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Effects of Water and Nitrogen Addition on Biomass, Productivity, and Their Allocation in a Cropland-to-Grassland Conversion Site in Duolun County, Inner Mongolia: Postprint

Authors: Zhang Jinfeng, Xu Yuqing

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Abstract

This study examined the effects of nitrogen fertilization [N10: 10 g(N) m 2 a 1] and water addition (180 mm a 1) on vegetation biomass, productivity, and allocation patterns in grassland restored from cropland in Duolun County, Inner Mongolia, and compared them with enclosed grassland. The results showed: 1) Fertilization nearly doubled the aboveground biomass of the restored grassland; water addition increased the aboveground biomass by 17%~37%, but the effect was not statistically significant; 2) Neither fertilization nor water addition significantly affected belowground biomass, while water addition increased belowground net primary productivity (BNPP) by 35%~90%; 3) Fertilization decreased the root-to-shoot ratio and the ratio of belowground to aboveground net primary productivity (BNPP/ANPP) in the restored grassland, whereas water addition had no significant effect on either metric; 4) Fertilization increased the proportion of grasses and reduced biomass evenness in the restored grassland; after water addition, forb biomass increased by 128%, while the aboveground biomass of the dominant species Artemisia scoparia and Agropyron mongolicum was insensitive to water addition; 5) Following water and nitrogen addition, the total productivity, root-to-shoot ratio, and biomass of the restored grassland were substantially lower than those of the enclosed grassland. These findings indicate that the effects of water and nitrogen addition on biomass in restored grassland occur primarily in the aboveground component and are associated with species composition.

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Full Text

Responses of Plant Biomass and Net Primary Production to Nitrogen Fertilization and Increased Precipitation in Re-Grassed Croplands in Duolun County, Inner Mongolia, China

ZHANG Jinfeng[1,2], **XU Yuqing**[3]

[1] Laboratory of Quantitative Vegetation Ecology, Institute of Botany, Chinese Academy of Sciences, Beijing 100093, China

[2] College of Geographical Sciences, Fujian Normal University, Fuzhou 350007, China

[3] National Climate Center, China Meteorological Administration, Beijing 100081, China

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Abstract

Biomass and net primary productivity (NPP) are fundamental metrics that describe ecosystem structure and function, and their allocation patterns influence nutrient and water use efficiencies as well as erosion resistance. Excessive cultivation has intensified wind erosion and desertification in northern China, threatening both local economic development and ecological conditions in inland regions. Re-grassing abandoned croplands has become a common restoration measure in the agro-pastoral ecotone of northern China. Grassland vegetation in arid and semiarid regions is highly sensitive to nitrogen and water availability, yet the specific effects of nitrogen fertilization and increased precipitation on vegetation recovery in re-grassed croplands remain unclear.

This study investigated the responses of biomass and NPP to nitrogen addition [N10: 10 g(N) · m ^{2} · a ^{1}] and water supplementation (180 mm · a ^{1}, simulating a 50% precipitation increase) in re-grassed abandoned croplands in Duolun County, Inner Mongolia, comparing them with fenced grassland. The results revealed four key findings. First, fertilization nearly doubled aboveground biomass in re-grassed croplands, while water addition increased aboveground biomass by 17-37%, though this effect was not statistically significant. Second, neither fertilization nor water addition significantly affected belowground biomass, but water addition enhanced belowground net primary productivity (BNPP) by 35-90%. Third, fertilization reduced both the root-to-shoot ratio and the ratio of belowground to aboveground NPP (BNPP/ANPP) in re-grassed croplands, whereas increased precipitation had no significant effect on these metrics. Fourth, fertilization increased the proportion of perennial grasses while decreasing biomass evenness. In contrast, water addition increased forb biomass by 128% after two years, while the dominant species *Artemisia scoparia* and *Agropyron mongolicum* showed no significant response to water supplementation. Finally, total productivity, root-to-shoot ratios, and biomass in all treated re-grassed croplands remained substantially lower than those in fenced grassland. These results demonstrate that water and nitrogen addition primarily affect aboveground biomass in re-grassed croplands, with effects that are species composition-dependent.

Keywords: Re-grassing cropland; Fertilization; Increased precipitation; Vegetation restoration; Community composition; Biomass allocation; Grassland biomass

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Introduction

Biomass and productivity are fundamental data for characterizing ecosystem structure and function, and serve as important criteria for evaluating the success of degraded ecosystem restoration. Grassland biomass allocation exhibits strong plasticity in response to environmental changes. At the community scale, biomass allocation influences community assembly, structure, and function by affecting interspecific competition and species coexistence. The root-to-shoot ratio, meanwhile, impacts water and nutrient use efficiency, soil erosion resistance, and resource utilization strategies in ecosystems. Understanding changes in biomass, productivity, and their allocation is particularly important for restoring ecological functions in re-grassed croplands.

Primary productivity in arid and semiarid ecosystems is generally low and particularly sensitive to precipitation and nitrogen addition. Numerous studies have shown that grassland productivity is closely related to precipitation patterns, yet responses to simulated precipitation changes are complex and may depend on grassland type and lag effects. In contrast, nitrogen addition effects on grassland productivity are more consistent. Research across various grassland types—including *Leymus chinensis* steppe in Inner Mongolia, Horqin sandy grassland, Loess Plateau grasslands, and alpine meadows—has consistently demonstrated that fertilization significantly increases community biomass. However, these studies have primarily focused on aboveground biomass and productivity responses, while understanding of belowground responses and biomass allocation changes remains limited. Moreover, most previous research has examined well-developed natural grasslands rather than re-grassed croplands, which have simpler community structures and vastly different species compositions. Species-level studies have revealed that plant biomass responses to precipitation changes and fertilization vary among species, yet research on how water and nutrient changes affect biomass, productivity, and allocation in re-grassed croplands remains scarce.

In the agro-pastoral ecotone of northern China, excessive cultivation has caused wind erosion and desertification that not only impacts local economies and ecology but also threatens ecological conditions in inland areas. Since 2000, the national government has implemented the Grain-for-Green program in this region. However, vegetation recovery following cropland abandonment has been very slow or has shown degradation trends. This study examines re-grassed croplands in Duolun County, Inner Mongolia, investigating vegetation biomass, productivity, and allocation responses to water and nitrogen treatments compared with fenced grassland. Our objective is to reveal the characteristics and mechanisms of vegetation responses to water and nutrient availability in semiarid re-grassed croplands, providing management recommendations and scientific guidance for promoting rapid, stable vegetation recovery and preventing soil desertification.

1.1 Study Site and Experimental Design

The study site was located near the Duolun Restoration Ecology Station of the Chinese Academy of Sciences in Xilingol League, Inner Mongolia (42°02 27 N, 116°17 59 E). The region has a temperate semiarid monsoon climate with mean annual precipitation of 389 mm, 70% of which occurs from June to August, and a mean annual temperature of 1.9 °C. The re-grassed croplands were originally grasslands converted to farmland in the late 1970s for spring wheat (*Triticum aestivum*), buckwheat (*Fagopyrum esculentum*), and flax (*Linum usitatissimum*) cultivation without fertilization or irrigation history. In 2000, the land was retired from agriculture and seeded with a mixture of *Agropyron mongolicum* and *Medicago sativa*. The dominant species were the planted *A. mongolicum* and naturally colonizing *Artemisia scoparia*, with chestnut soil as the soil type.

The experiment included four treatments: (1) control re-grassed cropland without fertilization or water addition (AC); (2) water-added re-grassed cropland simulating increased summer precipitation (ACW), receiving approximately 50% of mean annual precipitation; (3) nitrogen-fertilized re-grassed cropland (ACN) at 10 g(N) · m ² · a ¹; and (4) fenced grassland (GL) for natural restoration comparison. The fenced grassland had consistent soil and vegetation backgrounds with the pre-cultivation state: chestnut soil with dominant species *Stipa krylovii*, *Agropyron cristatum*, and *Artemisia frigida*. Water addition was applied via sprinkler irrigation, adding 15 mm weekly from early June to late August (12 weeks, total 180 mm). Fertilizer (urea) was applied manually in two equal splits at the end of May and mid-July (5 g(N) · m ² each). Treatments began in 2005, with experimental plots of 8 m × 8 m and seven replicates per treatment.

1.2.1 Aboveground Biomass Measurement

In ecosystems with short growth cycles such as grasslands and croplands, aboveground biomass reaches a maximum during the growing season that can be used to calculate annual aboveground net primary productivity (ANPP). Maximum biomass was determined using the harvest method. Around August 20 in both 2005 and 2006, one 2 m × 0.15 m quadrat was randomly selected in each plot, and vegetation was clipped to ground level by species. Litter was collected in paper bags and recorded. Biomass samples were oven-dried at 75 °C to constant weight and weighed, with total biomass calculated as the sum of dry weights for all species.

Based on life form and taxonomy, all species in each quadrat were classified into five groups: perennial grasses, annual grasses, perennial forbs, annual/biennial forbs, and semi-shrubs. The proportion of each group was calculated as the percentage of its dry weight relative to total community biomass. Species richness and community biomass evenness were measured using Patrick index (P) and Alatalo index (Ea), calculated as:

[Equation would appear here based on context]

1.2.2 Belowground Biomass and Productivity Measurement

Belowground biomass was measured using the soil core method. In late September 2006, two points were randomly selected in each plot, and soil was extracted using a 6-cm diameter root auger at three depths (0–10 cm, 10–20 cm, 20–40 cm). Roots were washed in 100-mesh bags, placed in paper bags, oven-dried at 75 °C to constant weight, and weighed to estimate belowground biomass.

Belowground net primary productivity (BNPP) was estimated using the ingrowth core method. At the beginning of the growing season (May) in both 2005 and 2006, soil was extracted with a 7.5-cm root auger at three depths (0–10 cm, 10–20 cm, 20–40 cm) from two random points per plot. Roots were removed using a 1-mm sieve, and root-free soil was returned to the original layers and marked. At the end of each growing season (late September), soil was re-sampled at the marked locations using a 6-cm auger, roots were washed, oven-dried at 75 °C, and weighed to estimate BNPP per unit area.

1.3 Data Analysis

Differences among fenced grassland and re-grassed cropland treatments (fertilization, water addition, and control) were analyzed using Least Significant Difference (LSD) tests in SPSS 13.0. Significance levels are expressed as P values, with $P < 0.05$ considered statistically significant.

2.1.1 Aboveground Biomass Responses

Aboveground biomass in fenced grassland (GL) was 114.9 g · m ^{2} in 2005 and 120.5 g · m ^{2} in 2006. In 2005, control re-grassed cropland (AC) biomass was 39% higher than GL ($P = 0.12$), while in 2006 there was no significant difference. Nitrogen-fertilized re-grassed cropland (ACN) biomass was 51% higher than AC in 2005 and 92% higher in 2006 (Figure 1, $P < 0.05$). Water-added re-grassed cropland (ACW) biomass was 17% higher than AC in 2005 and 37% higher in 2006, but these increases were not statistically significant ($P = 0.32$ and 0.10, respectively).

Nitrogen addition increased biomass of both dominant species in re-grassed croplands—*Agropyron mongolicum* and *Artemisia scoparia* (Figure 2a, b). Compared with AC, ACN increased *A. mongolicum* biomass from 110.2 g · m ^{2} to 155.1 g · m ^{2} in 2005 ($P = 0.07$) and from 69.9 g · m ^{2} to 160.8 g · m ^{2} in 2006 ($P = 0.03$).

A. scoparia biomass increased from 18.4 g·m ^{2} to 73.4 g·m ^{2} in 2005 (P = 0.05) and from 30.7 g·m ^{2} to 52.4 g·m ^{2} in 2006 (P > 0.05). After two years of fertilization, *A. mongolicum* showed both higher biomass and greater relative increase (130%) than *A. scoparia* (70%), indicating stronger competitive advantage under continuous nitrogen addition. Fertilization had no significant effect on forb biomass (Figure 2c).

Water addition had no significant effect on aboveground biomass of either *A. mongolicum* or *A. scoparia* (Figure 2, P > 0.05). After two years, perennial forb biomass in ACW plots was 128% higher than in control plots, though this difference was not significant (Figure 2c), likely due to low forb biomass and high spatial heterogeneity causing large variation among replicates.

2.1.2 Plant Functional Group Composition

In fenced grassland (GL), biomass composition in 2005 and 2006 consisted of perennial grasses (39% and 36%), perennial forbs (53% and 45%), and semi-shrubs (7% and 18%). Annual plants comprised less than 1% of biomass (Table 1). Re-grassed croplands showed markedly different composition. Control re-grassed cropland (AC) had perennial grass proportions of 70% and 55% in 2005 and 2006 (dominated by *A. mongolicum*), perennial forbs (mainly *M. sativa*, *Potentilla bifurca*, *Sonchus brachyotus*) at 15% both years, annual forbs (primarily *A. scoparia*) at 12% and 29%, and annual grasses (*Setaria* spp.) at approximately 2%. Fertilization tended to decrease perennial forb proportions, while water addition increased them (Table 1).

2.1.3 Community Biomass Evenness

Species richness in control re-grassed cropland (AC) was 6.0 in 2005 and 4.8 in 2006. After two years, water-added re-grassed cropland (ACW) showed significantly higher species richness than AC, while nitrogen-fertilized re-grassed cropland (ACN) did not differ significantly from AC. Both AC and ACN had lower species richness than fenced grassland (GL), while ACW was comparable to GL. Biomass evenness index in AC was 1.0 in 2005 and 1.2 in 2006, with no significant differences between AC, ACW, and ACN during the two-year treatment period. However, all three re-grassed cropland treatments had lower biomass evenness than GL (Figure 3, P < 0.05).

2.2 Belowground Biomass and Productivity

Belowground biomass in both fenced and re-grassed croplands decreased with soil depth, but re-grassed croplands showed greater biomass allocation to deeper layers (Table 2). In GL, root biomass in the 0–10 cm, 10–20 cm, and 20–40 cm layers accounted for 60%, 20%, and 20% of total biomass in the 0–40 cm profile, respectively. In re-grassed croplands (averaged across three treatments), these proportions were 52%, 20%, and 28%. Total belowground biomass in the 0–40 cm layer for AC, ACW, and ACN was only 47%, 52%, and 50% of that in

GL, respectively. Neither fertilization nor water addition significantly affected belowground biomass ($P > 0.05$).

Belowground productivity also showed distinct vertical stratification (Table 3). In GL, BNPP distribution across the three layers was 69%, 20%, and 11% in 2005, and 51%, 27%, and 21% in 2006. Re-grassed croplands allocated more productivity to deeper layers, with average distributions of 45%, 22%, and 32% in 2005, and 48%, 26%, and 26% in 2006. Fertilization did not significantly affect belowground productivity ($P > 0.05$), while water addition increased BNPP in the 0–40 cm layer by 90% in 2005 and 35% in 2006 ($P < 0.05$).

2.3 Total Biomass and Productivity

Fenced grassland (GL) had substantially higher total biomass (1,789.5 $g \cdot m^{2}$) and total productivity (741.0 $g \cdot m^{2} \cdot a^{1}$ in 2005 and 652.9 $g \cdot m^{2} \cdot a^{1}$ in 2006) than all re-grassed cropland treatments (Figure 4). While fertilization and water addition increased aboveground biomass (Figure 1), they did not significantly affect total biomass or total net primary productivity (Figure 4), likely due to the high proportion and large variability of belowground biomass. After two years, fertilization and water addition increased total productivity in re-grassed croplands by 37% and 41%, respectively.

2.4 Root-to-Shoot Ratios and Productivity Allocation

Fenced grassland (GL) had a root-to-shoot ratio (R/S) of 15.7 (Figure 5), while control re-grassed cropland (AC) had an R/S of only 7.3, which decreased to 3.8 with fertilization (ACN). Similarly, BNPP/ANPP ratios in re-grassed croplands (0.9–2.3) were much lower than in GL (4.4–5.5), with ACN showing ratios of 0.9–1.3 (Figure 5).

3.1 Biomass Recovery Following Re-Grassing

Re-grassed croplands had two dominant species: the naturally colonizing *Artemisia scoparia* and the planted *Agropyron mongolicum*. Five years after abandonment, *A. scoparia* had low cover and biomass, indicating slow natural vegetation recovery in semiarid regions. After seeding *A. mongolicum* and *Medicago sativa*, *A. mongolicum* became the dominant species with higher cover and biomass than *A. scoparia*, demonstrating that artificial seeding can accelerate restoration. However, due to seeding methods, density, and nutrient limitations, vegetation and litter cover remained low at only 53% five years after re-grassing.

Although vegetation cover in re-grassed croplands was lower than in fenced grassland, aboveground biomass did not differ significantly. The relatively high aboveground productivity per unit area was related to species composition and plant nitrogen status. Re-grassed croplands contained more annual herbs (13–29% of community biomass versus <1% in GL), which are early successional species that grow rapidly and quickly occupy aboveground space. Additionally, soil mineral nitrogen content and nitrogen turnover rates in re-grassed croplands were comparable to those in GL, but lower belowground biomass allowed plants greater access to nitrogen. According to balanced growth theory, when belowground nitrogen availability increases, plants prioritize aboveground biomass allocation to maintain high aboveground productivity.

Belowground biomass and productivity differed substantially between re-grassed and fenced grasslands. Average belowground biomass in the 0–40 cm layer across three re-grassed cropland treatments was only 50% of that in GL, and belowground productivity was 20–50% of GL values. Even after fertilization and water addition, total productivity in re-grassed croplands remained far below that of fenced grassland, indicating that natural grasslands can maintain higher productivity through self-sustaining water and nutrient cycles and more effectively transfer aboveground assimilates belowground (evidenced by BNPP/ANPP ratios of 4.4–5.5 in GL versus 1.0–2.3 in re-grassed croplands). These differences relate to species composition and plant age: (1) re-grassed croplands contained more annual plants, while fenced grasslands were dominated by perennials with longer root lifespans that accumulate extensive root systems over time; and (2) plants in fenced grasslands were generally older, with perennial roots increasing in density and biomass with age.

3.2 Effects of Fertilization on Biomass and Productivity

Fertilization significantly increased aboveground biomass in re-grassed croplands in the short term but did not promote new species establishment or increase species richness. Instead, fertilization primarily enhanced *A. mongolicum* biomass, thereby increasing community biomass and accelerating restoration through promoting the dominant species.

Biomass allocation in fertilized re-grassed croplands differed dramatically from fenced grassland. Fenced grassland had high belowground biomass, relatively low aboveground biomass, and a high root-to-shoot ratio (15.7). This allocation strategy enables plants to maximize water and nutrient uptake while minimizing transpiration losses, adapting to arid, nutrient-poor conditions. Fertilization increased aboveground biomass without changing belowground biomass, thereby reducing the root-to-shoot ratio. Numerous studies in semiarid regions have shown that large increases in aboveground biomass can enhance transpiration and create dry soil layers, potentially degrading the water environment and causing grassland or forest decline if not properly managed.

Asymmetric competition for nitrogen often alters species composition and reduces biodiversity in fertilized grasslands. This study found that perennial grasses gained competitive advantage after fertilization, with their biomass proportion increasing significantly. Higher grass proportions can inhibit biological soil crust formation and legume colonization, limiting ecosystem nitrogen accumulation through biological fixation. Thus, fertilization has dual effects: it rapidly increases aboveground biomass and benefits soil conservation through grass dominance, yet the substantial aboveground biomass increase and grass proportion elevation may hinder self-recovery of water and nutrient cycles, limiting sustainable vegetation development.

3.3 Effects of Increased Precipitation on Vegetation Recovery

Water is the most critical factor limiting vegetation recovery in semiarid regions, with greater precipitation generally accelerating restoration. In this study, increased summer precipitation had modest effects on aboveground and belowground biomass but significantly enhanced belowground productivity, demonstrating positive but limited effects on vegetation recovery.

The lack of significant biomass response in dominant species (*A. mongolicum* and *A. scoparia*) may relate to two factors. First, seed germination in semiarid regions occurs primarily in April–May, while summer precipitation additions mainly affect summer moisture with minimal spring impact. For *A. mongolicum*, 6% soil moisture is the critical threshold for germination, but surface soil moisture rarely reaches this level in April–May. Second, both species are drought-tolerant, and natural precipitation during the July–August wet season meets their physiological water requirements, making additional rainfall less impactful. Previous studies have found no significant differences in *A. scoparia* biomass accumulation under different water stress levels, and limited effects of precipitation addition on *A. mongolicum* hay yield. Conversely, perennial forbs showed high sensitivity to water addition, with biomass increasing 128% after two years. Thus, species composition strongly influences how increased precipitation affects biomass recovery in re-grassed croplands.

In summary, fertilization significantly promotes aboveground biomass in re-grassed croplands in the short term, but alters biomass allocation patterns substantially compared with natural grasslands. Therefore, fertilization should be combined with other management practices to regulate aboveground biomass and promote rapid, sustainable restoration. Short-term summer precipitation increases have limited effects on biomass, largely depending on the species composition of re-grassed croplands.

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