Postprint: Theoretical and Technical Research on Yield Improvement of Winter Wheat and Summer Maize in the Hebei Low Plain Area

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Date: 2017-10-20T00:00:00+00:00

Abstract

As the primary grain production increase zone of the Bohai Sea Grain Bin, the low- to medium-yield farmland in the eastern low plains of Hebei experiences winter wheat and summer corn yields primarily constrained by low soil fertility, freshwater resource scarcity, and substantial yield fluctuations induced by climate anomalies. By selecting suitable varieties, rationally coordinating sowing and harvest dates, optimizing planting patterns, and implementing supporting tillage and field management techniques, there exists tremendous potential to enhance the utilization potential and efficiency of aboveground light and heat resources and soil water and nutrient resources during crop growth periods, while mitigating adverse impacts of climate variability. This study examined the effects of optimizing growth periods for winter wheat and summer corn, adjusting summer corn planting patterns, subsoiling sowing of summer corn, increasing potassium fertilizer application for summer corn, and increasing phosphorus and organic fertilizer application for winter wheat on the yields of both crops through field plot experiments combined with demonstration area trials. The main research findings are as follows: Appropriate delayed sowing of winter wheat (no later than October 15), coupled with moderately increased seeding rates, does not affect population development or yield levels during the growth period. The early-maturing variety 'Xiaoyan 81' enters the grain-filling stage earlier, experiences less damage from late-season dry-hot winds, and maintains stable grain weight and yield without quality reduction. Advancing summer corn sowing by 10 days (June 10 versus June 20) increased yield by 17.2% on average, while delaying harvest by 8 days (October 2 versus September 24) increased grain weight by 19.5%. Based on the varietal characteristics of winter wheat and summer corn, rational matching of growth periods enables stable yield and quality improvement for winter wheat while fully exploiting the yield potential of summer corn. Modifying summer corn planting patterns and appropriately increasing planting density significantly improved summer corn yield;

more suitable patterns include 40 cm and 80 cm wide-narrow row planting and 38 cm equal row spacing planting, whereas the 20 cm and 100 cm wide-narrow row pattern is unsuitable, with yields increasing by over 15% under the more suitable patterns. Long-term rotary tillage mechanically compacted the plow pan; subsoiling sowing for summer corn increased yield by up to 31.3% and the subsequent wheat crop by 5.6%, but continuous subsoiling showed no significant yield-increasing effect. Increasing potassium fertilizer application at summer corn sowing increased yield by 2.6%. Increasing phosphorus fertilizer application for winter wheat increased yield by 7.4%; increasing organic base fertilizer application increased yield by 6.8%; combined organic base fertilizer and phosphorus application increased yield by 8.8%, but without significant additive effects. Therefore, through suitable variety selection and timely growth period coordination, planting pattern adjustment, timely subsoiling to disrupt the plow pan, and rational application of quick-acting and organic fertilizers, gradual and stable increases in winter wheat and summer corn yields can be achieved, making full use of the abundant and concentrated precipitation and light-heat resources during the corn growing season, tapping the yield potential of summer corn, and the grain production increase model of stabilizing summer wheat and increasing autumn corn better aligns with the future development needs of this region.

Full Text

Research on Exploiting Wheat-Maize Grain Yield Theory and Technology in the Eastern Low Plain of Hebei Province*

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Supported by the National Key Technology R&D Program of China (2013BAD05B05, 2013BAD05B02) and Hebei S&T Special Fund for the "Bohai Granary" Project.

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Abstract

Medium- and low-yield fields in the low plains of eastern Hebei Province represent critical areas for grain production enhancement in the "Bohai Granary" project. Winter wheat and summer maize yields in these regions are primarily constrained by low soil fertility, shortage of freshwater resources, and substantial yield fluctuations caused by climate anomalies. Through selection of appropriate cultivars, rational coordination of sowing and harvest dates, optimized planting patterns, and supporting tillage and field management technologies, there exists tremendous potential to increase yields by improving the utilization efficiency of aboveground light and thermal resources and underground water and nutrient resources during crop growth periods while mitigating adverse effects of climate change. This study investigated the effects of optimizing growth periods for winter wheat and summer maize, adjusting summer maize planting patterns, subsoiling-sowing of summer maize, increasing potassium application for summer maize, and increasing phosphorus and organic fertilizer application for winter maize on crop yields through field plot experiments combined with demonstration trials. The main results were as follows: Appropriate late sowing of winter wheat (no later than October 15) with moderately increased seeding rate did not affect population establishment or yield level. The early-maturing cultivar 'Xiaoyan 81' entered the grain-filling period earlier, suffered less damage from late-season dry-hot wind, and maintained stable grain weight and yield without quality reduction. Advancing summer maize sowing by 10 days (June 10 vs. June 20) increased yield by 17.2% on average, while delaying harvest by 8 days (October 2 vs. September 24) increased grain weight by 19.5%. Based on the growth period characteristics of winter wheat and summer maize cultivars, rational coordination of growth periods makes it possible to achieve stable, high-quality winter wheat production while fully exploiting the yield potential of summer maize. Changing summer maize planting patterns with appropriately increased planting density significantly improved and stabilized yields. The more suitable planting patterns were 40 cm + 80 cm wide-narrow row planting and 38 cm equal-row spacing, while 20 cm + 100 cm wide-narrow row spacing was unsuitable. Yield increases exceeded 15% under the more appropriate planting patterns.

Long-term rotary tillage mechanically compacted the plow pan layer. Subsoiling-sowing of summer maize increased yield by 31.3% and the subsequent wheat crop by 5.6%, though continuous subsoiling showed no significant additional yield benefit. Potassium application at summer maize sowing increased yield by 2.6%. Phosphorus application for winter wheat increased yield by 7.4%, organic basal fertilizer application increased yield by 6.8%, and combined phosphorus and organic fertilizer application increased yield by 8.8%, though without obvious additive effects. Therefore, through appropriate cultivar selection and growth period coordination, planting pattern adjustment, timely subsoiling to break the plow pan layer, and rational application of quick-release and organic fertilizers, gradual and stable yield increases for winter wheat and summer maize can be achieved. This approach fully utilizes the abundant and concentrated precipitation and light-thermal resources during the maize growing season, tapping the yield potential of summer maize. A grain production model that stabilizes summer crops and increases autumn crops better meets future development needs in this region.

Keywords: winter wheat; summer maize; yield increase; cultivar characteristics; growth period coordination; planting pattern; subsoiling; fertilization; Hebei low plain region

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1.1 Regional Background

This study was conducted at the Nanpi Eco-Agricultural Experimental Station of the Chinese Academy of Sciences and the Baifangzi demonstration area of the "Bohai Granary" project in Nanpi County. Nanpi County, a key demonstration county for the "Bohai Granary" initiative, is located in a warm temperate semi-humid continental monsoon climate zone. Winters are cold with little snow, springs are dry and windy, summers are hot and rainy, and autumns are predominantly sunny. The climate features concurrent rainfall and heat with relatively abundant light-thermal resources. Extreme temperatures range from -27.6°C to 41.4°C, with an annual mean temperature of 12.3°C. Annual sunshine totals 2,938.6 hours, and total annual radiation is 559.2 kJ · cm ^{2}. Annual precipitation ranges from 264.9 mm to 1,199.1 mm, averaging 550 mm, and is concentrated in the maize growing season during July-August [Figure 1: see original paper]. In recent years, the probability of temperatures exceeding 30°C during the late grain-filling stage of winter wheat (May 25 to June 10) has shown an increasing trend, while multi-year average sunshine hours have exhibited a decreasing trend.

The county' s elevation is mostly below 20 m. Soils belong to two categories: fluvo-aquic and saline soils, with four subcategories: brownized fluvo-aquic, ordinary fluvo-aquic, salinized fluvo-aquic, and meadow saline soils. Ordinary fluvo-aquic soils account for 76% of the total area. Soil organic matter content is low, with nitrogen, available phosphorus, and available potassium contents all lower than those in the piedmont plain region, resulting in generally poor soil fertility. County-wide averages are 0.815 g · kg ^{1} total nitrogen, 20.0 mg · kg ^{1} available phosphorus, 137.3 mg · kg ^{1} available potassium, and 13-15 g · kg ^{1} organic matter.

1.2 Experimental Design

Field plot experiments and large-area demonstrations were conducted during the 2011-2012 and 2012-2013 growing seasons. The experiments included: (1) winter wheat sowing date and rate trials, (2) winter wheat cultivar comparison trials, (3) summer maize sowing date trials, (4) summer maize late harvest effects on grain filling trials, (5) summer maize planting structure adjustment trials, (6) summer maize subsoiling-sowing trials, (7) summer maize potassium application trials, and (8) winter wheat phosphorus and organic fertilizer application trials. Specific designs were as follows:

Winter wheat sowing date and rate trial: The cultivar 'Xiaoyan 81' was used with three sowing dates (October 7, October 14, and October 21) and three seeding rates (3.7575×10 , 4.5×10 , and 5.25×10 plants · ha ^{1}), forming nine treatments with four replications each. The trial was implemented in field plots of 50 m^2 at the Baifangzi demonstration area.

Winter wheat cultivar comparison trial: Three cultivars ('Xiaoyan 81' , 'Xiaoyan 60' , and 'Heng 4399') were compared, with each cultivar planted in 0.3 ha plots.

Summer maize sowing date trial: Three cultivars ('Xianyu 335', 'Zhengdan 985' , and 'Zhongke 11') were sown on three dates (June 10, June 15, and June 20), forming nine treatments with four replications each. The trial was conducted in 50 m^2 plots at Baifangzi with a planting density of 6×10 plants · ha ^{1}.

Summer maize late harvest effects on grain filling trial: Using cultivar 'Zhengdan 958' , ears were sampled every two days from September 24 to October 2, with 10 ears of similar growth selected each time for 100-grain weight determination.

Summer maize planting structure adjustment trial: Using cultivar 'Xianyu 335' at 6.75×10 plants · ha ^{2}, four planting patterns were tested: 60 cm equal row spacing (control), 40 cm + 80 cm wide-narrow rows, 20 cm + 100 cm wide-narrow rows, and 38 cm equal row spacing. Each treatment had four replications in 60 m^2 plots at the Nanpi Experimental Station.

Summer maize subsoiling-sowing trial: Using cultivar 'Xianyu 335' at 6×10 plants · ha ^{2}, subsoiling-sowing with an integrated machine was compared with conventional non-subsoiling planting, with each treatment occupying 0.3 ha at Baifangzi.

Summer maize potassium application trial: Using cultivar 'Zhengdan 958', potassium fertilizer at 37.5 kg(K O) · ha ^{2} was applied at sowing, compared with a no-potassium control, with each treatment occupying 0.3 ha at Baifangzi.

Winter wheat phosphorus and organic fertilizer trial: Using cultivar 'Xiaoyan 81' , treatments included: (1) normal phosphorus application (172.5 kg(P O) · ha ^{2}) as control, (2) increased phosphorus (207 kg(P O) · ha ^{2}), (3) organic fertilizer (60 m^3 · ha ^{2} cattle manure with 14.8% organic matter), and (4) combined increased phosphorus and organic fertilizer. Each treatment occupied 0.3 ha at Baifangzi.

1.3 Field Management and Index Measurement

Except for experimental treatments, field management was consistent across all plots with adequate irrigation throughout the growth period. Conventional field surveys were conducted at various growth stages: for winter wheat at emergence, pre-winter, regreening, jointing, booting, flowering, and grain-filling; for summer maize at emergence, large trumpet, tasseling-silking, and grain-filling stages. Density and biomass measurements were taken. Key physiological indices were measured at critical growth stages (winter wheat flowering and summer maize tasseling-silking), including leaf photosynthetic rate, canopy light interception, canopy temperature, and plant architecture characteristics. Yield measurements were taken at harvest from experimental and demonstration plots. After harvest, grain yield was determined using a thresher. Samples were taken at harvest: 60 stems for winter wheat and 3 plants for summer maize for analysis.

1.4 Data Analysis

Data were statistically analyzed using SPSS 13.0, and graphs were produced using Microsoft Office 2007.

2.1 Cultivar Yield Potential and Rational Growth Period Coordination

Grain yield formation is primarily determined by individual and population growth vigor and the duration of grain filling. Strong growth vigor enhances resource utilization capacity (light, heat, nutrients, water), photosynthetic rate, and stress resistance, allowing yield potential to be more closely approached with sufficient grain-filling time. Maximum daily temperatures exceeding 30°C during the late wheat growth stage cause premature leaf senescence and yield reduction, with losses reaching 10-20% in severe regions or years. Elevated post-anthesis temperatures reduce wheat yield and cause complex changes in grain composition, affecting quality. Late-season dry-hot wind represents one of the greatest obstacles to achieving winter wheat yield potential and quality improvement in this region, disrupting normal physiological maturation and reducing grain weight and quality. Selecting early-maturing wheat cultivars with earlier anthesis and faster late-stage grain-filling rates can help avoid dry-hot wind damage and improve yield and quality.

When wheat is under optimal combinations of cultivar, sowing date, and density, maximum tiller numbers before winter and in spring produce the highest yields. Appropriate sowing dates enable full utilization of light, heat, and water resources, facilitating robust seedling establishment and reasonable population structure with coordinated development of spike number, grains per spike, and thousand-grain weight. Appropriate late sowing of winter wheat does not significantly affect growth progression or yield. Field trials with different sowing dates and rates showed that moderately increasing seeding rate with delayed sowing did not significantly affect final yield . Climate change trends indicate increasing probability of temperatures above 30°C before winter wheat harvest, which is unfavorable for late grain filling [Figure 1: see original paper]. Early-maturing cultivars enter the grain-filling period earlier and suffer less dry-hot wind damage, enabling more complete grain filling. As shown in [Figure 2: see original paper], the early-maturing cultivar 'Xiaoyan 81' showed no significant yield difference compared with other cultivars in this region, with stable grain weight. In 2013 compared with 2012, grain weights of the other two cultivars differed by 10-22%.

In the double-cropping system of the Huang-Huai-Hai region, early sowing of summer maize with medium-maturity cultivars can increase effective accumulated temperature after silking, ensuring sufficient accumulated temperature and grain-filling time during the late growth stage to achieve yield increases. In the annual winter wheat-summer maize double-cropping system, growth periods constrain effective and full utilization of climate resources by both crops. Although the maize growth period is relatively short, the high temperatures and abundant rainfall during this period concentrate rich climate resources, offering greater yield improvement potential. Early-sown maize achieves complete and vigorous seedlings with stronger individuals and populations, advancing tasseling and silking. Summer maize sowing date trials showed that early sowing increased yield by 3.4-21.6% (average 17.2%) compared with late sowing [Figure 3: see original paper]. Early sowing advanced the growth progression, helping avoid pollination impacts from rainy weather in late July to early August. More importantly, it advanced the grain-filling period, and grain-filling rates were higher in the early high-temperature environment. In late September, clear and sunny weather provided suitable conditions for grain filling. However, harvest in this region begins in late September, and early harvest affects complete grain-filling and maturity. Increased light during the post-flowering grain-filling period enhances dry matter accumulation and grain-filling rate, significantly improving summer maize yield. Grain weight directly affects summer maize yield and quality. Besides low-temperature effects on grain filling, delayed harvest 更有利于 increased grain weight and improved quality. Enhancing photosynthetically active radiation use efficiency from silking to maturity can improve source-sink relations and increase production capacity and adaptability under stress conditions. Harvest date trials showed that harvesting on October 2 increased grain weight by 19.5% compared with September 24 [Figure 3: see original paper]. As long as continuous low temperatures do not occur prematurely, maize grain-filling continues until the milk line appears, producing plump grains with high yield and quality.

2.2 Maize Canopy Structure Optimization and Suitable Planting Patterns

High summer maize yields are primarily achieved through "population structural gains," with further exploitation of "individual functional gains" in high-density populations. Compensation among yield performance parameters is the main mechanism for high-yield maize cultivars to achieve high yields. The harvest index of maize can reach above 0.5, with over 80% of grain yield directly derived from post-anthesis photosynthetic products, meaning yield is primarily determined by population structure from silking to milk stage. Maintaining a high harvest index while increasing and stabilizing overall field biomass is the basic prerequisite for achieving high and stable maize yields. Multi-year trials and demonstrations indicate that further increasing population density and biomass levels in this region requires more rational planting patterns. Planting pattern trials showed that increasing density to 6.75×10 plants·ha ^{2} and changing from conventional 60 cm equal row spacing to 40 cm + 80 cm wide-narrow row planting or 38 cm equal row spacing 更有利于 yield improvement and stability, with yield increases exceeding 15% under suitable patterns [Figure 4: see original paper].

Different planting patterns affect leaf area at different leaf positions, influencing field canopy structure. Suitable equal and wide-narrow row planting patterns enhance leaf area near the middle ear position [Figure 5: see original paper]. Improved photosynthetic capacity of leaves near the ear position facilitates grain filling and yield formation. Among different planting patterns, light interception at the canopy bottom showed little difference, while light interception by leaves near the ear position was significantly affected [Figure 5: see original paper]. Therefore, based on cultivar plant-type characteristics, adjusting and optimizing appropriate row and plant spacing can further exploit summer maize yield potential.

2.3 Root Zone Soil Tillage and Fertilization Management

Different tillage methods based on regional soil characteristics and environmental conditions facilitate crop yield potential exploitation. In the winter wheat-summer maize double-cropping system of this region, winter wheat sowing involves one mechanical rotary tillage operation, generally not exceeding 15 cm depth. Mechanical compaction and shallow tillage have created a dense plow pan layer that restricts root growth and affects crop development, particularly for crops with extensive root systems and high soil aeration requirements. High-yield maize cultivars achieve higher yields under subsoiling conditions primarily through positive super-compensation among yield performance parameters. Subsoiling-sowing trials showed that subsoiling increased summer maize yield by 31.3% in the first year and the subsequent wheat crop by 5.6% [Figure 6: see original paper]. After wheat harvest with straw return, simultaneous subsoiling and sowing significantly improved maize yield while also benefiting the following winter wheat. Field water-holding capacity in the 0-35 cm soil layer increased by 7.4% with subsoiling compared with conventional rotary tillage, with the highest biomass and economic yields under subsoiling. Subsoiling depth exceeding 30 cm broke the plow pan layer, improving deep soil water storage and moisture retention and facilitating root absorption of water and nutrients over a larger volume. Subsoiled maize showed significantly better growth than non-subsoiled maize, ultimately translating into yield advantages. However, subsoiling should not be performed frequently, as this yield advantage was not evident with continuous subsoiling for two consecutive years. Subsoiling once every three or more years may be more effective and economical.

In desalinized fluvo-aquic soils with low fertility, the high multiple-cropping index of the winter wheat-summer maize system removes substantial potassium from soil annually. Even when returning straw potassium to soil as equivalent fertilizer potassium, the effect on increasing available potassium is far less than direct potassium application. Potassium application and straw return significantly increase various forms of available potassium, reflecting the weak potassium fixation capacity of fluvo-aquic soils, allowing applied potassium to remain in available forms. High-yield summer maize continuously absorbs N, P, and K nutrients throughout the growth period. Nitrogen and potassium application significantly increases summer maize yield, with N and K being the main nutrient limiting factors. Recovery rates are 18.05% for N, 14.55% for P O , and 18.34% for K O, with 1.62 kg N, 0.69 kg P O , and 1.83 kg K O required per 100 kg of economic yield. Potassium application at summer maize sowing increased yield by 2.6% [Figure 7: see original paper]. Combined straw return and potassium application can increase maize yield and total nutrient absorption while maintaining soil potassium balance and increasing available potassium content, playing an important role in sustaining soil potassium fertility.

Phosphorus fertilizer recovery rate is generally only 10-25%, with 75-90% of applied phosphorus accumulating in soil as various phosphate forms. In rainy years, the groundwater table in this region frequently rises to the surface, causing short-term waterlogging that can lead to loss of accumulated phosphates. Increased phosphorus application as basal fertilizer before winter wheat sowing significantly increased yield by 7.4% [Figure 7: see original paper], while also supplementing phosphorus demand during the summer maize season. Organic fertilizer application also significantly increased winter wheat yield by 6.8%. However, combined organic and phosphorus fertilizer application increased yield by 8.8% without showing additive effects. Soil organic matter increase is a long-term process of soil fertility improvement, while quick-acting nutrients show more obvious yield effects in the short term.

The Hebei low plain region, as a major grain production area of the "Bohai Granary," contains extensive medium- and low-yield fields with tremendous yield improvement potential. Considering the regional climate and environmental resource characteristics and limiting factors in winter wheat-summer maize production, this study synthesized grain yield improvement theory and technology from three aspects and proposed suitable approaches for this region.

First, the "double early and double late" annual planting system for winter wheat and summer maize. Based on the growth period characteristics of different cultivars, select salt-tolerant, drought-resistant, early-maturing winter wheat cultivars for early wheat harvest and early maize sowing (double early), combined with appropriately delayed maize harvest and timely late wheat sowing (double late). While maintaining stable winter wheat yield and quality, this system exploits the yield potential of summer maize, forming a locally adapted planting system that improves resource use efficiency (water, nutrients, light, heat) and reduces environmental pressure.

Second, "stable summer, increase autumn" with summer maize planting pattern adjustment. The winter wheat season' s drought and irrigation dependence constrain yield improvement and conflict with water resource shortages and ecological degradation. Improving winter wheat water use efficiency and reducing irrigation dependence to achieve stable production and quality better meets regional grain production requirements. The summer maize season' s rich climate resources offer substantial yield improvement potential, with the main limiting factor being appropriate canopy structure for greater biomass production. Adjusting row and plant spacing with moderately increased density can significantly improve and stabilize yields. At 6.75×10 plants • ha ^{2}, the 40 cm + 80 cm wide-narrow row and 38 cm equal row spacing patterns are most suitable.

Third, subsoiling to break the plow pan layer combined with phosphorus and potassium fertilization. Most regional soils are desalinized fluvo-aquic soils with low fertility that experience groundwater rise and short-term waterlogging in rainy years. Simultaneous straw return and subsoiling break the plow pan layer, improve soil structure, and expand the root zone for nutrient and water absorption. Basal phosphorus application for winter wheat and potassium application for maize improve soil nutrient status and increase annual yields. The combination of full straw return, subsoiling-sowing of summer maize, and increased phosphorus and potassium application gradually improves soil fertility while addressing short-term phosphorus and potassium deficiencies, benefiting annual yields.

Grain production improvement is a coordinated evolutionary process of cultivar renewal and soil fertility enhancement. Coupling cultivar growth progression with local environmental conditions and efficient utilization of aboveground light-thermal resources and underground water-nutrient resources by individual plant-type characteristics and population structure are fundamental to achieving yield potential. Optimization of plant spatial configuration, including canopy structure for photosynthesis and root structure for absorption, affects light distribution and photosynthetic characteristics while influencing microenvironmental factors (water, heat, air) that affect photosynthetic efficiency and yield. Through appropriate cultivar selection and corresponding tillage, cultivation, and management measures, rational population structure can be shaped to improve canopy ventilation and light conditions, thereby enhancing population yield potential and achieving gradual and stable crop yield improvement.

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