Research progress on the impact of climate change on wheat production in China (#99665)

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Research progress on the impact of climate change on wheat production in China

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It is crucial to elucidate the impact of climate change on wheat production in China. This article provides a review of the current climate change scenario and its effects on wheat cultivation in China, along with an examination of potential future impacts and possible response strategies. Against the backdrop of climate change, several key trends emerge: increasing temperature during the wheat growing season, raising precipitation, elevated CO_2 concentration, and diminished radiation. Agricultural disasters primarily stem from oscillations in temperature and precipitation, with the northern wheat region being mostly affected. The impact on wheat production is manifested in a reduction in the area under cultivation, with the most rapid reduction in spring wheat, and a shift in the centre of cultivation to the west. Furthermore, climate change accelerates the nutritional stage and shortens phenology, causing increased yields in northern areas. While future climate change may stimulate wheat yield potential, it could cause climate-induced issues such as weeds, diseases, and pests worsen, thereby posing challenges to the sustainability of farmland. To cope with climate change, this article suggests regional ecological construction of farmland, breeding of high-resistance and high-yield varieties, adopting advanced agricultural management techniques, introducing biological control of new species through scientific introduction, and establishing monitoring and early warning systems. These measures aim to increase the resilience of farmland to environmental stress, improve its sustainability and fertility, reduce pests and weeds, actively respond to extreme weather events, and provide real-time monitoring of the affected area and the recovery status of farmland.

Research Progress on the Impact of Climate Change on Wheat Production in China

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ABSTRACT

It is crucial to elucidate the impact of climate change on wheat production in China. This article provides a review of the current climate change scenario and its effects on wheat cultivation in China, along with an examination of potential future impacts and possible response strategies. Against the backdrop of climate change, several key trends emerge: increasing temperature during the wheat growing season, raising precipitation, elevated CO_2 concentration, and diminished radiation. Agricultural disasters primarily stem from oscillations in temperature and precipitation, with the northern wheat region being mostly affected. The impact on wheat production is manifested in a reduction in the area under cultivation, with the most rapid reduction in spring wheat, and a shift in the centre of cultivation to the west. Furthermore, climate change accelerates the nutritional stage and shortens phenology, causing increased yields in northern areas. While future climate change may stimulate wheat yield potential, it could cause climate-induced issues such as weeds, diseases, and pests worsen, thereby posing challenges to the sustainability of farmland. To cope with climate change, this article suggests regional ecological construction of farmland, breeding of high-resistance and high-yield varieties, adopting advanced agricultural management techniques, introducing biological control of new species through scientific introduction, and establishing monitoring and early warning systems. These measures aim to increase the resilience of farmland to environmental stress, improve its sustainability and fertility, reduce pests and weeds, actively respond to extreme weather events, and provide real-time monitoring of the affected area and the recovery status of farmland.

Key words: Climate change; Yield; Nutritional stage; Planting area

INTRODUCTION

The ongoing global warming trend persists, with the period between 2015 and 2022 registering as the warmest eight years within the span of the 19th and 20th centuries. And 2022 stands out as one of the warmest three years witnessed thus far in the 21st century. Meanwhile, China's annual average surface temperature has been rising at a rate of 0.26°C/10 years (1951-2020), an increase of about 1.8°C from 1951 to 2020, and an increase of 0.92°C from 2021 to 2022 (National Climate Centre, 2023). The rise in temperature is accompanied by the melting of frozen ground and rising sea levels, thereby augmenting the propensity for compounded extreme weather occurrences, resulting in substantial regional rainfall and ecological aridity (Peterson et al.,2008). The year 2021 saw a delayed and subdued onset of the rainy season in the southern regions of China, juxtaposed with an early and intensified manifestation in the northern territories, with Zhengzhou, Henan receiving 552.5 mm of rainfall. The frequency of extreme high temperature events in China has shown a significant increasing trend (1961-2022), with 2022 registering the highest frequency of such events since 1961. These observed climatic shifts predominantly attribute to human emissions of greenhouse gases, with a contribution rate of 76% (Gray, 2007). Therefore, encompasses multifaceted challenges including temperature elevation, intensified precipitation, ecological aridity, and heightened CO2 concentrations, all of which intricately intertwine with crop production dynamics, thereby engendering considerable risks to the stability of crop yields.

Wheat is one of China's most important staple crops, with the second largest planted area after maize and rice in 2019 and a total yield of 1.3360×108 t, accounting for 20.1% of total cereal production (Huang et al., 2017). Statistical data reveal a discernible contraction in cultivated acreage, witnessing a reduction of 9.38×105 hectares between 2016 and 2019. Although the total yield continued to increase, the growth rate slowed down (Huang et al., 2017; Zhang et al.,2023). Therefore, the diminishing cultivated area emerges as a pivotal constraining factor influencing aggregate wheat production (Zhao et al., 2018). Breaking the wheat mono-yield barrier to achieve ultra-high yields is crucial to ensure wheat food security. Moreover, against the background of global climate change, the pursuit of enhanced yield thresholds encounters heightened challenges (Dan et al.,2024; Zhang et al.,2021). Thus, elucidating the contemporary and prospective ramifications of climate change on indigenous wheat cultivation ecosystems and yields assumes pivotal significance. Such attempts not only provide a theoretical underpinning for realizing ultra-high wheat productivity but also furnish cogent insights for climate change appraisal frameworks.

SURVEY METHODOLOGY

The primary retrieval tools used for our research are Google Scholar and the China National Knowledge Infrastructure (CNKI) database, with a few Chinese articles being retrieved from the latter. The objective of this paper is to provide a comprehensive literature review on the impact of climate change on wheat in China. Firstly, we reviewed the effects of climate change on wheat by conducting a search for relevant literature abstracts using the keywords "China wheat" and "climate" in the past three years. Based on relevance, we initially outlined the review from both current and future perspectives of climate change on Chinese wheat. Next, we expanded the search terms to include "China wheat," "climate," "temperature," "carbon dioxide," "radiation," "yield," "growth and development," and conducted a selection of literature from the past five years. After selecting abstracts, we will download full-text articles for further review to determine the positive or negative impacts of climate on wheat production in China. In addition, we have selected some highly cited but older publications as theoretical foundations or references.Our literature selection process was conducted objectively and impartially, taking into account the publication status of the literature. For example, in light of the lack of recent literature regarding wheat phenology and different wheat regions in China, we included papers from 2018 and 2019. The objective of this paper is to provide a comprehensive and objective review of how Chinese wheat responds to climate change. When selecting keywords, all the terms were used in conjunction with "China" to focus the search specifically on China rather than other regions. Additionally, given the abundance of wheat research within China, we utilized the CNKI database, the largest Chinese-language database, to select a portion of the literature. However, it should be noted that these selected papers are globally accessible and constitute only a small proportion of the overall review.

EFFECTS OF CLIMATE CHANGE ON ~~THE~~ WHEAT GROWING ENVIRONMENT

Characteristics of climate change

Greenhouse gas emissions have accelerated the rise in global temperatures (Valone 2021). If global temperatures rise by 1.5°C, the average temperature during the winter wheat growth period will increase by 0.6-1.4°C; if temperatures rise by 2.0°C, the average temperature during the growth period will increase by 0.9-1.8°C. For different wheat areas, the temperature increase is greater in spring wheat areas than in winter wheat areas, with the southwest wheat area showing a greater difference than the northern wheat area (Ye et al.,2020; Wang et al.,2023; Yang et al.,2023). Among the winter wheat areas, Xinjiang emerges as the locus of the most substantial temperature rise, juxtaposed with the northwestern winter wheat areas recording comparatively modest increases. Notably, the Southwest Winter Wheat Area and the Huang-

Huai Winter Wheat Area exhibit the largest and smallest temperature changes within the winter wheat ambit, respectively (Sun et al., 2018). The smallest winter wheat area has an annual temperature increase of 0.43°C, 0.35°C and 0.54°C for average, maximum and minimum temperature, respectively (Chen et al., 2018; Sun et al., 2024). In the spring wheat area (2002-2018), discernible escalations are observed in both average and minimum temperatures, with no significant interannual difference in the highest temperature, especially from the flowering to the ripening period (Ye et al., 2021). It is evident that climate change has increased the average temperature in domestic wheat areas, with differences between spring and winter wheat areas, and a greater impact on spring wheat areas than on winter wheat areas.

Climate change can lead to heavy regional precipitation and ecological drought (Peterson et al., 2008). In China, relative precipitation levels during the wheat growing season (2006-2010) exhibited a notable increase of 9.1-11.3% compared to the historical period spanning from 1986 to 2005 (Sun et al., 2018). However, discernible trends indicate a slight decrement in annual precipitation across the central and eastern regions of China (1961-2017) (Song et al., 2019). For wheat areas, the increase in precipitation is slightly greater in spring wheat areas than in winter wheat areas. Except for the Xinjiang spring wheat area, all spring wheat regions observed heightened precipitation levels, with the northern spring wheat area registering the most substantial increment. In ~~the~~ winter wheat area, with the exception of the northern winter wheat area and select locales in the central and western regions, an overall uptick in precipitation was observed, with the largest increase in the Huang-Huai winter wheat area (Sun et al., 2018; Nie et al., 2019). Evidently, climate change has engendered spatially and temporally changes in precipitation, with spring wheat territories witnessing a comparatively greater increase in precipitation than their winter wheat counterparts.

Climate change also affects factors such as solar radiation and CO_2 concentrations (Peterson et al., 2008; Gray, 2007). Due to the large amount of pollutants emitted into the air by human activities (Xiong et al., 2012), solar radiation in China decreased by about 0.23 W/(m^2·yr) from 1960 to 2000 (Tang et al., 2011). China's atmospheric CO_2 concentration was about 365 ppm in 2000, and it exceeded 400 ppm in 2016 (Deng et al., 2020), an increase of 9.6%. This dual trend of rising CO_2 concentrations alongside diminished solar radiation underscores the impact of climate change on these pivotal environmental parameters.

In summary, the ramifications of climate change extend to an elevation in average temperatures across domestic wheat-growing regions, an erratic spatial and temporal precipitation pattern, augmented CO_2 concentrations, reduced solar radiation, and a disproportionately greater impact on spring wheat territories. Considering the interaction of these changes, climate change presents substantial challenges to the cropping system, growth processes, and the stability and enhancement of wheat yields.

Characteristics of agricultural meteorological disasters

There are many agricultural meteorological disasters affecting wheat, including drought, hail, heavy rain, high temperature and frost damage, with drought and frost damage being the most important meteorological disasters (Gray, 2007; Ye et al., 2020; Zou et al., 2021). Between 1991 and 2009, agricultural meteorological observation stations documented 5902 instances of wheat-related disasters, with natural disasters due to abnormal precipitation being the most common, followed by temperature. High temperatures and low rainfall leading to drought accounted for 79.2% of the total disaster occurrences, while excessive precipitation contributed to 4.0%, and frost damage accounted for 1.32% (Zhang et al., 2013). On average, approximately 4.3×107 hectares of land are affected annually by these natural disasters. Notably, the collective impact of floods, droughts, and frosts covers an average annual area of 3.6×107 hectares (Jiang et al., 2016). These observations underscore the primary role of precipitation and temperature fluctuations in precipitating agricultural meteorological disasters across the nation.

In terms of regions, the Northern Wheat Region is a meteorological disaster-prone area, with Gansu being the most affected province (Zhang et al., 2013), with the most affected provinces being Heilongjiang, Shandong and Henan, and the least disaster resilient provinces being Shanxi and Inner Mongolia (Yu et al., 2017). The spatial pattern of disasters from 1950 to 2013 shows that there are more flood disasters in the middle and lower reaches of the Yellow River and the Yangtze River basin, while drought is more common in the North China Plain and the Loess Plateau (Zhang et al., 2013). The central and south-western regions have more drought (Guan et al., 2015), while the north-western region has more frost damage and the north-eastern region has more drought (Yu et al., 2017). This spatial disparity in meteorological disasters highlights the Northern Region as a high-risk area, delineating significant regional variations in vulnerability.

The frequency of disasters in the wheat reproductive stage is higher than in the nutritional stage (Hussain et al., 2016). From 1991 to 2009, the disaster rate before jointing was 25.1%, which increased to 74.9% after jointing. Among the disaster types, 72% of drought, 88.1% of heavy rain and 100% of high temperature disasters occurred during the reproductive stage. Therefore, anomalies in atmospheric circulation resulting in uneven rainfall distribution (Jiang et al., 2016) and frequent extreme temperatures (Guan et al., 2015), as well as the spatial diversity of disasters, are more prevalent in the reproductive stage. This situation calls for strengthening the resilience and adaptability of wheat varieties, alongside the implementation of innovative field management strategies during the later stages of growth.

EFFECTS OF CLIMATE CHANGE ON WHEAT PRODUCTION

Impact on wheat phenology

Both winter and spring wheat, as well as different wheat regions, respond differently to climate change, resulting in differences in phenology (Valone, 2021; Ye et al., 2020; Inouye 2022; Wang et al., 2022). The phenology of both winter and spring wheat increases with increasing precipitation, with winter wheat being more sensitive to precipitation. Winter wheat phenology decreases with increasing mean temperature, while spring wheat phenology shows the opposite trend (Wang et al., 2022). The response of wheat regions to climate is reflected in area and centre of gravity, with significant effects of precipitation and temperature on area, contributing 11.1-13.1% and 9.7-14.1% respectively (Fan et al., 2018; Tao et al., 2014; Liu et al., 2018). Temperature has a significant effect on the centre of gravity, with a positive drive for winter wheat and the opposite for spring wheat. From 1949 to 2014, the planting area experienced a turning point in the 1970s, with a decrease rate of 0.89×104 and 1.99×104 $ha \cdot a^{-1}$ for winter wheat, and an increase rate of 0.27×104 $ha \cdot a^{-1}$ followed by a decrease rate of 8.46×104 $ha \cdot a^{-1}$ for spring wheat. The centre of gravity of planting shifted 31 km from Henan to the northwest for winter wheat and 692 km from Inner Mongolia to the southwest for spring wheat (Valone, 2021; Liu et al., 2018). It is evident that climate change has led to a shortened phenology, resulting in a reduction in wheat area and a shift of the centre of gravity to the west.

Climate change has accelerated the growth process of wheat (Zhao et al., 2018; Yang et al., 2023; Sun et al., 2018). From 1981 to 2010, climate change led to earlier flowering and maturity (Inouye, 2022), resulting in a 0.23 $d \cdot a^{-1}$ shortening of the nutritional stage and 0.06 $d \cdot a^{-1}$ lengthening of the reproductive stage (Wang et al., 2022). In 2010, the nutritional stage was shortened by 6.9 days and the reproductive stage was lengthened by 1.8 days. Different growth stages of wheat were affected differently: the sowing, emergence and three-leaf stages were delayed by 0.19 d/a, 0.06 d/a and 0.05 d/a respectively, while the tillering, jointing, booting, heading, flowering and ripening stages were advanced by 0.02 $d \cdot a^{-1}$, 0.15 $d \cdot a^{-1}$, 0.17 $d \cdot a^{-1}$, 0.19 $d \cdot a^{-1}$ and 0.10 $d \cdot a^{-1}$ respectively (Wang et al., 2022). It is evident that climate change has led to a shortening of the phenology and an acceleration of the growth process.

In summary, climate change has led to a reduction in area and a shift in the centre of gravity, with a much higher rate of reduction in spring wheat area than in winter wheat. This has led to uncertainty about investment in agricultural infrastructure. The shortened phenology and accelerated growth stages pose new challenges for wheat variety breeding and field management.

Impact on the wheat management system

Adaptive management of wheat fields can mitigate the negative effects of climate change (Dan et al., 2024; Valone, 2021; Ye et al., 2021). Field irrigation can increase the temperature tolerance of wheat (Liu et al., 2021). Irrigation reduces the stress of high temperatures during wheat growth and improves water use efficiency. Water use efficiency in the central region increased by 34.2%, and with rising temperatures, water use efficiency also increased, especially in dry years (Wu et al., 2020). Spring wheat uses redundant growth during the nutritional stage to cope with temperature increases during the reproductive stage. Controlling the timing and amount of irrigation can reduce this redundancy and also help to alleviate the stress of high temperatures (Bai et al., 2021). In the Hetao region, delaying the heading stage by 15 days and applying 50-70 mm of irrigation resulted in increased yields and incomes (Bai et al., 2020). The sowing date can alter the accumulated temperature of wheat, thereby regulating its growth and development (Dreccer et al., 2013; Shang et al., 2023). Late sowing of winter wheat reduces the pre-winter accumulated temperature, delays tillering during the seedling stage and consequently delays flowering, with the optimum late sowing being 5-7 days (Ren et al., 2019;).

Early sowing of spring wheat can extend the growth period of wheat (nutritional stage, reproductive stage) and reduce the average temperature during the growth stages to cope with rising temperatures (Xiao et al., 2016; Li et al., 2022). In addition, greenhouse gas emissions can be reduced through the timing and amount of fertiliser application, combined application of organic and inorganic fertilisers and other methods (Lyu et al., 2019; Li et al., 2023), while soil management practices can reduce carbon footprints and mitigate climate change impacts (Zhang et al., 2021; Shang et al., 2023). Therefore, it is evident that field management practices such as irrigation, sowing dates, fertilisation and tillage can adjust wheat growth and development or greenhouse gas emissions and thus serve the purpose of addressing climate change.

Effects on wheat grain yield

External environmental changes such as temperature, precipitation, CO_2 and radiation have been identified as pivotal determinants shaping yield dynamics (Peterson et al., 2008; Gray, 2007; Zhao et al., 2018; Zhang et al., 2021; Lyu et al., 2019; Li Y.et al., 2023; Li S et al., 2023). From 1981 to 2009, wheat yields in the northern regions exhibited an increment ranging from 0.9% to 12.9%, juxtaposed with a decrease ranging from 1.2% to 10.2% observed in the southern regions (Tao et al., 2014). An increase in temperature is beneficial for the accumulation of organic matter during the grain filling period, leading to an increase in yield (He et al., 2020). Specifically, a temperature elevation of 1.5°C corresponds to a yield increase of 2.8%, while a 2.0°C rise yields an 8.3% increment (Wang et al., 2023). Wheat yield variability is influenced by rainfall in May, with 70-78% of the variability attributed to precipitation. Excessive precipitation weakens photosynthesis during the grain filling period and can induce Fusarium head blight, which reduces grain quality (Song et al., 2019). It is evident that precipitation exerts a significant impact on both flowering and grain-filling phases, with diminished precipitation correlating with reduced yields (Yu et al., 2018; Geng et al., 2023). Reduced radiation contribute to yield reduction, albeit partially mitigated by increased CO_2 concentrations (Xiong et al., 2012). Conclusively, the multifaceted effects of climate change manifest both positive and negative repercussions on yield dynamics, culminating in augmented production in northern regions juxtaposed with diminished output in southern regions.

Winter and spring wheat varieties exhibit high sensitivity to temperature fluctuations, albeit with discernible differences in their yield response dynamics (Wang et al., 2022; Fan et al., 2018; Tao et al., 2014; Liu et al., 2018; Ren et al., 2019; Wang et al., 2023; Xiao et al., 2016; Li et al., 2022). From 1980 to 2000, an increase in temperature promoted an increase in wheat yield, with an increase of 1.4-9.6%. After 2000, the effect of temperature increase on yield varied between regions (Wang et al., 2022), with an average temperature increase of 1℃ leading to a yield increase of 2.1% in the north and a yield decrease of 4.0% in the south. The critical temperature for the average temperature during the growing season is 8.6°C, with a decrease in yield when the temperature exceeds this threshold and an increase in yield when the temperature is below the threshold (Valone, 2021; Chen et al., 2018; Ye et al., 2021). Evidently, the escalating temperatures have engendered divergent impacts on winter and spring wheat yields across geographical regions, winter wheat and spring wheat yields have increased in the north, while winter wheat yields have decreased in the south.

In summary, the impact of climate change has resulted in amplified production of northern winter (spring) wheat while concurrently precipitating diminished production of southern winter wheat (Xiao et al., 2016). However, it is imperative to acknowledge that winter wheat encompasses a substantial majority, ranging between 93.6% and 95.3%, of China's aggregate wheat output (Huang et al., 2017). Consequently, the contemporary challenge lies in the pursuit of attaining heightened yields in northern wheat territories alongside the imperative of ensuring stable yields in southern winter wheat regions.

IMPACTS OF FUTURE CLIMATE CHANGE ON WHEAT PRODUCTION

Favourable effects

Future climate change is expected to be more severe, characterized by sustained elevations in average temperature and CO_2 concentration, alongside exacerbated spatial and temporal variability in precipitation patterns (National Climate Centre, 2023; Peterson et al., 2008; Gray, 2007; Ye et al., 2021; Tao et al., 2014; Qin et al., 2015; Prodhan et al., 2022). By the mid-21st century, it is anticipated that temperatures will escalate by 1.2-2.2°C by 2045 and by 1.5-3.8°C by 2085, precipitating a further contraction of the growing season (Xiao et al., 2018; Wang et al., 2024). By 2050, the nutritional phase is expected to be shortened by 6.25 days (Wang et al., 2022), while the reproductive phase will be lengthened by 1.5 days (He et al., 2015), resulting in an overall shortening of the growth period. However, empirical investigations have delineated a critical threshold for the nutritional stage shortening at 14 days, below which the impact on wheat production remains statistically insignificant (Rezaei et al., 2015; Riedesel et al., 2023). Lengthening the reproductive stage allows wheat to accumulate more organic matter, which increases grain weight. It is clear that forthcoming climate change will precipitate a compression of phenological stages and a further acceleration of the growth process (Saddique et al., 2020; Zhang et al., 2021).

In addition, precipitation is expected to increase by more than 75% over the next 30-50 years (Xiao et al., 2018). This anticipated increase holds promise in mitigating the impact of drought while fostering heightened water utilization during the growing season in northern regions, consequently engendering a projected yield increase ranging between 3.2% and 4.1% per unit area (Geng et al., 2019). In southern regions characterized by substantial non-agricultural water consumption, the curtailed availability of irrigation water is expected to stimulate improvements in water use efficiency (Xiao et al., 2018). Moreover, the escalating concentration of CO_2 in the atmosphere is expected to alleviate competition between wheat and other crops such as soybeans and maize, thereby expanding opportunities for intercropping and partially counteracting reductions in cultivated area (Geng et al., 2019; Abdalla et al., 2020; Hao et al., 2019; Long et al., 2010; Deng et al., 2022).

Adverse effects

The increase in temperature leads to an earlier and longer reproductive stage, making it more susceptible to heat stress in the later stages (Chen et al., 2016; He et al., 2022). Furthermore, the temperature rise augments the potential for evapotranspiration, thereby diminishing soil moisture availability, particularly in arid and semi-arid regions, consequently engendering yield losses (Ju et al., 2013). In addition, the significant increase in global precipitation will further increase the unevenness of its spatial and temporal distribution (Peterson et al., 2008; Gray, 2007; Sun et al., 2018; Song et al., 2019; Nie et al., 2019), increasing the occurrence of floods and droughts (Ren et al., 2012). Perennial rainfall may exacerbate pest and disease incidences, while the reduction of irrigation in southern regions is anticipated to curtail yield per unit area (Xiong et al., 2010; Liu et al., 2022). The increase in CO_2 concentration will increase the intercrop index and increase weed growth (Altieri et al., 2015; Amoak et al., 2022), potentially leading to a rapid decline in soil fertility (Ramankutty et al., 2002; Pal et al., 2022). Extreme droughts may exacerbate soil moisture depletion, further exacerbating the challenges faced by wheat production (Tao et al., 2003). It is clear that climate change is not conducive to the sustainability of wheat production.

PROBLEMS AND PROSPECTS

The increase in temperature ~~and~~ CO_2 concentration (Gray, 2007; Valone, 2021), ~~the increase in~~ precipitation (Peterson et al., 2008) and the uneven spatial and temporal distribution of precipitation (Sun et al., 2018; Nie et al., 2019) resultant from climate change, directly impinge upon wheat phenology (Wang et al., 2022; Fan et al., 2018; Tao et al., 2014; Liu et al., 2018) and photosynthetic processes (Song et al., 2019; He et al., 2020), exacerbate the stress of agricultural adversities on growth and development (Wan et al., 2022), and causes differences in grain quality (Ji et al., 2023). In addition, climate change exerts indirect influences on wheat production through its repercussions on pest and disease dynamics (Altieri et al., 2015), weed growth, soil nutrients and other factors (Kaur et al., 2022).

Furthermore, the contraction of the wheat sown area, particularly for spring wheat, and the concomitant truncation of the nutritional stage, precipitating a commensurate diminution in phenological duration, have culminated in yield reductions (Tao et al., 2014). The increase in production in the north and the decrease in production in the south due to climate change have increased the production potential, but reduced sustainability (Saddique et al., 2020).

Hence, the imperative for regional ecological refinement of farmland emerges, not only as a conduit for catalyzing agricultural modernization (Rai et al., 2023) but also as a mechanism for bolstering the self-regulatory capacities inherent within agricultural systems (Xu et al., 2022).

The adoption of high-resilience cultivars coupled with judicious cultivation practices stands poised to underpin the attainment of ultra-high yields (Zubair et al., 2023). Additionally, the integration of biological control methodologies holds promise in mitigating yield losses attributed to pestilence and weed proliferation (Baker et al., 2020). Moreover, the institution of a meticulously crafted scientific monitoring and early warning framework emerges as indispensable for safeguarding agricultural productivity (Yu et al., 2022).

Regional ecological construction

Agricultural shelterbelts are an indispensable part of agricultural ecological construction (Shi et al., 2011). Within shelterbelts, the wind speed at 2 metres above the ground is reduced by 10-20% at a distance of 20-150 metres from the shelterbelt (Ujah et al., 1984). Such mitigation facilitates enhanced soil water retention, curtails soil evaporation rates, and augments soil moisture availability (Zhu et al., 2021), thus mitigating drought stress in wheat cultivation (Wang et al., 2023; Chen et al., 2018). Furthermore, shelterbelts serve as a sink for CO2 absorption, thereby mitigating the pace of climate change (Li et al., 2023). Shelterbelts accelerate the decomposition of organic matter, fostering an enrichment in soil organic matter levels, particularly polysaccharide fractions, and thus contribute to the restoration of soil fertility (Dhillon et al., 2017; Vicente et al., 2023). Evidently, shelterbelts can improve the resilience and and sustainability of agricultural landscapes.

Breeding superior varieties and appropriate agronomic practices

Breeding superior varieties is an effective way to improve crop resistance to environmental stresses and increase yields (Mondal et al., 2021). Confronted with the climate change, there arises an imperative to develop cultivars endowed with robust traits such as heat tolerance, drought resistance, flood resilience, and pest resistance, alongside heightened photosynthetic efficiency (Peterson et al., 2008; Gray, 2007; Sun et al., 2018; Nie et al., 2019). It is also necessary to conduct targeted breeding based on the characteristics of different regions (Mondal et al., 2021). For example, in southern Xinjiang, where 80% of wheat fields are intercropped with fruit trees, shade-tolerant varieties need to be bred (Li et al., 2019). For instance, in southern Xinjiang, where 80% of wheat cultivation occurs in tandem with fruit tree intercropping systems, there arises a necessity for the development of shade-tolerant varieties (Xiong et al., 2010). Crop management techniques can regulate wheat growth and development to achieve stable and increased yields (Clegg et al., 2022; Ferreira et al., 2021). It is clear that the strategic deployment of highly resistant cultivars and targeted crop management can ensure stable and increased yields.

Biological control techniques

Biological control, a versatile technology, holds significant promise across various agricultural domains (Yu et al., 2022; Ferreira et al., 2021). Increasing biodiversity, such as birds, bees, butterflies, spiders, etc., serves to mitigate the deleterious impact of pests and diseases on crop yields while enhancing yield stability (Perennes et al., 2023). The Global Catalogue of Biological Controls shows that 55% of biological controls achieve the objective of weed control (Schwarzländer et al., 2018; Schaffner et al., 2020). However, it is imperative to acknowledge the concomitant risk of biological invasion (Ray et al., 2020). Evidently, the strategic enhancement of species diversity coupled with judicious scientific introductions of novel species for biological control represents a potent avenue for addressing the challenges posed by climate change.

Scientific Monitoring and Early Warning System

The climate monitoring and early warning system is constantly developing and adopting new technologies and methods, which is an important measure to cope with climate change (Ginkel et al., 2021). The establishment of single monitoring and early warning systems for drought, high temperature and frost can improve the accuracy of the system (Howe et al., 2022). In addition, satellite remote sensing and geographic information systems can provide real-time feedback on areas affected by crop disasters and recovery conditions (Adedeji et al., 2020). Therefore, climate monitoring and early warning systems combined with crop disaster situations assumes paramount importance for agricultural resilience.

In conclusion, the impact of climate change on wheat production is complex, engendering both positive and negative outcomes. Addressing these challenges necessitates a comprehensive approach, encompassing regional ecological engineering, breeding of superior varieties, biological control techniques, and a scientific monitoring and early warning system. These concerted measures hold the potential to stabilize and enhance wheat production in the face of climate change.

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SUPPLEMENTAL MATERIAL

Yuchen Fan and Yaqi Yuan contributed significantly to the data analysis and manuscript preparation. Yachao Yuan and Wenjing Duan contributed to review the manuscript. Zhiqiang Gao contributed to the conception oe manuscript. All authors have agreed to the published version of the manuscript.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Abdalla, M., Song, X., Ju, X., Topp, C. F., & Smith, P. (2020). Calibration and validation of the DNDC model to estimate nitrous oxide emissions and crop productivity for a summer maize-winter wheat double cropping system in Hebei, China. *Environmental Pollution, 262*, 114199. 10.1016/j.envpol.2020.114199

Adedeji, O., Olusola, A., James, G., Shaba, H. A., Orimoloye, I. R., Singh, S. K., & Adelabu, S. (2020). Early warning systems development for agricultural drought assessment in Nigeria. *Environmental Monitoring and Assessment, 192*, 1-21. 10.1007/s10661-020-08730-3

Altieri, M. A., Nicholls, C. I., Henao, A., & Lana, M. A. (2015). Agroecology and the design of climate change-resilient farming systems. *Agronomy for sustainable development, 35*(3), 869-890. 10.1007/s13593-015-0285-2

Amoak, D., Luginaah, I., & McBean, G. (2022). Climate change, food security, and health: Harnessing agroecology to build climate-resilient communities. *Sustainability, 14*(21), 13954. 10.3390/su142113954

Bai, G. S., Du, S. N., & Miao, Q. F. (2021). Effects of supplementary irrigation on the growth of film-mulched spring wheat in Hetao irrigation area during heading stage. *Journal of Zhejiang University (Agriculture and Life Sciences), 47*(1), 21-31. 10.3785/j.issn.1008-9209.2020.03.181

Bai, G., Du, S., & Miao, Q., (2020). Effects of supplementary irrigation on the growth of film-mulched spring wheat in Hetao irrigation area during heading stage. *Journal of Zhejiang University (Agriculture and Life Sciences)*, (10),15-19. 10.3785/j.issn.1008-9209.2020.03.181

Baker, B. P., Green, T. A., & Loker, A. J. (2020). Biological control and integrated pest management in organic and conventional systems. *Biological Control, 140*, 104095. 10.1016/j.biocontrol.2019.104095

Chen, C. Q., Lu, W. T., Sun, X. S., & Yu, H. (2018). Regional differences of winter wheat phenophase and grain yields response to global warming in the Huang-Huai-Hai plain in China since 1980s. *International Journal of Plant Production, 12*, 33-41. 10.1007/s42106-017-0004-9

Chen, Y., Zhang, Z., Wang, P., Song, X., Wei, X., & Tao, F. (2016). Identifying the impact of multi-hazards on crop yield—a case for heat stress and dry stress on winter wheat yield in northern China. *European journal of agronomy, 73*, 55-63. 10.1016/j.eja.2015.10.009

Clegg, G., Haigh, R., & Amaratunga, D. (2022). Towards an improved understanding of participation in natural hazard early warning systems. *International journal of disaster resilience in the built environment, 13*(5), 615-631. 10.1108/IJDRBE-11-2020-0120

Dan, J., Shi, S., Sun, H., Su, Z., Liang, Y., Wang, J., & Zhang, W. (2024). Micro/nanomotor technology: the new era for food safety control. *Critical Reviews in Food Science and Nutrition, 64*(7)*,* 2032-2052. 10.1080/10408398.2022.2119935

Deng, A., Guo, H., Hu, J., Jiang, C., Liu, P., & Jing, H., (2020) Temporal and distribution characteristic of CO_2 concentration over China based on GOSAT satellite data. *National Remote Sensing Bulletin, 24*(3):319-325. 10.11834/jrs.20208324.

Deng, X., Liang, L., Wu, F., Wang, Z., & He, S. (2022). A review of the balance of regional development in China from the perspective of development geography. *Journal of Geographical Sciences, 32*(1), 3-22. 10.1007/s11442-021-1930-0

Dhillon, G. S., Gillespie, A., Peak, D., & Van Rees, K. C. (2017). Spectroscopic investigation of soil organic matter composition for shelterbelt agroforestry systems. *Geoderma, 298*, 1-13. 10.1016/j.geoderma.2017.03.016

Dreccer, M. F., Chapman, S. C., Rattey, A. R., Neal, J., Song, Y., Christopher, J. J. T., & Reynolds, M. (2013). Developmental and growth controls of tillering and water-soluble carbohydrate accumulation in contrasting wheat (Triticum aestivum L.) genotypes: can we dissect them?. *Journal of Experimental Botany, 64*(1), 143-160. 10.1093/jxb/ers317

Fan, L., Liang, S., Chen, H., Hu, Y., Zhang, X., Liu, Z., .Wu, W., & Yang, P. (2018). Spatio-temporal analysis of the geographical centroids for three major crops in China from 1949 to 2014. *Journal of Geographical Sciences, 28*, 1672-1684. 10.1007/s11442-018-1536-3

Ferreira, F. V., & Musumeci, M. A. (2021). Trichoderma as biological control agent: Scope and prospects to improve efficacy. *World Journal of Microbiology and Biotechnology, 37*(5), 90. 10.1007/s11274-021-03058-7

Geng, G., Yang, R., Chen, Q., Deng, T., Yue, M., Zhang, B., & Gu, Q. (2023). Tracking the influence of drought events on winter wheat using long-term gross primary production and yield in the Wei River Basin, China. *Agricultural Water Management, 275*, 108019. 10.1016/j.agwat.2022.108019

Geng, X., Wang, F., Ren, W., & Hao, Z. (2019). Climate change impacts on winter wheat yield in Northern China. *Advances in Meteorology*, 1-12. 10.1155/2019/2767018

Gray, V. (2007). Climate change 2007: the physical science basis summary for policymakers. *Energy & Environment, 18*(3-4), 433-440. 10.1260/095830507781076194

Guan, Y., Zheng, F., Zhang, P., & Qin, C. (2015). Spatial and temporal changes of meteorological disasters in China during 1950–2013. *Natural Hazards, 75*, 2607-2623. 10.1007/s11069-014-1446-3

Hao, T., Zhu, Q., Zeng, M., Shen, J., Shi, X., Liu, X., .Zhang, F., & de Vries, W. (2019). Quantification of the contribution of nitrogen fertilization and crop harvesting to soil acidification in a wheat-maize double cropping system. *Plant and Soil, 434,* 167-184. 10.1007/s11104-018-3760-0

He, D., Fang, S., Liang, H., Wang, E., & Wu, D. (2020). Contrasting yield responses of winter and spring wheat to temperature rise in China. *Environmental Research Letters, 15*(12), 124038. 10.1088/1748-9326/abc71a

He, L., Asseng, S., Zhao, G., Wu, D., Yang, X., Wei, Z., Jin, N., & Yu, Q. (2015). Impacts of recent climate warming, cultivar changes, and crop management on winter wheat phenology across the Loess Plateau of China. *Agricultural and Forest Meteorology, 200*, 135-143. 10.1016/J.AGRFORMET.2014.09.011

He, Y., Hu, X., Xu, W., Fang, J., & Shi, P. (2022). Increased probability and severity of compound dry and hot growing seasons over world's major croplands. *Science of the Total Environment, 824*, 153885. 10.1016/j.scitotenv.2022.153885

Howe, P. W., & Naumova, E. N. (2022). Poverty and famines 2.0: the opportunities and challenges of crisis modeling and forecasting. *Journal of Public Health Policy, 43*(3), 329-334. 10.1057/s41271-022-00354-w

Huang, J. K., Wei, W. E. I., Qi, C. U. I., & Wei, X. I. E. (2017). The prospects for China's food security and imports: Will China starve the world via imports?. *Journal of integrative agriculture, 16*(12), 2933-2944. 10.1016/S2095-3119(17)61756-8

Hussain, M., Farooq, S., Jabran, K., Ijaz, M., Sattar, A., & Hassan, W. (2016). Wheat sown with narrow spacing results in higher yield and water use efficiency under deficit supplemental irrigation at the vegetative and reproductive stage. *Agronomy, 6*(2), 22. 10.3390/agronomy6020022

Inouye, D. W. (2022). Climate change and phenology. Wiley Interdisciplinary Reviews: *Climate Change, 13*(3), e764. 10.1002/wcc.764

Ji, W., Hu, X., Qiu, X., Liu, B., Tang, L., Zhu, Y., .Gao, W., & Liu, L. (2023). Effects of pre-anthesis low-temperature stress on the mineral components in wheat grains. *Frontiers in Plant Science, 14,* 1221466. 10.3389/fpls.2023.1221466

Jiang, L., & Cui, X., (2016,) Analysis on variation tendency and cause of China's agrometeorological hazards in the latest 20 years. *Torrential Rain and Disasters, 35*(2): 102-108. 10.3969/j.issn.1004-9045.2016.02.002

Ju, H., van der Velde, M., Lin, E. Xiong, W., & Li, Y., (2013) The impacts of climate change on agricultural production systems in China. *Climatic Change 120,* 313–324 . 10.1007/s10584-013-0803-7

Kaur, M., Malik, D. P., Malhi, G. S., Sardana, V., Bolan, N. S., Lal, R., & Siddique, K. H. (2022). Rice residue management in the Indo-Gangetic Plains for climate and food security. A review. *Agronomy for Sustainable Development, 42*(5), 92. 10.1007/s13593-022-00817-0

Li, H., Zhou, Y.,xi*n, W., Wei, Y., Zhang, J., & Guo, L. (2019). Wheat breeding in northern China: achievements and technical advances. *The Crop Journal, 7*(6), 718-729. 10.1016/j.cj.2019.09.003

Li, J., & Lei, H. (2022). Impacts of climate change on winter wheat and summer maize dual-cropping system in the North China Plain. *Environmental Research Communications, 4*(7), 075014. 10.1088/2515-7620/ac814c

Li, M., Du, C., Jiang, P., Luan, W., & Chen, D. (2023). Simulation of China's potential rice yields by coupling land system evolution and climate change. *Science China Earth Sciences, 66*(8), 1776-1788. 10.1007/s11430-022-1114-5

Li, S., Wang, S., Shi, J., Tian, X., & Ye, X. (2023). Integrated mulching and nitrogen management strategies influence carbon footprint and sustainability of wheat production on the Loess Plateau of China. *Field Crops Research, 297*, 108928. 10.1016/j.fcr.2023.108928

Li, Y., Wang, R., Chen, Z., Xiong, Y., Huang, Q., & Huang, G. (2023). Increasing net ecosystem carbon budget and mitigating global warming potential with improved irrigation and nitrogen fertilization management of a spring wheat farmland system in arid Northwest China. *Plant and Soil, 489*(1), 193-209. 10.1007/s11104-023-06006-6

Liu, X., Liu, W., Tang, Q., Liu, B., Wada, Y., & Yang, H. (2022). Global agricultural water scarcity assessment incorporating blue and green water availability under future climate change. *Earth's Future, 10*(4), e2021EF002567. 10.1029/2021EF002567

Liu, Y., Chen, Q., Ge, Q., & Dai, J. (2018). Spatiotemporal differentiation of changes in wheat phenology in China under climate change from 1981 to 2010. *Science China Earth Sciences, 61*, 1088-1097. 10.1007/s11430-017-9149-0

Liu, Y., Zhang, J., & Ge, Q. (2021). The optimization of wheat yield through adaptive crop management in a changing climate: evidence from China. *Journal of the Science of Food and Agriculture, 101(*9), 3644-3653. 10.1002/jsfa.10993

Long, H., Liu, Y., Li, X., & Chen, Y. (2010). Building new countryside in China: A geographical perspective. *Land use policy, 27*(2), 457-470. 10.1016/j.landusepol.2009.06.006

Lyu, X., Wang, T., Ma, Z., Zhao, C., Siddique, K. H., & Ju, X. (2019). Enhanced efficiency nitrogen fertilizers maintain yields and mitigate global warming potential in an intensified spring wheat system. *Field Crops Research, 244*, 107624. 10.1016/j.fcr.2019.107624

Mondal, S., Sallam, A., Sehgal, D., Sukumaran, S., Farhad, M., Navaneetha Krishnan, J., Kumar, U., & Biswal, A. (2021). Advances in breeding for abiotic stress tolerance in wheat. *Genomic designing for abiotic stress resistant cereal crops,* 71-103. 10.1007/978-3-030-75875-2_2

Moravec, V., Markonis, Y., Rakovec, O., Svoboda, M., Trnka, M., Kumar, R., & Hanel, M. (2021). Europe under multi-year droughts: how severe was the 2014–2018 drought period?. *Environmental Research Letters, 16*(3), 034062. 10.1088/1748-9326/abe828

National Climate Centre. Blue Book on Climate Change in China(2020) [M]. Beijing: *China Science Publishing & Media Ltd*, 2023.07..

Nie, H., Qin, T., Yang, H., Chen, J., He, S., Lv, Z., & Shen, Z. (2019). Trend analysis of temperature and precipitation extremes during winter wheat growth period in the major winter wheat planting area of China. *Atmosphere, 10*(5), 240. 10.3390/atmos10050240

Pal, S. C., Chowdhuri, I., Das, B., Chakrabortty, R., Roy, P., Saha, A., & Shit, M. (2022). Threats of climate change and land use patterns enhance the susceptibility of future floods in

India. *Journal of environmental management, 305*, 114317. 10.1016/j.jenvman.2021.114317

Perennes, M., Diekötter, T., Hoffmann, H., Martin, E. A., Schröder, B., & Burkhard, B. (2023). Modelling potential natural pest control ecosystem services provided by arthropods in agricultural landscapes. *Agriculture, Ecosystems & Environment, 342*, 108250. 10.1016/j.agee.2022.108250

Peterson, T. C., McGuirk, M., Houston, T. G., Horvitz, A. H., & Wehner, M. F. (2008). Climate variability and change with implications for transportation. *Transportation Research Board, 90*(2.3). 10.9774/GLEAF.978-1-909493-38-4_2

Prodhan, F. A., Zhang, J., Hasan, S. S., Sharma, T. P. P., & Mohana, H. P. (2022). A review of machine learning methods for drought hazard monitoring and forecasting: Current research trends, challenges, and future research directions. *Environmental modelling & software, 149*, 105327. 10.1016/j.envsoft.2022.105327

Qin, X., Zhang, F., Liu, C., Yu, H., Cao, B., Tian, S., Liao, Y., & Siddique, K. H. (2015). Wheat yield improvements in China: Past trends and future directions. *Field Crops Research, 177*, 117-124. 10.1016/j.fcr.2015.03.013

Rai, A. K., Bana, S. R., Sachan, D. S., & Singh, B. (2023). Advancing sustainable agriculture: a comprehensive review for optimizing food production and environmental conservation. *Int. J. Plant Soil Sci, 35*(16), 417-425. 10.9734/IJPSS/2023/v35i163169

Ramankutty, N., Foley, J. A., Norman, J., & McSweeney, K. (2002). The global distribution of cultivable lands: current patterns and sensitivity to possible climate change. *Global Ecology and biogeography, 11*(5), 377-392. 10.1046/j.1466-822x.2002.00294.x

Ray, P., Lakshmanan, V., Labbé, J. L., & Craven, K. D. (2020). Microbe to microbiome: a paradigm shift in the application of microorganisms for sustainable agriculture. *Frontiers in Microbiology, 11*, 622926. 10.3389/fmicb.2020.622926

Ren, A., Sun, M., Wang, P., Xue, L., Lei,M., Xue, J., Gao, Z., & Yang, Z. (2019). Optimization of sowing date and seeding rate for high winter wheat yield based on pre-winter plant development and soil water usage in the Loess Plateau, China. *Journal of integrative agriculture, 18*(1), 33-42. 10.1016/S2095-3119(18)61980-X

Ren, G., Ding, Y., Zhao, Z., Zheng, J., Wu, T., Tang, G., & Xu, Y. (2012). Recent progress in studies of climate change in China. *Advances in Atmospheric Sciences, 29*, 958-977. 10.1007/s00376-012-1200-2

Rezaei, E. E., Siebert, S., & Ewert, F. (2015). Intensity of heat stress in winter wheat—phenology compensates for the adverse effect of global warming. *Environmental Research Letters, 10*(2), 024012. 10.1088/1748-9326/10/2/024012

Riedesel, L., Möller, M., Horney, P., Golla, B., Piepho, H. P., Kautz, T., & Feike, T. (2023). Timing and intensity of heat and drought stress determine wheat yield losses in Germany. *PLoS One, 18*(7), e0288202. 10.1371/journal.pone.0288202

Saddique, Q., Li Liu, D., Wang, B., Feng, P., He, J., Ajaz, A., Ji, J., Xu, J., Zhang, C., & Cai, H. (2020). Modelling future climate change impacts on winter wheat yield and water use: A case study in Guanzhong Plain, northwestern China. *European Journal of Agronomy, 119*, 126113. 10.1016/j.eja.2020.126113

Schaffner, U., Hill, M., Dudley, T., & D'Antonio, C. (2020). Post-release monitoring in classical biological control of weeds: assessing impact and testing pre-release hypotheses. *Current opinion in insect science, 38,* 99-106. 10.1016/j.cois.2020.02.008

Schwarzländer, M., Hinz, H. L., Winston, R. L., & Day, M. D. (2018). Biological control of weeds: an analysis of introductions, rates of establishment and estimates of success, worldwide. *BioControl, 63*, 319-331. 10.1007/s10526-018-9890-8

Shang, Y., Wang, S., Lin, X., Gu, S., & Wang, D. (2023). Supplemental irrigation at jointing improves spike formation of wheat tillers by regulating sugar distribution in ear and stem. *Agricultural Water Management, 279*, 108160. 10.1016/j.agwat.2023.108160

Shi, X., Li, Y., & Deng, R. (2011). A method for spatial heterogeneity evaluation on landscape pattern of farmland shelterbelt networks: A case study in midwest of Jilin Province, China. *Chinese Geographical Science, 21,* 48-56. 10.1007/s11769-011-0440-x

Soliman, M. S., Shalabi, H. G., & Campbell, W. F. (1994). Interaction of salinity, nitrogen, and phosphorus fertilization on wheat. *Journal of Plant Nutrition, 17*(7), 1163-1173. 10.1080/01904169409364796

Song, Y., Linderholm, H. W., Wang, C., Tian, J., Huo, Z., Gao, P., Song, Y., & Guo, A. (2019). The influence of excess precipitation on winter wheat under climate change in China from 1961 to 2017. *Science of the Total Environment, 690*, 189-196. 10.1016/j.scitotenv.2019.06.367

Su, R., Zhang, Z., Chang, C., Peng, Q., Cheng, X., Pang, J., He,H., & Lambers, H. (2022). Interactive effects of phosphorus fertilization and salinity on plant growth, phosphorus and sodium status, and tartrate exudation by roots of two alfalfa cultivars. *Annals of botany, 129*(1), 53-64. 10.1093/aob/mcab124

Sun, H., Wang, Y., & Wang, L. (2024). Impact of climate change on wheat production in China. *European Journal of Agronomy, 153*, 127066. 10.1016/j.eja.2023.127066

Sun, R., Han, X., Pan, J., Xiong, W., & Ju, H., (2018). The impact of 1.5℃and 2.0℃global warming on wheat production in China. *Climate Change Research, 14*(6): 573-582. 10.12006/j.issn.1673-1719.2018.090

Tang, W. J., Yang, K., Qin, J., Cheng, C. C. K., & He, J. (2011). Solar radiation trend across China in recent decades: a revisit with quality-controlled data. *Atmospheric Chemistry and Physics, 11*(1), 393-406. 10.5194/acp-11-393-2011, 2011.

Tao, F., Yokozawa, M., Hayashi, Y., & Lin, E. (2003). Future climate change, the agricultural water cycle, and agricultural production in China. *Agriculture, ecosystems & environment, 95*(1), 203-215. 10.1016/S0167-8809(02)00093-2

Tao, F., Zhang, Z., Xiao, D., Zhang, S., Rötter, R. P., Shi, W., Liu, Y., Wang, M., Liu, F., & Zhang, H. (2014). Responses of wheat growth and yield to climate change in different climate zones of China, 1981–2009. *Agricultural and Forest Meteorology, 189*, 91-104. 10.1016/j.agrformet.2014.01.013

Ujah, J. E., & Adeoye, K. B. (1984). Effects of shelterbelts in the Sudan savanna zone of Nigeria on microclimate and yield of millet. *Agricultural and Forest Meteorology, 33*(2-3), 99-107. 10.1016/0168-1923(84)90063-7

Valone, T. F. (2021). Linear global temperature correlation to carbon dioxide level, sea level, and innovative solutions to a projected 6 C warming by 2100. *Journal of Geoscience and Environment Protection, 9*(03), 84. 10.4236/gep.2021.93007

Ginkel, V. M., & Biradar, C. (2021). Drought early warning in agri-food systems. *Climate, 9*(9), 134. 10.3390/cli9090134

Vicente, L. C., Gama-Rodrigues, E. F., Aleixo, S., Gama-Rodrigues, A. C., & Andrade, G. R. P. (2023). Chemical composition of organic carbon in aggregate density fractions under cacao agroforestry systems in South Bahia, Brazil. *Journal of Soil Science and Plant Nutrition*, 1-15. 10.1007/s42729-022-01083-5

Wan, W., Liu, Z., Li, J., Xu, J., Wu, H., & Xu, Z. (2022). Spatiotemporal patterns of maize drought stress and their effects on biomass in the Northeast and North China Plain from 2000 to 2019. *Agricultural and Forest Meteorology, 315*, 108821. 10.1016/j.agrformet.2022.108821

Wang, F., Zhan, C., & Zou, L. (2023). Risk of crop yield reduction in China under 1.5 C and 2 C global warming from CMIP6 models. *Foods, 12*(2), 413. 10.3390/foods12020413

Wang, S., Niu, Y., Shang, L., Li, Z., Lin, X., & Wang, D. (2023). Supplemental irrigation at the jointing stage of late sown winter wheat for increased production and water use efficiency. *Field Crops Research, 302*, 109069. 10.1016/j.fcr.2023.109069

Wang, S., Sun, N., Zhang, X., Hu, C., Wang, Y., Xiong, W., Zhang, S., Colinet, G., & Wu, L. (2024). Assessing the impacts of climate change on crop yields, soil organic carbon sequestration and N2O emissions in wheat–maize rotation systems. *Soil and Tillage Research, 240*, 106088. 10.1016/j.still.2024.106088

Wang, Y., Zhang, X., Shi, J., & Shen Y. (2022) Climate change and its effect on winter wheat yield in the main winter wheat production areas of China[J]. *Chinese Journal of Eco-Agriculture, 30*(5): 723−734. 10.12357/cjea.20210702

Wu,Y., Zhu, J., Zhu, D., & Li, D. (2020) Meta-analysis on influencing factors of irrigated winter wheat yield and water use efficiency in China. *Journal of Irrigation and Drainage, 39*(2): 84-92. 10.13522/j.cnki.ggps.2019049

Xiao, D., Bai, H., & Liu, D. L. (2018). Impact of future climate change on wheat production: a simulated case for China's wheat system. *Sustainability, 10*(4), 1277. 10.3390/su10041277

Xiao, D., Tao, F., Shen, Y., & Qi, Y. (2016). Combined impact of climate change, cultivar shift, and sowing date on spring wheat phenology in Northern China. *Journal of Meteorological Research, 30*(5), 820-831. 10.1007/s13351-016-5108-0

Xiong, W., Holman, I., Lin, E., Conway, D., Jiang, J., Xu, Y., & Li, Y. (2010). Climate change, water availability and future cereal production in China. Agriculture, *Ecosystems & Environment, 135*(1-2), 58-69. 10.1016/j.agee.2009.08.015

Xiong, W., Holman, I., Lin, E., Conway, D., Li, Y., & Wu, W. (2012). Untangling relative contributions of recent climate and CO_2 trends to national cereal production in China. *Environmental Research Letters, 7*(4), 044014.10.1088/1748-9326/7/4/044014.

Xu, J., Gu, B., & Tian, G. (2022). Review of agricultural IoT technology. *Artificial Intelligence in Agriculture, 6*, 10-22. 10.1016/j.aiia.2022.01.001

Yang, J., Tian, F., Zhou, H., Wu, J., Han, X., Shen, Q., ... & Zhang, J. (2023). CO_2 and temperature dominate the variation characteristics of wheat yield in China under 1.5° C and 2.0° C warming scenarios. *Theoretical and Applied Climatology, 154*(1), 627-641. 10.1007/s00704-023-04574-2

Ye, J., Gao, Z., Wu, X., Lu, Z., Li, C., Wang, X., Chen, L., Cui, G., Yu, M., Yan, G., Liu, H., Zhang, H., Wang, Z., Shi, X., & Li, Y. (2021). Impact of increased temperature on spring wheat yield in northern China. *Food and Energy Security, 10*(2), 368-378. 10.1002/fes3.283

Ye, Z., Qiu, X., Chen, J., Cammarano, D., Ge, Z., Ruane, A. C., Liu, L., Tang, L., Cao, W., Liu, B., & Zhu, Y. (2020). Impacts of 1.5 C and 2.0 C global warming above pre-industrial on potential winter wheat production of China. *European Journal of Agronomy, 120*, 126149. 10.1016/j.eja.2020.126149

Yu, H., Zhang, Q., Sun, P., & Song, C. (2018). Impact of droughts on winter wheat yield in different growth stages during 2001–2016 in Eastern China. *International Journal of Disaster Risk Science, 9,* 376-391. 10.1007/s13753-018-0187-4

Yu, T., Mahe, L., Li, Y., Wei, X., Deng, X., & Zhang, D. (2022). Benefits of crop rotation on climate resilience and its prospects in China. *Agronomy, 12*(2), 436. 10.3390/agronomy12020436

Yu, X., Lu, Y., Ji, Z., Luo, X.,Cai, M. (2017). Change trend of agricultural meteorological disasters and the relationship with grain yield in recent 45 years[J]. *Resources and environment in the yangtze basin, 26*(10), 1700-1710. 10.11870/cjlyzyyhj201710022

Zhang, S., Wang, H., Sun, X., Fan, J., Zhang, F., Zheng, J., & Li, Y. (2021). Effects of farming practices on yield and crop water productivity of wheat, maize and potato in China: A meta-analysis. *Agricultural Water Management, 243*, 106444. 10.1016/j.agwat.2020.106444

Zhang, X., Wan, X., & Liu, P. (2023). The impact of participation in agricultural industry organizational models on crop yields: evidence from Chinese wheat growers. *Scientific Reports, 13*(1), 17779. 10.1038/s41598-023-43879-0

Zhang, Y., Niu, H., & Yu, Q. (2021). Impacts of climate change and increasing carbon dioxide levels on yield changes of major crops in suitable planting areas in China by the 2050s. *Ecological Indicators, 125*, 107588. 10.1016/j.ecolind.2021.107588

Zhang, Z., Wang P., Chen Y., Zhang S., Tao F., & Liu X., (2013) Spatio-temporal changes of agrometrorological disasters for wheat production across China since 1990. Acta Geographica Sinica, 68(11): 1453-1460. 10.11821/dlxb201311001

Zhao, J., Yang, X., & Sun, S. (2018). Constraints on maize yield and yield stability in the main cropping regions in China. *European Journal of Agronomy, 99,* 106-115. 10.1016/j.eja.2018.07.003

Zhu, J., & Song, L. (2021). A review of ecological mechanisms for management practices of protective forests. *Journal of Forestry Research, 32*(2), 435-448. 10.1007/s11676-020-01233-4

Zou, T., Chang, Y., Chen, P., & Liu, J. (2021). Spatial-temporal variations of ecological vulnerability in Jilin Province (China), 2000 to 2018. *Ecological Indicators, 133*, 108429. 10.1016/j.ecolind.2021.108429

Zubair, H., Afzal, A. H., Shahid, M. U., Ali, U., Iftikhar, H. U., Abuzar, A., Zaib, M., &

Marium, A. (2023). Historical Overview of the Chinese Agricultural Sciences And Technological Development. *Curr. Rese. Agri. Far. 4*(4), 35-45. 10.18782/2582-7146.206

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The escalating trend of global climate warming, characterised by rising temperatures and increased carbon dioxide concentration, has resulted in the frequent occurrence of extreme compound weather events, which present significant challenges to crop production. Concurrently, the area planted with wheat in China has been gradually declining. The stability of yield and supply is primarily dependent on the ability to consistently achieve a higher yield per unit area. However, this balance is easily constrained by climatic conditions. Consequently, it is of paramount importance to accurately assess the response of global climate change and Chinese wheat to these changes in order to maintain the stability of wheat production in China, a populous nation. Furthermore, the strategies proposed in this paper for Chinese wheat under climate change provide theoretical foundations for ensuring the security of global wheat production. The research findings are also highly promising. The analysis indicates that the most significant impacts on Chinese wheat are due to increasing temperatures and precipitation, which result in shortened phenological phases and a westward shift in planting centres. Ultimately, this leads to an increase in wheat yield potential, although it is necessary to address the issue of weeds and pests. These conclusions are of significant importance for the prediction of Chinese wheat production and offer crucial references for both major wheat-producing nations and populous consumer countries globally. In addition, measures such as high-resistance varieties, high-standard farmland construction and the establishment of monitoring systems not only provide response strategies to the problem of Chinese wheat production, but also provide theoretical references for the global development of wheat.

In the context of ongoing climate change, this study focuses on Chinese wheat as a representative case, examining the shortened nutritional stage of wheat and assessing the

increased yield potential. These findings serve as a reference for wheat-growing and populous nations such as China, India, the United States and Russia in predicting wheat growth and yield potential. In addition, the strategies proposed in this paper for Chinese wheat to cope with climate change also provide insights for similar wheat-growing regions facing challenges. This is particularly important for food-secure nations such as Nigeria and other underdeveloped countries in Africa, as it provides theoretical references for actively addressing future climate change and ensuring the stability and supply of wheat production. Moreover, in the future, we will conduct a continuous analysis of the response situations of wheat in other regions under climate change. This can not only enhance or supplement the research on the climate aspect of world wheat, but also provide a theoretical basis and reference for the world wheat to actively respond to climate warming.