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Effects of Plant Density and Fertilization on Optimization of Maize Yield

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Abstract Maize is a globally important staple crop, and optimizing its yield through agronomic practices remains a primary focus in agricultural research. This study investigates the effects of plant density and fertilization strategies on maize yield optimization, emphasizing their individual and combined influences. We examined how different plant densities, ranging from low to high, affect yield potential under varying environmental and management conditions, and identified the optimal densities for specific agronomic scenarios. Additionally, we explored the role of nutrient management-particularly nitrogen, phosphorus, potassium, and micronutrients-highlighting precision and site-specific fertilization strategies that enhance crop productivity. The interaction between plant density and fertilization was also analyzed, revealing their synergistic impact on yield response, plant morphology, and soil health. A regional case study conducted in the North China Plain further demonstrated the practical implications of integrated density-fertilization regimes. This study underscores the significance of genotype × environment × management interactions and points to the need for adaptive, innovative practices to achieve sustainable yield gains. Future research should aim to refine optimization models and promote evidence-based recommendations for diverse agroecological contexts.

Keywords Maize yield; Plant density; Fertilization strategy; Agronomic optimization; Sustainable agriculture

1 Introduction

Maize (*Zea mays* L.) is a very important food crop worldwide. It is not only a staple food for humans, but is also widely used as feed and industrial processing. Because it can adapt to the climate and soil of different regions and has high yields, it is important for food security and economic development in many places (Shi et al., 2016; Shao et al., 2024a). As the population grows, the demand for maize is also increasing, so increasing maize yields is becoming increasingly important.

To grow maize well, some key planting methods are indispensable, such as planting density and fertilization methods. Too high or too low density will affect the use of sunlight, the accumulation of dry matter, and the efficiency of nutrient and water use. Fertilization, especially the use of nitrogen fertilizer, will also directly affect the ability of maize to absorb nutrients and carry out photosynthesis, thereby affecting the yield (Du et al., 2021; Li et al., 2021; Meng et al., 2022; Shao et al., 2024b). However, if the density and fertilizer amount are not used appropriately, not only may the yield decrease, but fertilizer will also be wasted and it will be bad for the environment. Recent studies have found that if the planting density and fertilizer amount can be reasonably matched according to the local climate and soil conditions and the characteristics of different maize varieties, the yield of maize and resource utilization can be significantly improved, which is also more conducive to sustainable development (Al-Naggar et al., 2015; Lai et al., 2022; Tian et al., 2022; Wu et al., 2024).

This study mainly summarizes the current research results on the effects of planting density and fertilization on maize yield. The focus is on analyzing how these two factors affect maize yield, resource utilization efficiency and sustainability under different regions and management methods. We refer to the results of multiple field trials and meta-analyses, hoping to provide some well-founded suggestions for scientific maize planting and increasing yields.

2 Plant Density and Maize Yield

2.1 Effects of high vs. low plant densities

Planting more densely often allows maize to make more full use of resources such as sunlight and nutrients, so that the yield per unit area may increase. However, planting too densely can easily cause maize to compete for resources, such as light and nutrients, which will affect their growth and ear development (Figure 1) (Djalović et al., 2024). If the density is too high, the leaf area and photosynthesis capacity cannot keep up, and the leaves age quickly, which will cause the yield to stagnate or even decrease (Wu et al., 2023). On the other hand, planting too sparsely reduces competition, but it will also waste land and resources, and fail to use up the sunlight and nutrients of a piece of land, resulting in a lower yield per hectare (Assefa et al., 2018).

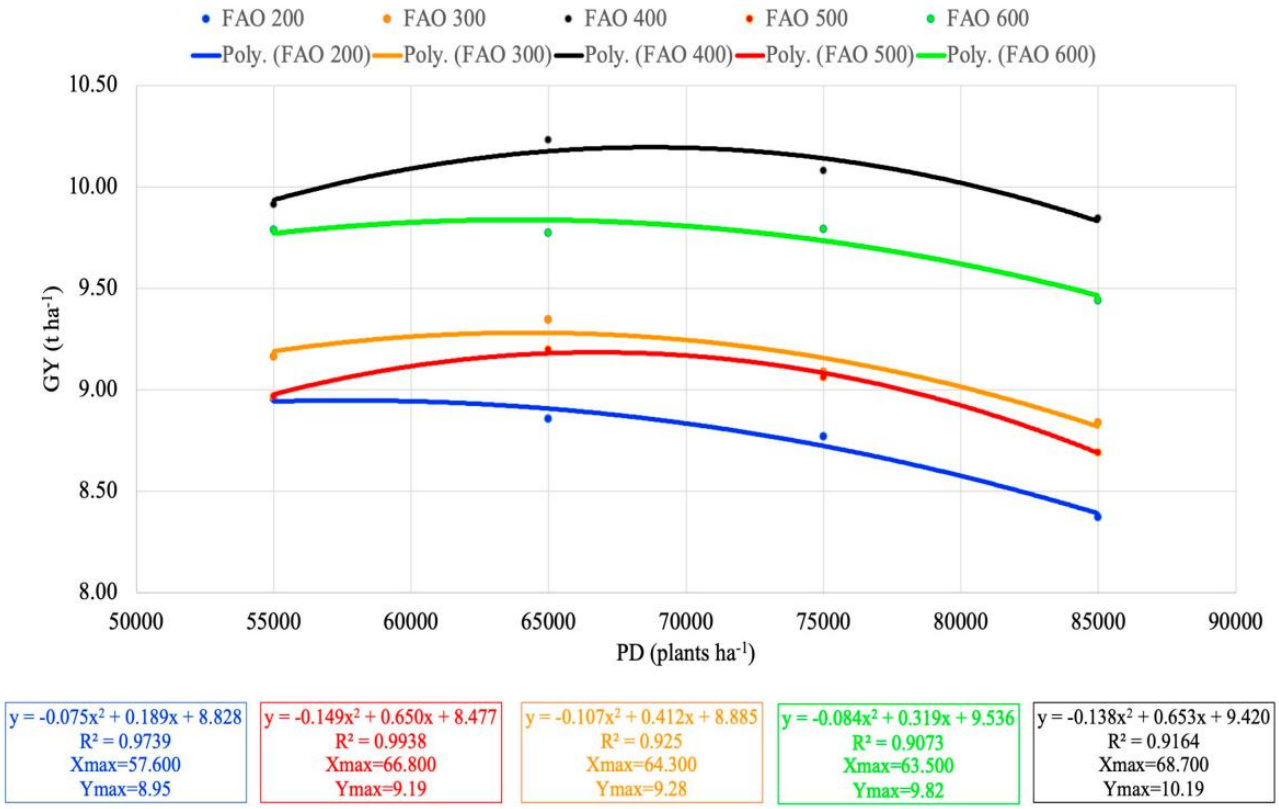

Figure 1 Regression model trendlines of grain yield depending on planting density, categorized by FAO groups. R^2 = coefficient of determination; Xmax = estimated maximal planting density; Ymax = estimated maximal grain yield (Adopted from Djalović et al., 2024)

2.2 Optimal plant density under different conditions

The most suitable density for planting maize actually depends on the specific situation, such as the variety selected, the climate, the soil, and how to manage it. On the calcareous soil of the Southern Pannonian Basin, the most suitable density for hybrids of different maturity is about 57 600 to 68 700 plants per hectare. In North America, the density of maize planting there has been increasing in recent years, especially in high-yield areas, where the density has increased and the yield has also increased significantly (Lacasa et al., 2020). In the model of planting maize and peanuts together, 9 plants/square meter is considered to be a relatively ideal density, which can ensure maize yield without affecting the peanut harvest (Zhang et al., 2020). In addition, the study found that if the density can be arranged according to the local sunlight intensity, the effect will be better. In places with strong solar radiation, the planting density can be appropriately increased (Liu et al., 2021).

2.3 Interaction with other agronomic factors

Planting density often needs to be coordinated with other planting management methods, such as how much nitrogen fertilizer to apply and what variety to use. If the density is increased, the amount of nitrogen fertilizer should usually be adjusted accordingly to ensure that the yield does not drop and that resources are better utilized

(Du et al., 2021). Some studies have found that if the density is appropriately increased and the amount of nitrogen fertilizer is reduced, the utilization efficiency of nitrogen fertilizer can be improved, and the yield will not necessarily decrease, and may even increase (Shi et al., 2016). Different maize varieties are also quite different. Some varieties are naturally suitable for high-density planting, such as hybrids with compact plant shapes and suitable maturity periods (Ye et al., 2023). In addition, climatic conditions such as precipitation, soil fertility, and latitude will also affect the effect of planting density on yield. Therefore, the best way is to determine the density and management method based on local actual conditions.

3 Fertilization Strategies for Optimized Yield

3.1 Nitrogen management and maize productivity

If you want to increase maize production without wasting fertilizer or polluting the environment, nitrogen fertilizer must be used appropriately. Generally speaking, if nitrogen fertilizer is used at about 180 to 200 kg per hectare, the yield is very good, and the effect is similar to high nitrogen application, but the damage to the environment will be much less, for example, nitrates are not easily lost, and there is less residue in the soil (Yang et al., 2017). If nitrogen fertilizer is applied deeper, such as about 25 cm, it can be more absorbed by maize, which is also conducive to dry matter accumulation and yield increase. This method will be more effective if combined with appropriate planting methods (Zheng et al., 2023; Tian et al., 2024). In some places, maize needs to absorb a lot of nitrogen after silking. In this case, applying some nitrogen fertilizer in the later stage may help increase yield. But whether it works depends on the local climate and soil conditions (Fernández et al., 2020). On the contrary, applying too much nitrogen fertilizer not only does not help with yield, but also brings some negative effects, such as wasting fertilizer, polluting water sources, and is bad for the environment (Medina-Cuéllar et al., 2021).

3.2 Role of phosphorus, potassium, and micronutrients

In addition to nitrogen fertilizer, phosphorus (P), potassium (K) and some trace elements are also very important. If you want to grow high-yield maize, these fertilizers are also indispensable. Using nitrogen, phosphorus and potassium together, especially with organic fertilizers, can not only increase yields, but also improve soil and increase water use efficiency (Abdo et al., 2022). In addition, if organic fertilizers or biofertilizers are used to replace part of chemical fertilizers, especially when applied together with natural stimulants such as humic acid and amino acids, the yield will not only not decrease, but may be more stable. It can also reduce dependence on chemical fertilizers and reduce environmental pollution (Jiang et al., 2024).

3.3 Site-specific and precision fertilization approaches

The soil, weather, and crop requirements in different places are different, so fertilization cannot be a one-size-fits-all approach. It would be more reasonable to adjust the amount and depth of fertilization according to local actual conditions. For example, according to the different growth periods of maize, combined with weather and soil conditions, deep fertilization and irrigation fertilization can allow maize to absorb better, increase yields, and save costs (Xu et al., 2020; Yan et al., 2021). Using chemical fertilizers and organic fertilizers together, and then using some data-based methods to arrange fertilization time and amount according to the actual needs of crops, can more effectively support the continued high yield of maize (Zhai et al., 2022).

4 Combined Effects of Plant Density and Fertilization

4.1 Yield response under varying combinations

Studies have found that appropriately increasing the planting density and reducing the amount of nitrogen fertilizer can simultaneously increase maize yield and fertilizer utilization efficiency (Figure 2). For example, planting 30% more maize than traditional practices and reducing nitrogen fertilizer by 15% to 30% can increase yield by 6% to 13%, and the efficiency of nitrogen fertilizer use is also higher (Du et al., 2021). This approach is particularly suitable for years with normal water volume or sufficient water sources. It can also be used in semi-arid areas or places with irrigation. However, whether the density is too high or too much nitrogen fertilizer is used, it may eventually lead to a mediocre yield or even a decrease in yield. Therefore, the two must be properly matched, not just more or less (Lai et al., 2022).

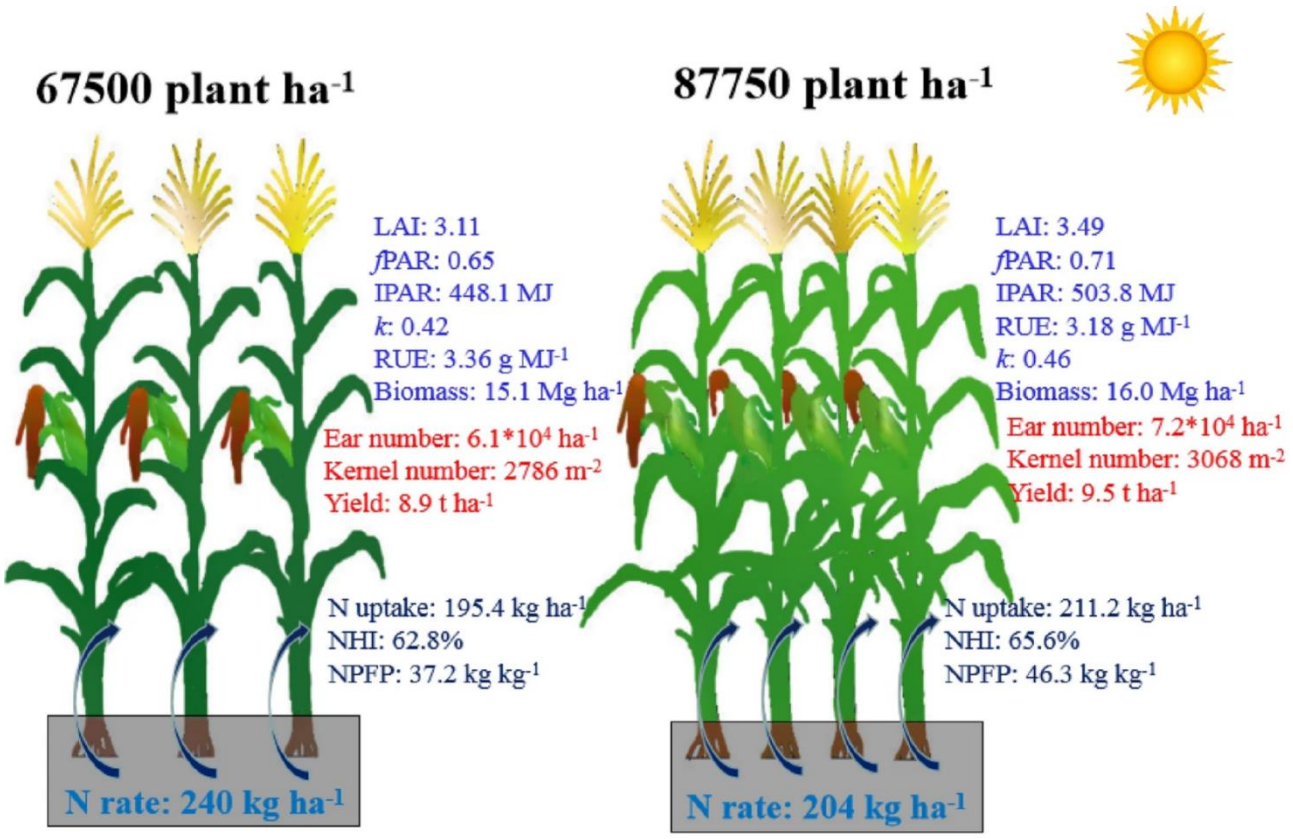

Figure 2 Schematic representation of the processes involved in the canopy development, radiation capture and radiation use efficiency, N uptake and N use efficiency and yield. All data in the figure were averaged by two experiment years. *LAI* leaf area index, *fPAR* fraction of PAR intercepted, *IPAR* cumulative intercepted PAR, *RUE* radiation use efficiency, *k* light extinction coefficient, *NHI* N harvest index, *NPFP* N partial factor productivity (Adopted from Du et al., 2021)

4.2 Physiological and morphological adjustments

Planting more densely and applying the right fertilizer will change the physiology and appearance of maize, thus helping to increase yield. For example, the leaf area becomes larger, the light can be more fully utilized, and more dry matter is accumulated, all of which will make the maize grow better (Shi et al., 2016). In terms of appearance, the stems and ears of maize will become thinner when the density is high, but the plants will grow taller and the ears will be higher. If the right fertilizer is added, the number of grains will also increase, and the biomass of the whole plant will also increase. These adjustments will also make the leaves of maize greener, enhance the photosynthesis capacity, and improve the ability to absorb nutrients (Meng et al., 2022; Han et al., 2024).

4.3 Long-term effects on soil health and productivity

In the long run, if the density is higher and the fertilizer is less, it can not only ensure stable yields, but also help protect the soil. This approach can reduce nitrogen fertilizer waste, reduce nitrate loss, and increase net income (Wu et al., 2024). Studies have also found that this approach can also increase the activity of enzymes involved in nitrogen metabolism in the soil and reduce nitrate residues in the soil, which is good for soil quality and reduces the possibility of pollution (Wei et al., 2023). This combination of "dense planting + less fertilizer" can not only increase yields but also take care of the environment. It is a sustainable development approach.

5 Case Study: Regional Trial in the North China Plain

5.1 Background and study design

The North China Plain is an important maize-producing area in my country. This region has to ensure both increased grain production and reduced environmental pressure, which is a heavy task. To address these issues, researchers conducted a regional experiment. They combined farmer questionnaires, crop models, and field trials to assess the gap between maize yield and actual yield, identify the main factors limiting yield, and test the

effectiveness of some new planting methods (Figure 3). The experiment focused on several key points, such as planting density, number of fertilizations, and irrigation methods. They compared farmers' usual planting methods with a new method called "high-yield and high-efficiency management (HH management)" to see how big the difference in effect was (Wang et al., 2023a).

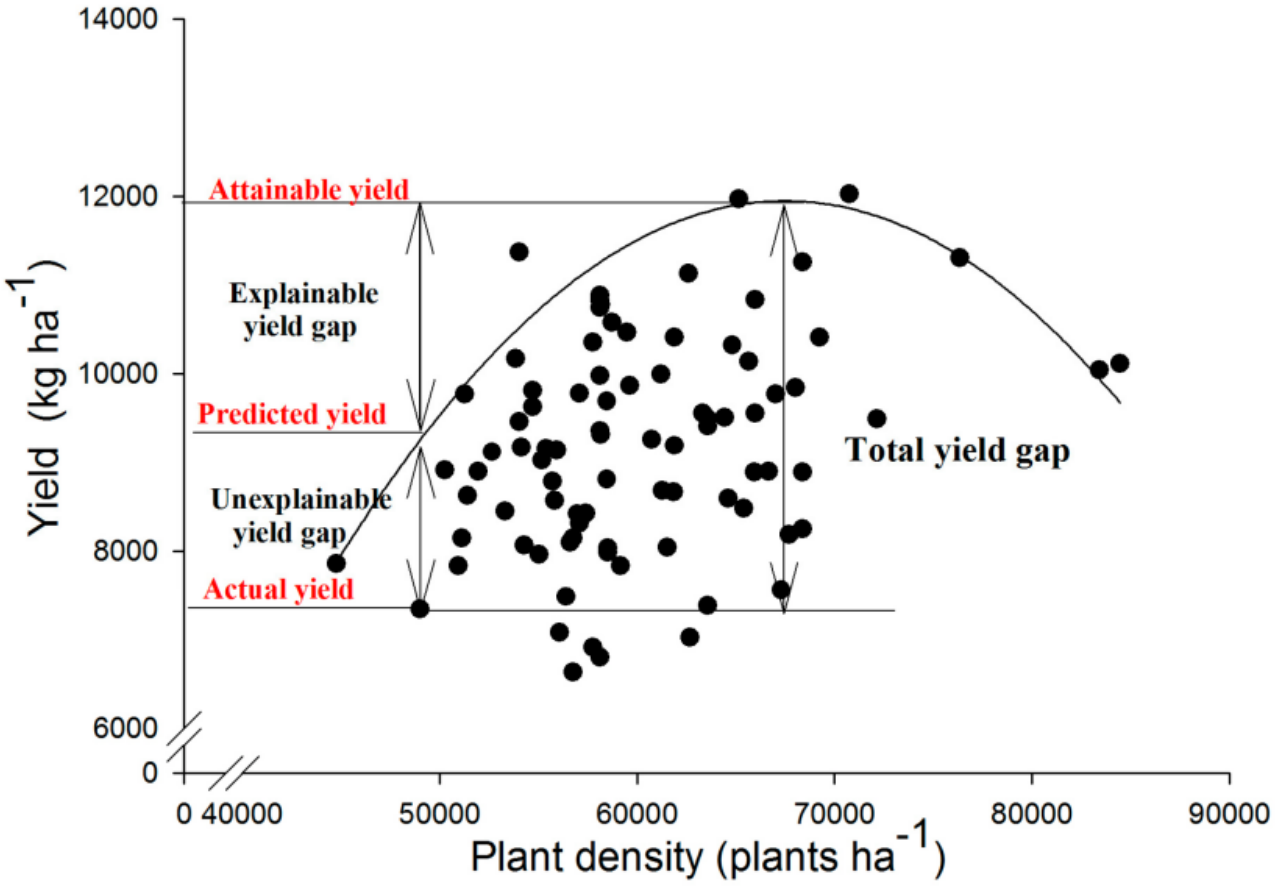

Figure 3 Relationship between summer maize yield and plant density in Laoling in 2015. The curved black line is the boundary line; the values of the upper, middle, and lower horizontal lines are the attainable yield, predicted yield, and actual yield on farms, respectively. The total yield gap is the difference between the attainable yield and the actual yield; the explainable yield gap is the difference between the attainable yield and the predicted yield; and the remainder is the unexplainable yield gap (Adopted from Chen et al., 2018)

5.2 Key findings and observations

The results of the experiment found that there is a large gap between the actual yield of summer maize in the North China Plain and the achievable high yield, indicating that there is still a lot of room for increase in yield. The key factors affecting yield are whether the planting is dense enough, whether the fertilizer is applied correctly, and whether the irrigation is kept up. Some farmers who performed well have significantly higher yields and more efficient use of fertilizers, such as nitrogen, phosphorus, and potassium are not wasted, and they also earn more. By improving household and field management, they increased grain production by 30% to 35%, fertilizer utilization by 32% to 48%, and profits by 14% to 62%. After adopting optimized management, the yield per hectare was 2.7 tons higher than before, the utilization efficiency of nitrogen fertilizer increased by 38%, and the greenhouse gas emission intensity was reduced by 28% (Wang et al., 2023b). However, the survey also found that many small farmers used too much fertilizer, especially nitrogen fertilizer, but the yield was not higher, indicating that fertilization methods need to be improved (Ren et al., 2020).

5.3 Implications for broader adoption

This regional trial shows that some seemingly simple and inexpensive adjustments, such as increasing planting density, improving fertilization time and amount, combined with overall management methods, can enable small

farmers to grow better maize, use resources more efficiently, and earn more money (Wang et al., 2023c). These methods can also protect the environment, such as reducing greenhouse gas emissions and fertilizer waste. The study also shows that this approach is not only suitable for the North China Plain, but can also be promoted in other maize-growing areas with similar problems to narrow the yield gap and promote greener and more efficient agricultural development.

6 Challenges and Future Perspectives

6.1 Variability in genotype × environment × management interactions

Maize yields are affected by many factors, especially the interaction between variety, climate, and planting methods. The relationship between these three factors is complex. In recent years, climate change has become more and more obvious, with extreme heat, irregular rainfall, drought, and heat waves becoming more common. These will affect maize yield and stability (Zhang et al., 2023). Methods such as planting density and fertilization are not equally effective everywhere. It depends on local climate conditions and whether the maize variety is suitable. Therefore, the key to increasing yields is to choose the right variety according to local conditions and combine it with appropriate management methods (Xiao et al., 2020). In the future, characteristics such as drought resistance, heat resistance, long growth period, and more efficient use of resources will become increasingly important. Because they can help maize grow well in various environments (Wu et al., 2025).

6.2 Limitations in current research and practice

Many current studies only look at one factor, such as fertilization or seed density, and the time period is not long. This makes us not have a clear understanding of their long-term effects in different environments. At the same time, there is a lack of detailed research that combines weather forecasting, management methods and variety improvement. In reality, there are also many difficulties, such as farmers lacking money, not being able to buy good seeds, or not knowing how to use these new methods. These problems particularly affect small farmers and farmers in developing countries (Waqas et al., 2021). In addition, social problems such as gender inequality and poverty also make it difficult to promote many good technologies (Cairns et al., 2021).

6.3 Innovations for enhanced optimization

To make progress in the future, we need to combine precision agriculture, climate-adaptive breeding, and data-supported decision-making methods. For example, adjusting planting time, selecting late-maturing varieties that are heat-resistant and drought-resistant, or combining mulching with mulch can help improve yields and water conservation efficiency under climate change (Huang et al., 2020). In terms of new technologies, gene editing tools such as CRISPR can help us breed maize varieties that are more resistant and more resource-efficient (Gong et al., 2015). At the same time, with the help of machine learning and model simulation, we can make more reasonable planting recommendations based on the conditions of different regions. These methods can support our goals of high yields and environmental protection, and also help global food security.

7 Conclusion

If you want to increase maize yields, planting properly and applying fertilizers reasonably are the key. Planting more densely, choosing varieties that can adapt to high density, and adding scientific water and fertilizer management, there is hope for increased yields. The ideal density recommended globally is about 8.7 plants per square meter. This density, combined with the right amount of nitrogen fertilizer, can make maize more productive, while also making better use of water and fertilizer. If too much fertilizer is used, it will not only be of no benefit, but will waste money and may pollute the environment. During the planting process, if the leaf and branch structure of maize can be better managed, such as making light and nitrogen fertilizer more reasonably distributed among plants, it can also further improve resource utilization and narrow the yield gap.

Overall, farmers can start from the following aspects: plant more densely, but within a reasonable range; choose varieties suitable for dense planting; apply fertilizer according to the actual needs of crops, taking into account soil and weather conditions. At the same time, it is also important to promote some precise management methods that are adapted to local conditions. For example, arranging irrigation and fertilization according to different growth periods can not only increase yields, but also improve quality, save resources, and put less pressure on the

environment. In order to make these good methods more quickly available, extension departments and policymakers can do more publicity and training to help farmers learn new technologies, especially small farmers. At the same time, policies can encourage everyone to adopt efficient and low-pollution planting methods, such as rational fertilizer use and improved management methods.

As long as we reasonably arrange the planting density and fertilization methods without disturbing existing farming, there is still room for improvement in maize yields. If these practices can also be combined with new technologies such as variety improvement and precision agriculture, it will help us achieve the two goals of increasing food production and protecting the environment at the same time. In order to make these goals a reality, continuous research, technological innovation and policy support are needed to ensure that maize yields are high and sustainable.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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