

Research Progress on the Effects of Alfalfa on Farmland Runoff Nitrogen in the Arid Northwest Region of China

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Abstract

Water scarcity in the arid northwest region of China, coupled with agricultural non-point source pollution, particularly nitrogen loss via farmland runoff, has become a critical issue threatening regional water environment security. Compared to traditional engineering measures, ecological interception technologies utilizing plant-microbe combined systems show great potential. Alfalfa (*Medicago sativa* L.), as an important leguminous forage, possesses unique advantages in controlling nitrogen loss due to its strong nitrogen fixation capacity and ecological adaptability. This review aims to systematically elaborate the core mediating role of soil microorganisms in alfalfa's regulation of the farmland nitrogen cycle, with a focus on analyzing how alfalfa achieves dual control effects-"increasing source" and "reducing flow"-on farmland runoff nitrogen in the arid northwest region through biological nitrogen fixation, stimulation of rhizosphere nitrogen transformation, and construction of microbial ecological networks. Finally, the review summarizes the limitations of current research and provides prospects for future research directions, intending to offer a theoretical basis for managing agricultural non-point source pollution and achieving green sustainable development in the arid northwest region.

Keywords

Alfalfa; Runoff Nitrogen; Nitrogen Cycle; Arid Northwest Region.

1. Introduction

The arid northwest region of China is characterized by concentrated rainfall, high evaporation, and a fragile farmland ecosystem [1]. The pursuit of high yields has led to excessive application of nitrogen fertilizer, far exceeding crop demand, resulting in the accumulation of large amounts of nitrogen, primarily as nitrate, in the soil [2-3]. During heavy rainfall or irrigation events, this nitrogen is highly susceptible to loss via surface runoff and leaching, leading not only to fertilizer waste but also causing environmental problems such as water eutrophication. Controlling farmland runoff nitrogen has become a major challenge for both agriculture and environmental sectors in this region [4-5].

Alfalfa is a high-quality leguminous forage widely cultivated in the arid northwest region, playing a significant role in dryland farming systems and soil-water conservation [6]. Beyond its direct soil and water conservation functions (reucing runoff generation), the profound value of alfalfa lies in its influence on soil nitrogen cycling processes through root-soil-microbe interactions. The core driver of this process is the soil microbiome. Therefore, investigating how soil microorganisms mediate alfalfa's control over runoff nitrogen is crucial for developing and optimizing alfalfa-based ecological interception technologies.

2. Direct and Indirect Pathways of Alfalfa in Controlling Runoff Nitrogen

2.1. Direct Physical Interception and Biological Uptake

Extensive Root System: Alfalfa possesses a deep and dense root system that effectively stabilizes soil and reduces soil and water loss, thereby physically diminishing the carrier (sediment) and total amount of nitrogen transported via runoff.

Efficient Nitrogen Uptake: As a high-yield forage, alfalfa requires substantial nitrogen throughout its growth period to build biomass, thereby directly absorbing and immobilizing inorganic nitrogen from the soil. This reduces the soil nitrogen pool, consequently decreasing the available nitrogen source for loss at its origin.

2.2. Core Mediating Role of Soil Microorganisms

2.2.1. Biological Nitrogen Fixation – "Increasing Source" to Reduce Fertilizer Dependence

Alfalfa forms a symbiotic nitrogen-fixing system with rhizobia (e.g., *Sinorhizobium meliloti*). This process, directly mediated by microorganisms, converts inert atmospheric N_2 into NH_3 , which is readily usable by plants.

Mechanism: Alfalfa attracts rhizobia via root exudate signal molecules, leading to nodule formation. Within the nodules, leghemoglobin creates an anaerobic environment for nitrogenase, enabling efficient nitrogen fixation.

Significance for Nitrogen Control: In rotation or intercropping systems, cultivating alfalfa can significantly reduce or even eliminate the need for chemical nitrogen fertilizers. This not only lowers the initial nitrogen load introduced by fertilization but also, by providing an endogenous nitrogen source, cuts off the primary "source" of farmland nitrogen pollution, fundamentally alleviating the pressure of runoff nitrogen loss.

2.2.2. Rhizosphere Regulation – "Reducing Flow" through Activation and Immobilization

The unique rhizosphere microdomain formed by alfalfa root activity is a hotspot for microbially-driven nitrogen transformations.

Rhizodeposition Effect: Alfalfa roots continuously release exudates (e.g., sugars, organic acids) and sloughed-off materials (root cap cells, senescent root hairs). These carbon-rich substances provide ample "fuel" for rhizosphere microorganisms.

Priming Effect and Microbial Nitrogen Immobilization: The input of substantial exogenous carbon can prime soil microbial activity, prompting them to vigorously assimilate and immobilize soil inorganic nitrogen (particularly nitrate nitrogen) to build their own cells (synthesizing DNA, proteins, etc.). This process is known as microbial nitrogen immobilization. The immobilized nitrogen is temporarily stored in microbial biomass, effectively reducing the concentration of nitrate nitrogen in the soil solution and making it less susceptible to being washed away during rainfall-runoff events.

Influencing Nitrification/Denitrification Processes: The alfalfa rhizosphere environment may influence the community structure and activity of ammonia-oxidizing archaea/bacteria and denitrifying bacteria by altering pH, oxygen status, and secreting specific compounds. Although complete denitrification leads to gaseous nitrogen losses (N_2O , N_2), appropriate regulation can slow down nitrification, reduce the rate of nitrate production, and align it with the rhythms of plant uptake and microbial immobilization.

2.2.3. Shaping a Healthy Soil Microbial Network

Long-term alfalfa cultivation can significantly improve the soil micro-ecological environment. **Increased Microbial Biomass and Diversity:** Alfalfa systems typically exhibit higher soil organic

matter and microbial biomass carbon/nitrogen, supporting more complex and stable microbial communities.

Enhanced Ecological Functional Redundancy: A diverse microbial community implies that various steps of the nitrogen cycle (immobilization, nitrification, denitrification, etc.) can be performed by multiple microbial taxa with similar functions. This functional redundancy strengthens the system's resistance to external disturbances (e.g., drying-rewetting cycles, temperature fluctuations), making the nitrogen regulation function more stable and sustainable.

3. Considerations for the Specificity of the Arid Northwest Region

In the arid northwest region, the microbially-mediated processes described above exhibit unique characteristics:

Water Stress: Drought can inhibit microbial activity. However, alfalfa, as a drought-tolerant plant, extends its roots into deeper soil layers to maintain water access, thereby extending the nitrogen control effect to deeper soil profiles. Furthermore, drought may make microorganisms more inclined to immobilize nitrogen for survival.

Soil Physicochemical Properties: Soils in the arid northwest are typically alkaline and low in organic matter. Alkaline conditions affect nitrification rates, while alfalfa, through rhizodeposition increasing organic carbon, can effectively ameliorate this situation, creating a more favorable habitat for microorganisms.

Temperature Fluctuations: Pronounced diurnal and seasonal temperature variations affect the succession and activity rhythms of microbial communities. The perennial nature of alfalfa helps establish a relatively stable rhizosphere microenvironment, buffering the impact of sharp temperature changes on key microbial functions.

4. Research Status and Prospects

4.1. Current Research Status

Current research has progressed from phenomenological observation to mechanistic exploration. Numerous field experiments have confirmed that alfalfa-involved rotation systems can significantly reduce nitrogen loss. The application of molecular biology techniques (e.g., high-throughput sequencing, qPCR, stable isotope probing) enables scientists to precisely identify key microbial taxa involved in the nitrogen cycle (e.g., nitrogen-fixing bacteria, ammonia-oxidizing bacteria, denitrifying bacteria) in the alfalfa rhizosphere and analyze their dynamic changes.

4.2. Challenges and Future Prospects

Refined Mechanistic Understanding: Current knowledge is clearer on "who is doing it" (species identification) but remains limited regarding "how they do it" (specific metabolic pathways, interspecies interactions) and "when and where they do it" (spatiotemporal dynamics). Future research needs to integrate multi-omics technologies (metagenomics, metatranscriptomics, metabolomics) with continuous dynamic monitoring under real field conditions.

Development of Key Microbial Inoculants: Screening and breeding efficient rhizobia and other beneficial functional microorganisms (e.g., phosphate-solubilizing bacteria with strong nitrogen immobilization capacity) adapted to the stresses (drought, salinity, alkalinity, low fertility) of the arid northwest region, and developing specific microbial inoculants for use in combination with alfalfa varieties to enhance their nitrogen control efficacy.

Optimization of Planting Patterns: In-depth study of the feedback mechanisms between belowground microbial communities in intercropping or rotation systems of alfalfa with

gramineous crops (e.g., corn, wheat), and how these affect the overall nitrogen use efficiency and loss risk of the system. Exploration of optimal width and management practices for alfalfa grass filter strips placed along farmland drainage pathways.

Model Integration and Prediction: Parameterizing the microbially-mediated nitrogen cycling processes and integrating them into agricultural ecosystem models to more accurately predict the long-term control effectiveness of alfalfa systems on farmland runoff nitrogen in the arid northwest region under different climate and management scenarios.

5. Conclusion

The control of farmland runoff nitrogen by alfalfa in the arid northwest region is a comprehensive ecological process core-mediated by soil microorganisms. It operates not only through simple physical interception and plant uptake but also, more profoundly, by reducing external input via symbiotic nitrogen fixation and promoting microbial immobilization and transformation of nitrogen through the rhizosphere priming effect, thereby achieving in-depth regulation of the soil nitrogen pool. Deeply untangling the intrinsic working mechanisms of this "plant-microbe" combined system and, based on this knowledge, developing precise field management strategies and efficient microbial products hold profound significance for constructing a resource-efficient and environmentally friendly modern agricultural system in the arid northwest region, ensuring regional water security and ecological security.

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