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Optimizing Nitrogen Management in Maize Production: Insights from a Comprehensive Analysis in the US Corn Belt Under Diverse Climatic Conditions

Salman Anwar
Kohat University of Science and Technology Kohat (KUST)
***Correspondence**: slmnanwr.kust39@gmail.com

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This academic review delves into the intricate dynamics of nitrogen management in maize production, focusing on the US Corn Belt with an emphasis on cold climates. The study employs a comprehensive approach, utilizing empirical data from the MRTN database, SHAPE framework, and Bayesian regression modeling to analyze Economically Optimal Nitrogen Rates (EONRs) and maize yields. The Adapt-N tool and model simulations further contribute to the exploration of soil health indicators and nitrogen accessibility under varying climatic conditions. The research reveals a nuanced relationship between temperature, soil organic matter, and nitrogen availability, offering valuable insights for optimizing nitrogen utilization efficiency and minimizing environmental impacts in diverse agricultural settings. The findings underscore the need for adaptive strategies considering the complexities of climate, soil characteristics, and agronomic practices to enhance nitrogen management in maize cultivation.

Keywords: Corn Belt, Nitrogen Rates, Soil Health Indicators, Complexities of Climate.

Introduction:

Maize grain yield (GY) has witnessed significant growth over recent decades, attributed partly to the more efficient utilization of nitrogen (N) fertilizers in high-yielding varieties. In the state of Illinois, maize covers approximately 5.0 million hectares, constituting 30% of the total geographical area. This crop receives substantial amounts of N fertilizer [1]. The intricate interplay of weather patterns, soil characteristics, crop growth, and N loss pathways poses challenges in aligning fertilizer management with crop N demand, potentially leading to either under- or over-application of N. Excessive N losses not only contribute to climate warming through heightened soil nitrous oxide emissions but also result in nutrient pollution in water resources. On a larger scale, maize production systems in Illinois, situated within the Mississippi River Basin, contribute approximately 20% of nitrate loading to the Gulf of Mexico. Therefore, developing N management practices that enhance maize GY while minimizing adverse environmental impacts is imperative for this region [2].

In Illinois, the predominant practices involve applying N fertilizer either late in the fall (fall-applied N, FN) in the form of ammonia—often with a nitrification inhibitor—or early in the spring, typically as ammonia, preceding or around the time of planting (spring-applied N, SN). The unpredictability of wet spring weather, capable of causing delays in maize planting and other field activities, is a key factor influencing farmers to conduct land preparation, including N fertilizer application, in the preceding fall [3]. Additionally, the fall N application aligns with management considerations such as fertilizer availability, pricing, and workload distribution. However, the practice of applying N fertilizer 5–6 months prior to crop establishment and the commencement of active crop N uptake increases the risk of N losses through leaching or denitrification. Despite FN being a prevalent practice in this region, a consensus has not been reached regarding its efficacy concerning crop yield, nitrogen use efficiency (NUE), and environmental sustainability [4].

Prior research has indicated that early-season weather is a crucial determinant influencing the impact of FN compared to SN on crop yield. Bundy concluded that FN is 10–15% less effective than SN for maize cropping systems in the U.S. Midwest. In contrast, [5]found no disparities in maize GY among FN, SN, and split N applications (fall and spring portions) in the southeastern U.S. In a three-year field experiment, [6]observed lower maize GY with FN compared to SN in 1999 but found no differences in 1997 and 1998. They attributed the reduction in crop uptake for FN in 1999 to an exceptionally wet early spring, leading to increased leaching and/or denitrification losses, while years with normal precipitation exhibited similar crop uptake and yields. Conversely, in dry years, limited precipitation can hinder the transport of inorganic N to plant roots, resulting in lower N losses and similar N recovery efficiency under different fertilizer application timings. In addition to precipitation, the N rate is a crucial factor influencing the impacts of SN vs. FN [7]. A 5-year field experiment in Minnesota showed that maize GY was 14% higher in SN (9.4 Mg ha-1) than FN (8.2 Mg ha-1) at 134 kg N ha-1; however, increasing the fertilizer amount to 202 kg N ha-1 narrowed the GY differences between SN (10.5 Mg ha-1) and FN (10.0 Mg ha-1) to 5%. Given the complex interactions among weather patterns, fertilizer rate, and soil properties regulating the impact of fertilizer application timing on GY, a more quantitative understanding of the conditions favoring higher yields and NUE under SN is essential [8].

The world's current production systems face heightened vulnerability to climate change, as highlighted by various studies. This changing climate poses a significant threat to crop production, particularly jeopardizing food security in arid to semi-arid climatic regions. Elevated temperatures and unpredictable rainfall patterns adversely affect the developmental phases, growth, and yield of crops, with arid regions experiencing more pronounced impacts. The variability in climatic projections is a crucial aspect of climate change studies, encompassing long-term temperature shifts, fluctuations in rainfall distributions, increased CO_2 levels, and heightened occurrence of extreme weather events [9]. Maize, a vital crop for food security, faces increased demand in developing countries due to its diverse uses domestically, commercially, and industrially, including biofuel production. However, maize production is highly susceptible to extreme weather events induced by climate variability. Temperature changes, especially under elevated conditions, can disrupt optimal growth and development, shorten growing seasons, and ultimately reduce yields. Maize's physiological and metabolic processes require specific climatic conditions for proper growth. Variations in temperature ranges can lead to decreased maize production, particularly under high day and night temperatures [10].

Many maize genotypes in these regions are highly susceptible to elevated temperature and drought stress. Utilizing crop genotypes with enhanced water-use efficiency becomes crucial to cope with water scarcity conditions. Given the vulnerability of reproductive phases to high temperatures, determining the optimum sowing time is essential for enhancing the sustainability of the current cropping system. Future projections indicate a potential temperature increase, posing a significant threat to successful maize production due to heat stress and decreased availability of essential resources like water and nutrients [11]. While elevated CO_2 has some positive effects on growth and yield, being a C4 crop, maize might have limited advantages in photosynthetic accumulation for biomass production. Additionally, studies on future climate scenarios suggest that the interactive effects of CO_2, projected temperature rise, and rainfall variability could potentially offset the positive impact of increased CO_2 concentration. The prediction of more frequent unexpected heat stress spells in the region poses a serious threat to sustainable maize production, altering maize phenology, growth, development, and yield and ultimately endangering food security [12].

In the face of these challenges, crop growth models serve as innovative tools to assess the impacts of crop management practices, such as sowing dates and plant genetics, in interaction with the environment. These models, including the Decision Support System for Agro-technology Transfer (DSSAT), offer a comprehensive system analysis approach to evaluate various crop management aspects like planting dates, irrigation, and nutrient application. Specifically, the CSM-CERES-Maize model under DSSAT has been employed for evaluating maize crop management factors, including irrigation, water, and nitrogen [13]. These models also play a crucial role in assessing the impact of climate change on maize production under different scenarios. Notably, the structural development under CERES-Maize has led to the creation of the CSM-IXIM-Maize model under DSSAT, incorporating factors such as leaf area, grain number, cob growth, integration, partitioning, and yield for improved simulations. Given the prime importance of accurate crop phenology predictions in evaluating the effects of changing climate on crop yield, these models offer valuable insights, helping address uncertainties in yield simulations. The Agricultural Production Systems Simulator (APSIM) is another model with the capability to simulate the effects of thermo-temporal variations on crop growth, development, and physiology, providing alternative management practices for sustainable crop production [14].

Climate Change Scenario Generation, GCM Selection, and Crop Model Evaluation:

Climate change scenario generation and the selection of Global Climate Models (GCMs) involved a multi-step process. The historic daily weather data spanning 35 years, encompassing variables such as solar radiation, temperature, precipitation, and more, were designated as the baseline dataset (1980–2015). Rigorous quality testing was conducted following standard protocols to ensure data reliability [15]. This baseline dataset served as the foundation for projecting future climate scenarios using the outputs from 29 GCMs from the Coupled Model Inter-comparison Project (CMIP5) [16]. For an in-depth understanding of the methodology employed in executing baseline climatic data with daily variations, comprehensive insights are provided in related studies. Mean and variability change scenarios were established utilizing a stretched distribution approach related to quantile mapping, a technique elucidated in the relevant literature, to calibrate all GCMs. Subsequently, climate change scenarios for the mid-century period (2040–2069) under the representative concentration pathway 8.5 (RCP 8.5) were developed [17].

To refine the GCM selection, five GCMs with higher confidence for temperature and precipitation during the maize growing season were identified out of the 29 GCMs, based on maximum consensus. The criteria employed included the percentage precipitation change versus mean temperature change in the scenarios, following a specified approach. These selected GCMs were then categorized into distinct groups, Hot Wet, Hot Dry, Middle, Cool Wet, and Cool Dry, each associated with specific characteristics [18]. Several GCMs relied on the ensemble standard, considering deviation in temperature and rainfall variations during the maize growing season. Carbon dioxide (CO_2) concentrations of 380 ppm for baseline conditions and 571 ppm for mid-century conditions were applied under RCP 8.5 [19].

The escalated use of nitrogen (N) in agricultural systems is a pressing concern, driven by growing apprehensions about energy consumption, environmental impacts, and the rising costs of N fertilizers. Nitrogen application in agriculture raises significant water quality concerns, contributing to issues such as hypoxia in estuaries and contamination of rural groundwater, with far-reaching societal impacts. Additionally, nitrogen gaseous emissions stand as the primary source of greenhouse gases in US agriculture, exerting a substantial influence on fine particle air pollution [20]. The focus of this study is on maize, a widely cultivated crop for commercial purposes, heavily reliant on nitrogen fertilization. Despite the higher physiological efficiency of maize production systems, leading to increased yield per unit of nitrogen accumulation, the overall recovery efficiency of nitrogen fertilizer consumption remains low. Studies reveal a noteworthy surge in nitrate leaching and nitrous oxide emissions when nitrogen rates surpass the "optimum" threshold for maize production. Striking a balance between nitrogen rates above or below the optimal level presents farmers with a challenging task, often leading to the overuse of nitrogen [21].

Precise calculation of crop nitrogen demands becomes crucial to mitigate nitrogen misuse in agricultural fertilization. However, the complexity of interactions among climate, agronomic practices, soil properties, and seasonal weather poses a formidable challenge. Estimating the appropriate nitrogen rate proves difficult due to the unpredictable nature of nitrogen dynamics in both spatial and temporal dimensions. This research aims to delve into the distinctive characteristics of cold climates and their impact on optimal nitrogen fertilizer rates. It seeks to explore the methodologies and environmental factors influencing the selection of optimal nitrogen rates. Additionally, the study will evaluate climate-related aspects in determining the ideal nitrogen rate, a domain that has received limited attention [22]. Managing a soil-crop nitrogen system across diverse climates is intricate, given the intricate interplay between natural and artificial factors, further influenced by unexpected meteorological events. Strategies such as cultivar selection, rotation, cover crop utilization, tillage techniques, and irrigation/drainage systems fall under agronomic management, considering intrinsic resource elements. Previous nitrogen applications, including their origin, placement, and timing, along with meteorological factors like temperature, precipitation, and solar radiation, are critical considerations, incorporating both risk and pricing factors [23].

Climate and soil-related elements contribute significantly to the mineralization of soil organic matter (SOM), impacting nitrogen availability. The nitrogen content in the soil and its disparity with the crop's nitrogen requirements affect the economic optimal nitrogen rate (EONR), maximizing net profit from nitrogen application. Soil texture, pH level, and organic debris characteristics influence the nitrification process, with soil texture being a fundamental yet mostly unchanging trait in temperate zones. Colder climates exhibit higher concentrations of Soil Organic Matter (SOM), affecting nitrogen availability. Freeze-thaw cycles accelerate mineralization processes, influencing soil nitrogen dynamics through the breakdown of soil aggregates and the release of organic molecules and osmolytes by microorganisms.

Contrarily, regions with higher temperatures experience delayed manifestations of the conversion of organic nitrogen into minerals. Although these areas exhibit elevated levels of both total and labile soil organic matter (SOM), the impact of intrinsic soil characteristics on the net nitrogen (N) mineralization process remains uncertain. Slower rates of aerobic decomposition and an increased risk of denitrification losses during prolonged wet periods contribute to this uncertainty. Additionally, extracting water from freezing conditions during cold winters exacerbates the prolonged soil saturation during spring thaws, leading to substantial denitrification losses. In cold environments, higher levels of total and easily decomposable organic matter may facilitate nitrogen mineralization. However, reduced evapotranspiration, resulting in lower soil temperatures and increased soil moisture, does not necessarily translate to enhanced nitrogen accessibility for crops [24].

Factors Related to Climate and Agricultural Management:

Cropping System:

Employing cropping and agronomic techniques that enhance soil health can effectively increase the reservoir of labile organic matter. Growing a crop with residual biomass before another crop significantly augments nitrogen availability in the soil, especially in fertilized cropping systems.

Manure Application:

The reduction of ammonia, influenced by factors such as application timing and soil incorporation, significantly impacts nitrogen availability. Manure application, though influenced by climatic conditions, can be a crucial factor in managing nitrogen levels.

Cover Crops:

The quantity of nitrogen cover crops provided to the next cash crop varies based on factors like cover crop type, biomass, carbon-to-nitrogen ratio, and termination timing. In colder areas, cover crops, especially legumes, face challenges due to limited heat units, restricting their effectiveness in supplying nitrogen to subsequent crops.

Double Cropping:

Implementing double cropping practices can enhance income and biomass output, thus increasing nitrogen supply to support soil organic matter. However, colder climates may pose limitations on the extent of development beyond the primary cropping season.

Yield Potential:

The importance of yield potential in determining the Economic Optimum Nitrogen Rate (EONR) is recognized, with regions in colder climates often having lower crop production capacities. Advancements in crop genetics tailored for colder climates, such as shorter-season maturity classes, are expected to improve grain production and nitrogen utilization efficiency.

Reproductive Control (4R Concept):

The 4R strategy, emphasizing the appropriate rate, place, timing, and source of nutrient application, faces challenges in effective nitrogen management due to the complex nature of real production environments, including climate variability. Implementing the "right" response for each component remains challenging due to chronological and geographical discrepancies [25]. In summary, effective nitrogen management in agriculture necessitates a comprehensive understanding of diverse factors, including climate, soil characteristics, and various agronomic practices, to optimize nitrogen utilization efficiency and minimize environmental impacts. Soil nitrogen accessibility varies with temperature, with crops in warmer climates quickly absorbing synthetic nitrogen sources like urea, anhydrous ammonia, and ammonium and nitrate salts. Ammonium and nitrate, readily accessible nitrogen forms, are also present in organic sources like manure.

However, the gradual release of nitrogen from organic sources occurs through a prolonged process of biologically facilitated decomposition, influenced by spatial distribution and environmental conditions. In colder regions, the emission of nitrogen from biologically dependent sources is often delayed [26]. Optimal timing for nitrogen application is crucial, considering its direct impact on the synthesis capacity. Anhydrous ammonia, commonly used in the autumn season, is more suitable for cooler, drier locations, as nitrogen losses are less common in such conditions. Enhanced Efficiency Fertilizers (EECs) can reduce nitrogen loss and slow down nitrogen transformations, particularly beneficial in cold climates where lower early season temperatures may limit the need for extensive nitrogen conversions.

Benefits of Employing Nitrogen Management Methods in Colder vs Warmer Places:

Fluctuation of EONR:

The interplay between soil and management features, along with climatic components, contributes to the fluctuation of Economically Optimal Nitrogen Rates (EONRs). Studies show that higher rainfall during side dressing periods results in higher EONRs in North America.

Impact of Low Temperature:

Low temperatures significantly influence the variability in nitrogen levels, affecting potential gains and losses. Weather elements and their interaction with site-specific factors present challenges in predicting nitrogen response.

Nitrogen Rate Equivalents:

The mass balancing technique, considering crop nitrogen requirements and N credits from soil and crop management, is employed to determine N fertilizer recommendations. Calculators, calibrated for geographical factors, may recommend lower N rates in cold climates compared to warm regions.

Maximum Return to N (MRTN):

This approach, considering variations in grain and fertilizer prices, provides tailored suggestions for specific states or areas based on extensive field tests. It replaces the mass balance technique in several US Corn Belt states.

Sensory Apparatus:

Seasonal measurements indirectly consider climate effects by adjusting at the regional level based on where trials are conducted. Soil testing, proximal or distant sensing techniques, and single leaf samples offer insights into the interplay between climate, management practices, and meteorological conditions [27].

Model Types:

Dynamic biophysical models, incorporating soil, weather, and management variables, provide individual recommendations for nutrient N based on time and place. Sensors in these models offer real-time monitoring of nitrogen in soil and crops, considering climate-related impacts.

Results and Discussion:

In this comprehensive review, computer models and data analysis take center stage, offering a profound exploration of nitrogen management techniques and their climatic impacts, particularly in cold climates, where research has been limited. The primary focus is on evaluating the yield of the US Corn Belt in comparison to the Economic Optimum Nitrogen Rate (EONR). The US Corn Belt, characterized by a flat landscape with horizontal isotherms, witnesses a linear decline in average annual temperatures from east to west. The isohyets of precipitation, extending from north-northeast to south-southwest, underscore diverse rainfall patterns. Leveraging the MRTN database, which encapsulates extensive empirical data from over a thousand maize nitrogen (N) response experiments in the US Corn Belt, the study facilitates a meticulous comparison of Economically Optimal Nitrogen Rates (EONRs) and maize yields.

An in-depth analysis specifically narrows down on the northern tier states (Minnesota, Wisconsin, and Michigan) within latitudes 42–45 ◦N, and their adjacent southern counterparts (Iowa, Illinois, and Ohio) within latitudes 39–42 ◦N. This comparative exploration unveils a linear decrease in average annual temperatures with increasing latitude, thereby influencing precipitation patterns. Employing the SHAPE framework with Bayesian regression modeling, the study delves into soil health indicators shaped by climatic and edaphic conditions. A particular emphasis is laid on scrutinizing the influence of mean annual temperature (MAT) within the temperature range of 5 to 15 ◦C on soil characteristics affecting nitrogen accessibility. Furthermore, the Adapt-N tool, a cloud-based nitrogen decision system, takes center stage in conducting simulation-based assessments for two distinct sites in the US Corn Belt – one colder in North Central Wisconsin and the other warmer in South Central Illinois.

The SHAPE study unravels noteworthy variations in soil organic matter contents across regions, and the simulation-based assessment with Adapt-N factors in elements such as planting dates, soil organic matter values, crop maturity class, and yield potential. The overarching analysis of US Corn Belt crop production concerning EONR highlights a linear relationship between lower crop yields and lower optimal nitrogen rates for economic efficiency. This trend is particularly pronounced in colder northern states in contrast to their southern counterparts, with state averages from the MRTN database aligning seamlessly with the overall trendline. Transitioning to the combined N response trial, which indicates a significantly higher value (R2 = 0.062) compared to individual trials, the study unveils intriguing insights. Particularly, for a simple maize and soybean rotation without organic inputs, the aggregated N response trial exhibits notable distinctions.

The study drills down further into specific states, highlighting significant differences in output and EONR. For instance, Michigan (MI) and Ohio (OH) in the eastern Corn Belt exhibit a 0.4 Mg ha−1 yield difference and a 28 kg ha−1 EONR difference. In the Central Corn Belt, Illinois outshines Wisconsin with a 3.2 Mg ha−1 higher yield and a 77 kg ha−1 elevated nitrogen rate for maximum economic yield (EONR). This temperature-driven gradient from north to south generally results in decreased crop yield and EONR, with subtle variations in regions like Minnesota (MN) and Iowa (IA). Lower temperatures, even with slight yield differences, lead to reduced EONRs. A quantitative analysis deploying SHAPE functions unravels a consistent decline in soil organic carbon (SOC) concentration from 3.0% to 2.0% with an increase in mean annual temperature (MAT) from 5 to 15 ◦C. This decline encompasses 33%, 40%, and 48% reductions for SOC, POXC (Active C), and ACE Protein, respectively. Notably, the components of soil organic matter (SOM) that are readily decomposable are better preserved in colder climates, and their proportions to SOC decrease within the 5 to 15 ◦C temperature range. The critical wet aggregate stability, vital for root formation and hydrological function, undergoes a decrease from 42% to 15% within this temperature range.

The study then shifts its focus to the utilization of the Adapt-N tool in model simulations, indicating that the maize growth stage at the warmer site in Illinois reaches V15, while in Wisconsin's colder region, it is V13. Lower temperatures impose constraints on growing degree days, potentially diminishing crop growth. Simulated N mineralization is identified as 17 kg N ha−1 lower in the colder area, with substantial annual rainfall fluctuations over the 60 days after planting in both locations. The study posits that temperature restrictions may contribute to reduced organic matter cycling, thereby affecting nitrogen mineralization and, consequently, nitrogen availability for crops. In a distinct facet, the study navigates through the nuanced data suggesting a higher level of Soil Organic Matter (SOM) at 4.5% in Illinois compared to 3% in Wisconsin [28]

Both areas exhibit notable seasonal variations. Recommended nitrogen rates for the Illinois site by Adapt-N range from 151 to 196 kg ha−1, with a standard deviation of 14 kg ha−1. For the cooler Wisconsin site, recommended nitrogen rates range from 56 to 151 kg ha−1, with a standard deviation of 27 kg ha−1. Seasonal variation aligns with the findings of[29], indicating that weather accounts for 67% of the fluctuations in maize EONR. The Adapt-N modeling experiment demonstrates that nitrogen mineralization tends to be reduced at colder temperatures, despite higher levels of soil organic matter. The discrepancy in the lower optimal nitrogen rate in Wisconsin cannot be accounted for by the net nitrogen credit from post-plant soil organic matter mineralization in Illinois. The impact of climate on nitrogen losses is insignificant. The higher grain production levels in Illinois compared to Wisconsin may be attributed to a stronger nitrogen rate, resulting in a 3.2 Mg ha−1 increase. The concept is reinforced by the significant correlation between lower maize EONRs in cooler regions and decreased crop yields due to reduced nitrogen demand. The model can integrate the impact of climate by considering factors such as yield trends, soil health, and agronomy, elucidating fluctuating seasonal patterns caused by meteorological influences.

Table 1:EONR for maize after soybean trials in regions of the US Corn Belt organized by longitude and latitude [1].

	Western Corn Belt States (Lowest MAP)			**Central Corn Belt States**			**Eastern Corn Belt States (Highest MAP)**			**Mean**	
		EONR kg ha^{-1}	**Avg Yield Mg ha^{-1}**		**EONR kg ha^{-1}**	**Avg Yield Mg ha^{-1}**		**EONR kg ha^{-1}**	**Avg Yield Mg ha^{-1}**	**EONR kg ha^{-1}**	**Avg Yield Mg ha^{-1}**
Northern	Minnesota (n = 165)	159	13.3	Wisconsin HYP (n = 58)	124	11.9	Michigan (n = 54)	176	11.8	153	12.3
Southern	Iowa (n = 178)	165	13.1	Illinois North + Central (n = 430)	201	15.1	Ohio (n = 256)	204	12.2	193	13.5

Conclusion

Estimating the nitrogen (N) needs of maize is challenging due to complex and ever-changing factors that influence nitrogen availability and optimal nitrogen rates. Agronomic techniques, soil conditions, and production potential play crucial roles in this estimation. A dataset analysis from the US Corn Belt showed that colder states in the region had lower average yields and Energy Output to Nitrogen Ratio (EONRs) compared to their warmer southern neighbors. The studies consistently demonstrated a correlation between Economic Optimum Nitrogen Rate (EONR) and crop output, but this relationship exhibited greater diversity than solely attributed to environmental conditions. When the average yearly temperature decreases, SHAPE functions can be employed to model soil health data patterns and observe a rise in soil organic matter stocks, particularly in labile components. This phenomenon is likely due to extended periods of cold weather resulting in a reduction in the overall pace of decomposition throughout the year.

Model simulations confirmed these patterns, indicating that fields in colder climates had higher levels of soil organic matter (SOM) but not higher levels of mineralized nitrogen (N). Sites in colder climates also had significantly lower average optimal nitrogen (N) rates compared to warmer climates, with these rates varying seasonally due to weather patterns. The reduced yield potentials seen at colder locations accounted for the range of average optimal nitrogen rates. Abductive inferences from various data sources consistently indicate a correlation between colder temperatures and higher levels of SOM-related nitrogen stocks. However, it's crucial to note that increased nitrogen availability for crops is not necessarily a result of this connection. Equivalent Operating Nuclear Reactor (EONR) values are commonly reduced in colder geographical areas, mainly due to decreased yield estimations. However, the seasonality of weather is a crucial factor impacting EONR in all areas. To make progress in nitrogen management, a versatile approach considering weather, climate, and agronomic factors in specific agricultural settings is essential.

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