Postprint: Assessment of Maize Yield Gap and Production Potential in Inner Mongolia Based on Density Network Trials and the Hybrid-Maize Model

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Abstract

Quantifying the yield gap and production potential of maize in Inner Mongolia using scientific methods is of great significance for rationally planning maize yield increase pathways and industrial development in Inner Mongolia. This study employed a combined approach of variety × density networking experiments and Hybrid-Maize model simulations, utilizing the highest measured yields from high-yield challenge fields and average farmer yields in various ecological regions of Inner Mongolia since 2006, to systematically analyze the maize yield gap and production potential for the entire Inner Mongolia region and its six major ecological zones. The results showed that simulated yields, high-yield records, experimental yields, and farmer yields in all ecological zones exhibited a gradual increase from east to west. The simulated yield potential of maize in Inner Mongolia was 14.9 t hm 2, the high-yield record was 14.4 t hm 2, and the experimental yield was 11.1 t hm 2; farmer yields achieved 49% of the simulated yield potential, 51% of the high-yield record, and 66% of the experimental yield. The yield gaps based on model simulation (YGM), high-yield records (YGR), and experimental yields (YGE) were 7.5 t hm 2, 7.0 t hm 2, and 3.8 t hm 2, respectively. The short-term production potential based on YGE reached 35.252 million t, which is 1.6 times the current total production level, with a short-term yield increase potential of 11.919 million t. Among these, the four league cities of Hulunbuir, Xing' an League, Tongliao, and Chifeng in eastern Inner Mongolia will contribute 61% to the regional yield increase, while Hohhot City and Bayannur City in the western part will contribute 16%. The main cause of the large YGE was improper cultivation management practices; narrowing the YGE requires addressing the actual problems limiting maize yield increase in each ecological zone, gradually achieved through comprehensive improvement of cultivation techniques, technology simplification, and technology delivery to

farmers.

Full Text

Assessment of Maize Yield Gap and Production Potential in Inner Mongolia Based on Networked Variety-Density Tests and the Hybrid-Maize Model

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Abstract

Quantifying maize yield gaps and production potential in Inner Mongolia using scientific methods is crucial for rationally planning yield improvement pathways and industrial development. This study combined cultivar × density network trial data with Hybrid-Maize model simulations, utilizing the highest measured yields from high-yielding fields and average farmer yields across Inner Mongolia' s ecological regions since 2006 to systematically analyze maize yield gaps and production potential at both regional and six ecological zone scales. Results showed that simulated yields, recorded high yields, experimental yields, and farmer yields all increased progressively from east to west across ecological regions. The modeled yield potential for Inner Mongolia was 14.9 $t \cdot hm^{-2}$, the highest recorded yield was 14.4 $t \cdot hm^{-2}$, and the experimental yield was 11.1 $t \cdot hm^{-2}$. Farmer yields achieved 49% of the modeled yield potential, 51% of the highest recorded yield, and 66% of the experimental yield. The yield gap based on modeled yield potential (YGM), highest recorded yield (YGR), and experimental yield (YGE) was 7.5 $t \cdot hm^{-2}$, 7.0 $t \cdot hm^{-2}$, and 3.8 $t \cdot hm^{-2}$, respectively. Based on YGE, the short-term production potential reached 35.252 million tons, representing 1.6 times the current production level, with a short-term yield increase potential of 11.919 million tons. The four eastern leagues of Hulunber, Xing' an, Tongliao, and Chifeng will contribute 61% of this regional increase, while the western cities of Hohhot and Bayannur will contribute 16%. Inappropriate cultivation management practices were identified as the primary cause of large YGE values. Narrowing YGE requires addressing region-specific constraints through comprehensive cultivation technique improvement, simplification, and farmer adoption.

Keywords: Maize; Network variety-density test; Hybrid-Maize model; Yield gap; Production potential

1. Materials and Methods

1.1 Networked Density Trials

Experimental yield represents the production obtained under local ecological conditions with optimized management practices guided by experts, involving relatively low costs and minimal environmental risk. Given substantial climatic and production condition differences among ecological regions in Inner Mongolia' s main maize-producing areas, networked density trials were conducted from 2011 to 2013 across six ecological zones: the eastern cold region of the Great Khingan Mountains (Hulunber City), southern warm region of the Great Khingan Mountains (Xing' an League), West Liao River Plain (Tongliao City), Yan Mountain Hilly region (Chifeng City), Tumochuan Plain (Hohhot City), and Hetao Plain (Bayannur City). The multi-year average yield at the highest-yielding density was used as the experimental yield. Geographic coordinates of trial locations and 60-year (1951-2012) average meteorological parameters during the maize growing season (solar radiation, daily maximum temperature, daily minimum temperature, precipitation) are presented in Table 1 .

The variety × density networked trials used 'Zhengdan 958' (substituted by 'Demeiya 1' in Hulunber due to incomplete maturity), 'Xianyu 335' , and two locally dominant cultivars per region (Table 2). Four planting densities were established: 45,000, 60,000, 75,000, and 90,000 plants$\cdot$hm^{-2}. All locations implemented soil testing-based fertilization according to local maize nutrient requirements to ensure adequate N, P, and K supply, with irrigation and weed management following local production practices. At physiological maturity, two complete rows without gaps were harvested, and grain yield was determined after ear drying (14% moisture content) to calculate plot yield.

1.2 Modeled Yield Potential Using the Hybrid-Maize Model

The Hybrid-Maize model was employed to simulate maize yield potential. This model combines the maize development and organ growth modules from the CERES-Maize model with photosynthesis and respiration modules from the INTERCOM and WOFOST generic crop models, incorporating additional new modules to quantitatively describe maize growth processes using mathematical formulas based on climate, soil characteristics, and management factors. Meteorological data inputs (1951-2012) were obtained from the nearest weather stations to trial sites, including daily maximum temperature, minimum temperature, mean relative humidity, precipitation, sunshine hours, and wind speed. Planting density was derived from the variety × density network trial results, while other parameters such as sowing date and cultivar GDD matched local production practices.

1.3 Highest Recorded Yield and Average Farmer Yield

The highest recorded yield represents the maximum yield achieved by farmers under optimal ecological conditions with expert guidance, regardless of cost or environmental risk. Data were compiled from 81 high-yielding field measurements across 10 years (2006–2015) in each ecological region. Average farmer yields were based on 2013 data (the highest-yielding year in the past decade) from the *Inner Mongolia Statistical Yearbook*.

1.4 Parameter Calculations

Yield gap based on modeled yield potential (YGM) = Modeled yield potential -Farmer yield (1)
Yield gap based on highest recorded yield (YGR) = Highest recorded yield - Farmer yield (2)
Yield gap based on experimental yield (YGE) = Experimental yield -Farmer yield (3)
Short-term production potential = Experimental yield × Local maize planting area (4)
Short-term production gap = YGE × Local maize planting area (5)
Long-term production potential = Modeled yield × Local maize planting area (6)
Long-term production gap = YGM × Local maize planting area (7)

1.5 Data Analysis

Data were analyzed using Microsoft Excel 2003 and plotted with Sigmaplot 10.0.

2. Results

2.1 Experimental Yield and Optimal Density of Maize in Inner Mongolia’ s Ecological Regions

Figure 1 [Figure 1: see original paper] illustrates the relationship between maize yield and planting density obtained from the networked density trials. Except for the Hetao Plain (Bayannur City), the highest-yielding density for all other ecological regions was approximately 75,000 plants $\cdot$ hm^{-2}, with yields decreasing slightly but not significantly at densities exceeding this level. The Hetao Plain achieved its maximum experimental yield of 13.9 t $\cdot$ hm^{-2} at 90,000 plants $\cdot$ hm^{-2}, followed by the Tumochuan Plain (Hohhot City) at 13.3 t $\cdot$ hm^{-2}. The West Liao River Plain (Tongliao City) and Yan Mountain Hilly region (Chifeng City) produced experimental yields of 12.3 t $\cdot$ hm^{-2} and 10.8 t $\cdot$ hm^{-2}, respectively, at 75,000 plants $\cdot$ hm^{-2}. Both the eastern cold region (Hulunber City) and southern warm region (Xing’an League) of the Great Khingan Mountains yielded approximately 8.2 t $\cdot$ hm^{-2} at 75,000 plants $\cdot$ hm^{-2}.

2.2 Comparison of Modeled, Recorded, Experimental, and Farmer Yields Across Ecological Regions

Statistical values for the four yield platforms across regions are presented in Table 3 . The average modeled yield potential for Inner Mongolia was 14.9 t $\cdot$

hm^{-2} (range: 4.2-22 $\mathrm{t \cdot hm}^{-2}$). The average highest recorded yield was 14.4 $\mathrm{t \cdot hm}^{-2}$ (range: 8.4-19.2 $\mathrm{t \cdot hm}^{-2}$). The experimental yield averaged 11.1 $\mathrm{t \cdot hm}^{-2}$ (range: 3.1-18.9 $\mathrm{t \cdot hm}^{-2}$), while the regional farmer yield was 7.4 $\mathrm{t \cdot hm}^{-2}$. Overall, yields for all four platforms increased from east to west.

Among the four irrigated regions, Bayannur City exhibited the highest modeled yield potential at 18.0 $\mathrm{t \cdot hm}^{-2}$, followed by Chifeng City (17.3 $\mathrm{t \cdot hm}^{-2}$), Tongliao City (17.0 $\mathrm{t \cdot hm}^{-2}$), and Hohhot City (16.7 $\mathrm{t \cdot hm}^{-2}$). The highest average recorded yield occurred in Chifeng City (17.2 $\mathrm{t \cdot hm}^{-2}$), followed by Bayannur City (16.8 $\mathrm{t \cdot hm}^{-2}$) and Tongliao City (16.3 $\mathrm{t \cdot hm}^{-2}$), which achieved 99%, 93%, and 96% of their yield potentials, respectively. Hohhot City had the lowest recorded yield at 15.7 $\mathrm{t \cdot hm}^{-2}$ (94% of potential). Bayannur City also recorded the highest farmer yield (9.5 $\mathrm{t \cdot hm}^{-2}$), exceeding Tongliao City (7.7 $\mathrm{t \cdot hm}^{-2}$) and Chifeng City (7.5 $\mathrm{t \cdot hm}^{-2}$), while Hohhot City had the lowest farmer yield (6.7 $\mathrm{t \cdot hm}^{-2}$).

In rainfed regions, Xing' an League showed higher modeled yield potential (10.6 $\mathrm{t \cdot hm}^{-2}$) than Hulunber City (9.7 $\mathrm{t \cdot hm}^{-2}$). The highest recorded yields averaged 10.7 $\mathrm{t \cdot hm}^{-2}$ in Xing' an League and 9.6 $\mathrm{t \cdot hm}^{-2}$ in Hulunber City. Farmer yields in both rainfed regions were approximately 6.3 $\mathrm{t \cdot hm}^{-2}$.

2.3 Yield Gap Analysis Across Inner Mongolia' s Ecological Regions

Yield gaps calculated from modeled yield, highest recorded yield, and experimental yield (YGM, YGR, and YGE) are shown in Table 4 . Regional YGM and YGR were 7.5 $\mathrm{t \cdot hm}^{-2}$ and 7.0 $\mathrm{t \cdot hm}^{-2}$, respectively, with farmer yields achieving 49% and 51% of these potentials. The regional YGE was 3.8 $\mathrm{t \cdot hm}^{-2}$, with farmer yields reaching 66% of experimental yields.

Among irrigated regions, Hohhot and Chifeng cities exhibited the highest YGM and YGR values. YGM values were 10.0 $\mathrm{t \cdot hm}^{-2}$ and 9.8 $\mathrm{t \cdot hm}^{-2}$, respectively, with farmer yields achieving only 40% and 43% of yield potential. YGR values were 8.9 $\mathrm{t \cdot hm}^{-2}$ and 9.7 $\mathrm{t \cdot hm}^{-2}$, with farmer yields reaching 43% and 44% of recorded high yields. Tongliao City showed intermediate values (YGM = 9.3 $\mathrm{t \cdot hm}^{-2}$, YGR = 8.6 $\mathrm{t \cdot hm}^{-2}$), with farmer yields achieving 45% and 47% of respective potentials. Bayannur City had the lowest YGM and YGR (8.5 $\mathrm{t \cdot hm}^{-2}$ and 7.4 $\mathrm{t \cdot hm}^{-2}$), with farmer yields reaching 53% and 56% of potentials.

In rainfed regions, Xing' an League had YGM and YGR values of 4.1 $\mathrm{t \cdot hm}^{-2}$ and 4.2 $\mathrm{t \cdot hm}^{-2}$, respectively, with farmer yields achieving approximately 61% of both potentials. Hulunber City showed slightly lower values (YGM = 3.4 $\mathrm{t \cdot hm}^{-2}$, YGR = 3.3 $\mathrm{t \cdot hm}^{-2}$), with farmer yields achieving 65% and 66% of potentials.

Based on YGE, Hohhot City exhibited the largest yield gap at 6.6 $\mathrm{t \cdot hm}^{-2}$, with farmer yields achieving only 51% of experimental yields. Hulunber City and Xing' an League had YGE values of approximately 1.8 $\mathrm{t \cdot hm}^{-2}$, with farmer yields achieving about 77% of experimental yields. Tongliao City, Bayannur

City, and Chifeng City showed intermediate YGE values of 3.3–4.5 $\mathrm{t \cdot hm^{-2}}$, with farmer yields achieving 63–69% of experimental yields.

In 2015, Inner Mongolia' s maize planting area reached 3.467 million hectares. According to the national "Sickle Bend Region Maize Structure Adjustment Plan (2016-2020)," Inner Mongolia, as a key region spanning the northeast cold area, northern farming-pastoral ecotone, and northwest wind-sand arid zone, will reduce maize area by approximately 333,000 hectares, essentially returning to 2013 levels. Therefore, this analysis uses 2013 planting areas by league/city to calculate production potentials and yield targets based on yield gap results.

Among the three yield gap levels, narrowing YGM and YGR presents substantial difficulty under current production conditions and should be considered long-term objectives. This study therefore uses modeled yield potential and YGM to evaluate long-term production targets. Conversely, experimental yield represents achievable production in the short term through optimized management under local ecological conditions with low cost and environmental risk, making YGE appropriate for assessing short-term production potential.

As shown in Table 5 , long-term production potential for the entire region would reach 47.19 million tons, 2.2 times current production levels, with a long-term yield increase potential of 23.851 million tons. The four eastern leagues (Hulunber, Xing' an, Tongliao, and Chifeng) would contribute 69% of this increase, while the western region (Hohhot and Bayannur) would contribute 13%. Short-term production potential would reach 35.252 million tons (1.6 times current production), with a short-term yield increase potential of 11.919 million tons. The eastern four leagues would contribute 61% of this short-term increase due to their large planting areas, while the western region would contribute 16%.

Tongliao and Chifeng cities showed the greatest short-term production potential at 9.654 million tons and 5.928 million tons, respectively, with short-term yield increase potentials of 3.582 million tons and 1.827 million tons. Hohhot City had the smallest short-term production potential (2.014 million tons) but, due to its large YGE, its short-term yield increase potential (994,000 tons) exceeded that of Hulunber, Xing' an, and Bayannur. Although Hulunber and Xing' an leagues had short-term production potentials of 3.956 million tons and 4.263 million tons, their small YGE values (~1.8 $\mathrm{t \cdot hm^{-2}}$) limited their short-term yield increase potential to 904,000–931,000 tons. Bayannur City had a short-term production potential of 2.679 million tons but the smallest yield increase potential (856,000 tons) due to its relatively small planting area.

Regional-scale yield gap and production potential analysis provides crucial policy-level guidance for crop production planning and technical approaches to overcome limiting factors. Accurate estimation of yield platforms and gaps is essential. Reviewing literature on Inner Mongolia maize production potential reveals several methodological issues: (1) yield platform estimations often rely on limited sample data or empirical values, with experimental yields based on variety trial data without considering cultivation practices, particularly density effects; (2) small sample datasets are used for regional estimates without zone-specific quantification, applying uniform assumptions (e.g., all rainfed) across regions with different conditions; (3) production potential analyses often use arbitrarily uniform yield increase ratios or increments. These issues can cause substantial bias in production potential quantification.

This study addresses these limitations by using multi-year variety × density network trials to determine experimental yields at optimized densities, 10-year datasets from 81 high-yielding locations to quantify regional high-yield records, and 60-year meteorological data to simulate yield potentials. This approach improves data representativeness and provides scientific density parameters for Hybrid-Maize model simulations. The modeled yield potential of 4.2-22 $t \cdot hm^{-2}$ (average 14.9 $t \cdot hm^{-2}$) substantially exceeds previous estimates of 3.0-8.2 $t \cdot hm^{-2}$ using the Thornthwaite memorial model, primarily because the latter lacked field condition and management input data and treated all of Inner Mongolia as rainfed without distinguishing water management conditions—limitations overcome by the Hybrid-Maize model. The close agreement between modeled yield potential and recorded high yields validates the density network trial-assisted simulation approach.

The estimated YGM and YGR of 7.0–7.5 $t \cdot hm^{-2}$, with farmer yields achieving approximately 50% of potential (49–51%), and regional YGE of 3.8 $t \cdot hm^{-2}$, with farmer yields achieving 66% of experimental yields, align with results from Meng et al. and Licker et al., though with smaller variation ranges and higher experimental yield achievement proportions, likely due to this study’ s finer regional scale and higher precision.

Results based on YGE indicate that Inner Mongolia’ s short-term production potential could reach 35.252 million tons, 1.61 times current production levels, demonstrating substantial capacity for improvement through YGE reduction. Research shows that large YGE values primarily result from inappropriate cultivation management. Meng et al. identified key limiting factors for reducing YGE in China: (1) low planting density, inappropriate cultivar maturity, or unsuitable sowing dates leading to inefficient light and thermal resource utilization; Hybrid-Maize model assessments indicate that increasing density from 60,000 to 85,000 plants $\cdot hm^{-2}$ in the North China Plain could increase yields by 20-40%. (2) Extensive water and nutrient management. (3) Poor crop management practices, such as low seeding quality reducing stand uniformity and inadequate plant protection, with uneven emergence causing 4–12% yield losses. Hou et al. also identified soil conditions, such as plow layer constraints, as important factors limiting yield potential realization.

For Inner Mongolia, these common issues manifest differently across regions. In the rainfed southeastern Great Khingan Mountains region (Hulunber, Xing’ an, northern Chifeng hilly areas), YGE values of only 1.8–1.9 $t \cdot hm^{-2}$ indicate good realization of climatic production potential, with primary constraints being low population density (average 55,000 plants $\cdot hm^{-2}$), poor soil drought resistance and water retention, and insufficient fertilizer (especially nitrogen) input. Solutions include moderately increasing density while improving seeding quality, enhancing soil improvement through deep tillage and organic fertilization to improve water retention and drought buffering capacity, and optimizing fertilizer management to prevent nutrient deficiency in dense populations.

In the West Liao River Plain and Yan Mountain Hilly irrigated regions (Tongliao, Chifeng), YGE values of 3.3–4.5 $t \cdot hm^{-2}$ indicate mismatched water-fertilizer management with crop demand, deteriorating soil structure, and poor stand uniformity due to limited cultivar density tolerance and suboptimal seedbed preparation, resulting in severe periodic drought stress and substantial water-fertilizer waste. Recommendations include promoting water-saving irrigation and drip fertigation to synchronize water-fertilizer supply with population demand, deep tillage with straw incorporation to improve soil quality and water-nutrient retention capacity, selecting density-tolerant cultivars, and precision seeding to increase density to approximately 75,000 plants $\cdot$ hm^{-2}, thereby improving resource use efficiency and exploiting the high-yield potential of these core production areas.

In the western Tumochuan and Hetao Plains, larger YGE values of 4.4–6.6 $t \cdot hm^{-2}$ indicate substantial untapped light and thermal resource potential. Primary constraints include low population density, poor soil quality, severe drought stress, and excessive fertilizer input. Solutions involve selecting density-tolerant, high-yielding cultivars with appropriate maturity, improving seed quality and planting density, adjusting sowing dates to enhance resource use efficiency, improving soil quality through deep tillage, straw incorporation, and organic fertilization, strengthening irrigation infrastructure, reforming irrigation scheduling for timely water delivery, and implementing soil testing-based fertilization and integrated water-fertilizer management to improve use efficiency.

In summary, narrowing Inner Mongolia' s maize yield gap requires comprehensive cultivation practice improvements, a strategy validated in similar studies. Chen et al. achieved average yields of 13 $t \cdot hm^{-2}$ (86% of yield potential) across 66 sites using Hybrid-Maize model-driven integrated soil-crop management, with subsequent research demonstrating that such approaches can produce more grain with lower environmental costs to ensure future food security. The primary challenge in realizing short-term yield increase potential lies in simplifying region-specific, yield-gap-narrowing technologies for farmer adoption, requiring systematic training of agricultural extension personnel in improved management concepts and simplified techniques, as well as multidisciplinary collaboration among agronomy, soil science, agroecology, and extension to develop yield-enhancing, efficiency-improving approaches suited to Inner Mongolia' s current production conditions and future development needs.

Under China' s broader agricultural development context of "structural adjustment and mode transformation," scientifically assessing Inner Mongolia' s maize yield gaps and production potential and exploring effective gap-narrowing pathways is essential. This study combined density network trials with the Hybrid-Maize model to quantitatively evaluate maize yield gaps and production potential across Inner Mongolia and its ecological regions. The modeled yield potential was 14.9 $t \cdot hm^{-2}$, the highest recorded yield was 14.4 $t \cdot hm^{-2}$, and the experimental yield was 11.1 $t \cdot hm^{-2}$, with farmer yields achieving 49%, 51%, and 66% of these levels, respectively. The three yield gaps (YGM, YGR, YGE) were 7.5 $t \cdot hm^{-2}$, 7.0 $t \cdot hm^{-2}$, and 3.8 $t \cdot hm^{-2}$, respectively. Based on YGE, short-term production potential reached 35.252 million tons, with a short-term yield increase potential of 11.919 million tons. Narrowing YGE requires region-specific, multidisciplinary collaboration to achieve comprehensive cultivation technique improvement, simplification, and farmer adoption.

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