

EFFECTS OF AMMONIUM-BASED FERTILIZERS ON WINTER WHEAT YIELD AND GRAIN QUALITY

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Abstract

This study evaluated the effects of ammonium nitrate and ammonium sulfate fertilization on winter wheat yield and grain quality under field experimental conditions. Grain yield and major quality parameters, including protein content, gluten content, thousand kernel weight, and test weight, were determined. Nitrogen was applied at five fertilization rates: b1 - N0, b2 - N50, b3 - N100, b4 - N150, and b5 - N170 kg N ha⁻¹, to assess crop response to increasing nitrogen supply. The results indicated that both nitrogen source and application rate significantly affected grain yield, with higher nitrogen rates promoting increased productivity. Nitrogen fertilization also exerted a pronounced effect on grain quality traits, leading to higher protein and gluten contents, while thousand kernel weight and test weight showed distinct responses depending on nitrogen form and dose. Overall, the study demonstrates that optimizing nitrogen source and application rate is essential for achieving a balanced improvement in winter wheat yield and grain quality under intensive cropping systems. These findings provide practical guidance for nitrogen management strategies aimed at sustainable wheat production systems.

Key words: ammonium nitrate, ammonium sulfate, grain quality, nitrogen fertilization, protein content.

INTRODUCTION

Wheat (*Triticum aestivum* L.) is one of the most important cereal crops worldwide, providing a major source of calories and protein for the global population. Its strategic role in food security is expected to intensify as climate change, population growth, and dietary shifts increase the pressure on agricultural systems to produce higher yields without compromising grain quality and food safety (Curtis & Halford, 2014; Smuleac et al., 2020; Gherasimescu et al., 2023). In this context, nitrogen (N) nutrition remains a central factor governing wheat productivity and grain quality, yet also represents one of the most complex and controversial aspects of cereal crop management due to its environmental footprint and economic cost (Hawkesford, 2014).

Nitrogen is the primary limiting nutrient for wheat growth and yield formation, exerting strong influence on canopy development, photosynthetic capacity, grain number, and grain filling processes. At the same time, nitrogen availability directly affects the synthesis and accumulation of storage proteins

in the grain, which determine functional quality traits such as protein content, gluten strength, and bread-making performance (Blandino et al., 2020). However, excessive or inefficient N fertilization has negative consequences, including nitrate leaching, greenhouse gas emissions, and an increased risk of reduced nitrogen use efficiency (NUE), all of which challenge the sustainability of intensive wheat production systems (Hawkesford, 2014; Chitu et al., 2024).

The need to balance high yield with acceptable grain quality is increasingly complicated by climate change. Rising temperatures, altered precipitation patterns, and increased frequency of extreme weather events have been shown to affect nitrogen uptake dynamics and protein accumulation in wheat grains (Asseng et al., 2019; Smuleac et al., 2020). Climate-driven changes in crop phenology may shorten grain filling periods or decouple nitrogen uptake from carbohydrate accumulation, leading to reductions or increased variability in grain protein concentration (Asseng et al., 2019). Under these conditions, optimizing fertilizer strategies becomes a crucial adaptation measure

to maintain both yield stability and quality standards.

Grain protein concentration is one of the most important quality parameters in wheat, particularly for bread-making and industrial processing. While higher nitrogen availability generally increases protein content, the relationship between yield and grain protein often shows a dilution effect, whereby increased carbohydrate deposition reduces protein concentration at high yield levels (Curtis & Halford, 2014). This trade-off highlights the need for fertilization strategies that improve nitrogen partitioning to the grain rather than merely stimulating vegetative growth.

In addition to nitrogen, sulfur (S) nutrition has gained increasing attention in wheat production systems. Sulfur is a constituent of essential amino acids such as cysteine and methionine and is directly involved in the formation of gluten proteins that determine dough viscoelastic properties. Several studies have demonstrated that insufficient sulfur supply may limit the effectiveness of nitrogen fertilization, reducing protein quality despite adequate or high nitrogen inputs (Ereku et al., 2012; Hrivna et al., 2015). As atmospheric sulfur deposition has declined significantly due to air pollution control measures, sulfur deficiencies have become more common in agricultural soils, particularly in high-yielding cereal systems (Raffan et al., 2020).

The interaction between nitrogen and sulfur nutrition is therefore critical for wheat grain quality. Research has shown that combined N and S fertilization improves gluten composition, enhances protein functionality, and contributes to more stable bread-making quality under varying environmental conditions (Blandino et al., 2020; Wilson et al., 2020). Moreover, sulfur availability influences nitrogen metabolism in the plant, affecting amino acid synthesis and nitrogen assimilation efficiency (Tabak et al., 2020). These interactions underline the importance of evaluating fertilizer sources that supply both nitrogen and sulfur in an agronomically and environmentally efficient manner.

Among mineral nitrogen fertilizers, ammonium nitrate and ammonium sulfate are widely used due to their high solubility and rapid nitrogen

availability. Ammonium nitrate provides both nitrate and ammonium forms of nitrogen, offering flexibility in plant uptake, while ammonium sulfate supplies nitrogen exclusively in ammonium form along with a substantial amount of sulfur. Comparative studies have demonstrated that the form of nitrogen influences root uptake patterns, soil nitrogen dynamics, and ultimately crop yield and quality (Wang et al., 2015). In dryland and temperate environments, ammonium-based fertilizers may affect nitrate accumulation at different soil depths, with implications for nitrogen losses and plant availability (Wang et al., 2015).

Several authors have reported significant differences in wheat response depending on the nitrogen form applied. Jan et al. (2011) showed that both source and timing of nitrogen application affected wheat productivity, emphasizing the importance of synchronizing nitrogen availability with crop demand. Similarly, Tabak et al. (2019) demonstrated that ammonium nitrate enriched with ammonium sulfate improved both yield and grain quality of winter wheat, while also influencing soil chemical properties. These findings suggest that integrating sulfur into nitrogen fertilization strategies may enhance NUE and quality outcomes.

Grain quality assessment extends beyond protein and gluten concentration to include physical parameters such as thousand kernel weight (TKW) and test weight, which reflect grain filling efficiency and market acceptance. Nitrogen fertilization has been shown to influence these parameters, although responses vary depending on environmental conditions, cultivar, and fertilizer form (Hrivna et al., 2015). Increased nitrogen rates often enhance grain protein while showing variable effects on kernel weight, highlighting the need to optimize fertilizer regimes that do not compromise physical grain quality.

In recent years, food safety considerations have added a new dimension to fertilizer management in wheat. Free asparagine concentration in wheat grain is a precursor for acrylamide formation during high-temperature processing, such as baking and toasting. High nitrogen availability and sulfur deficiency have been associated with increased free asparagine

accumulation, raising concerns about food safety despite improvements in grain protein content (Fritz, 2020; Raffan et al., 2020). Studies have emphasized that balanced N and S nutrition is crucial for minimizing asparagine levels while maintaining desirable quality traits (Wilson et al., 2020; Oddy et al., 2023).

Environmental variability further complicates the relationship between fertilization and grain quality traits. Oddy et al. (2023) highlighted that year-to-year differences in temperature and rainfall significantly influence free asparagine concentration, underscoring the need to account for environmental effects when evaluating fertilizer strategies. Similarly, Asseng et al. (2019) indicated that climate-driven changes may alter protein responses to nitrogen fertilization, reinforcing the importance of adaptive nutrient management under future climatic scenarios.

Late-season nitrogen application has been proposed as a strategy to improve grain protein concentration without excessive yield stimulation. Blandino et al. (2020) demonstrated that late N fertilization significantly affected gluten composition and technological quality in high-protein wheat grown under humid Mediterranean conditions. However, the effectiveness of such strategies depends on nitrogen form, sulfur availability, and environmental context, making it necessary to evaluate their performance under diverse agronomic conditions.

Despite extensive research on nitrogen fertilization, gaps remain regarding the comparative effects of ammonium nitrate and ammonium sulfate across a wide range of nitrogen rates, particularly in relation to combined yield, quality, and food safety parameters. While studies have addressed individual aspects of nitrogen or sulfur fertilization, integrated assessments that consider multiple quality indicators - such as protein content, gluten concentration, thousand kernel weight, and test weight - remain limited. Furthermore, the variability in crop response across nitrogen doses highlights the need for dose-response studies that identify thresholds beyond which additional nitrogen provides diminishing or negative returns (Tabak et al., 2020).

Given the increasing pressure to improve nitrogen use efficiency and reduce environmental impacts, understanding how different ammonium-based fertilizers influence wheat performance is of both scientific and practical importance. The choice of fertilizer source, rate, and nutrient composition must align with agronomic goals, environmental constraints, and quality requirements of the wheat processing industry. As global wheat production systems face mounting challenges from climate change and sustainability demands, research that integrates yield performance, grain quality, and nutrient efficiency remains essential (Curtis & Halford, 2014; Asseng et al., 2019, Sitnicki et al., 2024). In this context, evaluating the effects of ammonium nitrate and ammonium sulfate fertilization across multiple nitrogen rates provides valuable insight into optimized nutrient management strategies for winter wheat. Such studies contribute to the development of balanced fertilization recommendations that enhance productivity while ensuring grain quality and food safety under current and future agricultural conditions.

MATERIALS AND METHODS

The research was carried out at the Didactic and Experimental Station (SDE) Timișoara, Romania, during the agricultural seasons 2023-2025. The area is characterized by a temperate continental climate, favorable for winter wheat cultivation, with moderate rainfall and temperature conditions specific to western Romania.

The soil of the experimental field is classified as cambic chernozem with phreatic moisture influence. This soil type is known for its high fertility, good structure, and adequate water-holding capacity. The soil showed medium to good supply with phosphorus and potassium, while nitrogen availability required fertilization (Crista et al., 2011). The experiment was organized as a bifactorial field trial using a randomized complete block design with three replications. The experimental factors were nitrogen fertilizer type and nitrogen application rate.

Two nitrogen fertilizer sources were studied (Factor A): a₁ - ammonium nitrate (AN); a₂ - ammonium sulfate (AS).

Nitrogen was applied in five different rates (Factor B): b₁ – N₀ (unfertilized control), b₂ – N₅₀, b₃ – N₁₀₀, b₄ – N₁₅₀, b₅ – N₁₇₀ kg N ha⁻¹.

These fertilization levels were chosen to evaluate the response of winter wheat yield and grain quality across a wide range of nitrogen supply.

Winter wheat was sown at the optimal sowing time recommended for the area, using a certified variety adapted to local conditions. The seeding rate ensured uniform plant population in all experimental variants.

Phosphorus and potassium fertilizers were applied uniformly across all plots before sowing, according to local soil recommendations. Crop management practices, including weed control, disease protection, and pest management, were applied equally to all treatments to eliminate non-fertilization effects. Nitrogen fertilizers were applied in two splits: the first application at the beginning of spring vegetation and the second at stem elongation. In ammonium sulfate treatments, sulfur was supplied through the fertilizer source.

At crop maturity, wheat was harvested from the central area of each plot. Grain yield was determined and expressed on a hectare basis at standard moisture content.

Grain samples were collected for laboratory analyses. Grain quality was evaluated through protein content, gluten content, thousand kernel weight, and test weight (hectolitre mass). Standard analytical methods were used for all determinations. Protein content, gluten content, and test weight were determined using a Granomat Pfeuffer analyzer, while thousand kernel weight was determined by counting and weighing the grains using a Kern&Sohn precision balance.

Statistical analyses were performed using STATISTICA 7 software, using one-way and multi-way analysis of variance (ANOVA), as well as cluster analysis. Calculations of marginal differences (LD) and the contribution of experimental factors and their interactions were performed in Microsoft Excel. Comparison of means was performed using Duncan's test using MSTAT-C software.

The effects of nitrogen fertilizer source, nitrogen rate, and year were evaluated, as well as their interactions. Differences between treatment means were considered significant at $p \leq 0.05$.

RESULTS AND DISCUSSIONS

Grain yield of winter wheat was strongly influenced by nitrogen fertilization, both in terms of fertilizer type and application rate (Table 1). In the unfertilized control (N₀), grain yield reached 2308 kg·ha⁻¹, reflecting the baseline productive potential of the cambic chernozem soil at SDE Timișoara. Application of nitrogen resulted in significant yield increases at all fertilization levels, with yields rising progressively from 3042 kg·ha⁻¹ at N₅₀ to 5390 kg·ha⁻¹ at N₂₀₀ (Table 1). All fertilized treatments showed very highly significant differences compared to the control.

Table 1. Grain yield (kg·ha⁻¹) of winter wheat as influenced by nitrogen fertilizer type and nitrogen rate

Nitrogen rate	N0	N50	N100	N150	N200	Mean
Ammonium nitrate	2308	2934	3792	4733	5237	3801
Ammonium sulfate	2308	3150	3933	4915	5543	3970
Relative yield (%)	100	128	164	189	209	–
Yield increase (kg·ha ⁻¹)	–	653	1473	2035	2501	–
Significance	–	***	***	***	***	–
<i>LSD (kg·ha⁻¹): 5% = 149; 1% = 181; 0.1% = 234.</i>						

Significance level: ***highly significant at $p \leq 0.001$

These results confirm the well-documented role of nitrogen as the primary yield-limiting nutrient in wheat production. Similar yield responses to increasing nitrogen rates were reported by Jan et al. (2011) and Hawkesford (2014), who emphasized that adequate nitrogen supply is essential for maximizing grain number and grain weight. The progressive yield increase observed in the present study indicates efficient nitrogen uptake and utilization under the given soil and climatic conditions.

Comparison between fertilizer types revealed a consistent yield advantage for ammonium sulfate over ammonium nitrate at all nitrogen rates (Table 1). The average yield obtained with ammonium sulfate was 3970 kg·ha⁻¹, compared to 3801 kg·ha⁻¹ for ammonium

nitrate, corresponding to a 4% increase. A similar advantage of sulfur-containing nitrogen fertilizers was reported by Tabak et al. (2019) and Tabak et al. (2020), who attributed this effect to improved nitrogen use efficiency and enhanced protein synthesis when sulfur was supplied together with nitrogen. Hrivna et al. (2015) also showed that sulfur fertilization contributes to higher wheat productivity, particularly on soils with moderate sulfur availability.

Thousand kernel weight (TKW) increased steadily with increasing nitrogen rates for both fertilizer types, indicating improved grain filling under enhanced nitrogen availability (Table 2). Under ammonium nitrate fertilization, TKW increased from 37.3 g in the control to 42.7 g at N200, while ammonium sulfate resulted in higher values, reaching 44.4 g at the highest nitrogen rate (Table 2).

Table 2. Thousand kernel weight (TKW, g) as influenced by nitrogen fertilizer type and nitrogen rate

Nitrogen rate	N0	N50	N100	N150	N200	Mean
Ammonium nitrate	37.3	39.6	40.2	42.8	42.7	40.43
Ammonium sulfate	37.3	39.9	41.8	43.4	44.4	41.23
Relative value (%)	100	107	110	116	119	–
Difference (g)	–	2.6	4.5	6.1	7.1	0.85

The observed increase in TKW is consistent with findings reported by Hrivna et al. (2015), who demonstrated that nitrogen fertilization improves kernel development and final grain weight. The superior response under ammonium sulfate fertilization is in agreement with Erekul et al. (2012), who highlighted the positive interaction between nitrogen and sulfur nutrition on grain filling processes. Sulfur plays a key role in amino acid synthesis and enzyme activity, which may explain the improved assimilate accumulation in the grain observed in the present study.

Test weight (hectolitre mass) showed a positive response to nitrogen fertilization, increasing with nitrogen rate regardless of fertilizer type (Table 3). Values increased from 76.7 kg·hl⁻¹ in the unfertilized control to approximately 79.7–79.8 kg·hl⁻¹ at higher nitrogen rates. Ammonium sulfate treatments consistently recorded slightly higher test weight values compared to ammonium nitrate (Table 3).

Table 3. Test weight (hectolitre mass, kg·hl⁻¹) as influenced by nitrogen fertilizer type and nitrogen rate

Nitrogen rate	N0	N50	N100	N150	N200	Mean
Ammonium nitrate	76.7	77.2	77.2	79.2	79.7	76.12
Ammonium sulfate	76.7	78.3	79.1	79.3	79.8	78.52
Relative value (%)	100	102	103	103	104	–
Difference (kg·hl ⁻¹)	–	1.6	2.4	2.6	3.1	0.40

Although absolute differences were relatively small, the average test weight was higher under ammonium sulfate fertilization (78.52 kg hl⁻¹) than under ammonium nitrate (76.12 kg hl⁻¹), indicating improved grain density and uniformity. These results suggest that combined nitrogen and sulfur supply contributed positively to kernel structure and endosperm development.

These results are in line with those reported by Tabak et al. (2019), who observed improvements in test weight following fertilization with ammonium nitrate enriched with ammonium sulfate. Although the absolute differences were relatively small, test weight is an important commercial quality indicator, and even minor increases may improve grain classification and market value.

Grain protein content increased significantly with increasing nitrogen rates for both fertilizer types (Table 4). Protein concentration increased from 10.65% in the unfertilized control to over 13.7% at the highest nitrogen rate.

This response confirms the strong relationship between nitrogen availability and protein accumulation in wheat grain, as widely reported in the literature (Hawkesford, 2014; Curtis & Halford, 2014).

Table 4. Grain protein content (%) as influenced by nitrogen fertilizer type and nitrogen rate

Nitrogen rate	N0	N50	N100	N150	N200	Mean
Ammonium nitrate	10.65	11.05	11.85	13.25	13.75	12.09
Ammonium sulfate	10.65	11.25	12.25	13.75	14.05	12.19
Difference (%)	–	0.60	1.60	3.10	3.40	0.08

At intermediate and high nitrogen rates, ammonium sulfate consistently resulted in slightly higher protein content than ammonium nitrate (Table 4). Mean protein content values were 12.09% for ammonium nitrate and 12.19% for ammonium sulfate, indicating a

modest but consistent advantage of sulfur-containing fertilization in improving grain protein concentration.

Similar findings were reported by Wilson et al. (2020) and Blandino et al. (2020), who demonstrated that sulfur availability enhances protein synthesis and improves gluten-forming protein fractions. Asseng et al. (2019) also emphasized that optimizing nitrogen nutrition is crucial for maintaining grain protein concentration under changing climatic conditions.

Wet gluten content followed a similar trend to protein content, showing a strong positive response to increasing nitrogen rates (Table 5).

Table 5. Wet gluten content (%) as influenced by nitrogen fertilizer type and nitrogen rate

Nitrogen rate	N0	N50	N100	N150	N200	Mean
Ammonium nitrate	20.31	23.21	26.26	28.38	29.43	25.51
Ammonium sulfate	20.31	23.33	26.42	29.84	30.35	26.05
Difference (%)	–	3.02	6.11	9.53	10.04	0.54

Values increased from approximately 20% in the unfertilized control to over 29% at higher nitrogen rates. Ammonium sulfate fertilization resulted in consistently higher gluten content compared to ammonium nitrate at all nitrogen levels.

The mean wet gluten content was 26.05% under ammonium sulfate fertilization, compared to 25.51% under ammonium nitrate. The higher gluten content observed with ammonium sulfate highlights the importance of sulfur availability for the synthesis of sulfur-containing amino acids essential for gluten protein structure and functional quality.

These results are consistent with those reported by Erekul et al. (2012) and Blandino et al. (2020), who showed that sulfur fertilization improves gluten quantity and quality by enhancing the synthesis of sulfur-containing amino acids essential for gluten structure. The positive effect of ammonium sulfate observed in the present study supports the conclusion that balanced nitrogen and sulfur nutrition is critical for achieving high bread-making quality.

The increase in nitrogen application rate led to a marked rise in protein and gluten yield per unit area, as a result of the simultaneous

increase in grain yield and in the concentration of these components (Tables 6 and 7). Compared with the unfertilized control (N0), nitrogen application rates of 150-200 kg N·ha⁻¹ resulted in approximately 2.9-3.0 fold increases in protein yield and more than threefold increases in gluten yield.

At all fertilization levels, ammonium sulfate produced higher protein and gluten yields than ammonium nitrate. The differences between fertilizer types increased with nitrogen rate, reaching maximum values of +58.7 kg·ha⁻¹ for protein yield and +141.1 kg·ha⁻¹ for gluten yield at the N200 rate. This trend indicates superior nitrogen use efficiency when sulfur is supplied together with nitrogen, due to its essential role in the synthesis of sulfur-containing amino acids and in the formation of gluten proteins.

Given that both grain yield and protein and gluten concentrations showed statistically significant differences among treatments, the observed differences in protein and gluten yield can be considered agronomically relevant. These results support the advantage of ammonium sulfate fertilization under the experimental conditions, contributing to higher production of technologically valuable grain components.

Table 6. Protein yield (kg·ha⁻¹) of winter wheat as influenced by nitrogen fertilizer type and rate

Nitrogen rate	Protein yield – AN (kg·ha ⁻¹)	Protein yield – AS (kg·ha ⁻¹)	Difference AS–AN (kg·ha ⁻¹)
N0	245.8	245.8	0.0
N50	324.2	354.4	+30.2
N100	449.4	481.8	+32.4
N150	627.1	675.8	+48.7
N200	720.1	778.8	+58.7
Mean	473.3	507.0	+33.7

Table 7. Wet gluten yield (kg·ha⁻¹) of winter wheat as influenced by nitrogen fertilizer type and rate

Nitrogen rate	Gluten yield – AN (kg·ha ⁻¹)	Gluten yield – AS (kg·ha ⁻¹)	Difference AS–AN (kg·ha ⁻¹)
N0	468.8	468.8	0.0
N50	681.0	734.9	+53.9
N100	995.8	1039.1	+43.3
N150	1343.2	1466.6	+123.4
N200	1541.2	1682.3	+141.1
Mean	1006.0	1078.4	+72.4

The combined interpretation demonstrates that increasing nitrogen rates significantly enhanced winter wheat yield and grain quality, while ammonium sulfate provided consistent advantages over ammonium nitrate across all evaluated parameters. These findings are in agreement with previous studies emphasizing the importance of integrated nitrogen and sulfur fertilization strategies for improving wheat productivity and technological quality (Hrivna et al., 2015; Tabak et al., 2020; Wilson et al., 2020).

The present results confirm and extend existing knowledge by demonstrating that, under cambic chernozem soil conditions and temperate continental climate, ammonium sulfate represents an effective nitrogen source for winter wheat, contributing to both higher yield and improved grain quality.

CONCLUSIONS

The results of this study demonstrate that nitrogen fertilization had a decisive influence on winter wheat yield and grain quality under the agroecological conditions of SDE Timișoara. Grain yield increased significantly with increasing nitrogen rates, regardless of fertilizer type, confirming nitrogen as the primary limiting nutrient for wheat productivity. All nitrogen-fertilized treatments produced very highly significant yield increases compared to the unfertilized control.

Among the two nitrogen fertilizer sources, ammonium sulfate consistently outperformed ammonium nitrate at equivalent nitrogen rates. The average grain yield obtained under ammonium sulfate fertilization was 4% higher than that recorded for ammonium nitrate, indicating improved nitrogen use efficiency when sulfur was supplied together with nitrogen.

Nitrogen fertilization also significantly improved grain quality parameters. Thousand kernel weight and test weight increased with nitrogen rate, reflecting enhanced grain filling and kernel density. Grain protein and wet gluten contents showed a strong positive response to increasing nitrogen supply, with slightly higher values recorded under ammonium sulfate fertilization. These results highlight the beneficial role of sulfur in

supporting protein synthesis and gluten formation.

At all nitrogen levels, ammonium sulfate generated higher protein and gluten yields than ammonium nitrate, highlighting the important role of sulfur in nitrogen assimilation and in the synthesis of gluten-forming proteins.

Overall, the study confirms that combined nitrogen and sulfur fertilization represents an effective strategy for achieving high yield and improved technological quality of winter wheat grown on cambic chernozem soils.

Based on the obtained results, the following practical recommendations can be formulated for winter wheat cultivation under similar soil and climatic conditions:

Nitrogen fertilization is essential for maximizing winter wheat yield and grain quality, with application rates of 100-150 kg N·ha⁻¹ providing a favorable balance between productivity and quality.

Ammonium sulfate is recommended as a nitrogen source, particularly on soils with low or moderate sulfur availability, due to its positive effects on yield, protein content, and gluten quality.

Split application of nitrogen, with doses applied at the resumption of spring vegetation and at stem elongation, is advised to improve nitrogen uptake efficiency and reduce potential losses.

Excessive nitrogen rates should be avoided, as yield increases beyond 150 kg N·ha⁻¹ were relatively smaller, while the risk of reduced nitrogen use efficiency may increase.

Integrating sulfur into nitrogen fertilization strategies is especially important for wheat intended for bread-making, where protein and gluten quality are critical.

These recommendations contribute to more efficient nutrient management and support sustainable winter wheat production systems.

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