Characteristics and Development Potential of Agricultural Light and Heat Resources in the Tarim Basin: A Postprint

Authors: Wen Di, Lü Aifeng, Taohui Li, Zhang Wenxiang

Date: 2025-02-27T15:50:02+00:00

Abstract

Agricultural light and heat resources are core advantageous resources in the Western Development national strategy for the Tarim Basin. However, comprehensive quantitative assessments of the development potential of agricultural light and heat resources in the Tarim Basin are currently scarce. Based on an analysis of the spatiotemporal evolution characteristics of agricultural light and heat resources in the Tarim Basin, a comprehensive evaluation index system was constructed, and methods such as the entropy weight-TOPSIS method and Mann-Kendall test were employed to conduct a quantitative assessment of the development potential of agricultural light and heat resources in the Tarim Basin. The results indicate that: (1) From 1990 to 2020, annual sunshine hours, annual total solar radiation, active accumulated temperature $ $10 °C, and annual average temperature of agricultural light and heat resources in the Tarim Basin showed an upward trend, while days with effective sunshine $ $3 h and annual evaporation showed a downward trend; (2) The agricultural light and heat resources in the Tarim Basin exhibit significant spatial imbalance, with different indicators showing distinct spatial differentiation characteristics, forming prominent spatial patterns of clustered distribution of high and low agricultural light and heat resources; (3) Significant spatial differences exist in the development potential of agricultural light and heat resources in the Tarim Basin, with an average development potential score of 0.199; the highest-scoring Cele County (0.578) is more than six times that of the lowest-scoring Kalpin County (0.094), forming a "multi-core" distribution pattern. The research results can provide references for the development and utilization of agricultural light and heat resources in the Tarim Basin and help improve local resource utilization efficiency.

Full Text

Characteristics and Development Potential Analysis of Agricultural Solar-Thermal Resources in the Tarim Basin

WEN Di[1], **LYU Aifeng**[2], **LI Taohui**[3], **ZHANG Wenxiang**[1]
[1]Key Laboratory of Plateau Geographic Processes and Environment Change of Yunnan Province, Faculty of Geography, Yunnan Normal University, Kunming, Yunnan 650500, China
[2]Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
[3]Key Laboratory of Meteorological Disasters and Climate Resources in the Greater Mekong Subregion, Yunnan University, Kunming, Yunnan 650091, China

Abstract

Agricultural solar-thermal resources represent a core advantage in the national strategy for the large-scale development of western China in the Tarim Basin. However, comprehensive quantitative assessments of the development potential of agricultural solar-thermal resources in this region remain scarce. Based on an analysis of spatiotemporal evolution characteristics of agricultural solar-thermal resources in the Tarim Basin, this study constructed a comprehensive evaluation index system and employed the entropy weight-TOPSIS method and Mann-Kendall test to quantitatively evaluate the development potential of agricultural solar-thermal resources in the basin. The results indicate that: (1) From 1990 to 2020, annual sunshine hours, total solar radiation, active accumulated temperature $ $10 °C, and annual average temperature all showed increasing trends, while effective sunshine days and annual evaporation exhibited decreasing trends. (2) Significant spatial heterogeneity exists in agricultural solar-thermal resources across the Tarim Basin, with different indicators displaying distinct spatial differentiation patterns, forming prominent spatial characteristics of high and low agricultural solar-thermal resource aggregation. (3) The development potential of agricultural solar-thermal resources shows substantial spatial variation, with a mean development potential score of 0.199. The highest score was observed in Cele County (0.578), more than six times greater than the lowest-scoring Keping County (0.094), creating a "multicore" distribution pattern. These findings can provide references for the development and utilization of agricultural solar-thermal resources in the Tarim Basin, helping to improve local resource utilization efficiency.

Keywords: Tarim Basin; agricultural solar-thermal resources; spatiotemporal pattern; development potential; entropy weight-TOPSIS method

1. Introduction

Agricultural production depends on numerous natural and socioeconomic conditions, among which light and heat resources are extremely important natural factors affecting crop production [?, ?]. Agricultural solar-thermal resources refer to the collective term for solar energy and thermal energy resources that a region can provide for agricultural production. The quantity, combination, and distribution of light and heat elements play a crucial role in regional agricultural production and socioeconomic development [?, ?]. In recent years, the development and utilization of solar-thermal resources have gradually attracted widespread attention [?, ?]. Numerous studies have examined the relationship between solar-thermal resources and crop growth, the variation characteristics of these resources, and their utilization efficiency [?, ?]. For example, research on the impact of solar-thermal resource changes during the growing season on the development period of *Lycium barbarum* in Zhongning County, Ningxia, found that solar-thermal resources can increase or decrease over time, demonstrating temporal instability [?, ?]. Other scholars have focused on the utilization efficiency of solar-thermal resources [?, ?], including the effects of different sowing dates, tillage methods, irrigation and fertilization approaches, and cultivation patterns on crop solar-thermal resource use efficiency. Overall, previous studies have enhanced our understanding of the importance and utilization of agricultural solar-thermal resources, but several limitations remain. First, existing research has primarily focused on temporal trends in agricultural solar-thermal resources while neglecting their inherent spatial heterogeneity [?, ?], with relatively insufficient investigation of spatial patterns and evolution characteristics. Second, while many studies have evaluated utilization efficiency under different scenarios, research on regional development potential remains inadequate, and a comprehensive assessment framework for agricultural solar-thermal resource development potential is still lacking. Third, agricultural solar-thermal resource conditions vary across different regions, making spatial pattern and development potential assessment studies highly practical and targeted for guiding regional resource development and agricultural planning [?, ?]. Additionally, current research scales have primarily focused on natural units such as cities [?] and provinces [?], with few studies examining smaller-scale natural units, particularly in Northwest China’ s inland regions where solar-thermal resources are extremely abundant.

The Tarim Basin, located in inland Northwest China, constitutes an important component of the Silk Road Economic Belt and a key region for consolidating poverty alleviation achievements. The Chinese government attaches great importance to the economic development and social stability of the Tarim Basin, which serves as a priority implementation area in the national “Western Development” strategy. However, the Tarim Basin is characterized by an arid climate, scarce water resources, extensive desert and Gobi landscapes, fragile ecological environments, and relatively poor agricultural production conditions [?, ?]. Nevertheless, the basin features long sunshine duration, abundant solar-thermal resources, and large diurnal temperature variations, making it suitable for developing characteristic agricultural products. With adequate development and utilization of solar-thermal resources, the Tarim Basin possesses considerable potential and advantages for agricultural development [**?**, **?**]. As socioeconomic development progresses and demands for modern agriculture and sustainable coordinated development intensify, new questions emerge for the Tarim Basin region: First, how have agricultural solar-thermal resources changed spatially over time? Second, what are the differences in agricultural solar-thermal resource development potential across different areas of the Tarim Basin, and which regions have greater development potential? Addressing these questions can help guide the rational and full development of solar-thermal resources, improve utilization efficiency, enhance agricultural productivity, and promote regional socioeconomic development and residents' living standards.

In summary, this study takes counties as natural units, analyzes the spatiotemporal pattern characteristics of agricultural solar-thermal resources in 42 counties of the Tarim Basin, constructs a comprehensive evaluation index system incorporating three dimensions—solar-thermal resource endowment, current agricultural resources, and agricultural ecological environment—and employs the entropy weight-TOPSIS method to evaluate the development potential of agricultural solar-thermal resources in the Tarim Basin. The study also proposes targeted development and utilization recommendations. The findings will help understand the advantages and limitations of agricultural solar-thermal resources in the Tarim region and provide valuable references for high-quality agricultural development.

1.1 Study Area Overview

The Tarim Basin is located in southern Xinjiang, China, and primarily comprises Kashgar, Hotan, Aksu, Bayingolin Mongol Autonomous Prefecture, and Kizilsu Kirghiz Autonomous Prefecture (Figure 1). The basin's landform exhibits a ring-shaped distribution, with gravel Gobi connected to mountains at the edges, vast deserts in the central area (including the Taklamakan Desert, China's largest desert), and alluvial fans and plains distributed between the edges and desert, where oases are located. The Tarim Basin has a temperate continental climate with an annual average temperature of 9-11 ℃ and a frost-free period exceeding 200 days. Situated deep inland, the climate is extremely dry with scarce precipitation, making drought its primary characteristic. Additionally, the basin features strong solar radiation, with annual sunshine hours exceeding 3,000 in the north and approaching 3,000 in the south, and total annual solar radiation of 575-627 $\mathrm{kJ \cdot cm^{-2}}$, indicating extremely abundant solar-thermal resources [**?**, **?**].

1.2 Data Sources

This study utilized climate, water resources, agricultural, and socioeconomic data for 42 counties in the Tarim Basin from 1990 to 2020. Annual sunshine hours, total annual solar radiation, effective sunshine days, active accumulated temperature $ $10 ℃, annual average temperature, and annual evaporation data were obtained from the Tarim Basin solar-thermal resource dataset produced by our research team, with a spatial resolution of 1 km. Water resource reserves, agricultural water use, effective irrigation area, proportion of agricultural land, and agricultural infrastructure investment cost data were sourced from the Xinjiang Water Resources Bulletin (1990-2020), Xinjiang Statistical Yearbook (1990-2020), and data collection by the scientific expedition team. Soil erosion rate, per capita GDP, total agricultural output value, drought and flood frequency, and proportion of degraded farmland data were obtained from the Xinjiang Statistical Yearbook (1990-2020), high-precision remote sensing climate datasets, and data collection by the scientific expedition team.

1.3 Mann-Kendall Trend Test

The Mann-Kendall (M-K) trend test is a non-parametric statistical method used to detect increasing or decreasing trends in time series data. Its advantages include not requiring specific distribution testing of the data series and not being affected by outliers, making it suitable for categorical and ordinal variables. The calculation formula is as follows:

$$S_k = \sum_{i=1}^{k} \sum_{j=1}^{i-1} a_{ij}, \quad k = 2, 3, \cdots, n$$

where $a_{ij} = \begin{cases} 1 & \text{if } x_i > x_j \\ 0 & \text{if } x_i \leq x_j \end{cases}$ for $j = 1, 2, 3, \cdots, i$. The order sequence S_k represents the cumulative count of values greater than previous values at time i.

Under the assumption of random independence, the statistical variable is defined as:

$$UF_k = \frac{S_k - E(S_k)}{\sqrt{Var(S_k)}}, \quad k = 2, 3, \cdots, n$$

where UF_k is the defined statistic, and $E(S_k)$ and $Var(S_k)$ are the mean and variance of the cumulative count S_k. When $X_1, X_2, \cdots, X_n$ are mutually independent with the same continuous distribution, these can be calculated as:

$$E(S_k) = \frac{k(k-1)}{4}$$

$$Var(S_k) = \frac{k(k-1)(2k+5)}{72}$$

The UF statistic is calculated through the forward time series X_n, while UB is calculated through the backward time series. Given a significance level of $\alpha = 0.05$, the critical value is ± 1.96. If $|UF_k| > 1.96$, the sequence exhibits a significant trend. If $UF_k > 1.96$, the sequence shows a significant upward trend; if $UF_k < -1.96$, it shows a significant downward trend; otherwise, no significant trend exists. If UF and UB intersect within the critical values, the intersection point indicates the timing of an abrupt change.

1.4 Comprehensive Development Potential Evaluation Method

The entropy weight-TOPSIS method combines entropy weighting with the TOPSIS approach. TOPSIS ranks evaluation objects by their distance from the ideal solution, identifying the optimal decision as the solution nearest to the positive ideal solution and farthest from the negative ideal solution [**?**, **?**]. Based on a constructed evaluation index system for agricultural solar-thermal resource development potential, this study used the entropy weight method to determine indicator weights and applied the TOPSIS model to comprehensively evaluate the development potential of agricultural solar-thermal resources in the Tarim Basin.

1.4.1 Index System Construction To scientifically evaluate agricultural solar-thermal resources in the Tarim Basin, we reviewed relevant literature on development potential evaluation [**?**, **?**] and, based on our understanding of the basin's agricultural solar-thermal resources and actual conditions of agricultural development and resource reserves, constructed an evaluation index system following principles of scientific rigor, systematicity, and data availability. The system comprises three dimensions: solar-thermal resource endowment, current agricultural resources, and agricultural ecological environment (Table 1).

Solar-thermal resources are crucial climate resources for agricultural production. For the endowment dimension, we selected six factors: annual sunshine hours, total annual solar radiation, effective sunshine days, active accumulated temperature $ $10 ℃, annual average temperature, and annual evaporation as evaluation indicators for light and heat resources. Beyond resource endowment and agricultural resource conditions, the agricultural ecological environment is also a critical factor determining whether solar-thermal resources can be effectively developed and utilized, making it an important dimension for comprehensive evaluation. Agricultural resources refer to the totality of resources utilized or available for agricultural economic activities, including natural and economic resources. Evaluating the current status of agricultural resources in the Tarim Basin provides strong internal support for developing agricultural solar-thermal resources. We selected water resource reserves, agricultural water use, effective irrigation area, proportion of agricultural land, and agricultural infrastructure investment cost as indicators. The agricultural ecological environment encompasses land, water, climate, and biological resources that directly or indirectly affect agricultural survival and development, serving as the foundation for agricultural production and the most important material basis for social production and development. We selected soil erosion rate, per capita GDP, total agricultural output value, drought and flood frequency [**?**], and proportion of degraded farmland as evaluation indicators for the agricultural ecological environment in the Tarim Basin.

To quantitatively analyze the development potential of agricultural solar-thermal resources in 42 county-level administrative units, we used national county-level administrative divisions as standard zones and processed the 1990–2020 data into multi-year averages for each administrative unit to ensure temporal and spatial consistency. Solar-thermal resource endowment data were derived from our team' s raster dataset, from which multi-year averages for 42 counties were extracted into Excel tables. Current agricultural resources and agricultural ecological environment data were obtained through data collection and remote sensing interpretation, processed into multi-year averages for 42 counties using Python and Excel. Missing regional data and temporal sequences were supplemented through linear interpolation and consistency testing.

1.4.2 Entropy Weight-TOPSIS Method 1) Data Standardization: Original data for 42 evaluation indicators from 42 counties were normalized to eliminate dimensional and magnitude inconsistencies. Based on indicator properties, we used the range standardization method:

$$R_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})}$$

where x_{ij} is the original data for indicator i in year j ($i = 1, 2, \cdots, m$; $j = 1, 2, 3, \cdots, n$), and R_{ij} is the standardized value between [0,1].

2) Indicator Weighting: We calculated the weight W_{ij} for indicator i:

$$f_{ij} = \frac{R_{ij}}{\sum_{j=1}^{n} R_{ij}}$$

$$E_i = -\frac{1}{\ln(n)} \sum_{j=1}^{n} f_{ij} \times \ln(f_{ij})$$

$$W_{ij} = \frac{1 - E_i}{\sum_{i=1}^{m} (1 - E_i)}$$

where f_{ij} represents the proportion of indicator i in evaluation object j, E_i is the information entropy of indicator i, and W_{ij} is the weight of indicator i.

3) Weighted Evaluation Matrix: Matrix Z is obtained by multiplying the standardized data matrix P with weight matrix W:

$$Z_{ij} = P_{ij} \times W_j$$

where Z_{ij} is the weighted result for indicator i in evaluation object j, n is the total number of indicators, m is the total number of evaluation objects, P_{ij} is the standardized data value, and W_j is the indicator weight.

4) Ideal Solutions: The positive ideal solution represents the best values for all indicators in the sample, while the negative ideal solution represents the worst values.

5) Distance Calculation: The distances from each sample to the positive and negative ideal solutions are calculated as:

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (Z_{ij} - Z_j^+)^2}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} (Z_{ij} - Z_j^-)^2}$$

where D_i^+ is the distance to the positive ideal solution and D_i^- is the distance to the negative ideal solution.

6) Relative Closeness: The relative Euclidean closeness is calculated as:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-}$$

where the closeness degree C_i ranges from [0,1], with higher values indicating better evaluation scores.

2. Results and Analysis

2.1 Interannual Variation of Agricultural Solar-Thermal Resources in the Tarim Basin

Overall, the increase in annual sunshine hours and total solar radiation provides more abundant energy for crop photosynthesis, while the appropriate increase in annual average temperature and active accumulated temperature \$ \$10 ℃ meets crop heat requirements [**?**], helping to extend the growing period and improve crop maturity and yield. The decrease in annual evaporation is beneficial for reducing water loss, providing better hydrothermal conditions for crops. Combined, these trends have improved agricultural solar-thermal resources and enhanced growing conditions for local agricultural products, thereby promoting agricultural development in the region.

Using linear fitting to analyze interannual trends across the entire Tarim Basin and different counties from 1990 to 2020 (with regional values calculated as averages across all counties), the results (Figure 2) show that annual sunshine hours, total solar radiation, active accumulated temperature $ 10℃, $andannualaveragetemperatureexhibitedincreasingtrends, withannualincreaseratesof0.67h\cdot yr^{\{-1\}, 0.03MJ\cdot m}\{-2\}\cdot yr^{\{-1\}, 4.86℃\cdot d\cdot yr}\{-1\}, and0.02℃\cdot yr^{\{-1\}, respectively.Effectivesunshinedaysandannualevaporationsh}$ 1}$ and 1.42 mm $\cdot$ yr^{-1}, respectively.

At the county level (Figure 3), significant spatial differences exist in interannual variation trends. Counties with increasing trends in sunshine hours and solar radiation are mainly concentrated in the central, northern, and southern regions, with the most pronounced increases in Keping County, Korla City, and Yanqi Hui Autonomous County. Decreasing trends are mainly distributed in the eastern and western peripheries. The spatial patterns of active accumulated temperature $ $10 ℃ and annual average temperature are similar, with increasing trends primarily in the southwestern region (most notably in Cele County, Yutian County, and Luopu County) and decreasing trends mainly in the northeastern region. All counties showed increasing annual average temperature, with more pronounced increases in the southwestern, northwestern, and southern regions. Counties with increasing evaporation are distributed across the eastern, western, and central regions (e.g., Yecheng County and Taxkorgan Tajik Autonomous County in the west, Aksu City in the center, and Ruoqiang County in the east), while decreasing evaporation occurs mainly in western counties such as Makit County, Keping County, and Hotan County.

2.2 Spatial Pattern of Agricultural Solar-Thermal Resources in the Tarim Basin

By calculating multi-year averages of the 42 evaluation indicators and mapping them using the natural breaks method, we analyzed the spatial distribution characteristics. Overall, agricultural solar-thermal resources in the Tarim Basin exhibit significant spatial heterogeneity, with clear spatial differentiation across indicators.

Counties with longer annual sunshine hours are concentrated in the eastern and central regions, including Ruoqiang County, Yuli County, and Yutian County, while shorter durations appear in the north and southwest (Hejing County, Luntai County, Hotan County). Total annual solar radiation shows a general pattern of higher values in the south and lower values in the north, with lower values in northern Hejing and Luntai Counties and higher values in southern Yutian, Minfeng, Ruoqiang, Yecheng, and Pishan Counties, attributable to lower latitudes in the south. Effective sunshine days are mainly distributed in the east, center, and parts of the west (Ruoqiang, Yutian, Minfeng, and Taxkorgan Tajik Autonomous Counties). The spatial distribution of active accumulated temperature $ $10 ℃ and annual average temperature is similar, with high-value areas concentrated in the basin’ s interior where lower altitudes result in higher temperatures and accumulated heat (e.g., Shaya County, Luopu County, Moyu County). Peripheral areas, particularly in the north and west with higher altitudes or latitudes, have relatively lower temperatures and accumulated heat. Higher annual evaporation occurs mainly in the east and south (Luopu, Yutian, Minfeng, Cele, and Qiemo Counties), while lower evaporation appears in northern and western areas with higher altitude and latitude.

2.3 Development Potential of Agricultural Solar-Thermal Resources in the Tarim Basin

Using the entropy weight-TOPSIS model, we calculated the development potential for 42 counties and classified them using the natural breaks method into five levels: low (0.093-0.130), relatively low (0.131-0.172), medium (0.173-0.221), relatively high (0.222-0.329), and high (0.330-0.578). The results reveal significant spatial disparities in development potential, with an average score of 0.199. The highest potential was in Cele County (0.578), nearly six times the average, while the lowest was in Keping County (0.094), less than half the average. The difference between the highest and lowest potential counties is substantial, with the former scoring more than six times the latter.

Spatially, the development potential shows pronounced heterogeneity, with high and relatively high potential counties distributed dispersedly, forming a “multicore” pattern. High-potential counties include Cele and Wushi, located in the southwest and northwest, respectively. Cele County has significantly higher annual average temperature, sunshine hours, solar radiation, effective sunshine days, and active accumulated temperature $ $10 ℃ than other regions, offering abundant resource endowment combined with favorable agricultural resource conditions and ecological environment. Wushi County has numerous effective sunshine days, moderate other solar-thermal conditions, but much lower evaporation, along with relatively good agricultural resource conditions and ecological environment, resulting in high comprehensive development potential. Relatively high-potential counties are mainly distributed in the east and west (Ruoqiang, Zepu, Taxkorgan Tajik Autonomous County). Low or relatively low potential counties are more concentrated in the western region, particularly Keping and Pishan Counties. Keping County has relatively low values for sunshine hours, solar radiation, active accumulated temperature $ $10 ℃, and annual average temperature, weak resource endowment, and poor agricultural resource conditions and ecological environment. Pishan County has relatively low sunshine hours and effective sunshine days but very high evaporation, poor agricultural resource conditions and ecological environment, resulting in low development potential.

3. Discussion

Based on the entropy weight-TOPSIS model calculations, we obtained the weights of 16 indicators for evaluating agricultural solar-thermal resource development potential in the Tarim Basin [?]. The weight data reveal that agricultural infrastructure investment (0.214), effective irrigation area (0.156), and water resources (0.138) have the most significant driving effects on agricultural output value, substantially higher than the weights of solar-thermal resource indicators themselves: annual sunshine hours (0.067), total solar radiation (0.059), active accumulated temperature \$ \$10 ℃ (0.052), annual average temperature (0.048), and annual evaporation (0.043). Solar-thermal resource elements have limited direct impact on agricultural output value but provide fundamental natural conditions [?], primarily influencing agricultural output indirectly by regulating crop growth cycles, improving yield and quality. However, utilizing solar-thermal resources depends on water resources and irrigation infrastructure support, particularly in water-limited regions like the Tarim Basin. Therefore, although solar-thermal resources are abundant, insufficient water resources and infrastructure constrain their contribution to agricultural output [?]. As solar-thermal resources increase annually, agricultural output potential also rises, but this improvement is limited by the availability of agricultural water and infrastructure. Consequently, future efforts in the Tarim Basin should prioritize investment in water resource management and infrastructure construction to fully leverage natural solar-thermal resources, improve resource utilization efficiency, and promote agricultural output growth.

From a spatial perspective, the heterogeneous distribution of solar-thermal resources in the Tarim Basin has important implications for regional agricultural layout and development strategy formulation. Through rational agricultural planning and management, regional advantages in agricultural solar-thermal resources can be fully exploited to promote high-quality local agricultural and socioeconomic development.

4. Conclusion

Through analysis of the spatiotemporal patterns of agricultural solar-thermal resources in 42 counties of the Tarim Basin and evaluation of their development potential using the entropy weight-TOPSIS method and Mann-Kendall trend test, we reached the following conclusions:

1) From 1990 to 2020, agricultural solar-thermal resources in the Tarim Basin showed clear trends: annual sunshine hours, total solar radiation, active accumulated temperature \$ \$10 ℃, and annual average temperature increased, providing more favorable conditions for crop growth; effective sunshine days and annual evaporation decreased.
2) Agricultural solar-thermal resources exhibit significant spatial heterogeneity across the Tarim Basin. Regions with higher sunshine hours and solar radiation are concentrated in the east and south, while lower values occur

in the north and southwest. Active accumulated temperature $ $10 ℃ and annual average temperature also show clear regional differences, gradually decreasing from southwest to northeast.

3) The development potential of agricultural solar-thermal resources varies significantly across the Tarim Basin, with an average score of 0.199. The highest score was in Cele County (0.578) and the lowest in Keping County (0.094), with the former being more than six times the latter.
4) The spatial distribution of development potential is highly uneven, with high and relatively high potential counties distributed dispersedly, forming a "multicore" pattern. High-potential counties include Cele and Wushi, while low-potential areas include Keping and Pishan Counties.

References

[1] Dhonde M, Sahu K, Murty V V S, et al. The application of solar driven technologies for the sustainable development of agriculture farming: A comprehensive review[J]. Reviews in Environmental Science and Bio/Technology, 2022, 21(1): 1-29.

[2] Pascaris A S, Chelsea S, Laurie B, et al. Integrating solar energy with agriculture: Industry perspectives on the market, community, and socio political dimensions of agrivoltaics[J]. Energy Research & Social Science, 2021, 75: 102023.

[3] Kumar C M S, Singh S, Kumar G M, et al. Solar energy: A promising renewable source for meeting energy demand in Indian agriculture applications[J]. Sustainable Energy Technologies and Assessments, 2023, 55: 102905.

[4] Liu S R. Technology development of electric traction rail traffic[J]. Strategic Study of CAE, 2000, 2(10): 59-62.

[5] Chen W L, Zheng M. Advancing the Great Western Development in the new era to form a new layout: An interpretation through the perspective of "Promoting Great Development through Greater Opening"[J]. Research on Development, 2024, 5(1): 1-12.

[6] Liu B, Yang G H, Zhang L P. Analysis and evaluation on the production potential of agricultural resources in South Xinjiang area[J]. Journal of Arid Land Resources and Environment, 2006, 20(3): 139-143.

[7] Guo H Y. Contribute of sunlight temperature water to wheat output in winter and exploitation of water resource in Loess Plateau of Longdong[J]. Journal of Arid Land Resources and Environment, 2004, 18(6): 128-131.

[8] Zhang S, Chen Z, Cao C, et al. Photothermal management agricultural films toward industrial planting: Opportunities and challenges[J]. Engineering, 2024, 35: 191-200.

[9] Lei L, Li J P, Ma L W, et al. A precise climate division of *Lycium barbarum*

in Zhongning County, Ningxia[J]. Non-wood Forest Research, 2020, 38(3): 104-111.

[10] Li S Y, Fang W S, Ma Z H. Changes of agricultural climate resources in Henan Province during summer maize growing season[J]. Journal of Henan Agricultural Sciences, 2012, 41(7): 21-26.

[11] Zhang W, Yan L L, Fu Z Q, et al. Effects of sowing date on yield of double cropping rice and utilization efficiency of light and heat energy in Hunan Province[J]. Scientia Agricultura Sinica, 2023, 56(1): 31-45.

[12] Mi N, Zhang F R, Zhao Y J, et al. Evaluating the radiation and thermal use efficiency of the integrated technology of maize straw returning with alternate tillage and density increase[J]. Journal of Agricultural Resources and Environment, 2021, 38(3): 475-483.

[13] Jiang L N, Li J N, Qi H Z, et al. Matter accumulation and transport of winter wheat and utilization of photothermal resources under different cultivation patterns[J]. Journal of Henan Agricultural Sciences, 2018, 47(12): 14-19.

[14] Yue W, Chen J H, Ruan X M, et al. Variation in characteristics of light and heat resource utilization efficiency of double-season rice and its impact on meteorological yield along the Yangtze River in Anhui Province[J]. Chinese Journal of Eco-Agriculture, 2019, 27(6): 929-940.

[15] Mansur S, Nurkamuri Y. Oasis land use change and its hydrological response to Tarim River Basin[J]. Geographical Research, 2010, 29(12): 2251-2260.

[16] Ye C H, Luan Q Z, Hu B K, et al. Agricultural climate resources change characteristics of Beijing and related impacts on maize planted in different zones and different growth periods[J]. Journal of Natural Resources, 2010, 25(8): 1350-1364.

[17] Hu Q, Pan F, Pan X, et al. Trends in agricultural heat and solar radiation resources in Northeast China: A multistage spatio-temporal analysis[J]. International Journal of Climatology, 2016, 36(6): 2461-2478.

[18] Yang P Y, Hu Q, Ma X Q, et al. Spatiotemporal variation of heat and solar resources and its impact on summer maize in the North China Plain over the period 1961-2015[J]. Chinese Journal of Agrometeorology, 2018, 39(7): 431-441.

[19] Wang C, Zhao H D, Feng N J, et al. Differences in light and heat utilization efficiency and yield of soybean in two ecological zones and their response to chemical control regulators[J]. Chinese Journal of Applied Ecology, 2018, 29(11): 3615-3624.

[20] Liu X Y, Chen L C, Zhao Q M, et al. Light and heat utilization efficiency of winter wheat and summer maize in northern region of Henan Province[J]. Journal of Henan Agricultural Sciences, 2012, 41(4): 29-33.

[21] Cai F, Zhang Y S, Chen P S, et al. Spatio-temporal characteristics of Liaoning's thermal resources in recent 50 years[J]. Journal of Natural Resources,

2009, 24(9): 1635-1646.

[22] Li T H, Zhang W X, Lv A F, et al. Temporal and spatial characteristics of heat resources in growing season in Yunnan Province, China[J]. Mountain Research, 2023, 41(3): 361-374.

[23] Liu M, Lv A F, Wu J J, et al. A Review of impacts of drought on agro-ecosystem[J]. Chinese Agricultural Science Bulletin, 2014, 30(32): 165-171.

[24] Liu C, Ren L Q, Li X J, et al. Evaluation to the solar energy resources in the sandy regions of Northern China from 1990 to 2019[J]. Plateau Meteorology, 2021, 40(5): 1213-1223.

[25] Liang Y L, Han M C, Bai L, et al. Spatial-temporal distribution variation characteristics of the agricultural climate resources over recent 30 years in China[J]. Agricultural Research in the Arid Areas, 2015, 33(4): 259-267.

[26] Zhou G X, Li P Q, Zhou X D. Impact of light, heat and water resources change in Western Liaoning Province on agricultural production[J]. Chinese Journal of Agrometeorology, 2011, 32(S1): 38-41.

[27] Zhang Z G, Zhang X L, Jia M W, et al. Spatiotemporal evolution characteristics of agricultural thermal resources in the Yellow River Basin from 1960 to 2020[J]. Journal of Shanxi Agricultural University (Natural Science Edition), 2024, 44(3): 119-130.

[28] He G, Kammen M D. Where, when and how much wind is available? A provincial scale wind resource assessment for China[J]. Energy Policy, 2014, 7(4): 116-122.

[29] Yu G A, Li Z W, Huang H Q, et al. Human impacts on fluvial processes in a very arid environment: Case of Tarim River in China[J]. Advances in Water Science, 2017, 28(2): 183-192.

[30] Zheng Y, He J, Zhang W, et al. Assessing water security and coupling coordination in the Lancang-Mekong River Basin for sustainable development[J]. Sustainability, 2023, 15(24): 131-133.

[31] Li Z, Luo Z, Wang Y, et al. Suitability evaluation system for the shallow geothermal energy implementation in region by entropy weight method and TOPSIS method[J]. Renewable Energy, 2022, 18(4): 980-996.

[32] Tang C C, Liu Y R, Wan Z W, et al. Evaluation system and influencing paths of the integration of culture and tourism of traditional villages[J]. Acta Geographica Sinica, 2023, 78(4): 980-996.

[33] Shen Y B, Wang C H, Chen Y. Variation of surface solar radiation and its influence on temperature change in three provinces of Northeast China[J]. Scientia Geographica Sinica, 2023, 43(11): 2045-2052.

[34] Xie Z H, Liu M, Yan X G, et al. Spatial pattern of important geological remains and evaluation of geotourism development potential in the Yellow River

Basin[J]. Journal of Desert Research, 2024, 44(3): 128-139.

[35] Dai W Y, Ma J C, Chen Y C, et al. Analysis of driving forces and dynamic evolution of water ecological security in the Gansu section of the Yellow River Basin[J]. Arid Zone Research, 2024, 41(10): 1662-1671.

[36] Liang Y L, Shen Y B, Bai L, et al. Assessment of solar energy resource and its exploitation potential in South China[J]. Journal of Applied Meteorological Science, 2017, 28(4): 481-492.

[37] Wang Y, Yang J, Chen Y, et al. Monitoring and predicting drought based on multiple indicators in an arid area, China[J]. Remote Sensing, 2020, 12(14): 2298.

[38] Deng X Y, Liu Y, Liu Z H, et al. Temporal-spatial dynamic change characteristics of evapotranspiration in arid region of Northwest China[J]. Acta Ecologica Sinica, 2017, 37(9): 2994-3008.

[39] Li T, Lv A, Zhang W, et al. Spatiotemporal characteristics of watershed warming and wetting: The response to atmospheric circulation in arid areas of Northwest China[J]. Atmosphere, 2023, 14(1): 131-133.

[40] Williams K B, Martin M D. Dynamic use of agriculture incentives to promote conservation[J]. Journal of Environmental Management, 2024, 370(1): 25.

[41] Zhang Y, Sun C J, Liu G, et al. Response of NDSI in the Tarim River Basin mountainous areas to climate change over the past 20 years[J]. Arid Zone Research, 2024, 41(10): 1639-1648.

[42] Xu Y H, Liu Q, Chen Y H, et al. Impact of land cover variations on surface albedo in Xinjiang and its surrounding Central Asian region[J]. Arid Zone Research, 2024, 41(10): 1649-1661.

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