Impact of Grazing Management on Soil Carbon-Nitrogen Cycling and Ecosystem Functions in Northwest Yunnan Plateau Wetlands: A Review Based on Studies in Napahai Wetland

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Abstract: The Northwest Yunnan Plateau Wetlands, as a critical ecological barrier on the southeastern margin of the Qinghai-Tibet Plateau, possess significant carbon sequestration capacity and biodiversity conservation value. In recent years, increasing grazing intensity and land-use changes have posed risks of wetland ecosystem degradation. This paper systematically reviews the effects of different grazing practices (trampling, disturbance by Tibetan fragrant pigs, and grazing exclusion) on soil physicochemical properties, carbon-nitrogen-phosphorus distribution, and ecological functions in Napahai Wetland. The results indicate that grazing significantly alters the physical structure and carbon-nitrogen accumulation capacity of topsoil (0–20 cm). Trampling-type grazing increases soil bulk density, while disturbance by Tibetan fragrant pigs reduces topsoil bulk density through soil loosening. Grazing exclusion (fencing) enhances vegetation coverage, significantly increasing active organic carbon components (POC, DOC, EOC) and microbial biomass carbon (MBC). Additionally, soil organic carbon (SOC) content in degraded meadows decreases by approximately 50% with intensifying degradation, showing significant correlations with soil moisture and bulk density. This study proposes adaptive management strategies, including optimized grazing intensity classification and stricter implementation of grazing exclusion policies, to support ecological restoration and carbon sequestration in plateau wetlands.
***Keywords*:** wetland; carbon cycle; napahai; carbon sequestration

1. Introduction

The Northwest Yunnan Plateau Wetlands (e.g., Napahai Wetland), located on the southeastern edge of the Qinghai-Tibet Plateau, represent typical alpine wetland ecosystems characterized by a unique "lake basin–lakeshore–mountain face" ecological structure[1]. These wetlands play a vital role in global carbon cycling (storing approximately one-third of terrestrial carbon) and serve as critical habitats for endangered species such as the black-necked crane[2]. However, expanding pastoral activities in Tibetan communities — shifting from single-species (yak) to multi-species (cattle, sheep, pigs) grazing — have significantly altered soil physicochemical properties and carbon-nitrogen cycling[3]. Soil compaction, vegetation degradation, and weakened carbon sequestration caused by overgrazing have become central challenges for regional ecological conservation[4]. This review synthesizes recent research on grazing management in Northwest Yunnan wetlands, analyzes mechanisms underlying grazing impacts on soil carbon-nitrogen dynamics, and proposes adaptive management strategies.

2. Effects of Grazing Practices on Soil Physical Properties

2.1 Spatial Heterogeneity of Soil Bulk Density and Compaction

Grazing directly modifies soil pore structure through livestock trampling. Studies show that trampling-type grazing (cattle and sheep) significantly increases topsoil bulk density (0–20 cm: 1.64 ± 0.03 g/cm³) and compaction, with diminishing effects at deeper layers (20–40 cm). In contrast, disturbance by Tibetan fragrant pigs (PDD) reduces topsoil bulk density (0.98 ± 0.04 g/cm³) through soil turnover but increases deep-layer compaction (Liu et al., 2023). Grazing exclusion areas (NG) exhibit intermediate bulk density (1.41 ± 0.05 g/cm³), indicating natural soil structure recovery[5]. These differences arise from animal behavior: cattle and sheep compact soil via repeated trampling, destroying non-capillary pores, while pig rooting enhances topsoil porosity [6].

2.2 Dynamic Responses of Soil Moisture and Aeration

Grazing impacts on soil moisture vary seasonally. During the rainy season,Tibetan fragrant pig grazing areas exhibit lower soil moisture due to reduced vegetation coverage and increased evaporation compared to exclusion zones. In dry seasons, pig rooting accelerates surface organic matter mineralization, leading to higher soil CO_2 flux. Grazing exclusion

improves soil water retention by restoring vegetation cover. For example, after 10 years of exclusion, soil moisture in swamp meadows increased from 38.65% to 66.30%, while bulk density decreased from 2.37 g/cm³ to 1.66 g/cm³.

3. Mechanisms of Grazing Impacts on Soil Carbon-Nitrogen Distribution

3.1 Vertical Distribution of SOC and Grazing Disturbance

SOC in Northwest Yunnan wetlands shows pronounced surface accumulation. Exclusion zones exhibit high topsoil (0–10 cm) SOC (58.75 g/kg), whereas severely degraded meadows retain only 29.19 g/kg. Grazing alters SOC accumulation by modifying vegetation biomass and litter input: trampling reduces surface SOC (28.94 ± 2.67 g/kg), while exclusion maintains higher levels (38.17 ± 2.05 g/kg). Notably, Tibetan fragrant pig disturbance reduces surface SOC but enhances deep-layer nitrogen mineralization, resulting in higher total nitrogen (TN) in 20–30 cm layers (0.95 ± 0.06 vs. 0.87 ± 0.01 g/kg).

3.2 Grazing Effects on Soil Nitrogen-Phosphorus Cycling

Grazing induces contrasting trends in nitrogen and phosphorus. Long-term trampling increases TN (STD: 1.56 ± 0.04 g/kg; NG: 1.90 ± 0.05 g/kg) but reduces TP [7]. This "nitrogen enrichment–phosphorus depletion" phenomenon relates to livestock excreta inputs and plant uptake: cattle and sheep excreta are nitrogen-rich, while phosphorus is immobilized by roots[8]. Exclusion promotes simultaneous TN and TP accumulation by reducing nutrient loss. After 10 years of exclusion, TN in swamp meadows increased from 5.58 g/kg to 12.98 g/kg, and TP from 0.48 g/kg to 0.64 g/kg.

4. Restoration of Soil Carbon Sequestration via Grazing Exclusion

4.1 Responses of Active Organic Carbon Components

Exclusion significantly enhances active organic carbon components, including particulate organic carbon (POC), dissolved organic carbon (DOC), easily oxidized organic carbon (EOC), and MBC. After 10 years of exclusion, DOC increased from 21.01 mg/kg to 35.33 mg/kg, and MBC from 73.26 mg/kg to 126.25 mg/kg. Redundancy analysis indicates that TN is the primary driver (>97% explanation rate) of active organic carbon dynamics, promoting microbial activity and organic matter transformation.

4.2 Spatiotemporal Changes in Carbon Pool Management Index

Carbon pool recovery correlates positively with exclusion duration. After 3, 8, and 10 years of exclusion, total organic carbon (TOC) in meadows increased to 54.20, 259.04, and 353.33 g/kg, respectively, with the carbon management index (CMI) rising from 40.92 to 73.26. Swamp meadows exhibit higher TOC accumulation rates (79.13 g/kg) due to anaerobic decomposition suppression.

5. Organic Carbon Characteristics and Drivers in Degraded Meadows

5.1 Carbon Loss Mechanisms Along Degradation Gradients

Meadow degradation reduces SOC by ~50%. Non-degraded meadows (0–50 cm) exhibit SOC density of 40.92 kg/m³, declining to 25.23 kg/m³ in severely degraded areas (Li et al., 2017). Reduced vegetation cover (92.7% to 54.8%) and root biomass are key drivers, diminishing litter input and accelerating erosion.

5.2 Coupling Between Soil Physicochemical Properties and Carbon-Nitrogen

SOC correlates significantly with soil moisture ($R^2 = 0.6948$) and bulk density ($R^2 = 0.58$). Redundancy analysis reveals that SOC loss in degraded meadows is driven by multiple factors: reduced vegetation biomass lowers carbon input, while increased bulk density (1.24 → 1.78 g/cm³) inhibits microbial decomposition.

6. Wetland Functional Assessment and Grazing Management Recommendations

6.1 Comprehensive Evaluation of Wetland Functions

Analytic hierarchy process (AHP) assessments indicate higher functional scores (0.811) in exclusion zones compared to grazing areas (0.505), reflecting superior performance in runoff regulation, carbon sequestration, biodiversity, and forage production. Swamp meadows exhibit higher ecological service value due to stable carbon storage.

6.2 Adaptive Management Strategies

(1) Classified Management Implement grazing intensity controls (e.g., restrict trampling-type grazing) and guide Tibet-

an fragrant pig grazing to low-sensitivity zones;

(2) Optimized Exclusion Duration: 10-year exclusion restores 80% carbon sequestration in swamp meadows, while meadows require longer periods;

(3) Monitoring Systems: Establish dynamic monitoring of active organic carbon (e.g., DOC, MBC) to evaluate management efficacy.

7. Conclusions and Perspectives

Carbon-nitrogen cycling in Northwest Yunnan Plateau wetlands is highly sensitive to grazing management. Trampling reduces carbon sequestration by altering soil structure, while moderate exclusion effectively restores active organic carbon and microbial functions. Future research should focus on: (1) ecological effects of multi-species grazing; (2) climate change-grazing interactions on carbon fluxes; (3) community-based participatory management. Multiscale integrated studies will provide robust scientific support for sustainable alpine wetland management.

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