Analysis of Spatiotemporal Characteristics of Winter Wheat Yield Gap in Henan Province Based on the AEZ Model (Postprint)

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Abstract

Analysis of various yield gaps can reveal the potential for yield improvement and the constraining effects of various limiting factors on yield enhancement within the study area. To investigate the impacts of climatic factors on winter wheat yield gaps in Henan Province under climate change, this study takes Henan Province as the research area and divides it into five type zones. Using data from 14 meteorological stations, the AEZ model was employed to calculate winter wheat production potential in the province from 1961 to 2013. Based on the yield gap method, three levels of yield gaps were calculated: YG1-2 (the gap between photosynthetic production potential and photo-thermal production potential), YG2-3 (the gap between photo-thermal production potential and climatic production potential), and YG2-a (the gap between photo-thermal production potential and field average yield). The results indicate that from 1961 to 2013, the photosynthetic production potential of winter wheat in Henan Province decreased, the photo-thermal production potential increased, and the climatic production potential remained essentially unchanged. Analysis of field average yields shows significant differences among the 14 stations, with an overall gradual increase in winter wheat yield. From a temporal perspective, the YG1-2 gap of winter wheat in Henan Province shows an overall decreasing trend; the YG2-3 gap exhibits a "V-shaped" pattern with a trough during 1981-1990; the YG2-a gap in zones I, II, and V shows a decreasing trend, while zones III and IV show a trend of first increasing then decreasing. From a spatial perspective, the YG1-2 and YG2-3 gaps of winter wheat in Henan Province decrease from north to south, while the YG2-a gap increases from east to west. The ranking of winter wheat yield increase potential across the zones is: Zone III > Zone V > Zone IV > Zone II > Zone I. Agronomic factors are the main factors limiting the narrowing of local winter wheat yield gaps. By improving agronomic factors, such as improving and updating winter wheat varieties, enhancing modern

agricultural production technologies, rational use of pesticides and fertilizers, and rational layout of high-quality wheat regions, the winter wheat yield gaps in this region can be narrowed.

Full Text

Analysis of Spatio-Temporal Characteristics of Winter Wheat Yield Gaps in Henan Province Based on the AEZ Model

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Abstract

Analyzing various yield gaps reveals both the potential for yield improvement and the limiting effects of different constraints on production within a study region. To investigate the impacts of climatic factors on winter wheat yield gaps in Henan Province under climate change, this study divided Henan into five agro-climatic zones and calculated winter wheat production potential from 1961 to 2013 using the AEZ model with data from 14 meteorological stations. Three levels of yield gaps were then quantified: YG1-2 (gap between photosynthetic potential and light-temperature potential), YG2-3 (gap between light-temperature potential and climate potential), and YG2-a (gap between light-temperature potential and field-average yield).

The results indicate that from 1961 to 2013, photosynthetic potential decreased, light-temperature potential increased, and climate potential remained essentially unchanged. Analysis of field-average yields revealed substantial variation across the 14 stations, with an overall upward trend in winter wheat production. Temporally, YG1-2 showed a decreasing trend, while YG2-3 exhibited a "V-shaped" pattern with its trough during 1981–1990. Zones I, II, and V showed decreasing YG2-a trends, whereas Zones III and IV displayed an initial increase followed by a decrease. Spatially, both YG1-2 and YG2-3 decreased from north to south, while YG2-a increased from east to west. The ranking of yield improvement potential across zones was: Zone III > Zone V > Zone IV > Zone II > Zone I. Agronomic factors represent the primary constraint limiting yield gap closure, and improvements through variety renewal, modern agricultural technology adoption, rational pesticide and fertilizer use, and optimized high-quality wheat zoning could effectively reduce regional yield gaps.

Keywords: Winter wheat; AEZ model; Yield gap; Spatio-temporal characteristics

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Introduction

Food security constitutes the foundation of sustainable development for human society and the national economy, with agricultural production systems serving as its critical safeguard. Rapid population growth has dramatically increased food demand, yet limited arable land and shrinking per capita farmland have progressively worsened food security challenges. Consequently, increasing grain production through yield improvements rather than area expansion has become essential. Since the 1990s, crop yield gap research has emerged as a vital branch of international crop science, revealing both production potential and the constraining effects of limiting factors—natural (climate, soil), technical, and economic.

Over the past century, dramatic global climate change has profoundly impacted social, economic, and ecological systems, becoming one of humanity’ s most serious environmental challenges. Agriculture ranks among the most climate-sensitive sectors, and studying yield gaps within the context of climate change enhances our understanding of how climatic factors constrain crop production. Liu et al. synthesized 64 recent studies on yield potential and gaps for the world’ s three major cereals, finding that farmers currently achieve 60%, 60%, and 53% of potential yields for wheat, rice, and maize, respectively—indicating substantial room for improvement. Liu et al. employed the APSIM-Maize model to analyze spatio-temporal patterns of yield gaps for spring maize in Northeast China from 1961–2010, revealing distinct latitudinal and longitudinal gradients. Liu et al. also investigated yield gaps at the field scale in Wuqiao County through farmer surveys, demonstrating that low- and medium-yield fields possess considerable improvement potential, with fertilizer input showing the greatest variation among farmers.

However, existing climate change impact studies on crop yield gaps have primarily focused on broad scales, rarely subdividing study areas into smaller zones. To enhance computational accuracy, this research divided Henan Province into five distinct planting zones with region-specific growth periods and applied monthly leaf area corrections for light-temperature potential calculations.

Henan Province, located in the transition zone between subtropical and warm temperate climates, possesses abundant climate resources and pronounced climate change characteristics. As one of China’ s most important commodity grain bases, Henan’ s grain production significantly impacts national food security. Analyzing the distribution characteristics of winter wheat yield gaps and their relationship with climate change is crucial for optimizing climate resource utilization, mitigating climate risks, and assessing potential climate change impacts on crop development.

1.1 Study Area Description

Henan lies at the intersection of north subtropical and warm temperate climate zones, exhibiting distinct transitional climate characteristics. During the winter wheat growing period (October to early June), the province enjoys relatively abundant solar energy, heat, and water resources with substantial agricultural potential. However, topographic and monsoonal influences create significant regional variations in climate resources. Additionally, its transitional location makes meteorological disasters that constrain wheat growth both severe and frequent.

Key climatic features during the winter wheat growing season include: suitable autumn temperatures; abundant autumn rainfall in central and southern regions but high interannual variability in western and northern planting areas; mild winters with scarce precipitation; rapid spring warming with ample sunshine but frequent spring droughts; and high summer temperatures vulnerable to dry-hot wind damage. These conditions result in extended tillering and spikelet differentiation periods but shortened grain-filling duration.

To capture regional heterogeneity, this study divided Henan into five zones: **Zone I** (Northern Henan) includes Anyang, Xinxiang, and Kaifeng; **Zone II** (Eastern Henan) includes Shangqiu, Xihua, Xuchang, and Baofeng; **Zone III** (Hilly Basin) includes Sanmenxia, Lushi, and Luanchuan; **Zone IV** (Southern Henan Plain and Nanyang Basin) includes Nanyang, Zhumadian, and Xixia; and **Zone V** (Southern Henan Rice-Wheat Rotation) includes Xinyang.

[Figure 1: see original paper] Climatic regionalization of winter wheat in Henan Province

1.2 Research Methods

This study employed the Agro-ecological Zone (AEZ) model to calculate winter wheat production potential, implemented through C programming. Data processing and charting were performed using Excel, while spatial distribution maps were generated using ArcGIS 10.2.

1.2.1 AEZ Model Description The AEZ model, developed by Kassam for the FAO Agro-ecological Zones Project, calculates crop potential productivity based on standard crop biomass and dry matter accumulation, sequentially applying corrections for temperature, leaf area, net dry matter production, and harvest index. These corrections are crop-specific and applied by growth stage.

The photosynthetic potential formula is:

$$Y_1 = y_0 + f_0(y_c - y_0) \cdot A_c \cdot R_s$$

where Y_1 represents photosynthetic potential (kg·hm ^{2}), y_0 is dry matter productivity under completely overcast conditions, y_c is productivity under clear-sky conditions, f_0 is the fraction of cloudy days, R_s is solar or shortwave radiation flux, and A_c is maximum effective incoming shortwave radiation on clear days.

Solar radiation (R_s) is calculated as:

$$R_s = (0.25 + 0.50 \cdot n/N) \cdot R_a$$

where n is actual sunshine hours and N is potential sunshine hours.

The light-temperature potential formula is:

For $y_m > 20$ kg • hm ^{2} • h ^{1}:

$$Y_2 = CL{\cdot}CN{\cdot}CH{\cdot}G{\cdot}[y_0{+}f_0{\cdot}(0.08{+}0.01{\cdot}y_m){\cdot}(y_c{-}y_0){+}(1{-}f_0){\cdot}(0.05{+}0.025{\cdot}y_m){\cdot}y_c]$$

For $y_m < 20$ kg • hm ^{2} • h ^{1}:

$$Y_2 = CL{\cdot}CN{\cdot}CH{\cdot}G{\cdot}[y_0{+}f_0{\cdot}(0.05{+}0.025{\cdot}y_m){\cdot}(y_c{-}y_0){+}(1{-}f_0){\cdot}(0.05{\cdot}y_m){\cdot}y_c]$$

where Y_2 is light-temperature potential (kg • hm ^{2}), CL is the leaf area growth correction coefficient (assuming effective leaf area index LAI=5), CN is net dry matter production correction coefficient (0.6 for cool climates, 0.5 for warm), CH is harvest index, G is total growth period days, and y_m is crop dry matter productivity (kg • hm ^{2} • h ^{1}).

Correction values (CL) of crop growth under different leaf area indexes

Monthly correction values (CL) for different regions in Henan during the growth period (derived from Table 1 based on LAI values at specific days after sowing)

The climate potential formula is:

$$Y_3 = Y_2 \cdot f(p)$$

where Y_3 is climate potential (kg • hm ^{2}) and $f(p)$ is the water correction function:

$$f(p) = \begin{cases} 1 & \text{if } P > ET_m \\ 1 - K_y \cdot (1 - P/ET_m) & \text{if } P < ET_m \end{cases}$$

where P is precipitation, K_y is crop response coefficient (1.0 for winter wheat), ET_m is actual evapotranspiration, and ET_0 is reference evapotranspiration calculated using the FAO Penman-Monteith equation.

1.2.2 Yield Gap Calculation Methods Yield gaps were calculated as differences between AEZ model potentials and actual yields. This study analyzed three levels:

- **YG1-2**: Gap between photosynthetic and light-temperature potentials, reflecting temperature constraints on photosynthetic potential
- **YG2-3**: Gap between light-temperature and climate potentials, indicating precipitation constraints on light-temperature potential
- **YG2-a**: Gap between light-temperature potential and field-average yield, representing combined climatic and production constraints on actual yields

1.3 Data Sources

Meteorological data (1961-2013) were obtained from the National Meteorological Information Center, including daily mean, maximum, and minimum temperatures, precipitation, sunshine hours, relative humidity, extraterrestrial solar radiation, solar hour angle, and latitude for 14 stations. Winter wheat yield data (1980-2013) were sourced from the Henan Statistical Yearbooks.

2 Results and Analysis

2.1 Field-Average Yields in Henan (1981-2010)

Analysis of 10-year average yields at 14 stations revealed substantial inter-station variation and a clear upward trend, with the most pronounced increase during 2001-2010.

[Figure 2: see original paper] The average yield of winter wheat per 10-year period at 14 sites in Henan Province (1981-2010)

2.2 Production Potential of Winter Wheat in Henan

2.2.1 Photosynthetic Potential From 1961-2013, photosynthetic potential ranged from 47,799.50 to 64,982.95 kg • hm ^{2}. The maximum occurred at Xinxiang (Zone I) and the minimum at Xinyang (Zone V). Zone I benefits from superior light conditions with 1,400-1,500 sunshine hours during the growing period and minimal overcast weather. Conversely, Zone V (southern rice-wheat rotation area) experiences adequate early-season light but pronounced light deficiency during the rainy spring period.

Twelve stations showed decreasing trends, while Luanchuan and Lushi (Zone III) exhibited increasing trends, with Luanchuan showing a stronger increase. Both stations, located in hilly basins at elevations of 750.5 m and 738 m respectively, receive stronger solar radiation. Their total growing-season sunshine hours increased over the 53-year period, contrasting with decreasing trends at other stations.

[Figure 3: see original paper] Photosynthetic potential of winter wheat at 14 stations in Henan Province (1961–2013)

2.2.2 Light-Temperature Potential Light-temperature potential ranged from 7,156.54 to 9,971.61 kg•hm ^{2}, with the maximum at Xinxiang (Zone I) and minimum at Lushi (Zone III). Zone I’ s favorable light-temperature conditions promote robust pre-winter seedlings and safe overwintering. Zone III’ s hilly terrain can support strong seedlings when planting is timely, but late planting combined with autumn drought increases winter mortality. While large diurnal temperature ranges benefit grain filling, spring drought limits spikelet number, making yield dependent primarily on spike density.

All 14 stations showed increasing light-temperature potential due to global warming, with Kaifeng exhibiting the strongest trend and Anyang the weakest.

[Figure 4: see original paper] Light-temperature potential productivity of winter wheat at 14 stations in Henan Province (1961–2013)

2.2.3 Climate Potential Climate potential ranged from 1,034.23 to 9,416.88 kg•hm ^{2}, with the maximum at Xinyang (Zone V) and minimum at Anyang (Zone I). Zone V receives 400–500 mm precipitation during the growing season with warm, rainy winters and springs, while Zone I suffers from low natural precipitation (150–200 mm), high spring drought risk, and severe late-season dry-hot wind damage.

Three stations (Shangqiu, Xihua, and Sanmenxia) showed increasing trends, while 11 stations decreased, with Xinyang showing the steepest decline and Shangqiu the strongest increase.

[Figure 5: see original paper] Climate potential productivity of winter wheat at 14 sites in Henan Province (1961–2013)

2.3 Yield Gap Analysis

2.3.1 Gap Between Photosynthetic and Light-Temperature Potentials (YG1-2) YG1-2 reflects thermal constraints on photosynthetic potential. The multi-year average YG1-2 was highest at Xinxiang (Zone I) and lowest at Xinyang (Zone V). Temporally, YG1-2 showed an overall decreasing trend. Spatially, YG1-2 decreased from north to south, indicating diminishing thermal limitations on photosynthetic potential toward the south.

[Figure 6: see original paper] Average YG1-2 yield gap per 10-year period at 14 stations in Henan Province (1961–2010)

[Figure 7: see original paper] Spatial distribution of YG1-2 yield gaps in Henan Province

2.3.2 Gap Between Light-Temperature and Climate Potentials (YG2-3) YG2-3 quantifies precipitation constraints on light-temperature potential, with larger values indicating greater water deficit impacts. The multi-year average YG2-3 was highest at Xinxiang (Zone I) and lowest at Xinyang (Zone V). Temporally, YG2-3 displayed a "V-shaped" pattern with a trough during 1981–1990. Spatially, YG2-3 decreased from north to south, consistent with Henan's precipitation pattern of abundance in the south and scarcity in the north.

[Figure 8: see original paper] Average YG2-3 yield gap per 10-year period at 14 stations in Henan Province (1961–2010)

[Figure 9: see original paper] Spatial distribution of YG2-3 yield gaps in Henan Province

2.3.3 Gap Between Light-Temperature Potential and Field-Average Yield (YG2-a) YG2-a represents the combined climatic and production constraints on actual yields. Due to data limitations, YG2-a was calculated for 1981–2011. The multi-year average was highest at Lushi (Zone III) and lowest at Xinxiang (Zone I). Zones I, II, and V showed decreasing YG2-a trends, while Zones III and IV increased initially then decreased. Spatially, YG2-a increased from east to west (Zone I < II < IV < V < III), reflecting intensifying combined constraints.

[Figure 10: see original paper] Average YG2-a yield gap per 10-year period at 14 stations in Henan Province (1961–2010)

[Figure 11: see original paper] Spatial distribution of YG2-a yield gaps in Henan Province

3 Conclusions and Discussion

This study's findings on yield gap trends align well with previous research on climate impacts on Henan's winter wheat and summer maize. While Wang et al. also used the AEZ model to evaluate Henan's wheat potential, this study differs by: (1) dividing Henan into five zones with region-specific growth periods for greater precision; (2) employing three distinct yield gap metrics rather than a single potential-to-actual yield ratio; and (3) analyzing both temporal trends and spatial distributions rather than focusing on typical years. Similar to Yu et al.'s work on summer maize, this study uses model-based potential calculations and spatio-temporal analysis, but differs in model selection (AEZ vs. stepwise correction), regional disaggregation, and the use of three yield gap indicators.

A limitation of this study is the exclusion of supplemental irrigation from climate potential calculations, which may overestimate YG2-3 in irrigated areas. Future work should incorporate irrigation effects to improve accuracy.

Key findings indicate that decreasing sunshine hours reduced photosynthetic potential while warming increased light-temperature potential, leaving climate potential relatively stable. The substantial increase in field-average yields over the past 30 years, despite stable climate potential, primarily reflects variety improvements, technological advances, rational input use, and optimized regional zoning. Temporally, YG1-2 decreased, YG2-3 showed a V-shaped pattern, and YG2-a trends varied by zone. Spatially, YG1-2 and YG2-3 decreased north-to-south, while YG2-a increased east-to-west, reflecting regional disparities in climate, population density, and economic development.

Based on these results, zone-specific recommendations include: supplemental irrigation and optimized management for Zone I; management refinement for the technologically advanced Zone II; government-supported technology transfer, increased inputs, and irrigation for the economically disadvantaged Zone III; combined organic-inorganic fertilization for Zone IV’ s low-fertility soils; and appropriate crop zoning for Zone V’ s rice-suitable conditions.

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Note: Figure translations are in progress. See original paper for figures.