Postprint: Effects of Reduced-Rate Application of Different Slow/Controlled-Release Urea on Spring Maize in the Loess Tableland Region

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Abstract

This study investigated, through field experiments under mulching conditions, the effects of reduced application rates of six slow/controlled-release urea types on spring maize yield, nitrogen use efficiency, and nitrogen accumulation in the Loess Tableland region, aiming to determine suitable varieties and application rates of slow/controlled-release nitrogen fertilizers for spring maize in this region and to provide theoretical basis and technical support for simplified and efficient fertilization techniques. Using spring maize variety 'Xianyu 335' as the test crop, nine treatments were established: no nitrogen treatment (N0), conventional farmer nitrogen practice [conventional urea, nitrogen rate 225 kg(N) · hm 2, N225], reduced conventional urea treatment [nitrogen rate 180 kg(N) · hm 2, N180], and six reduced-rate slow/controlled-release urea treatments [nitrogen rate 180 kg(N) · hm 2]. The six slow/controlled-release urea types were resin-coated urea, controlled-loss urea (CLU), sulfur-coated urea (SCU), urea-formaldehyde (UF), peptide urea, and stabilized urea. Aboveground plant samples and topsoil (0–20 cm) samples were collected at various growth stages of maize to analyze topsoil inorganic nitrogen content and determine maize plant nitrogen accumulation and yield. Nitrogen application significantly increased maize yield, with yield increase rates of 28%–65%. Compared with N225, N180 significantly reduced maize yield by 19.1%; however, single basal application of reduced-rate (20% reduction) slow/controlled-release urea showed no significant yield reduction effect, with SCU and CLU increasing yield by 4.5% and 2.7%, respectively. Compared with conventional farmer fertilization, N180 reduced economic benefit by 2,051 ¥ · hm 2; various slow/controlled-release urea types (except UF) increased maize nitrogen accumulation and improved nitrogen use efficiency by 2.26%–12.69%, with economic benefits increasing by 347–1,747 ¥ · hm 2; nitrogen use efficiency and economic benefit were highest for SCU and CLU. During the jointing to silking stage, the large nitrogen release

from slow/controlled-release urea may be one reason for the improved nitrogen uptake and use efficiency. Reduced-rate (20%) slow/controlled-release urea such as controlled-loss urea and sulfur-coated urea applied as a single basal application can maintain yield without reduction, improve nitrogen use efficiency and economic returns, and save labor costs, representing an option for simplified and reduced fertilization of spring maize in the Loess Tableland region.

Full Text

Preamble

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Effect of Different Rates of Slow/Controlled Release Urea on Nitrogen Content in Spring Maize in Loess Highlands

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Abstract: A field experiment was conducted under plastic film mulching conditions in the highlands of the Loess Plateau to study the effects of reduced-rate basal application of six types of slow/controlled release urea on spring maize grain yield, nitrogen use efficiency, and nitrogen accumulation. The objective was to identify suitable slow/controlled release nitrogen fertilizer types and application rates for spring maize production in this region, providing theoretical basis and technical support for simplified and efficient fertilization practices. The spring maize cultivar 'Xianyu 335' was used with nine treatments: no nitrogen (N0), conventional farmer practice [common urea at 225 kg(N)·hm ^{2}, N225], reduced common urea [180 kg(N)·hm ^{2}, N180], and six reduced-rate slow/controlled release urea treatments [180 kg(N)·hm ^{2}] including resin-coated urea (RCU), controlled-loss urea (CLU), sulfur-coated urea (SCU), urea formaldehyde (UF), polypeptide urea (PU), and stabilized urea (SU). Aboveground plant samples and topsoil (0–20 cm) samples were collected at different growth stages to analyze soil inorganic nitrogen content and determine plant nitrogen accumulation and grain yield. Nitrogen application significantly increased maize yield by 28%–65% compared to N0. Compared with N225, N180 significantly reduced grain yield by 19.1%, while none of the slow/controlled release urea treatments (20% reduction) showed significant yield reduction, with SCU and CLU increasing yield by 4.5% and 2.7%, respectively. Compared with conventional fertilization, N180 reduced economic benefit by ¥2,051·hm ^{2}, whereas slow/controlled release urea treatments (except UF) increased plant nitrogen accumulation and improved nitrogen use efficiency by 2.26%–12.69%, raising economic benefits by ¥347–1,747 · hm^{2}. SCU and CLU achieved the highest nitrogen use efficiency and economic benefits. The substantial nitrogen release from slow/controlled release urea during the huge bellbottom to silking stage may be one reason for improved nitrogen uptake and utilization. Basal application of reduced-rate (20%) controlled-loss urea and sulfur-coated urea maintained grain yield without reduction, improved nitrogen use efficiency and economic returns, and saved labor costs, making them viable options for simplified and reduced nitrogen fertilization in spring maize production on the Loess Plateau.

Keywords: Spring maize; Grain yield; Slow/controlled release urea; Nitrogen accumulation; Nitrogen use efficiency; Reduced nitrogen application

Introduction

Nitrogen fertilization is a crucial cultivation practice for increasing maize yield. However, in pursuit of high yields, nitrogen application rates in Chinese farmland have continuously increased, while nitrogen use efficiency remains around 32%—far below the 50%–60% achieved in developed countries—resulting in severe nitrogen waste. Excessive nitrogen application has also caused environmental problems including soil acidification, groundwater pollution, and greenhouse gas emissions. In recent years, rapid urbanization and increased rural-to-urban migration have created labor shortages in agricultural production. Therefore, research on reducing nitrogen input while improving efficiency is essential for maintaining crop yields, reducing nitrogen pollution, saving labor, and achieving agricultural simplification.

The Loess Plateau highlands represent a vast and important grain production base where spring maize (*Zea mays* L.) is a major crop. Current fertilization practices are monotonous, primarily relying on basal plus topdressing applications with excessive fertilizer rates and high labor input. Slow/controlled release fertilizers have attracted considerable attention in Chinese agriculture and fertilizer manufacturing since the 1990s. These fertilizers offer synchronized nutrient release with crop uptake, promoting growth, reducing nitrogen losses, and improving yield and nitrogen use efficiency, making them important technical products for simplified fertilization. Significant yield increases have been demonstrated in maize, winter wheat (*Triticum aestivum* L.), potato (*Solanum tuberosum* L.), rapeseed (*Brassica campestris* L.), and pepper (*Capsicum annuum* L.). Previous studies have shown that different slow/controlled release urea types can significantly increase soil total organic nitrogen content and improve nitrogen use efficiency. However, due to differences in control-release mechanisms, manufacturing processes, soil conditions, regional variations, and crop growth patterns, the effectiveness of different slow/controlled release urea types varies considerably across regions. While numerous studies have focused on single types of slow/controlled release urea in the North China or Northeast Plains, research on multiple slow/controlled release urea types with reduced application rates in the Loess Plateau highlands remains limited. This study selected six representative slow/controlled release urea types widely used in production to evaluate their effects as single basal applications at reduced rates on grain yield, nitrogen use efficiency, nitrogen accumulation, and topsoil inorganic nitrogen dynamics under plastic film mulching, aiming to provide a basis for simplified and reduced nitrogen fertilization techniques for spring maize in this region.

1.1 Experimental Site

The field experiment was conducted in 2016 at the Changwu Agricultural Ecology Experimental Station of the Institute of Soil and Water Conservation, Northwest A&F University, located in Wangdong Village, Hongjia Town, Changwu County, Shaanxi Province (107°40 E, 35°12 N) on the southern Loess Plateau at 1,200 m elevation. The region has a warm temperate semi-humid continental monsoon climate with average annual precipitation of 580 mm, mean annual temperature of 9.1°C, and frost-free period of 172 days, representing a typical rain-fed agricultural area. The experimental field had the following baseline fertility: total nitrogen 0.79 g · kg ^{1}, available phosphorus 7.78 mg · kg ^{1}, available potassium 142.9 mg · kg ^{1}, organic matter 13.58 g · kg ^{1}, and pH 8.06.

1.2 Experimental Design

The spring maize cultivar 'Xianyu 335' was used as the test crop. Six slow/controlled release nitrogen fertilizers were evaluated: resin-coated urea (RCU), controlled-loss urea (CLU), sulfur-coated urea (SCU), urea formaldehyde (UF), polypeptide urea (PU), and stabilized urea (SU). The experiment employed a completely randomized block design with nine treatments: no nitrogen (N0), conventional farmer practice [common urea at 225 kg(N) · hm ^{2}, N225], reduced common urea [180 kg(N) · hm ^{2}, N180], and six reduced-rate slow/controlled release urea treatments [180 kg(N) · hm ^{2}]. For N225, nitrogen was applied as both basal and topdressing (at the huge bellbottom stage) at a 3:2 ratio. All other treatments received nitrogen as a single basal application via furrow placement. All plots received 80 kg(K O) · hm ^{2} and 40 kg(P O) · hm ^{2} as basal fertilizers. The cultivation method was flat planting with plastic film mulching (half-film coverage), with inter-film planting. Each plot contained eight rows with three replications per treatment. Planting density was 65,000 plants · hm ^{2} with 55 cm row spacing and 25 cm plant spacing. Plot size was 40 m^2 (8.7 m × 4.6 m). Sowing occurred on April 23, 2016, and harvest on September 17, with a 147-day growth period. Nitrogen contents and prices of different fertilizers are detailed in .

1.3 Measurement Methods and Calculations

Yield and yield components: At maturity, two rows of spring maize were harvested from each plot to measure ear number and total fresh weight. Fifteen ears were randomly selected from these rows to evaluate ear traits, which were sun-dried and threshed for yield component analysis. Grain yield was calculated from the 15-ear sample (adjusted to 14% moisture content). Total nitrogen in plant organs (stem, leaf, tassel, bract, grain, and cob) was determined by H SO - H O digestion and analyzed using an AA3 continuous flow analyzer. Topsoil (0–20 cm) inorganic nitrogen content was extracted with 1 mol·L 1 KCl and measured with an AA3 continuous flow analyzer.

Key calculation formulas:

Economic benefit (¥·hm 2) = Grain yield × Grain price − Input cost (1)

Plant nitrogen accumulation [kg(N)·hm 2] = Grain dry weight × Grain N content + Other organ dry weight × Other organ N content (2)

Grain nitrogen accumulation [kg(N)·hm 2] = Grain dry weight × Grain N content (3)

Nitrogen harvest index (NHI, %) = (Grain N accumulation / Plant N accumulation) × 100 (4)

Nitrogen use efficiency (NUE, %) = (Plant N accumulation in N treatment − Plant N accumulation in N0) / N application rate × 100 (5)

Agronomic nitrogen efficiency (ANE, kg·kg 1) = (Yield in N treatment − Yield in N0) / N application rate (6)

Data were analyzed using one-way ANOVA and LSD multiple comparisons with SAS 9.1, and figures were prepared using Origin 8.0.

Results

2.1 Effects of Different Fertilization Treatments on Spring Maize Yield and Yield Components

As shown in , the highest grain yield was achieved with SCU (12,315 kg·hm 2), followed by CLU (12,108 kg·hm 2) and N225 (11,786 kg·hm 2). Compared with N0, nitrogen application significantly increased grain yield by 2,062–4,853 kg·hm 2, representing a 28%-65% increase. Relative to N225, N180 significantly reduced yield by 19.1%, while none of the slow/controlled release urea treatments showed significant yield reductions at the 20% reduced rate, with SCU and CLU increasing yield by 4.5% and 2.7%, respectively. Compared with N180, all slow/controlled release urea treatments significantly increased yield by 17.4%-29.3%, with no significant differences among the different slow/controlled release urea types. Grain number per ear followed a similar trend to yield. Nitrogen application significantly increased grain number by 111.6–178.4 compared with N0. N180 reduced grain number by 47.4 compared with N225, while slow/controlled release urea treatments showed no significant reduction. Compared with N180, all slow/controlled release urea treatments (except UF) significantly increased grain number by 38.4–66.8, with SCU and CLU showing significant increases of 35.3 and 36.3 compared with UF. The highest 1000-grain weight was observed with CLU (314.3 g), followed by SCU (312.8 g). Nitrogen application had limited effect on 1000-grain weight, with only CLU and SCU showing significant increases compared with N0.

2.2 Effects of Different Fertilization Treatments on Nitrogen Accumulation and Nitrogen Harvest Index

As presented in , the highest plant nitrogen accumulation occurred with CLU [197.20 kg(N) · hm^{2}], followed by SCU [191.82 kg(N) · hm^{2}] and N225 [191.18 kg(N) · hm^{2}]. Nitrogen application significantly increased plant nitrogen accumulation by 59.32–90.07 kg(N) · hm^{2} compared with N0. N180 significantly reduced plant nitrogen accumulation by 24.73 kg(N) · hm^{2} compared with N225, while slow/controlled release urea treatments showed no significant reduction. Compared with N180, all slow/controlled release urea treatments (except UF) significantly increased plant nitrogen accumulation by 8.1–30.75 kg(N) · hm^{2}. Grain nitrogen accumulation followed a similar pattern to plant nitrogen accumulation. Nitrogen application increased grain nitrogen accumulation by 35.06–76.98 kg(N) · hm^{2} compared with N0. N180 significantly reduced grain nitrogen accumulation by 30.11 kg(N) · hm^{2} compared with N225, while slow/controlled release urea treatments (except UF and SU) significantly increased grain nitrogen accumulation by 22.50–35.56 kg(N) · hm^{2} compared with N180. No significant differences in nitrogen harvest index were observed among nitrogen treatments compared with N0. N180 significantly reduced NHI compared with N225, while slow/controlled release nitrogen treatments (except UF and SU) significantly increased NHI compared with N180.

2.3 Effects of Different Fertilization Treatments on Nitrogen Use Efficiency and Economic Benefits

As shown in , the highest nitrogen use efficiency was achieved with CLU (50.04%), followed by SCU (47.05%). Slow/controlled release urea improved NUE compared with common urea. Relative to N225, slow/controlled release urea treatments (except UF) increased NUE by 2.26%–12.69%, with CLU and SCU showing significant increases of 12.69% and 9.70%, respectively. Compared with N180, all slow/controlled release urea treatments significantly increased NUE by 4.49%–17.08%. Agronomic nitrogen efficiency followed a similar pattern to NUE. N180 significantly reduced ANE by 7.77 kg · kg^{1} compared with N225, while slow/controlled release urea treatments increased ANE by 1.47–7.74 kg · kg^{1}, with SCU and CLU showing significant increases of 7.74 kg · kg^{1} and 6.59 kg · kg^{1}, respectively. The highest economic benefit was obtained with SCU (¥16,467 · hm^{2}), followed by CLU (¥16,233 · hm^{2}). Nitrogen application increased economic benefit by ¥2,526–6,324 · hm^{2} compared with N0. Among nitrogen treatments, N180 showed the lowest economic benefit (¥12,669 · hm^{2}). Compared with N225, N180 reduced economic benefit by ¥2,051 · hm^{2}, while slow/controlled release urea treatments (except UF) increased economic benefit by ¥347–1,747 · hm^{2}.

2.4 Effects of Different Fertilization Treatments on Stage-Based and Daily Nitrogen Accumulation

Plant nitrogen accumulation gradually increased throughout the growth period, while stage-based and daily accumulation rates showed an initial increase followed by a decrease (). From sowing to jointing stage, stage nitrogen accumulation was 10.39-13.93 kg(N)·hm ^{2} with daily accumulation of 0.26–0.35 kg(N)·hm ^{2}·d ^{1}, with SU showing the highest accumulation. The jointing to huge bellbottom stage represented the most vigorous growth period, with the highest stage nitrogen accumulation of 59.18–84.12 kg(N)·hm ^{2} and daily accumulation of 2.37-3.37 kg(N)·hm ^{2}·d ^{1}. Nitrogen accumulation decreased to varying degrees during the huge bellbottom to silking stage, with stage accumulation of 5.10-45.56 kg(N)·hm ^{2} and daily accumulation of 0.23–2.07 kg(N)·hm ^{2}·d ^{1}, with N225 showing the highest accumulation. From silking to milk stage, nitrogen accumulation was 25.61–71.29 kg(N)·hm ^{2} with daily accumulation of 0.91-2.55 kg(N)·hm ^{2}·d ^{1}. During the milk to maturity stage, stage accumulation was 3.04-36.14 kg(N)·hm ^{2} with daily accumulation of 0.09–1.10 kg(N)·hm ^{2}·d ^{1}. SCU and CLU showed significantly higher stage nitrogen accumulation than N225 during the silking to milk stage and milk to maturity stage, respectively.

2.5 Effects of Different Fertilization Treatments on Topsoil (0–20 cm) Inorganic Nitrogen Content

[Figure 1: see original paper] shows that different fertilization treatments resulted in significant differences in topsoil (0–20 cm) inorganic nitrogen content across growth stages. The N0 treatment remained consistently low, while nitrogen treatments showed substantial variation. At the jointing stage, SU significantly increased soil inorganic nitrogen content to 19.54 mg·kg ^{1}. At the huge bellbottom stage, RCU, CLU, and SCU significantly increased soil inorganic nitrogen content to 20.17 mg·kg ^{1}, 18.14 mg·kg ^{1}, and 20.28 mg·kg ^{1}, respectively. Due to topdressing at the huge bellbottom stage, N225 significantly increased soil inorganic nitrogen content to 17.09 mg·kg ^{1} at the silking stage. All treatments showed significant decreases in soil inorganic nitrogen content during the milk stage (5.03-7.62 mg·kg ^{1}), which remained relatively stable through maturity (5.17-7.56 mg·kg ^{1}).

Discussion and Conclusion

The period from the huge bellbottom stage to silking stage is when maize absorbs nutrients most rapidly and represents the peak nutrient use efficiency period. Consequently, topdressing at the huge bellbottom stage is the most important fertilizer application for maize. This study confirmed that conventional farmer practice (N225), which includes topdressing at the huge bellbottom stage, significantly increased topsoil (0–20 cm) inorganic nitrogen content at silking and achieved the highest stage nitrogen accumulation. This demonstrates that fertilization during critical growth stages enhances plant nitrogen accumulation and nitrogen use efficiency, thereby promoting yield formation. In contrast, the reduced-rate single basal application of common urea (N180) resulted in low topsoil inorganic nitrogen content at the huge bellbottom stage and very low nitrogen accumulation during the milk to maturity stage, indicating that single basal application of conventional nitrogen fertilizer does not match maize nitrogen demand patterns and causes nitrogen deficiency during later growth stages, reducing yield by 19.1%. However, topdressing at the huge bellbottom stage is labor-intensive and time-consuming, conflicting with current rural labor shortages. Can extending nitrogen fertilizer effectiveness reduce topdressing frequency, and can slow/controlled release fertilizers meet the requirement of single basal application?

Unlike the 20% reduced-rate single basal application of common urea (N180), various slow/controlled release urea types applied as single basal applications did not significantly reduce maize yield, with SCU and CLU even showing yield increases, demonstrating clear slow-release effects. This was confirmed by the dynamic changes in topsoil (0–20 cm) inorganic nitrogen content during the growth period. RCU, SCU, and CLU released nitrogen concentrated during the huge bellbottom stage, with significantly higher topsoil inorganic nitrogen content than common urea treatments, which aligns with maize nitrogen demand patterns. Consequently, these treatments resulted in greater plant nitrogen accumulation and higher nitrogen use efficiency.

Under 20% nitrogen reduction with single basal application, SCU and CLU significantly increased grain number per ear and plant nitrogen accumulation compared with N180, thereby improving both yield and nitrogen use efficiency. These results are consistent with previous findings that slow/controlled release nitrogen fertilizers significantly improve yield and nitrogen use efficiency compared with conventional nitrogen fertilizers at equivalent nitrogen rates, though the effectiveness varies among different slow/controlled release urea types in the Loess Plateau highlands. UF showed a slightly increasing then decreasing trend in topsoil inorganic nitrogen content, likely because UF fertilizer must be degraded by microorganisms before plant uptake, resulting in slower nitrogen release. During the high nitrogen demand period (jointing to huge bellbottom stage), insufficient nitrogen release could not meet plant requirements, directly affecting crop growth and yield formation. Consequently, UF showed poor performance in plant nitrogen accumulation and yield.

Compared with conventional farmer practice, 20% reduced-rate single basal application of common urea significantly reduced yield by 19.1%, while slow/controlled release urea treatments showed no significant yield reduction. Although most slow/controlled release urea types (except UF) have higher prices, their reduced-rate single basal application improved nitrogen use efficiency, maintained high yields, and reduced fertilizer and labor costs, resulting in higher economic benefits than conventional practice. UF showed lower economic benefits than conventional practice due to mismatched nutrient release patterns with maize nitrogen demand, relatively low yield, and high fertilizer price.

Considering grain yield, nitrogen use efficiency, and dynamic changes in topsoil (0–20 cm) inorganic nitrogen content, controlled-loss urea (CLU) and sulfur-coated urea (SCU) are recommended as suitable slow/controlled release nitrogen fertilizers for reduced-rate, high-efficiency application in spring maize production on the Loess Plateau. These options can reduce nitrogen application, lower labor input, decrease nitrogen residues, and improve both economic and social benefits of fertilization.

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