Strategic Study of CAE 2022 Vol. 24 No.5
DOI 10.15302/J-SSCAE-2022.05.011

Exploring Water-and-Land-Adapted Spatial Layout of Crop Planting in North China

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Abstract: North China has specific regional advantages in the overall economic and social development of the country, and water resources is the most prominent factor affecting the sustainable development of this region. This study focuses on the spatial layout of land for water- and land-adapted planting in North China. Based on the analysis of the agricultural planting structure and water and land resource layout in North China in the current year (2018) while considering varied population, climate, socioeconomic scenarios, and water resource constraints, we propose a scheme for optimizing the agricultural planting layout in North China that adapts to local water and land resource conditions. We suggest reducing the burden on the production and supply of commercial grains and other commercial agricultural products in North China. To improve the regional water resource carrying capacity, Hebei province should alleviate its water shortage through water transfer. Shanxi province should improve its agricultural water use efficiency through agricultural mechanization and modernization. Shandong and Henan provinces can moderately fallow land and improve forest and grass coverage. We also recommend to optimize the spatial layout of agricultural planting and adjust the planting structure to adapt to water. In shallow groundwater overexploitation areas, and in Tianjin City and the southeastern Hebei Plain, where deep groundwater overexploitation is severe, semi-arid land planting systems and structures that adapt to precipitation should be developed, and the specific recuperation period should be determined according to the rate of groundwater recharge.
Keywords: North China; water balance; land spatial planning; water-adapted land use; matching of water and land resources; water-adapted planting

1 Introduction

To perform land space planning scientifically and optimize the patterns of land development, utilization, and protection, we need to take measures that adapt to water conditions. With the overall goal of achieving a balance between the supply and demand of water resources in terms of land space planning, ecological restoration, and ecological system construction, sorting the current situation and existing problems of land space development and utilization and proposing land space utilization strategies that adapt to the conditions of water and soil resources are of great significance. North China has regional advantages in many aspects and has a significant impact on the overall economic and social development of China. Under the condition of water resource shortage, regional agriculture has provided key support for ensuring national food security and for promoting the comprehensive development of rural areas, but it also presents challenges with negative ecological and environmental effects in many aspects, especially the problem of compound drawdown cones resulting from groundwater overdraft for many years, which threatens the sustainable development of irrigation agriculture. Therefore, to clarify the existing problems with water and soil resources, we propose a regional agricultural planting layout plan to adapt to the

Received date: July 5, 2022; **revised date:** September 13, 2022
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Funding program: CAE Advisory Project "Strategic Research on Water Balance and Territorial Space Coordination (Phase I)" (2020-ZD-20)
Chinese version: Strategic Study of CAE 2022, 24(5): 089–096
Cited item: Huang Feng et al. Exploring Water-and-Land-Adapted Spatial Layout of Crop Planting in North China. *Strategic Study of CAE*, https://doi.org/10.15302/J-SSCAE-2022.05.011

conditions of water and soil resources for theoretical research and practical applications to promote the healthy development of agriculture in North China.

The North China region considered in this study includes the Beijing Municipality, Tianjin Municipality, Hebei province, Shanxi province, Shandong province, and Henan province. The regional population accounts for 24.6% of the total population of the country, and the corresponding cultivated area accounts for 21.2% of the overall area. Owing to its ample light and heat resources and fertile soils, the North China area has become the most important agricultural and animal husbandry production and commodity grain base in China and an important industrial manufacturing and urban agglomeration center. North China has a semi-arid and semi-humid monsoonal climate. The total water resources account for only 3.72% of that of the country, whereas the per capita water resources are approximately 16% of the national average [1]. Water resources constitute a major obstacle to economic and social development and the improvement of living standards of residents in North China. Moreover, it has become a key control factor to be considered in the new round of land space planning.

Most studies have focused on the allocation of water resources and agricultural water in North China [1–4]. Considering the new needs of the land space planning level [5], exploring the optimization of planting layouts in North China that adapt to the conditions of water and soil resources is necessary. Thus, we aim at the overall goal of water balance of land space planning, ecological restoration, and ecosystem construction. It analyzes the current situation of agricultural planting structure and water and soil resource layout of the main agricultural areas in North China (2018), while considering the constraints of population, economy, society, climate scenario, water resources carrying capacity, etc., to form an optimization plan for agricultural planting layout in North China and recommend countermeasures and suggestions. It should be noted that a large amount of data were involved in this study. Except for the data with reference sources, all data resulted from the modelling work of this research.

2 Current status and problems of agricultural planting and water–soil matching in North China

2.1 In the case of a slight reduction in the area of cultivated land, it still bears the responsibility of national food production

North China is an important grain-producing area. Since the reform and opening up, the proportion of the planting area of major crops (grains, vegetables, oilseeds, and fruit trees) in the country has been stable. During the same period, the national share of the total grain output in North China was stable with an average level of approximately 24.5%. The outputs of wheat, corn, millet, oil, and vegetables accounted for 45.7%–63.4%, 29.5%–39.6%, 41.2%–72.3%, 22.7%–36.3%, and 29.8%–40.5%, respectively. The proportion of cotton and bean production has decreased significantly; cotton production decreased from 26.3% in 1978 to 7.13% in 2021, whereas bean production decreased from 22.9% in 1991 to 9.44% in 2020 [6].

Although the area of cultivated land has declined, North China still bears the heavy responsibility for national food and food production, which is reflected in the improvement in the total planting area of crops and the increase in the output of bulk crops. For example, grain production increased from 9.187×10^7 t in 1992 to 1.711×10^8 t in 2020, and the output of wheat and corn increased from 2.555×10^7 t and 1.961×10^7 t in 1978 to 8.065×10^7 t and 8.103×10^7 t in 2020, respectively. From 1978–2021, oil production increased from 1.43×10^6 t to 1.078×10^7 t; cotton output decreased from 2.72×10^6 t to 5.2×10^5 t from 1983 to 2020. The bean output has experienced fluctuations, and the output range is 1.28×10^6–4.53×10^6 t [6].

The changes in the planting structure in North China are as follows. From 1978–2021, the proportion of grain crops in the total sown area is stable, with a maximum of 83.4% in 1978, a minimum of 65% in 2003, a multiyear average of 75.1%, and the proportion being 76.7% in 2020. The proportion of wheat-sown area to grain-sown area was 46.4% in 2006, 39.1% in 1981, 43.9% on average, and 43.1% in 2020. The proportion of the corn planting area to the grain planting area was 46.7% in 2016, 22.9% in 1984, 33.3% on average, and 45.1% in 2020. The proportion of the soybean planting area to the grain planting area decreased from 4.97% in 1978 to 2.06% in 2020. The proportion of oil crop planting areas to total crop planting areas increased from 4.13% in 1978 to 7.18% in 2020. The proportion of vegetable planting areas to crop planting areas increased from 2.54% in 1978 to 11.46% in 2020. From the perspective of planting structure, wheat accounts for over 40% of the high water-consumption crops in North China, and the proportion of vegetables has increased steadily [6].

DOI 10.15302/J-SSCAE-2022.05.011

2.2 Irrigation water efficiency and water productivity have been continuously improved, but the shortage of water resources has not been fundamentally alleviated

Considering the continuous reduction in precipitation in North China, according to the precipitation statistics and hydrological year classification results of the six provinces and cities in North China from 1981–2018, there were five low-water, six normal-water, and seven high-water years from 2001–2018. Among them, 2008–2013 was a continuous normal-water-year interval, 2003–2005 and 2016–2018 were two continuous high-water-year intervals, and the proportion of normal- and high-water years reached 72%. Over the past 20 years, the average annual precipitation in North China has been 601 mm. The average precipitation in low-water years is 522 mm, 601 mm in normal-water years, and 657 mm in high-water years. It can be seen that the trend of precipitation reduction in North China has eased since 2000.

The annual division of precipitation during the growth period of the winter wheat–summer maize system in North China shows that the growth period of winter wheat from 2001–2018 included four low-water years, seven normal-water years, and seven high-water years. Among them, 2012–2014 was a continuous normal-year interval, and 2015–2018 was a continuous high-water-year interval. Precipitation conditions have improved since 2010, and only 2011 was a low-water year. The growth period of summer maize was five low-water years, six normal-water years, and seven high-water years. Except for the low-water years of 2014–2015, the remaining years were either normal or high-water years. The growth period of spring corn was five low-water years, seven normal-water years, and six high-water years. Since 2010, there have been only three low-water years. Regardless of the annual distribution of precipitation or the annual distribution of precipitation during the growth period of the main crops, the normal- and high-water years in the first 20 years of the 21st century constitute the majority. However, from the perspective of long-term climate change trend, no matter in the normal- or high-water years, compared with the previous climate period (1970–2000), the 600 mm isoline of the precipitation line in North China has shifted to the Yellow River at the junction of Hebei, Shandong, and Henan provinces. This important change represents the obvious change in climate, and has important guiding significance for understanding the history of water consumption of the planting industry in North China in the past 20 years and performing the "water-adapted" planting restructure in the future.

During the growth period of winter wheat, winter wheat in different provinces in different hydrological years is in a state of precipitation deficit. Even in a high-water year, the average water deficit in other regions is 100–150 mm, except for the deficit in Henan province is less than 100 mm. The Hebei Plain, western Shandong, and northern Henan are regions with a relatively serious water deficit of wheat, with an average of 150–270 mm. The growth period of summer corn is dry, and the Hebei Plain, northwestern Shandong, and northern Henan are still facing a precipitation deficit. Therefore, from the perspective of the farmland water balance, the precipitation in northern Henan, northwestern Shandong, and the Hebei Plain under different hydrological year types cannot meet their respective water consumption needs. This zone is identified as "farmland water imbalance zone," which is highly consistent with the "groundwater over-extraction drawdown cone" in North China. Therefore, North China requires a considerable amount of irrigation to achieve its current crop output level. The total water consumption in the region increased from 7.802×10^{10} m^3 in 2000 to 7.836×10^{10} m^3 in 2020 with relatively slow growth. Agricultural water withdrawal increased from 5.354×10^{10} m^3 in 2000 to 4.197×10^{10} m^3 in 2020, representing a significant decrease of 21.6%. The proportion of agricultural water withdrawal to the total water withdrawal decreased from 68.6% in 2000 to 53.6% in 2020, which is significantly lower than the national average (62.1%), but the regional distribution varied greatly. For example, agricultural water withdrawal in Beijing accounts for only 7.9% of the total water withdrawal, while the corresponding proportions in Tianjin, Hebei, Henan, Shandong, and Shanxi are 37.1%, 58.9%, 52.1%, 60.2%, and 72.8%, respectively [7].

In North China, agricultural water withdrawal and its proportion of the total water withdrawal have decreased significantly under the condition of increasing agricultural production and a more intensive production mode, indicating that the efficiency of agricultural water withdrawal has improved significantly. The effective utilization coefficient of irrigation water in the region increased from 0.573 in 2000 to 0.647 in 2020, which is 14.5% higher than the national level. Tianjin has made significant progress in this regard. In 2020, the effective utilization coefficient of irrigation water in Tianjin was 0.72, which was 22.6% higher than that in 2000; 0.75 (18.9% higher) in Beijing, 0.617 (16.5% higher) in Henan, 0.646 (15.3% higher) in Shandong, and 0.675 (9.50% higher) in Hebei. The water productivity of grain crops in North China increased from 1.058 kg/m^3 to 1.543 kg/m^3, which was 22.8% higher than the national level [8]. During the same period, the average irrigation amount per *mu* (1 *mu* ≈ 666.67 m^2) of each province in North China decreased significantly, and was generally more than 50% lower than the national level. The average irrigation volume per *mu* in Hebei, Henan, Shandong, Beijing, Tianjin, and Shanxi decreased from 252 m^3 to 157 m^3 (37.7% decrease), 197 m^3 to 164 m^3 (16.7% decrease), 261 m^3 to 160 m^3 (38.7% decrease), 290 m^3 to 119 m^3 (34.1% decrease), 275 m^3 to 230 m^3 (16.4% decrease), and 270 m^3 to 171 m^3 (36.7% decrease) between 2000 and 2020, respectively [7].

The average annual precipitation in North China from 2000–2020 is 4.213×10^{11} m^3 (equivalent to water depth of 606 mm), of which the amount of surface water resources thus formed is 5.935×10^{10} m^3, groundwater resources is 5.841×10^{11} m^3, and the corresponding total water resources is 9.467×10^{11} m^3. The average annual total water withdrawal was 7.666×10^{10} m^3, including industrial water withdrawal of 1.262×10^{10} m^3 (16.5%), urban domestic water withdrawal of 1.242×10^{10} m^3 (16.2%), and agricultural water withdrawal of 4.846×10^{10} m^3 (63.2%) [7]. During the same period, the average annual water consumption of farmlands in North China was 706 mm. From the perspective of water balance (water consumption minus precipitation), the average annual water deficit of farmland in the past 20 years has been 100 mm, equivalent to 2.43×10^{10} m^3. (Note: By dividing the actual evapotranspiration (after the water deficit of crops is met) using the effective utilization coefficient (0.614) of irrigation water in 20 years, the average irrigation water in 20 years is 3.96×10^{10} m^3, which is approximately equal to the average actual irrigation volume of farmland in North China in 20 years (4.36×10^{10} m^3). The calculation results in this study, which were verified using the water balance equation, were consistent with the statistical results in the Water Resources Bulletin.)

According to the characteristics of farmland irrigation water consumption and precipitation water consumption in North China over the past 20 years [1], combined with the regional average water productivity (water consumption per ton of grain: 763 m^3) and average total grain output (1.438×10^8 t) [8], it can be estimated that the average annual water consumption of farmlands in North China is 1.097×10^{11} m^3, i.e., 3.78×10^{10} m^3 from irrigation water and 7.19×10^{10} m^3 from precipitation. Over the past 20 years, the average proportion of groundwater supply to the total water supply in North China has been 56%. Owing to the mismatch between the temporal and spatial distributions of irrigation demand and surface water sources, the proportion of groundwater in farmland irrigation is higher than 56%. The calculation results show that the annual average amount of groundwater pumped for irrigation in North China over the past 20 years has been 3.489×10^{10} m^3, accounting for 59.7% of the annual average groundwater resources, which is obviously high.

2.3 The matching of agricultural water and soil resources is unbalanced, and the contradiction between agricultural output and water resources carrying capacity is prominent

The agricultural water and soil resources in North China are highly mismatched. The water resources per unit of cultivated area were 208 m^3/*mu* (16.7% of the national level) in 2000 and 253 m^3/*mu* (18.6% of the national level) in 2018. There was a slight apparent increase; however, because the two years were high-water years and the cultivated land area was slightly reduced, the relevant changes were not statistically significant. From the perspective of land spatial distribution, the water resources per unit of cultivated area in Hebei (12.4% of the national average) and Shanxi provinces (14.8%) were the most unbalanced, whereas that in Tianjin City (19.8%), Henan province (20.6%), and Shandong province (22.2%) were all approximately 20% of the national level. Only that in Beijing is close to the national level (81.6%); however, this is related to the reduction in cultivated land caused by industrial policy adjustments in recent years. In terms of the time change of water–soil matching, the mismatch of agricultural water and soil resources in Tianjin was aggravated, whereas agricultural water–soil matching in other provinces tended to be balanced. The basic situation of serious water shortages in Tianjin and Hebei province and moderate water shortages in Shanxi province has not changed. In the context of current rapid economic and social development, it is difficult to reverse the highly mismatched situation of water and soil resources in the short term, which is a major challenge faced by food security in North China.

North China is an important area for guaranteeing China's food security; however, the shortage of water resources in this area is severe, with the per capita water resources and the proportion of soil and water resources allocation being significantly lower than the national average. Due to the decrease in water resources caused by climate drought and the increase in demand for water resources caused by the development of industrial cities, the total amount of agricultural water in this area is decreasing year by year. However, with the improvement of agricultural production conditions, crop output has steadily increased; for instance, the total grain output of the main wheat and corn producing provinces (i.e., Hebei, Henan, and Shandong) increased by 5.85×10^7 t in the past three decades, which is mainly owing to the substantial increase in the grain yield per unit area. The grain yields per unit area of wheat and corn increased by 200.9 kg/*mu* (an increase of 120%) and 179 kg/*mu* (an increase of 90%), but water consumption did not increase significantly with the increase of grain yield per unit area. Therefore, it can be assumed

DOI 10.15302/J-SSCAE-2022.05.011

that the continuous increase in agricultural output under the condition of reduced total agricultural water consumption is mainly due to the progress of agricultural science and technologies and the improvement in agricultural infrastructure. It should also be noted that under the trend of climate drying and warming in North China in the future, whether agriculture in there can continue to bear such a scale of production is a major problem that cannot be ignored.

In addition to meeting the regional demand for calories, agriculture in North China shoulders the important tasks of national food security. From 1998 to 2018, the food calorie supply in North China was sufficient, and the self-sufficiency rate continued to rise. However, the rigid growth in food consumption coexists with hard constraints on resources and the environment. While the supply capacity improved, cultivated land and water resources will inevitably present challenges, especially the severe supply and demand deficits in calories in Beijing, Tianjin, and Shanxi. Under the premise of not increasing the load of water and soil resources, maintaining the production capacity of the main grain-producing areas in Henan, Shandong, Hebei, and other provinces in the case of water-adapted production is a fundamental solution.

According to the evaluation results of the water and soil resource carrying capacity in North China, the matching coefficients of agricultural water and soil resources, sewage treatment rate, agricultural water use ratio, and reclamation rate in Beijing are Grade I, which is the main reason for the high carrying capacity of agricultural water and soil resources in Beijing. However, the high population density, high urbanization level, and low contribution rate of primary industries in Beijing restrict the scale of agricultural development. Therefore, the potential for agricultural development must be improved. Increasing grain output by improving the level of agricultural machinery power applications will increase the carrying capacity of agricultural water and soil resources. As a metropolis in North China, Tianjin, like Beijing, also has a high population density, high urbanization level, and a low contribution rate of the primary industry. Agriculture is not a primary industry in terms of development. Poor water quality in the region (the rate of reaching the standard in the water function area and the rate of sewage treatment are Grade IV) is also the main reason for the low carrying capacity of water and soil resources.

Hebei province has a large area and low population density compared with Beijing and Tianjin. Accordingly, the proportion of agriculture was slightly higher, and the contribution rate of the primary industry was 9.27%. Agricultural mechanization is relatively developed, and the power consumption per unit area of cultivated land and total power of agricultural machinery are Grade I. The main factor causing the low bearing capacity of water and soil resources in Hebei province is the low water quality (mainly poor quality water), such as the large amount of shallow salt water in the Heilonggang area (2–5 g/L of brackish water can be used annually at approximately 2.2×10^9 m^3). The water function zone compliance rate, sewage treatment rate, gross domestic product (GDP) of 10 000 CNY, and chemical oxygen demand of Hebei are all at the IV–V levels and require improvement. We should provide importance to the water quality in the region and optimize the carrying capacity of water and soil resources by improving the sewage treatment rate and reducing sewage discharge.

The carrying capacity of agricultural water and soil resources in Shanxi province is low in North China (only 0.362) and overloaded. The main reasons for this are the low matching coefficient of agricultural water and soil resources, high water consumption per 10 000 CNY of agricultural GDP, high proportion of agricultural water consumption, low effective irrigation rate of farmland, low power consumption per unit area of farmland, and low total power of agricultural machinery. These index grades also reflect that agricultural development in Shanxi province lags behind and that the low efficiency of agricultural water resource utilization has resulted in the waste of agricultural water resources. Only by promoting agricultural mechanization and modernization and promoting the development of water-saving strategies can the carrying capacity of water and soil resources in Shanxi province be substantially improved. Henan and Shandong provinces are in a critical state of carrying water and soil resources, mainly because of the high proportion of local reclamation and agricultural water at 48.58% in Henan province and 48.07% in Shandong province. Additionally, the low coverage of forest and grass is a factor affecting the carrying capacity of water and soil resources in Shandong province.

3 Optimal allocation of agricultural planting land space in North China under the constraint of water and soil resources

3.1 Dynamic prediction of agricultural development scale in North China

The carrying capacity of agricultural water resources is mainly reflected in two aspects: the carrying capacity of available agricultural water resources on the effective irrigation area of cultivated land, and water resources that can be used to irrigate the carrying capacity of grain produced by agriculture to the population of the river basin. Hebei, Shandong, Henan, and Shanxi are the core regions of national grain growth. The main constraints affecting regional grain production are the low development potential of surface water, overexploitation of groundwater, and an obvious shortage of water supply. The calculation model of carrying capacity in irrigation area, carrying capacity in grain production, and carrying capacity in population size is established by adopting multiple schemes. By considering the dynamic changes in water conservation, climate, technology, and other factors, the carrying capacity of agricultural water resources in North China under the condition of an annual average water inflow is discussed.

First, the amount of irrigation water available for agriculture in the region was analyzed. North China has developed production, a dense population, fierce competition for water in different industries, a large modulus of economic and social water demand, and relatively severe problems of water resource degradation, water resource shortages, water ecological degradation, and water environmental pollution. To realize sustainable development in North China, establishing a water resource allocation engineering system and comprehensively utilizing surface water, groundwater, water diversions from the Yellow River, south-to-north water diversions, and unconventional water sources is necessary. Therefore, 2025, 2030, and 2035 were selected as the target years for prediction. The water supply of the Yellow River, the Yangtze River, surface water, and groundwater were predicted according to the overall planning of the South-to-North Water Transfer Project, the planning of the Central/East Line Project, the Water Resources Bulletin, the planning report of the six provinces and cities in North China, and other data sources. The unconventional water supply volume in North China was calculated by comprehensively considering the planning of relevant industries and departments in each province, the technical and economic feasibility, and other constraints. The proportion of irrigation water was based on the changing trend of the proportion of irrigation water in each province from 2014–2018, and the proportion of irrigation water in each province in 2025, 2030, and 2035 was calculated to determine the available water for agricultural irrigation.

Second, the effective irrigation area that the region could carry was calculated according to the ratio of irrigation water supply to irrigation water use per *mu*. Spreading water-saving facilities can reduce the amount of irrigation water available for agriculture, thus increasing the area for effective irrigation. Future water-saving factors were predicted according to changes in water-saving areas over the past 10 years. Climate factors, such as warming and precipitation reduction, will increase the average irrigation water per *mu*, thereby adversely affecting the effective irrigation area. According to the calculations, the effective irrigation area that can be carried by irrigation water in 2025, 2030, and 2035 in the six provinces and cities in North China is higher than that in the current year. For example, by 2025, Beijing could carry 7.42%–17.3% more irrigation areas, Tianjin 42.78%–97.54%, Hebei 29.11%–46.77%, Henan 17.22%–28.82%, Shandong 17.92%–29.64%, and Shanxi 0.7%–16.23%. The increase in Beijing is small because water-saving facilities have been widely promoted (water-saving irrigation ratio is close to 1), whereas the increase in Henan and Shandong provinces is small because the average irrigation water per *mu* has reached a high level (difficult to further reduce). In 2030 and 2035, the effective irrigation area carried by irrigation water will further increase in the six provinces and cities of North China with a continuous increase in external water and continuous improvement of farmland water conservancy facilities.

Third, the grain output that a region can carry was calculated as the product of grain yield per *mu* and planting area, and the planting area was calculated according to the relationship between the irrigation area and planting area in the six provinces and cities in North China. Agricultural machinery farming, water-saving irrigation, fertilization, and other scientific and technological factors can improve grain yield. Based on the scientific and technological progress in recent years and the results of the literature review, the scientific and technological factor ranges in future years were predicted. Compared to the grain output of the current year, by 2025, Beijing, Tianjin, Hebei, Henan, Shandong, and Shanxi can carry 35.12%–49%, 59.21%–122.31%, 36.91%–57.1%, 20.93%–34.13%, 20.51%–33.76%, and 6.87%–24.41% more output, respectively.

Finally, the population size of the region is calculated as the ratio of the total grain output to per capita grain demand. In 2025, 2030, and 2035, the population of North China (excluding Beijing and Tianjin) will be higher than the actual population size of the current region to varying degrees, indicating a transfer of grain between different provinces. This result corresponds to the research conclusions of existing literature: Hebei, Henan, Shandong, and Shanxi are grain export areas, whereas Beijing and Tianjin are grain import areas.

The forecast results show that the irrigation water volume in North China will be 5.675×10^{10} m^3, 5.842×10^{10} m^3, and 5.818×10^{10} m^3, the supporting irrigation area is 346.6 million *mu*, 361.8 million *mu*, and 364.6 million *mu*, the supporting grain yield is 2.273×10^{11} kg, 2.419×10^{11} kg, and 2.487×10^{11} kg, and the population that can be carried is 588 million, 626 million, and 644 million in 2025, 2030, and 2035, respectively.

DOI 10.15302/J-SSCAE-2022.05.011

3.2 Optimization scheme of water-adapted planting for farmland water imbalance zone in North China

The northern part of Henan, the northwestern part of Shandong, and the Hebei Plain constitute the farmland water imbalance zone in China. Consider the Hebei Plain, where groundwater overdraft is relatively serious, as an example, the optimization scheme of water-adapted planting is discussed.

The groundwater overdraft areas in Hebei province are mainly distributed in the Hebei Plain, of which the shallow groundwater overdraft areas are distributed in the piedmont plain area of the Taihang Mountains to the west of the Hebei Plain (including Baoding City, Shijiazhuang City, Xingtai City, the west of Handan City, and some counties on the Zhangjiakou Dam), and deep groundwater overdraft areas are distributed in the Heilonggang area (mainly Cangzhou City, Hengshui City, Xingtai–Handan eastern counties, and the southern counties of Tangshan). The planting system for winter wheat and summer corn in this region is mainly based on pumping groundwater for irrigation, especially because of the shortage of natural precipitation during the growth period of winter wheat. Large amounts of groundwater must be pumped for irrigation to meet the growth requirements of winter wheat. To alleviate the decline in groundwater levels and maintain the sustainable exploitation of groundwater resources, the planting pattern of winter wheat in groundwater overmining areas should be adjusted in a timely manner, and the planting scale of vegetables with high water-consumption should also be adjusted. Thus far, two types of planting structure adjustment models are proposed to support water saving and mining reduction: keep the original winter wheat–summer corn system unchanged, reduce the annual winter wheat planting area, and achieve seasonal fallow. The planting scale of winter wheat is determined in advance according to the different combinations of hydrological year types by adopting the method of “water-adapted planting.”

Pumping groundwater for irrigation during the growth period of winter wheat is the major reason for the decline in groundwater level; therefore, reducing the planting area of winter wheat is a direct way to reduce irrigation water withdrawal. Based on the goal of irrigation water savings of 50 m^3/*mu* in the groundwater-overdrawn area of Hebei province, the planting proportion of winter wheat to be reduced in different hydrological years is discussed (this study calculates the irrigation water consumption based on the difference between precipitation and water consumption, and the unit irrigation water consumption is low owing to more precipitation in the high-water year. Under the same irrigation water saving goal, more winter wheat planting areas need to be reduced in the high-water year, whereas the opposite is true in the low-water year). As precipitation is the only natural source of water for winter wheat during its growth period, to make full use of precipitation resources and reduce groundwater extraction, the winter wheat planting mode of rainfall-adapted planting (mainly refers to adjusting the planting scale according to the hydrological year types, and the dryland wheat planting mode will be considered later) should become the focus of the current consideration. To achieve the goal of less planting in low-water years and more in high-water years, when taking irrigation water saving as a measure, the inter-annual variation of precipitation and the distribution of hydrological year patterns should be fully considered, i.e., the water saving goal in low-water years is low, the water saving goal in high-water years is high, and the overall water saving balance should be achieved. Additionally, water consumption during the growth period of winter wheat was the highest in the low-water year and lowest in the high-water year. Therefore, the water consumption during the growth period of winter wheat should be reduced as much as possible to adapt to rainfall-adapted planting modes.

Based on the above analysis, starting from the inter-annual distribution of precipitation, the relationship between water consumption and water saving of winter wheat irrigation, the planting area of winter wheat and irrigation quota and the goal of irrigation water saving in all combinations of hydrological year type and planting mode is further discussed, and the winter wheat planting mode “rainfall-adapted planting” is formulated accordingly.

3.3 Study on water-adapted planting system in North China

We comprehensively analyzed the effect of water-adapted planting of 31 diversified planting systems in the North China Plain in the past 30 years, clarified the optimized water-saving irrigation mode and water-saving potential of the traditional winter wheat–summer maize two-cropping system through long-term positioning test, and explored the adaptability indicators, such as groundwater consumption, yield, economic benefits, and water use efficiency, of 30 planting systems (including mono-cropping and rotation under rain-fed and irrigation conditions). From the perspective of water and soil adaptation in North China, it is necessary to consider light/heat/water resource endowments as a whole, develop diversified planting systems according to local conditions, and ensure the coordination of the sustainable utilization of water resources in North China with the dual security of food production and green agricultural development.

4 Optimization measures of agricultural planting layout in North China

4.1 Adjust regional function positioning

According to the current water resource situation, future climate change, and social development scenarios in North China, it is necessary to perform a reassessment and positioning adjustment of the grain and food security status in North China at the national level. This is particularly urgent for Beijing–Tianjin–Hebei, northern Henan, and northwestern Shandong, which are located in a groundwater overdraft area in North China. By meeting the economic development, urbanization construction, livelihood improvement of residents in North China and ensuring food security in North China and the rest of the country, the production and supply burden of commercial grain and other commercial agricultural products in North China can be moderately alleviated in the future. It is necessary to give the cultivated land, water resources, and ecosystem in North China time to recuperate, support the sustainability of food and food security in North China and the entire country in the future, and finally realize the water resources guarantee ability in North China that adapts to multiple objectives and reflects the background of internationalization and greening.

4.2 Strengthen water and soil adaptation

The development and utilization of water resources were high in the western region, and the development and utilization of land resources were high in the eastern region. The overall pattern of water and soil resources of "water shortage in the northwest and soil shortage in the southeast" reflects the extremely uneven distribution of water and soil resources in the country. The shortage of water resources is a key factor in the current situation of water–soil matching in North China. Improving the matching of agricultural water and soil resources is an effective way to improve the comprehensive benefits of agricultural production in North China. For Beijing and Tianjin, where the proportion of agricultural water consumption is much higher than the proportion of cultivated land area, and Shandong and Hebei provinces, where the proportion of agricultural water consumption is slightly higher than the proportion of cultivated land area, active measures should be taken to adjust the crop planting structure, switch to low-water consumption crops or expand the application of water-saving irrigation technology, strictly implement the water resources management system, and maintain the red line of water resources and cultivated land area.

4.3 Improve resource carrying capacity

The carrying capacity of water and soil resources in North China has obvious spatiotemporal variations, and the level of sustainable agricultural development in each province is constrained. Considering the dynamic evolution of water conservation, climate change, agricultural science and technology, and based on the dynamic prediction results of the future agricultural development scale in North China, it is clear that ways to improve the carrying capacity of water and soil resources in each province are as follows: Tianjin should take improving water quality as the main improvement measure, whereas in Hebei, the shortage of water resources can be alleviated through water diversion and other methods while improving water quality. Shanxi should vigorously promote agricultural mechanization and popularization of agricultural water saving, the improvement of agricultural water use efficiency, and the realization of agricultural modernization, while Shandong and Henan need to perform appropriate fallow (to reduce the area of cultivated land) and improve the coverage of forest and grass.

4.4 Optimize the spatial layout of agricultural planting

On the basis of comprehensive consideration of multiple objectives, such as hydrological year type, balance of groundwater extraction and replenishment, irrigation and water-saving objectives, food and nutrition, and heat safety, North China has made great efforts to adjust the spatial distribution of land for planting production, and substantially implemented water-decided land. In the deep groundwater overdraft area in North China, scientific methods and resolute measures should be taken to optimize the planting space layout of large water users of irrigation water demand represented by winter wheat (precipitation and water demand mismatched type) and vegetables (high water-consumption type). The reduction in production capacity caused by blocking groundwater extraction can be compensated for and balanced regionally and nationally. Particularly, in the southeastern Hebei Plain (Cangzhou City, Hengshui City, and Xingtai–Handan East counties) and Tianjin City, where deep groundwater overdraft is severe, and in the shallow groundwater overdraft areas (Taihang Mountain piedmont plain, northern Henan, and northwestern Shandong), it is necessary to adjust measures to local conditions strictly in accordance with local water resources, population, and socio-economic carrying capacities, and scientifically plan and reasonably allocate

DOI 10.15302/J-SSCAE-2022.05.011

agricultural and planting water resources. The rainfall-adapted semi-dry land planting system and structure needs to be developed, and the length of the recuperation period needs to be determined according to the rate of groundwater recharge.

4.5 Adjust planting structure according to water availability

In North China, in areas with severe groundwater overdrafts, the planting scale of high-water-consuming crops should be appropriately reduced, the proportion of fallow should be reasonably increased, and seasonal fallow and rain-fed planting modes of monocropping, and winter wheat–summer corn multiple cropping should be attempted. For areas with moderate groundwater overdraft, a grain-based diversified rotation pattern of cash crops (1.25 ≤ multiple cropping index ≤ 1.67) can be developed to increase the proportion of fallow, reduce water consumption, and improve economic benefits. For the grain functional area, it is recommended to retain the winter wheat–summer corn planting mode and promote the application of supporting comprehensive water-saving technologies, such as the optimized irrigation system of "two times of wheat irrigation and one time of corn irrigation," the agronomic water-saving measures of improving soil water use efficiency by storing moisture in dry farming, the engineering water-saving technology of water and fertilizer integration, such as drip irrigation/micro-sprinkler irrigation, and the biological water-saving technology of water-saving and drought-resistant varieties. Supporting specific water-saving management policies is also necessary.

5 Conclusion

North China is a key area for grain and food security. Although the precipitation conditions have improved in the past 20 years compared with the average of the past 30 years (1980–2010), compared with the previous climatic period (1970–2000), precipitation and water resources are still deceased as a whole, and groundwater overdraft is serious. Therefore, reducing groundwater exploitation is still a difficult task in the future. This study proposes the concept of sustainable development of agricultural distribution in North China to adapt to the conditions of water and soil resources, grasp one main line (water development), rely on two implementations (water production and water land), and highlight four key points (enhancing water and soil adaptation, improving resource carrying capacity, optimizing agricultural production layout, and adjusting planting structures with water). Based on the full consideration of climate change and economic and social development, the goal combination of hydrological year types, planting structures, water-saving irrigation is used to exert the effect of water-saving, yield protection, water-saving, and stable yield, reduce the demand for groundwater exploitation in the production of vegetables and fruits as much as possible, and pursue a win-win situation of water saving and grain abundance. The relevant research results enrich the existing research conclusions [9–13] and provide a path basis for solving the problem of food security and water use in North China.

To ensure the future food and food safety of production water in North China, it is necessary to consider delimiting the "red line of agricultural water security," which specifically includes the red line of total agricultural water use, the red line of effective utilization coefficient of irrigation water, the red line of total water consumption, and the red line of unit water consumption. In the future, the matching of agricultural water and soil resources with food and food security in North China should strengthen the adaptability of water and soil resources based on the aforementioned water resources and agricultural water use history.

References

[1] Huang F, Du T S, Wang S F, et al. Current situation and futuresecurity of agricultural water resources in North China [J]. Strategic Study of CAE, 2019, 21(5): 28–37. Chinses.

[2] Lai D R, Chen Y P, Qin H H, et al. Impacts of changing environmenton sustainable utilization of groundwater in the North ChinaPlain [J]. Journal of Water Resources and Water Engineering, 2021,32(5): 48–55. Chinses.

[3] Qin H H, Sun Z X, Gao B. Effects of agricultural water conservation and South-to-North Water Diversion on sustainable water management in North China Plain [J]. Resources and Environmentin the Yangtze Basin, 2019, 28(7): 1716–1724. Chinses.

[4] Liu C M. Agricultural water issues in China: Discussions on research highlights [J]. Chinese Journal of Eco-Agriculture, 2014,22(8): 875–879. Chinses.

[5] Zhu P T, Zhang L J. Multi-functional utilization evaluation of land space and zoning utilization strategy [J]. Land Resources Information, 2021 (3): 28–35. Chinses.

[6] National Bureau of Statistics. National data [EB/OL]. (2020-05-15) [2022-07-15]. https://data.stats.gov.cn/. [2022-07-15]. http://www.mwr.gov.cn/sj/tjgb/szygb/. Chinses.

[7] Ministry of Water Resources of the People's Republic of China. Water resources bulletin [EB/OL]. (2020-05-15) [2022-07-15]. http://www.mwr.gov.cn/sj/tjgb/szygb/. Chinses.

[8] China National Agricultural Technology Extension Service Center. China agricultural water use report in 1998—2020 [M]. Beijing: China Agriculture Press, 2021. Chinses.

[9] Wang H, Wang L, Yang G Y, et al. Agricultural water resource in China and strategic measures for its efficient utilization [J]. Strategic Study of CAE, 2018, 20(5): 9–15. Chinses.

[10] Zhou Z H, Yang B, Liu H Z, et al. Study on the influencing factors and security countermeasure of agricultural water in North China [J]. China Rural Water Resources and Hydropower, 2017 (8):24–27. Chinses.

[11] Yan P, Chen Y Q, Sui P. Status and trends of researches on agriculturalwater issues in North China: Based on bibliometric methods[J]. Journal of China Agricultural University, 2016, 21(9): 206–214. Chinses.

[12] Zhang G H, Fei Y H, Liu C H, et al. Adaptation between irrigation intensity and groundwater carrying capacity in North China Plain [J]. Transactions of the Chinese Society of Agricultural Engineering, 2013, 29(1): 1–10. Chinses.

[13] Zhang G H, Lian Y L, Liu C H, et al. Situation and origin of water resources in short supply in North China Plain [J]. Journal of Earth Sciences and Environment, 2011, 33(2): 172–176. Chinses.