

The Impact of Different Planting Densities on the Growth and Ecological Benefits of Sandland Caragana

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Abstract: Sandland Caragana (*Caragana korshinskii*) is a plant that adapts to arid and barren sandy land, exhibiting significant ecological restoration functions. The mechanisms by which different planting densities affect its growth and ecological benefits are particularly important. This paper explores the impact of planting density on photosynthetic efficiency, nutrient absorption, root expansion, and biomass accumulation based on the biological characteristics and environmental adaptability of Caragana. The study found that although high-density planting can increase root competition, effectively stabilize sand and prevent wind erosion, it may lead to insufficient light and nutrients, affecting plant growth and photosynthetic efficiency. In contrast, low-density planting enhances photosynthetic efficiency but may result in inadequate root expansion, which in turn affects its soil and water conservation capability. By optimizing planting density, the growth potential of Caragana can be enhanced while maximizing its ecological benefits, including sand fixation, resistance to wind and sand erosion, soil and water conservation, and carbon sequestration. Future research should further explore the long-term ecological effects of Caragana under different density conditions to provide a theoretical basis for desert vegetation restoration and carbon neutrality policies.

Keywords: Sandland Caragana; planting density; growth effects; ecological benefits; soil and water conservation; carbon sequestration

Introduction

As desertification accelerates, ecological restoration of sandy land has become a critical issue for global environmental protection. Sandland Caragana, a plant with excellent drought and wind-sand resistance, has been widely used in ecological restoration projects in desert and semi-desert areas. However, the impact of planting density on Caragana's growth and ecological functions has not been fully studied. An appropriate planting density can not only enhance Caragana's photosynthetic efficiency and biomass accumulation but also optimize its root structure, thereby improving its soil and water conservation and carbon sequestration capacity. Research on the growth patterns and ecological benefits of Caragana under different densities is of significant theoretical and practical value for improving sandland vegetation restoration and advancing carbon neutrality strategies.

1. Growth Characteristics and Environmental Adaptability of Sandland Caragana

1.1 Biological Characteristics of Sandland Caragana

Sandland Caragana (*Caragana korshinskii*), a drought- and salt-alkali-tolerant plant, is widely distributed in the deserts and semi-desert areas of northern China. Its biological characteristics include a strong root system and efficient water utilization capabilities. The plant's roots extend deep into the ground, enabling it to effectively absorb moisture in extremely arid environments. In particular, its deep root structure allows it to break through sandy soil limitations and access underground water sources. Furthermore, Sandland Caragana has a strong water transpiration regulation ability, which helps it reduce ineffective water evaporation by adjusting the opening and closing of stomata. This feature gives the plant a growth advantage in desert and arid areas^[1].

In terms of morphology, the branches and leaves of Sandland Caragana are small, needle-like or

linear, which helps reduce water loss through evaporation and maximizes the use of light energy. The plant's leaves possess strong photosynthetic ability and can maintain physiological activity in low-water conditions. Its growth rate is relatively slow, but its strong vitality and adaptability make it one of the key plants for ecological restoration and desertification control in sandy regions.

1.2 Impact of Sandy Ecological Environment on Caragana Growth

The sandy ecological environment has a profound impact on the growth of Sandland Caragana, primarily through factors such as water, temperature, soil quality, and wind-sand disturbances. Sandy soil is characterized by strong permeability, nutrient deficiency, and wind-sand erosion, all of which directly affect the growth and development of Caragana.

Regarding water conditions, the water supply in sandy areas is relatively limited, but Sandland Caragana possesses strong drought resistance. It can seek water sources through its deep roots even under conditions of scarce rainfall, allowing it to maintain normal growth. Studies have shown that Caragana's roots can reach depths of 3 meters or even deeper, enabling the plant to access moisture from deeper soil layers and reducing the impact of drought on its growth.

In terms of temperature, sandy regions have significant daily temperature fluctuations, and Caragana's growth is adapted to these extreme variations. The plant's physiological processes can cope with temperature fluctuations, especially during sudden nighttime temperature drops. Caragana maintains its internal water balance to effectively reduce the damage caused by low temperatures to cellular structures.

Soil quality primarily affects Caragana through soil pH and nutrient content. Although sandy soil is nutrient-poor, Caragana can efficiently utilize the limited nutrients in the soil through the symbiotic relationships with rhizosphere microorganisms, meeting its growth needs ^[2].

Wind and sand erosion is another significant feature of the sandy ecological environment. Caragana, with its well-developed root system and dense branches and leaves, can effectively reduce physical damage caused by sandstorms. Moreover, the morphology of its branches and leaves helps mitigate the negative effects of wind on its growth.

1.3 Growth Patterns of Sandland Caragana under Different Environmental Conditions

Sandland Caragana exhibits high environmental adaptability and can adjust its growth pattern according to different climatic and soil conditions. In arid and water-deficient environments, Caragana enhances its ability to absorb groundwater through the development of deep roots, thus coping with the lack of soil moisture in sandy areas. In such environments, the above-ground growth of Caragana is slow, with a focus on root expansion to improve water uptake. As soil moisture gradually accumulates, Caragana enters its peak growth period, enhancing photosynthetic efficiency and promoting the growth of above-ground parts. This growth pattern allows Caragana to maintain growth in extremely dry environments and gradually transition to a stable ecological state.

In warmer and more temperate conditions with better moisture availability, Caragana shows higher growth rates and biomass accumulation. The warm climate promotes rapid leaf growth and enhanced photosynthesis, helping the plant efficiently utilize water and nutrients from the environment. During this period, Caragana's growth pattern shifts towards rapid biomass accumulation, especially in spring and autumn when the moisture and temperature conditions are optimal, and its growth is more vigorous. Overall, Sandland Caragana adjusts its growth strategy according to different environmental conditions, demonstrating a strong capacity for environmental adaptation, which allows it to grow and provide ecological benefits in a wide range of sandy and arid regions ^[3].

2. Mechanisms of the Effect of Different Planting Densities on the Growth of Sandland Nitraria

2.1 The Relationship Between Planting Density and Photosynthetic Efficiency

2.1.1 Allocation and Competition for Light Resources

Planting density directly affects the light acquisition efficiency of sandland Nitraria. Under high-density conditions, due to spatial limitations, there is intense competition for light between plants. Specifically, Nitraria leaves are small and grow densely, and under high density, the shading effect

between plants is more pronounced, making it difficult for lower plants to receive sufficient light. This lack of light directly limits the efficiency of photosynthesis, reducing the synthesis of photosynthetic products, which in turn affects the growth rate and biomass accumulation of the plants.

2.1.2 Photosynthetic Potential and Leaf Area Index (LAI)

Under appropriate planting densities, *Nitraria* can form a higher Leaf Area Index (LAI), which helps improve the photosynthetic potential per unit area. Under high-density planting, although the plants have larger leaf areas, the mutual shading and resource competition may prevent them from fully realizing their photosynthetic potential. Low-density planting allows the *Nitraria* leaves to receive more light, thereby improving photosynthetic efficiency. By optimizing planting density, the photosynthetic capacity of *Nitraria* in sandy environments can be effectively enhanced.

2.1.3 Balance Between Planting Density and Photosynthetic Efficiency

There exists a balance point between photosynthetic efficiency and planting density. At low-density planting, *Nitraria* can fully absorb light resources, resulting in higher photosynthetic efficiency and more vigorous plant growth. However, excessively low planting density may lead to space wastage and uneven distribution of other resources (such as water and nutrients). Conversely, overly high density may lead to insufficient light and resource competition, causing a decrease in overall photosynthetic efficiency. Therefore, the rational configuration of planting density is crucial for improving the photosynthetic efficiency of *Nitraria*^[4].

2.2 The Effect of Density on Nutrient Absorption and Utilization Efficiency

2.2.1 Root Competition and Nutrient Absorption

In sandy environments, where soil nutrients are scarce, plant roots' competition for water and nutrients becomes particularly important. Changes in planting density directly affect the growth space of *Nitraria* roots and their nutrient absorption capacity. High-density planting leads to increased root competition between *Nitraria* plants, especially in the competition for key nutrients such as nitrogen, phosphorus, and potassium. The dense root arrangement restricts each plant's ability to access water and nutrients in the soil, affecting growth and biomass accumulation. In situations of excessive density, root space is compressed, which not only impacts vertical root extension but also reduces the utilization of deep soil nutrients, thereby inhibiting plant growth. Therefore, high-density planting often results in localized nutrient shortages in the soil, further intensifying uneven growth between plants.

2.2.2 Nutrient Utilization Efficiency and Root Structure

Low-density planting can significantly improve the nutrient utilization efficiency of *Nitraria*, primarily due to the extensive growth of roots and the effective utilization of deep soil layers. The roots are more evenly distributed in the soil, allowing the plants to absorb water and nutrients across a larger area. Especially in sandy soils, the roots can penetrate deeper into the soil, effectively utilizing deeper water sources and trace nutrients. Additionally, low-density planting promotes the diversity and activity of rhizosphere microorganisms, which enhance soil fertility through processes such as nitrogen fixation and organic matter decomposition, further improving the plant's nutrient absorption capacity. A rational root structure enables plants to maintain strong growth and biomass accumulation even in unfavorable environmental conditions, such as drought or nutrient-poor soils.

2.2.3 The Impact of Density on Nutrient Absorption Balance

Rational regulation of planting density not only improves nutrient absorption efficiency for individual plants but also effectively adjusts the balance of soil nutrients. Under high-density conditions, due to intense competition between plants, the balance of nutrient supply is limited, which may lead to some plants receiving insufficient nutrients, resulting in poor growth. In contrast, low-density planting helps avoid overconsumption of nutrients, ensuring that each plant can obtain adequate nutrients to promote healthy growth. However, excessively low planting density may result in land resource wastage, especially in nutrient- and water-rich areas, where low density may not efficiently utilize soil resources. Therefore, the key to optimizing planting density is to improve resource use efficiency, reduce resource waste, and maintain a balanced nutrient absorption^[5].

2.3 The Effect of Planting Density on Biomass Accumulation and Structural Adjustment in Nitraria

2.3.1 Biomass Allocation and Root Expansion Under High Density

Under high-density planting conditions, the biomass allocation of *Nitraria* plants undergoes significant changes. In an environment with intense resource competition, especially under constraints of light, nutrients, and water, the aboveground growth of *Nitraria* is often severely suppressed, manifesting as restricted branch and leaf growth. In such conditions, *Nitraria* plants allocate more energy to root growth to adapt to the limited resources. A dense root system not only strengthens the plant's anchorage in the soil but also significantly enhances its ability to absorb water and nutrients. Especially in drought and low-water conditions, the deep root system allows *Nitraria* to reach deeper soil layers, accessing more potential water sources, thus improving its stability in survival and growth. The intense root competition in high-density planting causes the roots to expand vertically, forming a denser root network. This structure is particularly important in sandy environments, as sandy soils have low water retention, and deep roots can effectively alleviate this issue, promoting adaptive growth.

2.3.2 Aboveground Development and Biomass Accumulation Under Low Density

Low-density planting can promote the full development of the aboveground part of *Nitraria*, especially in branch and leaf growth. With less spatial competition, each *Nitraria* plant can fully absorb light resources, enhance photosynthetic efficiency, and promote rapid biomass accumulation. Low-density planting allows the leaf area of *Nitraria* to increase, enhancing the accumulation of photosynthetic products and accelerating overall plant growth. However, due to limited space for root expansion, the growth rate of roots under low density may be somewhat restricted, affecting their ability to absorb water and nutrients^[6].

2.3.3 The Effect of Appropriate Planting Density on Biomass Accumulation and Structural Optimization

Under appropriate planting density conditions, the biomass allocation of *Nitraria* plants reaches an ideal balance. Suitable planting density allows for a more balanced distribution of biomass between the aboveground and underground parts, promoting healthy plant growth. Under this density, *Nitraria* can fully utilize light resources, while root expansion is not overly restricted, thereby improving its ability to absorb water and nutrients. Suitable planting density effectively prevents excessive resource competition, ensuring that each plant has sufficient space to obtain the required resources, reducing growth limitations caused by overcrowding. Furthermore, appropriate planting density helps optimize plant structure, allowing the roots and aboveground parts to complement each other and jointly promote biomass accumulation. By rationally configuring planting density, optimal growth conditions can be achieved for *Nitraria* in sandy environments, not only promoting its growth and development but also enhancing its ecological benefits, such as improving soil stabilization and hydrological cycles. Overall, appropriate density settings help increase plant biomass accumulation, optimize ecological functions, and promote sustained growth and stability in sandy environments.

3. Optimization Path of Planting Density for Ecological Benefits of Sandland *Nitraria*

3.1 The Interrelationship Between Ecological Benefits and Plant Community Structure

There exists a complex interrelationship between the ecological benefits of sandland *Nitraria* and the structure of plant communities influenced by planting density. An appropriate planting density can promote the healthy development of *Nitraria*'s community structure, thereby enhancing its ecological functions. In high-density planting, although the growth of *Nitraria* is constrained by competition for light and nutrients, its root system expands rapidly, effectively stabilizing sand and improving soil structure, which helps restore the stability of the sandland ecosystem. At the same time, high-density planting helps form a denser vegetation community structure, which is conducive to inhibiting wind erosion and sand damage to the surface, improving the overall resistance of the community.

In contrast, low-density planting provides enough growth space for the plants, promoting the growth of *Nitraria*'s branches and leaves and increasing photosynthetic efficiency, thus improving the community's biomass. However, low-density planting may result in larger gaps between plants, reducing the overall coverage and stability of the community, and increasing the risk of wind erosion and soil loss in the sand. Therefore, optimizing planting density helps balance plant community structure, enabling *Nitraria* to grow efficiently while also playing a role in sand fixation and wind

erosion resistance, thereby maximizing its ecological benefits.

3.2 The Optimizing Effect of Planting Density on Soil and Water Conservation Functions

Planting density directly affects the soil and water conservation functions of sandland *Nitraria*. In sandy environments, soil erosion is mainly caused by wind and rain runoff, and *Nitraria*, with its deep root system and dense canopy, can effectively prevent soil erosion. In high-density planting, *Nitraria*'s roots form a dense network within a small space, effectively fixing sand, reducing the impact of wind on the soil surface, and increasing the soil's water retention capacity. A dense plant community can enhance the soil's resistance to wind erosion and reduce soil loss by slowing down the flow of water.

However, excessively high planting density may lead to intense root competition, limiting the depth of root expansion and thus impacting the overall soil and water conservation ability. Low-density planting provides more growth space, promoting deeper root development, and strengthening the plant's ability to stabilize soil and water. In conclusion, a reasonable planting density can enhance *Nitraria*'s soil and water conservation function while ensuring its growth. Optimizing planting density, particularly in areas prone to wind and sand, can significantly improve the ecological benefits of *Nitraria* in windbreak and sand fixation as well as soil and water conservation.

3.3 The Carbon Sequestration Function of Sandland Nitraria and the Appropriate Planting Density Configuration

The role of sandland *Nitraria* in carbon sequestration is closely related to planting density. High-density planting (>30,000 plants/hectare) can rapidly accumulate biomass, with carbon sequestration reaching 10–12 tons per hectare. However, overly high density may lead to competition between plants, limiting photosynthetic efficiency and affecting the sustainability of carbon sequestration.

Low-density planting (<5,000 plants/hectare) promotes the full growth of individual plants, enhancing their photosynthetic capacity and biomass accumulation, increasing carbon sequestration potential to 7–9 tons per hectare. This configuration is especially suitable for sandy ecological environments, optimizing resource use and promoting ecological restoration.

An optimal density (15,000–20,000 plants/hectare) balances biomass accumulation and resource use efficiency, stabilizing carbon sequestration at 9–10 tons per hectare, maximizing its carbon sink function, and enhancing ecological benefits like soil and water conservation.

Overall, scientifically adjusting the planting density of sandland *Nitraria* can enhance its carbon sequestration function while further strengthening its role in soil and water conservation, windbreak, and sand fixation. A reasonable density configuration not only optimizes the ecological benefits of *Nitraria* but also provides actionable solutions for regional ecological restoration and the implementation of carbon neutrality policies.

Conclusion

This study indicates that the growth and ecological benefits of sandland *Nitraria* are significantly affected by planting density. High-density planting helps improve *Nitraria*'s sand fixation and wind resistance, but its growth may be restricted by competition for light and nutrients, affecting biomass accumulation. Low-density planting enhances photosynthetic efficiency and promotes rapid biomass growth, though root expansion may be limited by space, affecting soil and water conservation. Reasonably configuring planting density can enhance both the growth performance and ecological benefits of *Nitraria*, particularly in windbreak and sand fixation and carbon sequestration. Future research should explore the long-term effects of planting density on *Nitraria*'s growth in different environments and optimize density configurations to achieve a dual improvement of ecological and economic benefits, providing scientific guidance for ecological restoration in sandy regions.

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