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REVIEW

Quantitative design and production methods for sustainably increasing maize grain yield and resource use efficiency

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KEYWORDS

Maize, high yield, green production, quantitative design

HIGHLIGHTS

- The current key limiting factors for maize yield were summarized.
- Applying quantitative design to greenly increase maize grain yield.
- The green production methods can improve resource use efficiency and reduce environment burden.

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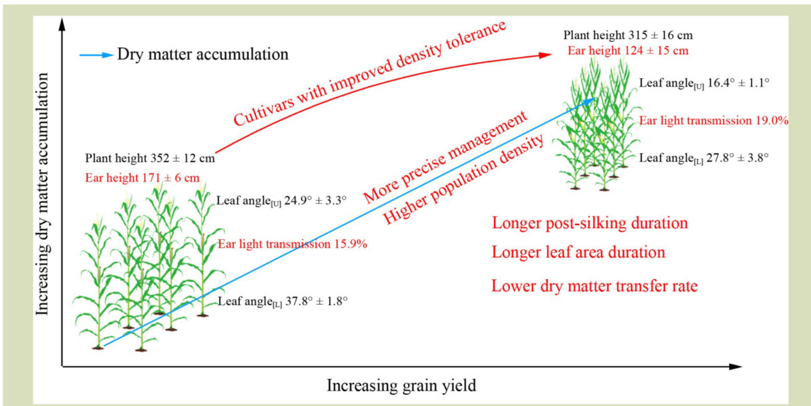
GRAPHICAL ABSTRACT



ABSTRACT

Due to continuous increases in the global population and the limited availability of arable land resources, issues related to food security have attracted increasing attention. Maize is the most productive and most widely planted food crop in China and has the highest yield potential among different crops. Increasing the yield of maize per unit area has become one of the key goals in agriculture in China. This study summarized the key limiting factors, such as solar radiation, temperature, water, soil resources and extreme weather events that currently limit the yield and resource use efficiency of maize production, as well as the main problems existing in the process of maize production, such as unsuitable cultivar selection, low planting density and inappropriate fertilizer application. Then the maize population was optimized on the basis of quantitative design principles. By this approach, crop planting density was matched with solar radiation levels, the population structure was matched with appropriate cultivars, and the plow layer-root system-canopy functions were matched with grain yield to ensure increases in grain yield and resource use efficiency in maize production. These factors can significantly improve maize production and related economic benefits, reduce production costs and environmental burdens, and provide a scientific basis and technical support for realizing sustainable agricultural development in China.

1 Introduction

Maize (*Zea mays*) is one of the most important food, feed and industrial crops, and the most direct way to ensure food security is to improve maize yield and supply[1]. Increasing maize yield per unit area is urgent given the limits of arable land area[2,3]. Environmental conditions and field management practices contribute significantly to yield improvements in modern maize[4].

Maize is grown in a wide range of regions in China[5,6], over a large geographical range[7] with significant climate differences between regions[8,9]. The heterogeneity of interregional climatic conditions results in substantial problems in maize production, especially those caused by extreme weather events, such as extreme drought and waterlogging, which limit increases in maize yield[10,11]. In addition, solar radiation and temperature directly affect photosynthesis and photosynthate accumulation[12,13], which are important driving forces for leaf photosynthesis and are important climatic factors that affect maize growth and development and determine the final grain yield[14–16]. However, in recent years, the quantity of global solar radiation has decreased due to climate change[17,18], resulting in weakened or even interrupted leaf photosynthesis during maize growth, which limits maize yield[19,20].

Cultivar selection and low planting density are the key factors limiting further improvements in maize yield. Maize cultivars have characteristics including growth traits, drought resistance, and resistance to pests and diseases. Flat-type cultivars are planted at low density, whereas compact-type cultivars are planted at high density[15]. In practice, suitable maize cultivars should be selected considering their traits, use, local planting conditions and other factors[21]. The reason why maize yield in China still differs substantially from that of the USA is that the maize planting density in China is much lower[22]. Appropriately increasing the planting density is an important way to increase maize yield, but the suitable planting density range is affected by both resource conditions, cultivars and planting methods. In addition, low-density planting results in a poor match with regional radiation and temperature conditions, which limits yield potential. In fact, there is a linear correlation between solar radiation and maize planting density, and the differences in solar radiation in different regions lead to different optimum planting densities[7,15]. Therefore, the use of quantitative design principles to match planting density with regional solar radiation and temperature patterns and to select modern high-yield maize cultivars, especially compact cultivars that allow for higher planting densities, can result in increases in biomass and grain yield due to longer photosynthesis durations to improve radiation use efficiency; these are among the most important ways to achieve further yield improvements.

Shallow soil tillage and unsuitable fertilizer application practices are also major factors that limit maize production. A shallow soil plow layer and a plow pan with varying degrees of compaction in the main maize production areas in China have caused severe obstacles with respect to the soil plow layer, and these adverse soil factors contribute to losses in maize yields ranging from 4.8% to 20.2%, which is calculated as a yield loss of 0.21–0.76 $t \cdot ha^{-1}$ on the basis of current yield levels[23,24]. In addition, current field management is relatively limited during maize production, and general-yield fields face problems such as excessive fertilizer application and low fertilizer use efficiency, while excessive fertilizer is frequently applied in high-yield fields[25,26]. Unsuitable fertilizer application practices reduce soil water storage and fertilizer retention capacity, resulting in low and unstable crop yields, ground water pollution, soil degradation and greenhouse gas emissions, as well as increases in the cost of maize production[15,27,28]. Calculated based on the actual production potential of maize, the loss of maize yield ranges from 2.53 to 1.09 $t \cdot ha^{-1}$[23]. There are still few ways to ameliorate the effects of soil plow layer obstacles and coordinate their relationships with the canopy to improve maize grain yield under dense planting[29]. Tillage practices can affect soil water retention capacity and thus affect maize yield; among these practices, deep scarification has been shown to provide significant improvements in soil structure, decreasing bulk density and increasing porosity, effectively alleviating soil compaction, incorporating stover residue, and promoting crop growth[30,31]. Deep scarification is applicable to various types of soils and regions, including clay and loam soils, and lands with a plow pan formed by long-term farming[32]. However, local soil conditions, cropping systems, climatic conditions and economic circumstances should be considered in selecting the appropriate frequency, timing, depth and method for deep scarification[31]. Fertilizer supply should be based on the demand of the maize crop for growth and development and to increase fertilizer use efficiency, which can alleviate negative environmental effects. As a precise regulation technology, drip fertigation technology can be used to achieve this goal and is an important way to increase maize grain yield and resource use efficiency.

Green agricultural practices are focused on the conservation of agricultural resources and environmental protection. They are important parts of ecologically sound development practices, crucial to achieving high-quality agricultural practices, and a significant measure for sustainable development in China. They are vital for ensuring food security and environmental health in China[15,33]. Through precise control of the crop growth environment and by performing quantitative analysis, yield is increased, grain quality is improved, resources are conserved and the environment is protected. In maize production, a comprehensive quantitative analysis of planting density, fertilizer application rates and methods, irrigation time and other high-yield parameters is used to study maize yield potential[34]. Scientifically-based crop production is determined by the physiologic characteristics and environmental needs of maize crops, which include selecting a suitable sowing time to avoid the influence of unfavorable climatic conditions, using of water-saving irrigation technology to guarantee water supply while reducing water wastage, and implementing a balanced fertilizer application strategy to avoid unsuitable fertilizer application and satisfy the demand of plants for nutrients without causing soil degradation or other agriculture-related environmental problems. These optimization strategies constitute a systematic quantitative design that can maximize the output to input ratios for resources, improve grain yield and quality, reduce environmental pressure, and realize the goal of increasing maize grain yield and resource use efficiency by ensuring the optimum environment for maize growth.

The aim of this study was to propose a systematic scheme for increasing maize grain yield and resource use efficiency considering factors such as climatic and soil conditions that affect maize growth in China on the basis of quantitative design principles, in which planting density is matched with solar radiation levels, population structures are matched with cultivars, sustainable crop production practices are used to increases maize yield, and efficient design is used to match plow layer-root-canopy functions. This approach is of considerable importance in promoting the sustainable and green development of agriculture and guaranteeing food security in China.

2 Quantitative design

2.1 Density patterns to match solar radiation levels

Planting density and solar radiation levels are important factors affecting crop yield[35,36]. Currently, there is scope for optimizing maize planting density in China, in response to solar radiation resources, which differ across ecoregions. Consequently, different approaches should be taken to increase maize density and yield[37–39]. Through shading experiments in Qitai and Yinchuan, it has been shown that the planting densities and yields in these regions are different because of the total quantity of solar radiation[40], and the optimal planting density is the density with the highest yield for a given the solar radiation level[41,42]. By matching the plant density with solar radiation level in different regions via precise quantitative design, the radiation use efficiency is improved because of an increase in radiation interception under dense populations, which improves yield potential[7,43,44] and reduces resource wastage. In north-west China, both the plant density and grain yield are the highest due to the abundant availability of solar radiation resources[45]. A previous study[15] found that solar radiation also decreased from west to east China, and that maize planting densities could be optimized to match the regional solar radiation levels, and that the yield potentials could also be greatly improved (Table 1). This finding indicates that the grain yield can be increased through matching planting density and solar radiation levels, which has been verified through yield records[15]. Another multiyear and multisite study was conducted in China at a total of 42 locations from 2007 to 2015, which found that the grain yield could be increased by 10.5%, 2.7%, 5.2%, and 10.3%, respectively, in the south-west, Huang-Huai-Hai, north and north-west maize regions, with an increase of 15,000 plants per hectare in density without additional inputs of nitrogen[46]. Therefore, matching the planting density to regional solar radiation levels is an

Table 1 Density and grain yield from west to east in five regions of China

Regions	Density (× 10^4 plants per hectare)			Yield ($t \cdot ha^{-1}$)		
	Farmers	Optimum	Record	Farmers	Potential	Record
1	6.4 ± 2.6	13.4 ± 6.9	12.3 ± 1.3	9.7 ± 0.98	24.0 ± 1.42	22.3 ± 0.4
2	7.0 ± 6.6	12.9 ± 9.2	10.4 ± 4.3	11.8 ± 0.34	24.2 ± 2.15	19.5 ± 0.8
3	7.1 ± 6.9	10.5 ± 6.4	10.0 ± 5.6	10.9 ± 1.08	19.9 ± 1.93	17.4 ± 0.0
4	5.8 ± 4.4	9.0 ± 6.2	8.8 ± 4.7	9.9 ± 1.33	17.9 ± 1.69	17.6 ± 1.5
5	5.5 ± 2.1	8.9 ± 5.0	8.2 ± 1.4	9.6 ± 0.55	15.4 ± 1.49	14.9 ± 2.2

Note: The five regions with average solar radiation levels of 1220, 1190, 1390, 1630, and 1680 $MJ \cdot m^{-2}$, respectively. The information is given are for farmers, the actual plant density or grain yield, optimum for highest grain yield, and record, the highest recorded density or yield in the region.

effective way to reduce maize yield gaps in different regions and improve yield potential.

2.2 Matching cultivars to population structure

The maize population structure greatly affects the vertical distribution of solar radiation, which in turn affects crop growth and development. For maize, excessively high plant density leads to an uneven distribution of solar radiation within the maize canopy, shortening the duration of photosynthesis and decreasing the photosynthetic efficiency of the maize population, which is unfavorable for photosynthate accumulation[4,47,48]. Therefore, an appropriate population structure is vital for improving maize yield under dense planting[49]. To some extent, the cultivar planted influences population structure. Cultivars that are adapted to high-density planting can be used to adjust the microclimate within populations[50], and the maize yield potential can be increased using high-density crop production[46,51,52].

Plant traits are different in different maize cultivars and are strongly affected by genotype. Plant traits determine the optimal vertical distribution of light under dense planting conditions[53,54]. A previous study showed that low planting density consistently results in a smaller leaf area index and lower yield level, so the authors recommended that cultivars with large leaf angles should be selected to avoid the underutilization of radiation resources as high yields are consistently associated with more precise management, and a consideration of plant traits is vital for optimizing the distribution of light in the canopy[55]. Cultivars with small leaf angles that are well adapted to dense planting should be selected for higher density planting (Fig. 1). Compact cultivars have longer post-silking durations, larger leaf area indices, smaller leaf angles, greater solar radiation transmittance and greater dry matter accumulation but lower translocation from vegetative organs[56]. In addition, compact maize cultivars have smaller upper leaf angles, which allows the middle and bottom leaves to intercept more solar radiation, and the decrease in solar radiation transmittance in all layers is smaller than for cultivars with large leaf angles with increasing density[57], which also contributes to higher photosynthetic productivity for compact cultivars. These characteristics increase the light transmittance with cultivars adapted to high-density planting and improve their radiation use efficiency[58]. At Qitai Farm in Xinjiang, China, we conducted a 4-year field experiment from 2017 to 2020 growing six of the highest-yielding maize hybrids, namely, SC704, Zhengdan 958, Liangyu 66, Xianyu 335, Denghai 618 and MC670. These cultivars were divided into three yield levels: high, medium and low[4]. We analyzed the morphological traits associated with these yield levels and summarized the characteristics associated with low and high yield, as shown in Fig. 2. The light transmittance at the ear layer was only 15.9% for cultivars with low yield whereas it was 19.0% for those with high yield[59]. In addition, compact maize cultivars had relatively large leaf orientation values and relatively high-yield potential[7,12], and are therefore the best choice for dense, high-yield populations. Through quantitative design and optimization of population structures and maize cultivars to improve solar radiation utilization, yield can be stabilized, with the yield potential increasing in the population, which is particularly important for increasing maize yield and improving efficiency.

2.3 Sustainably increasing maize yield and resource use efficiency by matching plow layer-root system-canopy functions

The physical and chemical properties of soil directly affect the morphological traits and distribution of the maize root system, and good soil conditions can promote the growth of the maize root system. In recent years, with a decrease in the frequency of tillage and the long-term use of the common agricultural

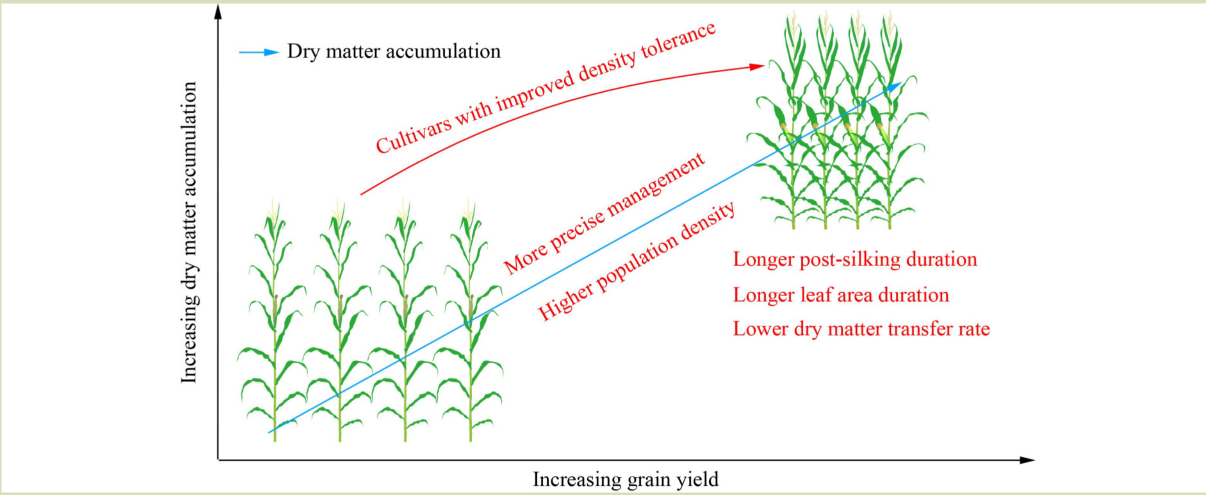


Fig. 1 Population characteristics of maize cultivars with low and high yield levels.

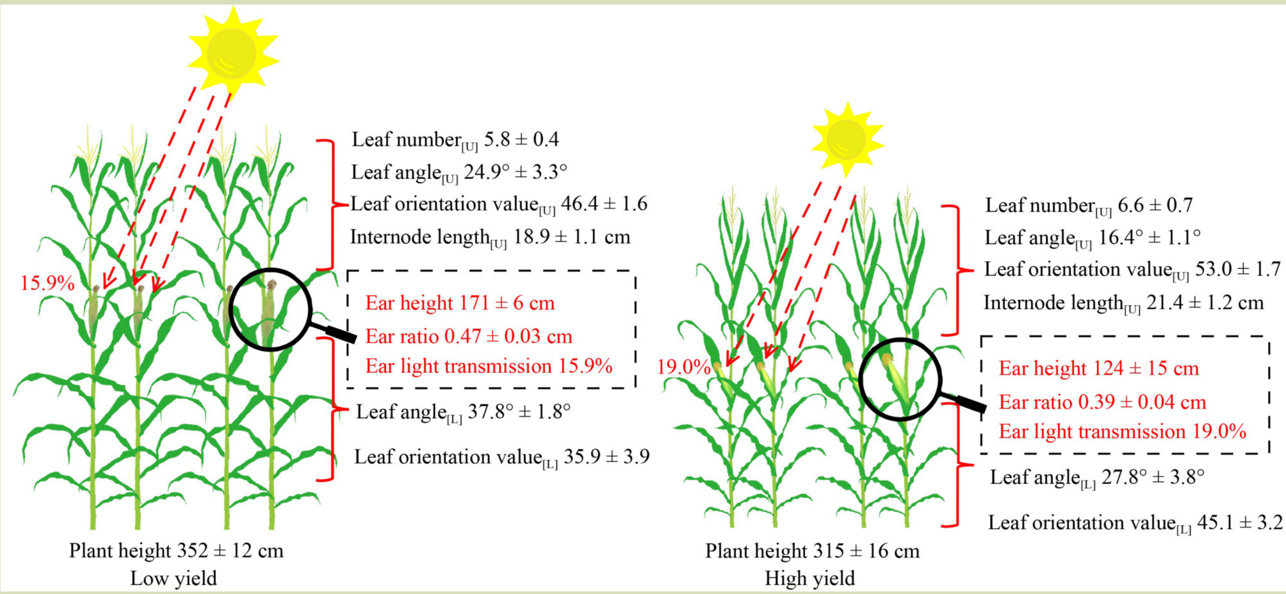


Fig. 2 Canopy characteristics of maize cultivars with low and high yields, for representative cultivars SC704 and Denghai 618, respectively. U, upper ear; and L, lower ear. Leaf angle is the angle between the leaf and the stem. Leaf orientation value is defined as $(90 - a) \times h / l$, where a is the leaf angle, h is the distance from the leaf base point to the zenith of the leaf, and l is the leaf length. Internode length is the average internode length. Ear ratio is the ratio of ear height to plant height. Ear light transmission is the intensity of light passing through the ear.

machinery, soils have become compact and dense, and the plow pan is now closer to the surface, which weakens the ability of the soil to retain water and fertilizer[4,60]. Thus water and nutrient stress can slow root growth, reduce root mass, affect root-shoot relationships and reduce the root-shoot ratio[61–64].

Ecological factors, such as solar radiation and temperature, affect leaf photosynthesis, and the availability of adequate solar radiation improves crop photosynthetic efficiency and enhances the assimilation and transport of matter[65,66], which then promotes the transport of photosynthetic products from aboveground to belowground parts in crops and regulates root growth[67,68]. A developed root system can further increase the absorption of water and fertilizer from the soil, which are then supplied for the growth of the aboveground parts and increase the root-shoot ratio (Fig. 3).

On the basis of these findings, it was determined that the establishment of an efficient population with a suitable relationship between belowground (root) and aboveground (canopy) areas under dense planting is beneficial for yield[69]. Generally, the root systems of high-density-adapted cultivars are much smaller than those of cultivars with poor adaptation to high-density planting, while the nutrient absorption capacity and water per unit root length may increase under high-density planting, which promotes an increase in the grain sink capacity and an improvement in sink regulation. Therefore, high-density-adapted cultivars are more suitable for the relatively crowded root spaces under high planting densities[70,71]. In contrast, the root systems of cultivars with large leaf angles are relatively large, which makes them suitable for relatively low-density planting[72].

Overall, the local plow layer, radiation level and temperature should be considered in determining the appropriate plant population, which then improves the photosynthetic efficiency of the population, optimizes canopy structure and improves radiation and temperature efficiency. Additionally, the root structure can be optimized to promote a good relationship with the plant aboveground parts for yield improvement[70,73,74].

3 Realization of sustainable increases in maize yield and resource use efficiency

As maize is the major food crop in China, increasing maize yield and resource use efficiency is particularly important for ensuring food security. In the global context of climate change, it is necessary to determine how limited resources can be used to realize this goal[30,45]. An increase in yield depends not only on the availability of elite cultivars but also on improvements in maize production methods. In a previous study, researchers used an extensive database obtained from the largest irrigated maize production domain located in Nebraska, USA to distinguish the separate contributions of several factors to yield improvement from 2005 to 2018. That study found the contribution of field management practices to grain yield was 39% and only 13% from improvement in genetic yield potential. In the future, crop yield gains will increasingly depend on improvements in agronomic practices[75]. A study growing six maize hybrids from different areas without water and nutrient stress at Qitai Farm in Xinjiang, China, in 2017 and 2018 found that the contribution of cultivars to grain yield was about 18%[58]. That study recommended regulating lodging resistance, improving uniformity and delaying senescence through precise regulation of yield under dense planting conditions to increase maize grain yield and resource use efficiency.

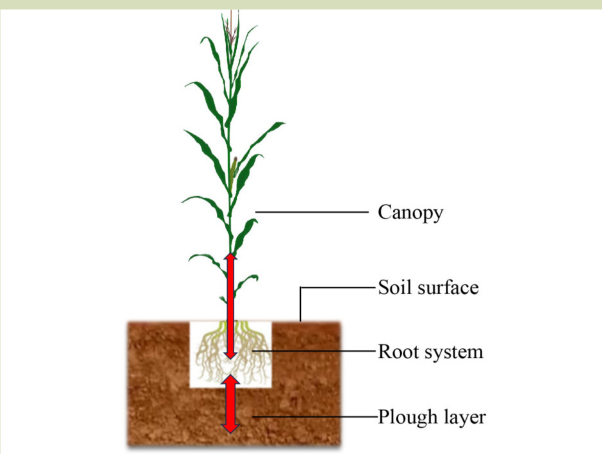


Fig. 3 Synergy in plow layer-root system-canopy functions. Bidirectional arrows indicate interactions among the plow layer, root system and canopy.

3.1 Cultivar selection

Before sowing, cultivars with strong disease resistance, suitable adaptation to high-density planting, high seed quality should be selected[23]. To improve the emergence rate, seeds should be precisely coated with agrochemicals needed to prevent diseases and pests according to local ecological conditions. In addition, the selected cultivars should have suitable growth periods adapted to local radiation and temperature conditions[37,38,47]. Considering that high-density planting can improve yield potential, cultivars that are high-density-adapted should have a small leaf angle, which can significantly improve light distribution and interception (Fig. 4).

3.2 Planting density

Increasing the planting density is an effective way to improve maize grain yield[76–78]. Plant density is determined by cultivar, soil fertility, local water supply, solar radiation and topographical characteristics. With increasing planting density, maize plants become taller and thinner, and resistance to lodging is reduced. An important approach for increasing the planting density and improving yield is preventing maize lodging. Excessively high planting density leads to competition for water, nutrients and light between individual plants and weakens light transmission through the canopy, which then

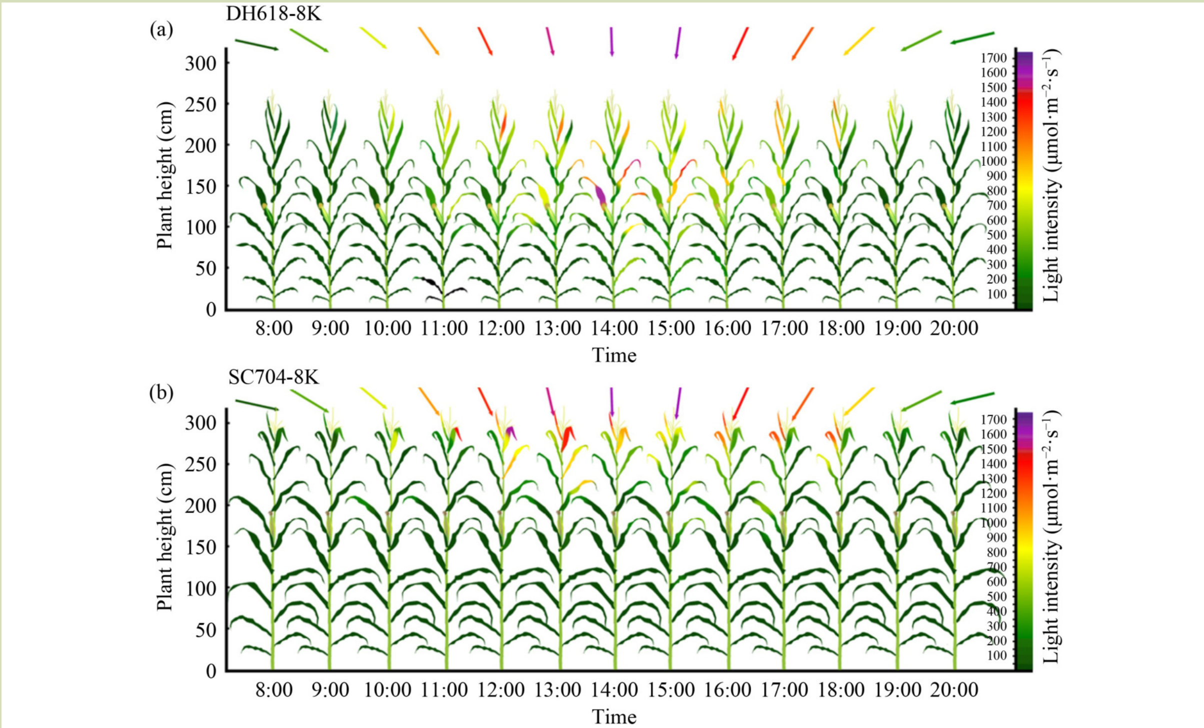


Fig. 4 Change in light intensity during the day in the canopies of cultivars of contrasting plant types. The high-yield cultivar Denghai 618 (a) is an erect type with a small leaf angle and cultivar SC704 (b) is a flat-type cultivar with a large leaf angle. Data were obtained by using a large number of light quantum sensors distributed near each leaf.

limits leaf photosynthesis[79–81]. In agricultural production, the row and plant spacing configuration can be optimized, and chemical agents are used to resist lodging and increase photosynthesis[82], thereby increasing the yield of maize. Therefore, the planting density should be increased on the basis of scientific analysis[56,83,84].

An earlier study found that maize grain yield could be greatly improved by matching the planting density with solar radiation levels in different regions from the west to east of China[15]. Therefore, relatively high densities should be matched with favorable environments and field management practices. According to our survey and the theory of light and temperature matching, the planting density corresponding to farmers, yield records and the highest density are 6.9×10^4, 10.5×10^4 and 13.5×10^4 plants per hectare in Northwest China, respectively; 6.0×10^4, 9.0×10^4 and 9.8×10^4 plants per hectare in North China; 6.3×10^4, 7.5×10^4 and 8.3×10^4 plants per hectare in the Huang-Huai-Hai region in China; and 4.8×10^4, 7.5×10^4 and 8.3×10^4 plants per hectare in Southwest China. At the optimum density, the maize population can achieve the maximum photosynthetic capacity and grain yield[85–87]. For example, in early research a yield record of 25.0 $t \cdot ha^{-1}$ was achieved in Qitai, Xinjiang in 2020[88], and another yield record of 25.1 $t \cdot ha^{-1}$ in Linzhi, Xizang in 2024[89].

3.3 Soil tillage

Straw incorporation in fields is an important conservation tillage practice, as are reduced-tillage and no-tillage, which all have positive effects on crop photosynthesis and grain yield[90–92]. Combined deep scarification and straw incorporation can increase soil microbial biomass carbon, accelerate soil organic carbon decomposition, improve the soil nutrient content[93,94] and soil porosity, improve the functions of the plow layer, promote root growth in deep soil, increase the supply of water and nutrients, and improve the ability of the soil to conserve water[95–97]. Long-term conservation tillage can increase the soil C-N ratio, which is beneficial for yield improvement and reduces environmental costs[98,99]. Therefore, straw incorporation optimizes the physicochemical properties of the soil, increasing maize yield while promoting agricultural sustainability.

3.4 Drip fertigation

Drip fertigation is a relatively new type of irrigation that integrates water and fertilizer application. Water and fertilizer are simultaneously applied to crops with via irrigation system according to crop demands. In general, drip irrigation is a common method through which water and fertilizer are uniformly supplied to crop roots via low-pressure drip pipes. A two-year field experiment conducted from 2020 to 2021 revealed that supplementary irrigation and appropriate fertilizer application can increase maize fertilizer-nitrogen use efficiency, affecting the accumulation and metabolic processes of nitrogen in the soil and in plants[32,100]. Our former works had examined maize grain yield potential in recent 20 years, in this time, field management measures have gradually improved and integrated drip fertigation methods have matured, through which maize plant density and grain yield can be effectively increased through the precise regulation of water and nutrients and the optimization of fertilizer-nitrogen use efficiency[23,79,101], with impacts on water resources and the environment. Currently, drip fertigation is widely used in Northwest China and is gradually being adopted in northeast, southwest and the Huang-Huai-Hai regions as well with corresponding increases in grain yield. Compared with standard irrigation of maize at low planting densities, drip fertigation combined with high planting density has the potential to improve grain yield by 71%, 61%, and 33% in Northwest, Northeast, and Southwest China, respectively, with the highest yield increase being in arid and semiarid areas, such as Northwest China (Fig. 5). Therefore, this approach has great potential for increasing maize yields[102]. In 2024, the area over which this technology was used was 400 × 10^4 ha, which accounted for about 9% of the total maize area in China. The use of this technology is increasing rapidly and will be important in ensuring food security and sustainable agricultural development in the future. However, all technologies have limitations. Although drip fertigation is highly effective in the arid and semiarid areas of Northwest and Northeast China, it has limitations. First, water resources are distributed unevenly in China. Farmers do not consistently apply this technology when there is enough precipitation; as a result, nutrients are not applied according to the demands of the maize crop. However, the average field area for each farmer is small in China, and smallholders are the main producers. Due to cost and income considerations, smallholders do not readily adopt this technology[103,104]. Therefore, this approach should be recommended in arid and semiarid areas of Northwest and Northeast China and in some regions in Southwest China and Huang-Huai-Hai, where severe seasonal drought often occurs[103–106].

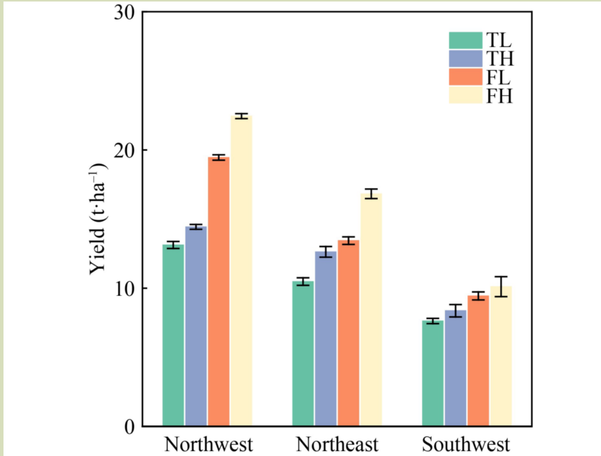


Fig. 5 Maize grain yields under different management practices. TL, traditional management at low density; TH, traditional management at high density; FL, fertigation at low density; FH, fertigation at high density; Northwest, 34°–48° N and 73°–105° E; Northeast, 48°–55° N and 118°–135° E; and Southwest, 22°–33° N and 98°–110° E.

4 Conclusions and prospects

By quantitatively matching the maize planting density and cultivar with solar radiation, temperature, water and soil resource levels, maize grain yield potential can be increased. On the basis of climate conditions, the present study divided the maize regions in China into four regions: Southwest, Huang-Huai-Hai, North and Northwest. Different field management conditions as well as cultivars exist in these different regions, which results in different maize yields. According to the results of this study, the use of quantitative design to sustainably increase maize yield and resource use efficiency could greatly improve yield without additional environmental costs. This can be achieved by matching the planting density with solar radiation levels, matching population structures with cultivars, and matching maize yields with tillage-root-canopy functions. These quantitative design approaches are suitable for different ecological regions across China. On the basis of these findings, cultivar selection, increased planting density, soil tillage practices and drip fertigation are suggested for maize production in different regions of China with different climatic conditions, which is beneficial for increasing maize grain yield and resource use efficiency.

With the change in the global climate and increasing pressure on resources and the environment, sustainable agriculture is receiving increasing attention[107,108]. Green agriculture is a necessary part of sustainable development and an inherent requirement for the development of agricultural practices. To date, remarkable success has been achieved in increasing maize grain yield and resource use efficiency through sustainable methods. However, limitations exist related to the complexity of the environments for maize production, the construction of field infrastructure, and the effects of traditional belief systems. In addition, with the aim of achieving high yields, some farmers use excessive resources, which in turn increases cost and reduces resource use efficiency[109]. Therefore, quantitative design approaches should be further optimized for larger regions with diverse environments. An advanced decision-making support and learning system could be developed to improve precision and practicability in agriculture. Through the adoption of this quantitative design approach, it is hoped that high yield, high resource us efficiency, high quality, ease of operation and green practices can be realized in future maize production.

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Compliance with ethics guidelines

Huaxiang Ji, Guangzhou Liu, Wanmao Liu, Yunshan Yang, Xiaoxia Guo, Guoqiang Zhang, Zhiqiang Tao, Shaokun Li, and Peng Hou declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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