor to maturity [11,12]. The unique developmental and depositional characteristics of nebkhas make them ideal carriers of proxies that can be used to study late-Holocene regional aeolian activity, the alternation between dry and wet conditions, hydrological characteristics, the ecological environment, and their evolution in arid and semi-arid desert regions [13–15]. In addition, since the dynamic changes in nebkhas, gobis, wadis, and dry lake basins in these regions are closely related, the formation and development of nebkhas also record the evolutionary history of the region's geomorphology [12]. Therefore, research on nebkhas can significantly enrich our understanding of aeolian geomorphology and global environmental change, but related research has been relatively rare [16,17].

In the present paper, we provide a comprehensive overview of the literature about nebkhas, including their evolution, formation conditions, and the environmental implications of their formation and development. Based on this review, we propose future focuses for nebkha research to resolve some of the deficiencies in environmental change research and to improve reconstructions of the past environment of arid and semi-arid desert regions.

2. Nebkha distribution and formation age

Widespread nebkhas develop at the leading edge of alluvial fans where the groundwater table lies at a depth of 1–3 m [11,18,19], in degraded grassland and farmland, in the desert-oasis ecotone, in the farming-pastoral zone, at the edge of sandy deserts, on both sides of rivers that run deep into sandy deserts, in alluvial plains, in the depression formed by a lake basin, in dry deltas, on the bank of a dry riverbed where the groundwater table lies at a depth of 2–5 m, and in parts of sandy coasts [20,21] in most of the world's

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arid, semi-arid, and sub-humid regions. Nebkhas are also found in alpine deserts, such as those found in mountain valleys and plateau basins, at altitudes above 4000–5000 m [22,23], and may be the only major aeolian landforms in some arid and semi-arid desert regions that have been badly disturbed by human activities such as over-cultivation and over-grazing [24]. These regions offer good moisture conditions and good conditions for plant growth, but also provide an abundant supply of erodible substances; together, these characteristics provide favorable conditions for the development of nebkhas [5,11]. Nebkhas exist in large areas of the southwestern United States [9,18], Africa [25,26] and the Middle East [23], and are one of the major aeolian landforms in China [27,28]. In total, nebkha areas cover about 5% of the world's land area [29].

Most of the existing nebkhas developed during the late Holocene, at a time that lies between the effects of geological and modern processes [20]. For example, the development of nebkhas in the American state of New Mexico has been shorter than 100 years [16], versus 30–200 years in the Sahel region of Africa [30,31], 300 years in China's Alashan Plateau [10,12], and more than 100 years in China's Lop Nur region [32,33]. The longest periods are more than 700 years in China's Bashang Plateau [11], and up to 1000 years at the southern edge of Taklimakan Desert, although nebkha ages in the central region of this desert may be as high as 4000 years [34].

3. Nebkha evolution, form, and profile characteristics

3.1. Evolution of nebkhas

Nebkhas result from the interaction between vegetation and the desert environment during the process of community succession [35,36]. In terms of their evolution, nebkhas are generally divided into four stages: embryonic, developing, stable, and activated [31]. Their form, soil characteristics, and vegetation conditions during each stage are described in detail by Du et al. [37]. Based on a synthesis of existing research, the evolution of nebkhas can be described as follows: First, desert-adapted shrubs persist or grow in sandy land that is subject to serious wind erosion and degradation, where they block sand carried by the wind, leading to deposition of this sand and the development of an embryonic nebkha [30]. During the subsequent developing stage, abundant sand transport caused the height to increase in proportion to the length and width, so the horizontal and vertical scales are obviously correlated [31,37]. The height growth rate depends mainly on the abundance of sand and the wind strength [11]. When the nebkha's development reaches the stable stage, limitations on the sand supply and strengthening of the turbulent flow in the flow field above and around the nebkhas lead to a balance between dune erosion and accumulation. At this point, the length and width of the nebkha continue to increase, but its height reaches a steady state. Nebkhas can also achieve a stable state when the wind weakens, but may begin to grow again once the sand and wind characteristics change. Finally, when the availability of sand decreases, the groundwater table falls, or the shrub dies, nebkhas enter the activation stage, in which they are subject to strong erosion and their height gradually decreases. However, the horizontal scale may continue to increase, and the nebkha only gradually disappears, so the correlation between the horizontal scale and the height of nebkha is not significant during the stable and activation stages [30].

3.2. Morphological characteristics of nebkhas

Nebkhas are typically either dispersed or clumped, and the formation and distribution mechanisms may be related to the type of shrub around which the nebkha forms [20]. The typical morphology of nebkhas is a sand dune that projects above the surrounding surface, with a round top and a gentle slope [24] (Fig. 1). The shape tends to be peltate during the early stages and irregular during the late stages, but can be roughly divided into two types based on the cross-sectional shape: conical and hemispherical [38]. When the shrub grows primarily vertically, and has small branches and a high plant density, it tends to forms a higher and approximately conical dune; if the shrub has a prostrate or creeping growth habit, and has small branches and a low plant density, it tends to form a lower and approximately hemispherical dune [39].

Due to the effects of wind erosion, the windward side of nebkhas is typically slightly steep and its vegetation cover is poor, whereas the leeward side tends to form a more gradual slope with a higher vegetation cover [5]. The height of nebkhas is mainly affected by their evolutionary stage, vegetation type, the richness of the sand supply, and the water supply [31,40]. As a result, the height of the nebkhas formed by *Caragana microphylla* is between 0.4 and 1.8 m, versus 0.13–4.5 m for *Nitratia* and 1–15 m for tamarisk species (*Tamarix* spp.), mainly as a result of differences in the height of the plant cluster [40]. The nebkha height is greatest during the activation phase, followed by the stable phase, the developing stage, and the embryonic stage, mainly as a result of changes in the vegetation and in the balance between erosion and accumulation during these stages [21,37]. In some regions, nebkhas may merge to form polymeric sand dunes that usually form a circle or extend downwind to form a chain [23,41].

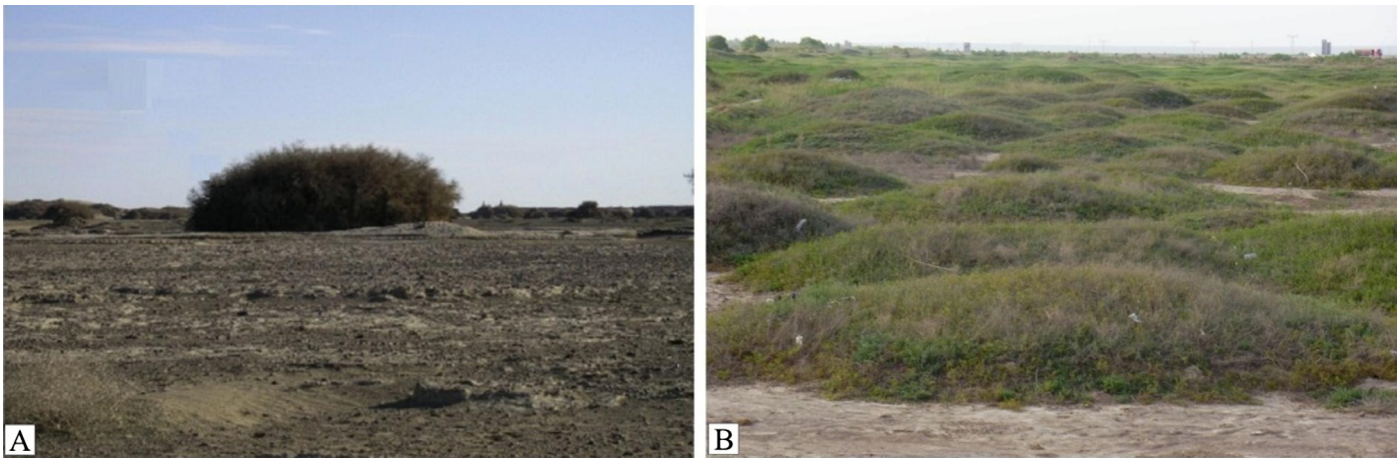

Fig. 1. (A) Isolated and dispersed *Tamarix* nebkhas in China's Alaxa Plateau. Source: Reference 10: (B) Aggregated and clustered *Nitraria* nebkhas in China's Mu Us Desert. Source: Jinchang Li.