Postprint: Maize Yield Potential in Different Ecological Zones of Jilin Province Based on the Hybrid-maize Model

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Abstract

To explore corn yield potential and further enhance comprehensive corn production capacity, this study utilized the Hybrid-maize model (validated in Northeast China) along with multi-year meteorological data to simulate corn yield potential under different varieties, sowing dates, densities, and their combinations across various ecological zones in Jilin Province [eastern humid ecological zone (Huadian), central semi-humid ecological zone (Gongzhuling), western semi-arid ecological zone (Qian' an)]. Quantitative analysis of factors affecting high and stable corn yield was conducted, and a high-yield corn system for different ecological zones in Jilin Province was constructed by considering yield potential variability and the production characteristics of varieties themselves. The results indicated that: 1) Adjusting sowing date is a crucial yield-increasing measure with varying performance across ecological zones: early sowing should be selected for humid zones with an appropriate sowing date around April 20, while semi-humid and semi-arid regions should delay sowing as much as possible with suitable sowing dates around mid-May. 2) The density accommodation capacity of different ecological zones exhibited the pattern: humid zone (Huadian) > semi-humid zone (Gongzhuling) > semi-arid zone (Qian' an), with optimal densities of approximately 90,000 plants$\cdot$hm^{-2}, 80,000 plants$\cdot$hm^{-2}, and 75,000 plants$\cdot$hm^{-2} for the three regions, respectively. 3) Varieties with longer growth periods demonstrated higher yield potential; in practice, late-maturing varieties should be selected according to regional ecological conditions, and the required effective growing degree days (GDD) during the growth period for varieties in semi-humid and semi-arid regions could be increased to above 1,600°C under current sowing conditions. 4) Compared with current production technologies, optimizing the combination of sowing date, density, and variety could increase the long-term average yield potential of the high-yield system by 14.39%-29.23%. This study can provide a theoretical basis for the proper application of high-yield measures and technical references for large-scale corn yield improvement in Jilin Province.

Full Text

Analysis of Yield Potential of Maize in Different Ecological Regions of Jilin Province Using the Hybrid-Maize Model

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Abstract

Jilin Province is a major maize production region in China, contributing significantly to national food security. However, due to limited cultivatable land and adjustments in planting structure, the potential for expanding maize acreage in Jilin is constrained. Future yield increases will therefore depend primarily on improving yield per unit area. This study employed the Hybrid-maize model—previously validated in Northeast China—along with long-term meteorological data to simulate maize yield potential under various combinations of varieties, sowing dates, and planting densities across three distinct ecological zones: the eastern humid region (Huadian), central semi-humid region (Gongzhuling), and western semi-arid region (Qian' an). The driving factors influencing high and stable yields were quantitatively analyzed, and a high-yield maize system was developed for each zone based on yield potential variability and variety characteristics. The results demonstrated that: (1) Adjusting sowing date is a critical yield-enhancing measure, but optimal timing differs by region—early sowing around April 20 is recommended for the humid zone, while the semi-humid and semi-arid zones benefit from delayed sowing in mid-May. (2) The capacity to accommodate high planting densities follows the order: humid zone (Huadian) > semi-humid zone (Gongzhuling) > semi-arid zone (Qian' an), with optimal densities of approximately 90,000, 80,000, and 75,000 plants$\cdot$hm^{-2}, respectively. (3) Longer-maturing varieties showed greater yield potential; under current sowing conditions, varieties requiring growing degree days (GDD) exceeding 1,600 ℃ are recommended for semi-humid and semi-arid regions. (4) Compared with current production practices, the optimized combination of sowing date, density, and variety increased long-term average yield potential by 14.39%-29.23%. These findings provide a theoretical basis for appropriate high-yield cultivation measures and technical guidance for large-scale maize production improvement in Jilin Province.

Keywords: Hybrid-maize model; ecological region; maize; yield potential; high-yield system; Jilin Province

Introduction

Jilin Province represents a critical maize production base in China, with planting area exceeding 3.4 million hectares, total output surpassing 28 million tons, and average yield reaching 7,900 $kg \cdot hm^{-2}$. The province' s maize acreage and total production account for 12% and 15% of national totals, respectively, with its yield per unit area, per capita availability, commercial output, transfer volume, and export volume ranking first nationally for consecutive years, thereby making vital contributions to national food security. However, due to constraints on cultivatable land resources and ongoing planting structure adjustments, the potential for further expanding maize acreage in Jilin is limited. Consequently, future production gains must rely primarily on yield per unit area improvement, making it imperative to fully exploit maize production potential as an effective pathway to comprehensively enhance comprehensive productivity.

Crop production potential refers to the maximum theoretical yield achievable under ideal environmental conditions, with photo-thermal potential generally considered the yield ceiling for a given region. This metric serves as a crucial indicator for scientifically evaluating regional food production capacity and development prospects, offering valuable reference for assessing food production capabilities and population carrying capacity. In recent years, policy support and technological advances have further elevated maize yield potential, with high-yield examples and demonstration areas continuously emerging. Previous high-yield research primarily focused on achieving yield breakthroughs through various cultivation measures or water and fertilizer applications, but paid insufficient attention to underlying processes and mechanisms. The development of key technologies and technical systems for exploiting high-yield potential remains exploratory, limiting the generalizability of individual research findings.

Crop growth simulation models quantitatively describe and predict crop growth dynamics under interactive effects of variety, environment, and management practices, serving as important tools for crop science research, management, and decision analysis. Previous studies have validated and applied various models to assess maize production potential across different regions. For instance, Wu et al. used the PS123 model to simulate photo-thermal potential in Hailun, Heilongjiang; Wang et al. employed the APSIM model to investigate spatiotemporal distribution of yield potential and gaps for spring maize in Heilongjiang; Li and Dai validated the CERES-Maize model in the Loess Plateau and North China Plain for potential productivity estimation. While these applications have positively contributed to agricultural production, these models require numerous input parameters, some of which are difficult to obtain, thereby limiting their practical application.

The Hybrid-maize model has been widely applied in China in recent years. Developed from extensive field experimental data, this model is sensitive to photothermal resource variations, requires minimal input parameters, and demonstrates high simulation accuracy. Its primary applications include evaluating yield potential and variability at target locations using long-term meteorological data, determining optimal cultivation measures by assessing yield outcomes under different variety, sowing date, and density combinations, and understanding factors limiting high yields. The model' s adaptability has been validated in the Loess Plateau, Northeast Plain, and other regions. However, previous research primarily focused on model validation, yield potential assessment, and yield gap evaluation. This study utilizes the validated Hybrid-maize model to simulate maize yield potential across different ecological zones in Jilin Province, quantitatively analyze factors influencing high and stable yields, and construct a high-yield maize system tailored to each zone, providing theoretical and technical guidance for proper implementation of high-yield measures and breakthrough from point to area-wide production improvement.

Materials and Methods

The Hybrid-Maize Model The Hybrid-maize model was developed in 2004 by researchers at the University of Nebraska-Lincoln. Its distinctive feature lies in integrating two previously representative international maize growth simulation approaches to create synergistic advantages. The model simulates potential maize growth, development, canopy photosynthesis, assimilate partitioning, and yield formation under both water-limited (rainfed) and non-water-limited (irrigated) conditions. Operating on a daily time step, temperature serves as the driving factor for crop development, canopy photosynthesis, organ growth, and maintenance respiration, enabling sensitive responses to environmental changes while requiring minimal parameter inputs. The model primarily needs daily meteorological data including solar radiation, maximum and minimum temperatures, precipitation, average wind speed, and relative humidity, along with management information such as sowing date, planting density, and variety GDD (growing degree days). The model has been extensively validated and applied in the United States, Indonesia, and many regions of China.

Study Sites and Scenario Simulation To understand spatiotemporal variability in maize yield potential across Jilin' s ecological zones, representative experimental sites were selected: Huadian (42°34 N, 127°02 E) in the eastern humid region, characterized by north temperate continental monsoon climate with 2,379 annual sunshine hours, 3.7 ℃ mean temperature, 2,731 ℃ active accumulated temperature above 10 ℃, 125 frost-free days, and 748.1 mm annual precipitation concentrated in July-August; Qian' an (45°01 N, 124°02 E) in the western semi-arid region, featuring mid-temperature continental monsoon climate with abundant light and heat resources (2,867 sunshine hours, 5.6 ℃ mean temperature, 2,885 ℃ active accumulated temperature, 146 frost-free days, <400 mm precipitation, and 1,875 mm evaporation); and Gongzhuling (43°24 N, 125°18 E) in the central semi-humid region, with temperate continental monsoon climate (2,712 sunshine hours, 5.5 ℃ mean temperature, 2,770 ℃ active accumulated temperature, 594.8 mm precipitation, and 144 frost-free days). Meteorological data from 2004-2013 were obtained from local weather stations. Solar radiation was calculated from sunshine hours, and evapotranspiration was derived from average wind speed using the model.

Two simulation scenarios were established: high-yield system construction measures and current management practices (control). Current management (based on farmer surveys and cultivation reports) used the widely planted variety 'Xianyu 335' (GDD=1,518 ℃), sowing date of April 30, and planting density of 60,000 plants · hm^{-2}. High-yield system scenarios included: (1) Sowing date studies starting April 20 at 10-day intervals until May 20 for the humid zone and May 30 for semi-humid and semi-arid zones, with current variety and 60,000 plants · hm^{-2} density; (2) Density studies with five gradients (45,000, 60,000, 75,000, 90,000, and 105,000 plants · hm^{-2}) using April 30 sowing date and GDD=1,518 ℃ variety; (3) Variety maturity studies with four GDD levels (1,100, 1,300, 1,500, and 1,700 ℃) using April 30 sowing date and 60,000 plants · hm^{-2} density.

Data Processing and Statistical Analysis Data processing and graphing were performed using Microsoft Excel 2010, while SPSS software was used for statistical analysis and plotting.

Results

Effects of Sowing Date Optimization on Maize Yield To elucidate how sowing date adjustments affect photo-thermal resource allocation and yield potential across Jilin' s ecological zones, 10-year meteorological data were used to simulate yield potential under varying sowing dates with current varieties and densities. The results revealed distinct regional responses to sowing date changes [Figure 1: see original paper]. In the eastern humid region (Huadian), lower temperatures throughout the growth period limited sowing date flexibility. Simulations indicated highest yield potential with April 20 sowing, with gradual decline as sowing delayed. Postponing to May 20 shortened the growth period due to frost risk, reducing long-term average yield by 1.60 t · hm^{-2} compared to April 20 sowing. In the semi-humid region (Gongzhuling), yield increased with delayed sowing, peaking on May 20, primarily because lower temperatures during reproductive growth extended grain-filling duration (Table 1). Further delay to May 30, while prolonging grain-filling, reduced yield likely due to frost risk and decreased total radiation. The western semi-arid region (Qian' an) also favored late sowing, with May 30 sowing yielding 2.0 t · hm^{-2} more than April 30, though frost risk reached 60%, indicating that moderate delay increases yield but excessive delay increases yield variability.

Effects of Planting Density Increase on Maize Yield Increasing density is a crucial measure for expanding sink capacity and source supply, thereby enhancing yield potential. Under current variety and sowing conditions, simulations examined yield potential responses to density adjustments [FIGURE:2, TABLE:2]. Yield potential increased with density up to an optimum, beyond which it declined, with regional variations in density response. The humid region achieved maximum yield potential at 90,000 plants $\cdot$ hm^{-2}, 0.5 t $\cdot$ hm^{-2} higher than at 75,000 plants $\cdot$ hm^{-2}. The semi-humid region also peaked at 90,000 plants $\cdot$ hm^{-2}, but with minimal difference from 75,000 plants $\cdot$ hm^{-2}. In the semi-arid region, yield potential peaked at 75,000 plants $\cdot$ hm^{-2}, declining with further density increases. Harvest index responses reflected these patterns: within optimal density ranges, harvest index increased with density across all zones, peaking at 75,000 plants $\cdot$ hm^{-2} before declining at higher densities. Yield variability also increased with density. Across all densities, yield potential ranked highest in the humid region (Huadian) and lowest in the semi-arid region (Qian' an), correlating with lower mean temperatures and longer growth periods with greater radiation interception in Huadian. These results demonstrate that density tolerance follows: humid region (Huadian) > semi-humid region (Gongzhuling) > semi-arid region (Qian' an). Under current conditions, reasonable densities range between 75,000–90,000 plants $\cdot$ hm^{-2}, not exceeding 90,000 plants $\cdot$ hm^{-2}.

Effects of Variety Maturity Selection on Maize Yield Variety selection significantly impacts biomass accumulation and yield, playing a crucial role in stable and increased production. Using current sowing dates and densities, this study examined how different maturity varieties affect photo-thermal resource utilization and yield potential [FIGURE:3, TABLE:3]. Despite minimal latitude differences among sites, variety selection ranges varied by ecological zone. The cool, humid region (Huadian) had narrow variety options due to low accumulated temperature; under current sowing dates, varieties with GDD of 1,400–1,500 ℃ were most suitable, with frost risk reaching 100% and yield declining sharply when GDD exceeded 1,600 ℃. In contrast, the semi-humid and semi-arid regions (Gongzhuling and Qian' an) could accommodate varieties with GDD up to 1,700 ℃, achieving yield potentials of 16.4 t $\cdot$ hm^{-2} and 15.6 t $\cdot$ hm^{-2}, respectively, though with 50% and 40% frost risk. Overall, yield potential increased with longer maturity periods across all zones, with higher yield potential in Gongzhuling likely due to greater total solar radiation during the growth period. Within suitable ranges, each 100 ℃ GDD increase in Huadian extended growth duration by approximately 19 days and increased yield potential by about 1.83 t $\cdot$ hm^{-2}, while in Gongzhuling and Qian' an, similar GDD increases extended duration by about 12 days and increased yield potential by approximately 1.70 t $\cdot$ hm^{-2}.

Construction of High-Yield Maize Systems for Different Ecological Regions in Jilin Integrating the above single-factor studies, high-yield systems were designed for each ecological zone based on yield potential, yield variability, practical feasibility, and variety characteristics. Model simulations comparing single-factor scenarios indicated that for the humid region (Huadian), early sowing and increased density were primary strategies, with the optimal system being: sowing on April 20, current variety ‘Xianyu 335’ (GDD=1,518 ℃), and density of 90,000 plants · hm^{-2}. For the semi-humid (Gongzhuling) and semi-arid (Qian’ an) regions, delayed sowing to mid-May was the main strategy to utilize favorable photo-thermal resources, with optimal densities of approximately 80,000 and 75,000 plants · hm^{-2}, respectively. Using current sowing dates, longer-maturing varieties could further enhance yield potential, with simulations indicating that GDD could be extended to 1,600 ℃ or higher for semi-humid and semi-arid regions. Compared with current systems, the optimized high-yield systems increased long-term average yield potential by 14.39%-29.23%, with the smallest increase in the humid region due to limited heat resources and smaller adjustment space, while semi-humid and semi-arid regions showed greater potential through optimized sowing date, variety, and density combinations, particularly through variety optimization.

Discussion

Sowing date is a critical factor affecting maize yield, influencing crop growth photo-thermal conditions, with temperature and light being primary ecological factors affecting growth duration. Previous research indicates that temperature changes from delayed sowing primarily affect growth period length and yield. Our sowing date simulations show that in semi-humid and semi-arid regions, although delayed sowing shortened total growth duration and reduced total radiation, lower late-season temperatures extended reproductive growth, enabling greater light interception and higher yield potential. In contrast, the humid region’ s lower temperatures throughout the growth period, while resulting in higher incident radiation, may severely affect leaf photosynthesis and grain-filling processes at temperatures below 19 ℃, with delayed sowing reducing biomass and harvest index, thereby decreasing yield. This confirms previous conclusions about temperature effects on yield from sowing date changes.

Planting density is among the most sensitive factors affecting crop yield. Optimal density establishes good population structure for efficient photo-thermal resource utilization and coordinated source-sink relationships. Under current variety and sowing conditions, simulations show that when density is below 75,000 plants · hm^{-2}, increasing density raises harvest index, indicating source limitation; above this threshold, harvest index declines, suggesting sink limitation. Minimal yield gains occur with further density increases, and in semi-arid regions, yields decline when density exceeds 75,000 plants · hm^{-2}. Under actual production conditions, excessive density increases risks of pests, diseases, and lodging.

The best maize varieties are those that fully utilize local photo-thermal resources, with longer growth seasons theoretically being preferable, as extended reproductive periods increase radiation interception, yield, and harvest index. However, in high-latitude Northeast China, low early-season temperatures and rapid late-season photo-thermal resource decline expose long-season varieties to adverse weather during reproductive growth, increasing yield variability and reducing stability. Our variety simulations indicate that varieties adapted to local ecological conditions may achieve the best long-term yield potential, while excessively long-season varieties face greater yield variability due to late-season weather fluctuations. Therefore, under current conditions in Jilin’ s different ecological zones, variety selection should follow local adaptation principles, favoring medium-late and late-maturing varieties.

Integrated analysis reveals that insufficient grain-filling duration causing inadequate sink capacity is a primary reason for low yields. Yield improvement requires sink expansion, which can be achieved through delayed sowing in heat-sufficient regions. Under current sowing conditions, density increase is also important for sink expansion and source strengthening, but excessive density creates new sink limitations. A combined strategy of moderate sowing delay and density increase can effectively utilize late-season photo-thermal resources, extend grain-filling duration, and meet sink demands. Selecting long-season varieties can increase sink capacity while maintaining source strength, provided that required GDD remains stable for normal maturity and high yield. The optimal strategy combines variety, sowing date, and density to modify grain-filling rates or duration through timely sowing and increased density, while long-season varieties increase early biomass to provide material basis for reproductive growth. The former facilitates grain establishment and late-filling, while the latter promotes slow leaf senescence and efficient photosynthate transfer during late growth stages. These analyses demonstrate the strong theoretical and practical value of the Hybrid-maize model in high-yield system construction.

Conclusion

This study quantitatively analyzed maize yield improvement potential across Jilin’ s ecological zones based on yield potential and variability, practical feasibility, and variety characteristics, constructing zone-specific high-yield systems. The main conclusions are: (1) Adjusting sowing date is an important yield-enhancing measure with zone-specific performance—early sowing around April 20 is suitable for the humid region, while semi-humid and semi-arid regions benefit from mid-May sowing. (2) Density tolerance follows: humid region (Huadian) > semi-humid region (Gongzhuling) > semi-arid region (Qian’ an), with optimal densities of approximately 90,000, 80,000, and 75,000 plants $\cdot$ hm^{-2}, respectively. (3) Under current sowing dates and densities, locally adapted varieties (GDD 1,500 °C) may provide the best long-term yield potential, though longer-season varieties offer higher yield potential. (4) Integrating these optimized management measures increased yield potential by 14.39%-29.23% compared with current production systems.

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