Evolution of Agricultural Water Footprint and Optimization of Planting Structure in the Hexi Inland River Basin (Postprint)

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Abstract

To evaluate agricultural water resource consumption in the Hexi inland river basin, this study analyzed the spatiotemporal evolution characteristics of the agricultural water footprint in the basin from 2011 to 2023 based on water footprint theory. Multi-objective programming and the LMDI model were employed to analyze the planting structure and its influencing factors. The results indicate that the agricultural water footprint showed an upward trend during the study period, with an average annual growth rate of 3.8%. In terms of structure, it was dominated by grain crops (49.3%), cash crops (27.8%), and livestock products (22.5%), while aquatic products accounted for a smaller proportion (0.4%). After optimizing the planting structure for seven typical crops, the planting areas of wheat, maize, tubers, and oil crops decreased by 3.89$\times10^{4}$ hm^{2}, 6.11$\times10^{4}$ hm^{2}, 1.19$\times10^{4}$ hm^{2}, and 0.91$\times10^{4}$ hm^{2}, respectively, while Chinese herbal medicines, vegetables, and orchard fruits increased by 1.75$\times10^{4}$ hm^{2}, 4.77$\times10^{4}$ hm^{2}, and 0.98$\times10^{4}$ hm^{2}, respectively. This optimization reduced the agricultural water footprint by 6.68$\times10^{8}$ m^{3} while increasing economic benefits by 6.75$\times10^{8}$ yuan. Analysis of influencing factors showed that economic factors played a major positive driving role in the growth of the water footprint (contribution rate of 58%), while technology (24.7%) and population factors (17.3%) exerted inhibitory effects. The research results provide a scientific basis for the efficient utilization and sustainable development of agricultural water resources in the basin.

Full Text

Preamble

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Evolution of Agricultural Water Footprint and Optimization of Planting Structure in the Hexi Inland River Basin LIU Xia, LI Xiaopeng (School of Agricultural and Forestry Economics and Management, Lanzhou University of Finance and Economics, Lanzhou 730020, China)

Abstract: To evaluate agricultural water resource consumption in the Hexi Inland River Basin, this study analyzes the spatio-temporal evolution of the agricultural water footprint in the basin from 2011 to 2023 based on water footprint theory. Furthermore, multi-objective programming and the Logarithmic Mean Divisia Index (LMDI) model were employed to analyze the planting structure and its influencing factors.

The results indicate that the agricultural water footprint exhibited an upward trend during the study period, with an average annual growth rate of 3.8%.

In terms of composition, the water footprint was dominated by grain crops (49.3%), cash crops (27.8%), and livestock products (22.5%), while aquatic products accounted for a relatively small proportion (0.4%).

Following the optimization of the planting structure for seven typical crops, the planting areas of wheat, maize, tubers, and oilseeds decreased by 3.89×10^4 hm^2, 6.11×10^4 hm^2, 1.19×10^4 hm^2, and 0.91×10^4 hm^2, respectively. Conversely, the areas dedicated to Chinese herbal medicines, vegetables, and orchard fruits increased by 1.75×10^4 hm^2, 4.77×10^4 hm^2, and 0.98×10^4 hm^2, respectively.

This optimization resulted in a reduction of the agricultural water footprint by 6.68×10^8 m^3, while simultaneously increasing economic benefits by 6.75×10^8 yuan.

Analysis of influencing factors revealed that economic factors served as the primary positive driver for the growth of the water footprint (with a contribution rate of 58%), while technological (24.7%) and demographic factors (17.3%) exerted inhibitory effects. These research findings provide a scientific basis for the efficient utilization of agricultural water resources and sustainable development within the basin.

关键词

Abstract

The Hexi inland river basin serves as a critical grain production base in Northwest China. However, the region faces severe challenges due to the mismatch between limited water resources and the intensive water demands of its agricultural sector. This study analyzes the spatio-temporal evolution of the agri-

cultural water footprint (AWF) in the Hexi region and investigates the driving factors behind these changes using the Logarithmic Mean Divisia Index (LMDI) method. Furthermore, we explore the potential for regional water conservation through the optimization of crop planting structures. Our findings provide a scientific basis for sustainable water resource management and agricultural planning in arid inland river basins.

1. Introduction

As one of the most arid regions in China, the Hexi inland river basin relies heavily on irrigation for its agricultural productivity. With the increasing pressure of climate change and socio-economic development, the contradiction between water supply and demand has become increasingly prominent. The concept of the "water footprint" provides a comprehensive framework for quantifying the total volume of water resources consumed during crop production, including both green water (effective rainfall) and blue water (irrigation water).

By analyzing the agricultural water footprint, we can better understand the efficiency of water use and the environmental impact of different cropping patterns. This study aims to decompose the factors influencing the agricultural water footprint in the Hexi region and propose an optimized planting structure to alleviate water stress while maintaining food security.

2. Methodology

2.1 Study Area

The Hexi region encompasses the Shiyang River, Heihe River, and Shule River basins. It is characterized by low precipitation and high evaporation rates, making agriculture almost entirely dependent on irrigation.

2.2 Calculation of Agricultural Water Footprint

The agricultural water footprint (AWF) is calculated as the sum of the blue water footprint (WF_{blue}) and the green water footprint (WF_{green}):

$$AWF = WF_{blue} + WF_{green}$$

The crop water requirement (ET_c) is determined using the Penman-Monteith equation as recommended by the FAO.

2.3 LMDI Decomposition Analysis

To identify the drivers of change in the AWF, we employ the Logarithmic Mean Divisia Index (LMDI) method. The total change in the water footprint is decomposed into four factors: the technology effect (water intensity), the structural effect (planting proportion), the economic effect (per capita area), and the population effect. The decomposition is expressed

Water resources are an indispensable and fundamental natural resource for agricultural production.

In the field of trace quantization, research has already spanned multiple dimensions. Some scholars have focused on specific optimization strategies and theoretical frameworks to improve the efficiency and accuracy of quantized models. These efforts include the development of novel algorithms designed to minimize information loss during the quantization process, as well as the exploration of hardware-aware techniques that tailor trace quantization to specific architectural constraints. Furthermore, recent studies have begun to address the scalability of these methods, ensuring that they remain effective as the complexity of neural network architectures continues to grow.

Introduction

As a vital resource, the supply status of seeds is directly related to national food security and the sustainable development of agriculture. In recent years, the integration of machine learning and deep learning into agricultural science has revolutionized the way researchers analyze seed quality and genetic traits. By leveraging advanced computational models, it is now possible to predict crop yields and assess seed viability with unprecedented accuracy.

[Figure 1: see original paper]

The stability of the seed supply chain is influenced by various factors, including climate change, soil degradation, and market fluctuations. To address these challenges, researchers are increasingly turning to data-driven approaches. For instance, the application of neural networks in processing hyperspectral imaging data allows for the non-destructive testing of seeds, ensuring that only the highest quality biological material enters the production cycle.

Furthermore, the optimization of seed distribution networks using complex algorithms ensures that resources are allocated efficiently across different geographical regions. This systematic approach not only mitigates the risks associated with seed shortages but also promotes biodiversity by preserving rare and resilient crop varieties. As we move toward a more digitized agricultural landscape, the synergy between traditional agronomy and modern computational techniques will be essential for maintaining global food stability.

Water footprint accounting has been conducted across various spatial scales, including global [**?**], national [**?**], and city levels.

Introduction

The continuous development of water resource management remains a critical priority. According to data from the 2023 China Water Resources Bulletin, agricultural water use accounts for a significant portion of total consumption, highlighting the urgent need for optimized irrigation strategies and sustainable practices.

Research has been conducted at various scales, including the municipal level [?] and the watershed level [?]. Furthermore, some scholars have focused their investigations on specific products and individual enterprises.

62.2%. However, against the backdrop of global warming, water resource shortages have become increasingly severe. This trend poses significant challenges to sustainable development and ecological stability across various regions. As temperatures rise, the intensification of the hydrological cycle alters precipitation patterns and increases evaporation rates, further exacerbating the imbalance between water supply and demand. Consequently, understanding the mechanisms of water scarcity in a changing climate is essential for developing effective mitigation and adaptation strategies.

acidic beverages [?], and others. Regarding the factors influencing water footprints, Wang et al. [?]

The mean value decreased by 6.6%, while agricultural water demand remained substantial.

factors affecting the water footprint of regional crop production. Nie Hanlin et al. [?] further advanced this research by quantifying···

To address this contradiction between supply and demand, the core challenge lies in achieving the efficient utilization of agricultural water resources. This objective requires a multi-dimensional approach that integrates advanced technological interventions with robust management strategies. By optimizing the allocation of limited water supplies, it is possible to maintain agricultural productivity while ensuring environmental sustainability.

Technological Innovations in Water Management

The primary driver for enhancing water use efficiency is the adoption of precision irrigation technologies. Modern systems, such as drip and micro-sprinkler irrigation, allow for the targeted delivery of water directly to the root zones of crops, significantly reducing losses due to evaporation and runoff. Furthermore, the integration of the Internet of Things (IoT) and remote sensing enables real-time monitoring of soil moisture levels and crop water requirements. These data-driven insights allow for the implementation of dynamic irrigation scheduling, ensuring that water is applied only when and where it is most needed.

Agronomic and Genetic Improvements

Beyond engineering solutions, agronomic practices play a vital role in mitigating water scarcity. Techniques such as conservation tillage, mulching, and the improvement of soil organic matter help enhance the soil' s water-holding capacity. Additionally, the development of drought-resistant and water-efficient crop varieties through molecular breeding and genetic engineering offers a long-term solution to maintaining yields under water-stressed conditions. Selecting crops that are better adapted to local climatic constraints is essential for balancing the regional water budget.

Policy Frameworks and Economic Incentives

Efficient water utilization also necessitates a supportive policy environment. Governments must establish clear water rights and implement equitable water pricing mechanisms that reflect the true scarcity of the resource. Economic incentives, such as subsidies for water-saving equipment or payments for ecosystem services, can encourage farmers to adopt more sustainable practices. Moreover, strengthening water user associations and promoting community-based management can improve the transparency and efficiency of water distribution at the local level.

Integrated Watershed Management

Finally, achieving high efficiency in agricultural water use requires an integrated perspective that considers the entire watershed. This involves the conjunctive use of surface water and groundwater, as well as the exploration of non-conventional water sources, such as treated wastewater and harvested rainwater. By managing water resources at the landscape scale, stakeholders can better coordinate the competing demands of agriculture, industry, and domestic sectors, thereby resolving the fundamental contradictions in water supply and demand.

Abstract

This study investigates the water footprint of winter wheat and summer maize in the Guanzhong Plain. By analyzing the blue and green water components, we aim to provide insights into the regional water resource utilization and agricultural sustainability.

Introduction

The Guanzhong Plain is a critical agricultural region in Northwest China, characterized by a double-cropping system of winter wheat and summer maize. Understanding the water footprint of these crops is essential for optimizing irrigation strategies and managing scarce water resources. The water footprint is generally categorized into “green water” (rainwater stored in the soil consumed by plants) and “blue water” (surface and groundwater used for irrigation).

Results and Analysis

Our findings indicate significant temporal and spatial variations in the water footprints of both crops.

[Figure 1: see original paper]

Blue and Green Water Footprint of Winter Wheat

For winter wheat, the blue water footprint constitutes a substantial portion of the total water consumption due to the relatively dry conditions during its growth cycle. The reliance on irrigation is particularly pronounced during the jointing and grain-filling stages. As shown in , the average blue water footprint for winter wheat in the study area was found to be significantly higher than the green water footprint, highlighting the pressure on local groundwater and surface water supplies.

Blue and Green Water Footprint of Summer Maize

In contrast, summer maize coincides with the regional rainy season. Consequently, the green water footprint plays a more dominant role in its development. However, supplementary irrigation (blue water) remains necessary during periods of drought or uneven precipitation distribution to ensure stable yields. The relationship between effective rainfall and crop evapotranspiration (ET_c) determines the ratio of these components.

Discussion

The total water footprint (WF_{total}) is calculated as the sum of the blue water footprint (WF_{blue}) and the green water footprint (WF_{green}):

$$WF_{total} = WF_{blue} + WF_{green}$$

Our analysis suggests that improving water-use efficiency (WUE) is paramount. By adopting precision irrigation and conservation tillage, the blue water footprint can be reduced without compromising crop yields. Furthermore, the spatial distribution of the water footprint reveals that the eastern part of the Guanzhong Plain faces higher water stress compared to the western regions, necessitating differentiated water management policies.

Conclusion

The study reveals that while summer maize utilizes green water more effectively, winter wheat remains highly dependent on blue water resources. These

has become an urgent problem that needs to be addressed.

The grey water footprint is primarily influenced by crop yield levels, average wind speed, and the rate of chemical fertilizer application.

Agricultural water consumption reached 3672.4×10^8 m^3, accounting for a significant portion of the national total water consumption.

Calculations were performed for various categories, including crops [?], animal products [?], wine [?], and carbon.

The water shortage problem is becoming increasingly severe. In 2023, China' s total water resources compared to the multi-year average···

This study explores the factors influencing different geographical regions through a comprehensive literature review and meta-analysis.

1. Introduction

In recent years, the rapid development of machine learning and deep learning has provided new methodological frameworks for analyzing complex spatial data. Understanding the heterogeneous drivers across various regions is critical for both theoretical advancement and practical policy-making. This research synthesizes existing findings to identify consistent patterns and significant anomalies in regional development.

[Figure 1: see original paper]

2. Methodology

2.1 Literature Selection and Data Collection

We conducted a systematic search across major academic databases, focusing on peer-reviewed studies published between 2010 and 2023. The selection criteria prioritized empirical studies that utilized quantitative models to assess regional variables. After initial screening, a total of N studies were selected for the meta-analysis.

2.2 Statistical Framework

To account for the diversity in study designs, we employed a random-effects model. The effect size for each study was calculated based on the standardized mean difference or correlation coefficients, depending on the available data. We define the global estimate θ as:

$$\theta = \sum_{i=1}^{k} w_i \theta_i / \sum_{i=1}^{k} w_i$$

where w_i represents the weight assigned to each individual study i, and θ_i is the observed effect size. To address potential heterogeneity, we utilized the I^2 statistic as described in [?].

3. Results and Discussion

The results indicate that economic infrastructure and human capital remain the primary drivers of regional growth. However, the influence of these factors varies significantly when adjusted for geographic scale.

As shown in , the impact of technological innovation is more pronounced in urban clusters compared to rural peripheries. This suggests a “digital divide” that may exacerbate regional inequalities if not addressed by targeted interventions. Furthermore, our meta-regression analysis reveals that environmental regulations, often viewed as a constraint, show a non-linear relationship with regional productivity, supporting the Porter Hypothesis in specific contexts [**?**].

3.1 Sensitivity Analysis

To ensure the robustness of our findings, we performed a leave-one-out sensitivity analysis. The results remained stable, indicating that no single study disproportionately influenced the overall meta-analytic

Introduction

In 1993, the British scholar Allan [**?**] first proposed the concept of virtual water. This concept refers to the amount of water resources required to produce a product or service, effectively representing the water “embedded” in commodities. The introduction of virtual water theory provides a new perspective for addressing regional water scarcity by suggesting that water-stressed regions can alleviate their local water deficits by importing water-intensive products from water-abundant regions.

Since its inception, the study of virtual water has evolved from simple conceptual definitions to complex quantitative assessments. Researchers have utilized various methodologies to calculate virtual water flows, including the bottom-up approach based on product water footprints and the top-down approach utilizing Input-Output (IO) analysis. These developments have enabled a more comprehensive understanding of how global trade redistributes water resources across different geographical scales.

The existing body of research has extensively investigated the factors influencing water footprints. These studies have revealed the underlying driving mechanisms behind changes in water footprints, highlighting how various socioeconomic and environmental variables interact to shape water consumption patterns. Through these analyses, researchers have been able to identify the primary determinants that lead to fluctuations in regional and sectoral water use, providing a critical foundation for developing more sustainable water management strategies.

Introduction

The concept of the water footprint has evolved significantly since its inception. Building upon these foundational ideas, Dutch scholar Hoekstra further expanded the theoretical framework in 2002. This development marked a critical shift in how researchers quantify and analyze human appropriation of freshwater resources across different scales.

This provides a basis for targeted water resources management. Within the context of water footprint sustainability, the evaluation of regional water stress and the optimization of consumption patterns are essential for achieving long-term ecological balance. By quantifying the volume of water used to produce goods and services, decision-makers can better identify sectors with high water intensity and implement strategies for more efficient allocation. This approach facilitates the transition from traditional water management to a more holistic framework that considers both direct and indirect water consumption across various spatial scales.

The concept of the water footprint was subsequently proposed, a theory that integrates virtual water with physical water resources. This framework provides a comprehensive approach to accounting for water use by considering both direct consumption and the indirect water embedded in products and services throughout their supply chains. By linking consumption patterns to water appropriation, the water footprint theory offers a more holistic perspective on water security and resource management than traditional measures of water withdrawal.

In terms of sustainability evaluation, scholars have been dedicated to constructing scientific evaluation indicators and frameworks to assess the long-term viability and impact of various systems. This research direction emphasizes the integration of environmental, social, and economic dimensions to provide a holistic view of development. By employing multi-criteria decision-making (MCDM) models and longitudinal data analysis, researchers aim to identify key drivers of sustainability and mitigate potential risks. These evaluative tools are essential for informing policy decisions and guiding organizational strategies toward more resilient and sustainable outcomes in an increasingly complex global landscape.

The concept of integration is defined as the total amount of resources, information, or capital accumulated by a country, region, or individual within a specific period. In the context of economic and social development, this definition emphasizes the temporal dimension of growth and the aggregation of diverse inputs. By analyzing these combinations over time, researchers can better understand the trajectory of development and the efficiency of resource allocation across different scales of governance and individual action.

index system [**?**]. For example, Qi et al. [**?**] conducted a study based on the water footprint accounting of Dalian City.

The total volume of water resources consumed during the process of consuming all products and services is defined as the water footprint. This concept provides a comprehensive framework for assessing the impact of human activities on freshwater systems, accounting for both direct and indirect water use throughout the entire supply chain. By quantifying the water required for production, processing, and distribution, the water footprint serves as a critical metric for understanding the relationship between consumption patterns and global water scarcity.

Results and Analysis

Based on the calculated results, we evaluated the sustainability of water resource utilization for the period of 2006–2007. The analysis indicates that during this timeframe, the regional water resource system faced varying degrees of pressure. By applying the established evaluation framework, we quantified the relationship between water supply capacity and the increasing socio-economic demand.

The findings suggest that while infrastructure developments provided a baseline for water security, the sustainability indices for 2006 and 2007 reveal a downward trend in certain sub-indicators, particularly regarding groundwater depletion and efficiency of industrial water use. These results highlight the critical need for integrated water resource management to balance ecological requirements with human consumption. Further examination of the data suggests that the climatic variations during these two years significantly influenced the recharge rates, thereby impacting the overall sustainability score of the hydrological system.

Introduction

The concept of the water footprint has received increasing attention as the global water crisis intensifies and water scarcity becomes a prominent constraint on sustainable development. The water footprint theory provides a comprehensive framework for quantifying the total volume of freshwater consumed, both directly and indirectly, to produce goods and services. Unlike traditional water withdrawal statistics, it accounts for the entire supply chain, offering a more nuanced perspective on human appropriation of freshwater resources.

As water resource management shifts from simple supply-side engineering to integrated demand-side management, the application of machine learning and deep learning techniques has become essential. These advanced computational methods allow researchers to model complex hydrological processes and predict future water demand with greater precision. By integrating multi-source data—including remote sensing, socio-economic indicators, and climate variables—machine learning models can identify non-linear patterns that traditional statistical methods often overlook.

The integration of water footprint analysis with predictive modeling is crucial for regional water security. Understanding the spatial and temporal dynamics of water consumption enables policymakers to implement more effective conservation strategies. Furthermore, by evaluating the "virtual water" flows embedded in international and inter-regional trade, the water footprint theory highlights the interconnectedness of global water systems and the potential for optimizing water use through informed economic and agricultural policies.

A systematic evaluation of the situation has been conducted, providing a scientific basis for regional water resource management.

received widespread attention, and scholars have conducted extensive research surrounding this theory.

scientific basis. Furthermore, some scholars utilize crop structure scenario analysis to evaluate potential outcomes.

Research primarily focuses on the following three areas: the quantification of water footprints, water footprint⋯

Introduction

Improving the sustainability of water resource utilization remains a critical challenge. Chu et al. [**?**] conducted a study on the North China region⋯

Factors Influencing and Sustainability Evaluation of Water Footprint

In the context of water footprint research, it is essential to analyze the underlying drivers that dictate water consumption patterns and to evaluate whether these patterns remain within the ecological limits of a given region. The sustainability evaluation of the water footprint serves as a critical tool for understanding the pressure exerted by human activities on freshwater resources.

Factors Influencing the Water Footprint

The water footprint of a region or industry is rarely static; it is shaped by a complex interplay of socio-economic and environmental variables. Key influencing factors typically include:

- **Economic Development:** As regional GDP increases, industrial and domestic water demands often rise. However, advanced economies may see a decoupling effect where technological efficiencies reduce the overall water footprint per unit of output.
- **Population Dynamics:** Population growth directly increases the demand for food, energy, and services, thereby expanding the blue and green water footprints. Urbanization further shifts consumption patterns toward more water-intensive lifestyles.
- **Technological Innovation:** Improvements in irrigation efficiency, water recycling technologies, and industrial processing play a pivotal role in mitigating the total water footprint.
- **Consumption Patterns:** Dietary shifts—particularly the increased consumption of meat and dairy—significantly elevate the virtual water content of a population’ s footprint.

Sustainability Evaluation of Water Footprint

Evaluating the sustainability of a water footprint involves comparing the total human appropriation of freshwater against the natural renewal capacity of the ecosystem. This is often quantified through several key indicators:

1. **Water Footprint Intensity:** This measures the efficiency of water use by calculating the water footprint per unit of GDP. A declining intensity suggests improved water-use efficiency and technological progress.
2. **Water Stress and Scarcity:** By comparing the total water footprint to the available renewable water resources, researchers can determine the degree of water stress. If the footprint exceeds the sustainable yield of local aquifers and rivers, the current consumption pattern is deemed unsustainable.
3. **Water Footprint Environmental Security:** This indicator assesses whether the water remaining in the environment is sufficient to maintain ecosystem health and biodiversity.

Through the integration of these factors and evaluation metrics, policymakers can identify specific areas where water management interventions are most needed. Ensuring a sustainable water footprint requires a transition toward more efficient production methods and more conscious consumption habits to balance human development with environmental preservation.

Adjusting the crop planting structure in the southern part of the plain is essential to promote groundwater recovery and ensure regional water security. In recent decades, the intensive cultivation of water-demanding crops has led to the continuous depletion of aquifers, resulting in significant environmental challenges such as land subsidence and the shrinkage of wetlands. By optimizing the spatial distribution of crops and introducing drought-resistant varieties, it is possible to significantly reduce the agricultural water footprint.

Strategic adjustments involve transitioning from traditional high-water-consumption patterns to more sustainable systems. This includes expanding the cultivation of low-water-use crops, such as minor cereals and oilseeds, and implementing fallow periods or “water-saving” crop rotations. Such measures are designed to balance the water requirements of the agricultural sector with the natural recharge rates of the groundwater system.

Furthermore, the integration of advanced irrigation technologies and precision agriculture plays a vital role in this structural shift. By aligning crop selection with local hydrological conditions, the southern plain can achieve a more resilient agricultural economy. These efforts not only mitigate the over-exploitation of groundwater but also contribute to the long-term ecological restoration and sustainable development of the region’ s agricultural landscape.

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4. Analysis of the Impact of the "Double Reduction" Policy on the Education Industry

4.1 Changes in the Market Environment

The implementation of the "Double Reduction" policy has brought about a fundamental shift in the market environment for the Chinese education industry. Previously, the K-12 after-school tutoring market was characterized by rapid expansion and high capital intensity. However, the new regulations have strictly prohibited academic tutoring during weekends and holidays and required existing institutions to register as non-profit entities. This has led to a significant contraction of the market size for traditional academic tutoring.

[Figure 1: see original paper]

As shown in [Figure 1: see original paper], the market valuation of major education companies plummeted following the policy announcement. This shift necessitates a strategic pivot for surviving firms, moving away from aggressive scale expansion toward sustainable, policy-compliant business models. The focus has shifted from "exam-oriented" tutoring to "quality-oriented" education, emphasizing the holistic development of students.

4.2 Transformation of Business Models

In response to the policy constraints, education enterprises have begun exploring diverse transformation paths. These primarily include:

1. **Quality-Oriented Education:** Shifting focus to non-academic subjects such as arts, sports, coding, and scientific innovation.
2. **Vocational Education:** Leveraging existing pedagogical expertise to provide training for professional certifications and adult education.
3. **Educational Technology (EdTech) Solutions:** Developing hardware and software to support public schools in improving classroom efficiency and after-school services.

The transition is not without challenges. As expressed in the following relationship, the total utility U of an education firm during transformation can be modeled as:

$$U = f(R, C, P)$$

where R represents the revenue from new business lines, C represents the transition costs (including personnel restructuring and brand repositioning), and P represents the degree of policy alignment. For a successful transition, firms must ensure that $\frac{\partial U}{\partial P} > 0$, meaning the business model must inherently align with the public welfare nature of education.

4.3 Impact on Educational Equity

One of the core objectives of the "Double Reduction" policy is to promote educational equity by reducing the financial burden on parents and the academic pressure on students. By restricting the "capitalization" of education, the policy aims to return the primary responsibility for education to the public school system.

[TABLE:

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Arid Regions

Despite extensive research covering various aspects of water footprint theory, studies specifically dedicated to agricultural water footprints remain relatively scarce. Most existing research focuses on accounting and basic analysis, lacking a systematic investigation into the spatio-temporal evolution and driving factors of agricultural water footprints in arid regions. Furthermore, current studies often emphasize single-objective optimization, failing to provide comprehensive research on agricultural cropping structure optimization that balances water resource utilization with economic benefits. Therefore, there is a need for further in-depth

research on the spatio-temporal evolution characteristics, driving factors, and cropping

rivers, with total water resources amounting to 36.84×10^8 m^3. As of 2023, the total population within the basin reached 4.22×10^6, of which the rural population accounted for 1.61×10^6.

The cultivated land area within the basin is 1.21×10^6 hm^2, with an effective irrigation area

of 9.61×10^5 hm^2, representing 79.4% of the total. In 2023, the province added 1.11×10^5 hm^2 of new high-efficiency

water-saving irrigation area, of which 9.13×10^4 hm^2 was located within the Hexi inland river basin [**?**].

1.2 数据来源

Analysis of Land Use and Landscape Pattern Changes in the Hexi Inland River Basin (Jiayuguan and Jinchang Cities), 2011-2023

1. Introduction

The Hexi inland river basin, located in the arid region of Northwest China, serves as a critical ecological barrier and a vital area for agricultural production. Over the past decade, this region has experienced significant socio-economic development and environmental shifts. Understanding the spatiotemporal dynamics of land use and landscape patterns in key industrial and oasis cities like Jiayuguan and Jinchang is essential for sustainable regional planning and ecological conservation. This study examines the period from 2011 to 2023 to identify the driving forces behind these transformations.

2. Study Area and Data Sources

The study focuses on the administrative regions of Jiayuguan and Jinchang, situated within the Hexi Corridor. These areas are characterized by a typical continental arid climate, where water availability is the primary constraint on ecological and economic activities.

Data for this research were primarily derived from multi-temporal satellite imagery and land cover products. We utilized the annual China Land Cover Dataset (CLCD) and integrated socio-economic statistical yearbooks to correlate physical changes with human activities. All spatial data were processed using ArcGIS and ENVI software to ensure consistency in projection and resolution.

3. Methodology

3.1 Land Use Transfer Matrix To quantify the transitions between different land use types, we employed a land use transfer matrix. This method allows for the calculation of the area gained or lost by specific categories, such as the conversion of barren land to industrial sites or the expansion of urban green spaces. The mathematical representation is given by:

$$S_{ij} = \begin{bmatrix} S_{11} & S_{12} & \cdots & S_{1n} \\ S_{21} & S_{22} & \cdots & S_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ S_{n1} & S_{n2} & \cdots & S_{nn} \end{bmatrix}$$

where S represents the area, n is the number of land use types, and i and j represent the land use types at the beginning and end of the study period, respectively.

3.2 Landscape Pattern Metrics To analyze the structural characteristics of

Optimizing crop structure pathways is essential for improving agricultural water resource utilization efficiency and ensuring regional food security. By strategically adjusting the spatial distribution and proportions of different crops, it is possible to align agricultural production with the natural carrying capacity of local water resources. This process involves evaluating the trade-offs between economic benefits, water consumption, and ecological sustainability.

[Figure 1: see original paper]

Current research indicates that traditional planting patterns often lead to excessive groundwater depletion in arid and semi-arid regions. To address this, structural optimization must integrate multi-objective programming models that account for varying climatic conditions and soil types. By prioritizing water-efficient crops and implementing advanced irrigation technologies, regions can achieve a more resilient agricultural system. Furthermore, the transition toward optimized crop structures requires policy support and market incentives to encourage farmers to adopt sustainable practices while maintaining their livelihoods.

Abstract

This study focuses on the primary grain crops—wheat, maize, and tubers—within the Hexi Corridor region, specifically covering the cities of Jinchang, Wuwei, Zhangye, and Jiuquan.

[Figure 1: see original paper]

Introduction

The Hexi Corridor is a vital agricultural production base in Northwest China. Understanding the spatial distribution and yield dynamics of its major crops is essential for regional food security and water resource management. This research analyzes the cultivation patterns of wheat, maize, and tubers across the four key administrative divisions: Jinchang, Wuwei, Zhangye, and Jiuquan. By examining these specific regions, we aim to provide a comprehensive overview of the agricultural productivity and the environmental factors influencing crop selection and output in this arid to semi-arid landscape.

Ensuring food security and achieving regional sustainable development are of critical importance.

Data on the yield and planting area of agricultural products, such as Chinese herbal medicines, were obtained from the *Gansu Provincial Statistical Yearbook*. The research focused on the primary production areas of traditional Chinese medicinal materials in Gansu Province, specifically targeting the cities of Dingxi and Longnan. To ensure the scientific rigor and representativeness of the data, we selected the main varieties of Chinese herbal medicines cultivated in these regions—including *Astragalus membranaceus*, *Codonopsis pilosula*, and *Angelica sinensis*—as the primary research subjects.

The dataset spans the period from 2010 to 2022, providing a comprehensive longitudinal view of agricultural trends. In addition to yield and area metrics, we incorporated meteorological data, such as average annual temperature, precipitation, and sunshine duration, sourced from the China Meteorological Data Service Center. These environmental variables are critical for understanding the fluctuations in crop productivity. To address the issue of missing values in certain years, we employed linear interpolation and moving average methods to ensure data continuity and integrity.

[Figure 1: see original paper]

The preliminary analysis of the data indicates a steady increase in the planting area of Chinese herbal medicines in Gansu Province over the past decade. However, the yield per unit area exhibits significant inter-annual variability, likely influenced by both climatic shifts and changes in agricultural management practices. By integrating these multi-source datasets, we aim to construct a robust machine learning model capable of predicting future yields with high precision, thereby providing a scientific basis for regional agricultural planning and policy formulation.

The data for this study were primarily sourced from the *Gansu Development Yearbook* and the *Gansu Statistical Yearbook*. Key indicators extracted from these records include the total rural population and the agricultural labor force. These datasets provide a comprehensive statistical foundation for analyzing the demographic shifts and socio-economic trends within the rural regions of Gansu Province. By utilizing these official yearbooks, the study ensures the reliability and longitudinal consistency of the demographic data required for the subsequent analysis.

The Hexi inland river basin is located in the arid region of Northwest China, where agriculture serves as the primary pillar of the regional economy and the foundation for social stability. Due to the extremely scarce precipitation and high potential evaporation characteristic of this arid climate, agricultural production in this area is almost entirely dependent on irrigation. Consequently, the Hexi region has become one of the most representative oasis agricultural zones in China. However, the sustainable development of agriculture in this basin faces severe challenges, including the over-exploitation of water resources, soil salinization, and the increasing vulnerability of the ecological environment under the influence of global climate change.

In recent years, the contradiction between the limited supply of water resources and the growing demand for agricultural expansion has become increasingly prominent. To address these issues, researchers and policymakers have focused on optimizing water resource allocation and improving water-use efficiency through advanced irrigation technologies and scientific management practices.

Understanding the complex interactions between hydrological processes, crop growth, and human interventions is crucial for ensuring food security and ecological integrity in the Hexi inland river basin. Future agricultural development in the region must balance economic benefits with environmental conservation to achieve long-term sustainability in this fragile arid ecosystem.

Data such as industrial output value were sourced from the *Gansu Provincial Water Resources Bulletin*. Primary agricultural production data, along with other socio-economic indicators, were obtained from the relevant statistical yearbooks and official government reports to ensure the accuracy and consistency of the dataset used in this study.

Water consumption accounts for as much as 86.6%. However, the region suffers from a severe shortage of water resources and⋯

Product unit prices are sourced from the *National Compilation of Agricultural Product Cost-Benefit Data*.

The uneven spatial and temporal distribution of water resources has become a critical bottleneck restricting local agricultural development. In response to this challenge, the present study focuses on the Hexi inland river basin from 2011 to 2023.

Based on the agricultural water footprint data of the river basin, this study systematically analyzes the spatio-temporal evolution characteristics and driving factors of the agricultural water footprint within the region. Simultaneously, a multi-objective planting structure optimization model is constructed to explore the optimal development paths for different crops under the dual objectives of high-efficiency water resource utilization and economic benefit maximization. The findings aim to provide a scientific basis and decision-making support for the sustainable utilization of agricultural water resources and the optimization of planting structures in the inland river basins of the Hexi region.

2.1 农业水足迹计算

This study is based on the water footprint theory proposed by the Dutch scholar Hoekstra [**?**].

By integrating existing research on agricultural water footprints [**?**], the following formulas are employed to calculate the agricultural water footprint:

AWF =∑Y i × VW i

where: AWF is the agricultural water footprint (10^8 m^3); Y_i is the yield of the agricultural product

(t); VW_i is the unit virtual water content of the i-th agricultural product (m^3· t^{-1}); i

1.1 研究区概况

The Hexi inland river basin is located in the arid region of Northwest China, situated in the central portion of the Hexi Corridor.

and market research data.

The study area encompasses several key administrative regions within Gansu Province, specifically covering the cities of Jiayuguan, Jinchang, Wuwei, and Zhangye.

As a representative crop type, this study selects the grain crops wheat, maize, and tubers.

⋯crops, industrial oilseeds, traditional Chinese medicinal materials, vegetables, orchard fruits, and livestock products.

Study Area

The study area encompasses five prefecture-level cities, including Zhangye and Jiuquan, with a total basin area of 24.48×10^4 km^2.

1. Introduction

The analysis covers 13 categories of agricultural products, including pork, beef, mutton, dairy products, poultry eggs, and aquatic products. These commodities represent the core components of animal protein consumption and play a vital role in food security and nutritional economics.

1.1 Scope of Agricultural Products

The study focuses on the production and consumption patterns of these 13 specific agricultural goods. By examining pork, beef, and mutton, we address the primary red meat sectors, while the inclusion of dairy, eggs, and aquatic products provides a comprehensive overview of the broader livestock and fisheries industries. Understanding the market dynamics of these products is essential for developing sustainable agricultural policies and ensuring stable supply chains.

[Figure 1: see original paper]

1.2 Methodology and Data Analysis

To evaluate the trends within these 13 categories, we utilize advanced statistical models and machine learning techniques. This approach allows for the identification of seasonal fluctuations and long-term growth trajectories in the production of high-demand items such as poultry and seafood. By integrating data from various stages of the supply chain, the research aims to provide a robust framework for price forecasting and resource allocation in the agricultural sector.

located in a temperate continental climate zone, the region experiences sparse precipitation, with the average annual rainfall being only

In the field of agricultural unit virtual water accounting, Chapagain et al. [?]

10 km, accounting for 57.5% of the total area of Gansu Province [Figure 1: see original paper]. This basin belongs to···

88.1 mm. The hydrological systems within the basin primarily include the Shule River, the Heihe River, and the Shiyang River.

Utilizing the Cropwat 8.0 software released by the FAO, researchers have quantified the virtual water content of global and national staple grains, such as wheat, corn, and rice. Ma Jing et al. [?] differentiated between northern and southern regions to systematically compare the variations in virtual water across food categories, including grains, fruits, vegetables, meat, eggs, and dairy. Sun Cai···

Zhi et al. [?] updated the provincial-level databases for 11 types of crops across the country. Subsequently, they further refined these datasets to incorporate more granular temporal and spatial resolutions, facilitating a more comprehensive analysis of agricultural trends.

We have completed a comprehensive census of virtual water for grain and major agricultural and livestock products—including vegetables, meat, eggs, milk, edible oils, aquatic products, fruits, and alcohol—across various provinces. Given the data gaps specifically concerning the Hexi inland river basin, this study adopts the calculation results for crops in Gansu Province provided by Sun Caizhi et al. [?]. The specific parameters utilized are presented in .

2.2.1 目标函数

1. Water Resource Utilization Objective (Minimization of Agricultural Water Footprint)

The primary objective for water resource utilization is the minimization of the agricultural water footprint. This objective aims to optimize the efficiency of water usage within the agricultural sector by reducing the total volume of freshwater consumed throughout the crop production process. By minimizing the water footprint, the model seeks to alleviate regional water stress and promote sustainable irrigation practices.

The mathematical formulation for this objective is defined as follows:

$$\min W = \sum_{i=1}^{n} \sum_{j=1}^{m} (WF_{blue,i,j} + WF_{green,i,j}) \times A_{i,j}$$

In this expression, W represents the total agricultural water footprint within the study area. The indices i and j denote the specific crop type and the subregional unit, respectively. The term $WF_{blue,i,j}$ refers to the blue water footprint (surface and groundwater consumed for irrigation), while $WF_{green,i,j}$ represents the green water footprint (rainwater stored in the soil consumed by plants). The variable $A_{i,j}$ signifies the total planting area for crop i in region j.

By integrating both blue and green water components, this objective function provides a comprehensive framework for evaluating water consumption. Minimizing this value ensures that crop selection and spatial allocation are optimized to match the local hydro-climatic conditions, thereby reducing the reliance on scarce blue water resources and maximizing the effective use of available precipitation.

1 Schematic diagram of the overview of the study area

min Z1 =∑X j Y j WF j

Evolution of Agricultural Water Footprint and Optimization of Planting Structures in the Hexi Inland River Basin

Abstract

The Hexi inland river basin is a critical ecological barrier in Northwest China and a vital grain production base. However, the region faces severe water scarcity, and the conflict between agricultural water use and ecological protection is increasingly prominent. This study analyzes the spatio-temporal evolution of the agricultural water footprint in the Hexi region and proposes an optimized planting structure to enhance water use efficiency. By integrating the water footprint theory with multi-objective optimization models, we aim to provide a scientific basis for sustainable water resource management and food security in arid regions.

1. Introduction

The Hexi Corridor, located in Gansu Province, is characterized by an extremely arid climate where agriculture depends almost entirely on irrigation. As the "Silk Road Economic Belt" develops, the demand for water resources has surged, leading to over-exploitation of groundwater and degradation of downstream ecosystems. Traditional water management focuses on supply-side engineering, but modern approaches emphasize demand-side management through the lens of the "water footprint." The agricultural water footprint (AWF) quantifies the volume of freshwater used to produce crops, including green water (rainfall), blue water (irrigation), and grey water (dilution of pollutants). Understanding the dynamics of AWF is essential for reconfiguring planting structures to align with the region' s carrying capacity.

2. Materials and Methods

2.1 Study Area Overivew The study area encompasses the Shiyang River, Heihe River, and Shule River basins. These basins exhibit distinct hydrological characteristics but share a common challenge: high potential evapotranspiration and low precipitation.

2.2 Calculation of Agricultural Water Footprint The total agricultural water footprint (WF_{total}) is calculated as the sum of the blue, green, and grey water footprints. Following the framework established by [**?**], the crop water requirement (ET_c) is estimated using the Penman-Monteith equation:

$$ET_c = K_c \times ET_0$$

Where K_c is the crop coefficient and ET_0 is the reference crop evapotranspiration. The blue water footprint (WF_{blue}) and green water footprint (WF_{green}) are derived based on effective rainfall and irrigation requirements during the growing season.

2.3 Planting Structure Optimization Model To optimize the planting

(108 m3)。

1 Parameters of unit virtual water content of

(3) Non-negativity constraints $X_j \geq 0$ $(j = 1, \dots, 7)$

Virtual water content per unit of agricultural products / $(m^3 \cdot t^{-1})$

The driving factors of footprint changes are decomposed into economic effects, population effects, and

GDP 0 ö AWF t æ GDP t A e = ΔAWF∑ç ln AWF t P e = ΔAWF∑(ln P t - ln P 0) ln

technical effects. The specific calculation formula is as follows [**?**]:

AWF 0 ö AWF t æ AWF t T e = ΔAWF∑ç ln

Based on the LMDI (Logarithmic Mean Divisia Index) model, the factors influencing agricultural water use in the Hexi inland river basin···

In the formula: A_e, P_e, and T_e represent the economic effect, population effect, and···

2.3 LMDI 分解法

Contribution of Technological Effects to the Changes in Agricultural Water Footprint in the Hexi Inland River Basin

In the formula: min Z_1 represents the objective of minimizing agricultural water footprint consumption (m^3);

X_j represents the planting area of crop j (hm^2); Y_j represents the yield of crop j

($t \cdot hm^{-2}$); WF_j represents the water footprint per unit of production for crop j ($m^3 \cdot t^{-1}$);

j denotes the crop types, which include wheat, maize, tubers, oilseeds, Chinese herbal medicines, vegetables, and orchard fruits.

The variation in the year (10^8 m^3); P_0, GDP_0, and AWF_0 represent

the rural population (10^4 persons), gross agricultural product (10^8 yuan), and agricultural water footprint (10^8 m^3) in the base year, respectively; P_t, GDP_t, and AWF_t represent the rural population (10^4 persons), gross agricultural product (10^8 yuan), and agricultural water footprint (10^8 m^3) in year t.

(2) Economic objective (maximization of economic benefits): $\max Z_2 = \sum X_j Y_j P_j$

Contribution degree (10^8 m^3); ΔAWF represents the change in the agricultural water footprint from the base year to year t.

3 结果与分析

In the formula, $\max Z_2$ represents the objective of maximizing economic benefits (expressed in Yuan), where P_j denotes⋯

2.2.2 约束条件

The agricultural water footprint showed a fluctuating upward trend (Figure 2 [Figure 2: see original paper]), rising from 66.00×10^8 m^3 to

represents the unit price of the crop (yuan $\cdot$ t^{-1}).

During the period from 2011 to 2023, the agricultural water footprint of the Hexi Inland River Basin

103.45×10^8 m^3, with an average annual growth rate of 3.8%. In 2017, there was a significant

(1) Sown area constraints

decrease to 77.09×10^8 m^3. This decline may be related to the "Gansu Provincial Soil and Water Conservation

By promoting high-efficiency water-saving irrigation technologies (such as drip irrigation and micro-sprinkling) and implementing measures to return farmland to

The utilization rate of cultivated land is a key factor affecting the water resources carrying capacity of the Hexi Inland River Basin.

forests and grasslands, the volume of water used for agricultural irrigation was effectively reduced. From 2017 to

$\sum X \leq \sum X$

total,2023

$0.7X\ j{,}2023 \leq X\ j \leq 1.3X\ j{,}2023$

The critical constraint on carrying capacity is water availability [?]. Research indicates that a moderate reduction in cultivated area can help alleviate agricultural water shortages [?]. Consequently, the total planting area for the seven selected crops should be maintained below the current 2023 levels.

Furthermore, considering that approximately 30% of farmers are willing to accept adjustments to their cropping structures, the magnitude of these adjustments should be capped at 30%. This constraint is essential to ensure both policy feasibility and farmer acceptance.

$\sum X\ Y\ WF \leq A$

During the period of 2020, the agricultural water footprint remained relatively stable, fluctuating around 77×10^8 m^3. This stability suggests that water consumption patterns within the agricultural sector have reached a state of equilibrium, despite potential shifts in crop distribution or climatic variations.

[Figure 1: see original paper]

The analysis of these trends indicates that while total water usage has not seen significant growth, the efficiency of water resource allocation remains a critical factor for sustainable development. Future projections should account for the impact of technological advancements in irrigation and the potential for further optimization of the agricultural water footprint to mitigate water scarcity risks.

between 10^8 and 79×10^8 m^3, followed by a rapid upward trend after 2020. Analysis of the 13 major categories of agricultural products reveals that food crops account for a significant portion of the agricultural sector.

···accounted for 49.3% of the water footprint, with wheat and maize serving as the primary contributing agricultural products. Cash crops and livestock products accounted for 27.8% and 22.5%, respectively, while···

Aquatic products account for the lowest proportion, at only 0.4%. In the Hexi inland river basin, wheat and maize alone account for 43.5% of the total agricultural water footprint. According to

2.2 Water Resource Constraints

Water resource constraints refer to the restrictive effects of regional water availability, quality, and accessibility on socio-economic development and ecological maintenance. In the context of industrial layout and urban expansion, these constraints manifest as the upper limits of carrying capacity that water systems impose on human activities.

The mathematical representation of water resource availability is typically defined by the total renewable water resources within a specific basin or administrative region. Let W_{total} represent the total available water supply, which can be expressed as:

$$W_{total} = W_{surface} + W_{ground} + W_{recycled} - W_{eco}$$

where $W_{surface}$ denotes surface water runoff, W_{ground} represents sustainable groundwater extraction, $W_{recycled}$ is the volume of reclaimed water, and W_{eco} is the minimum environmental flow required to maintain ecosystem health.

Under the framework of "the strictest water resources management system," the constraint condition for regional development is defined such that the total water demand D must not exceed the redline of total water use control W_{limit}:

$$D = \sum_{i=1}^{n} Q_i \cdot P_i \leq W_{limit}$$

In this equation, Q_i represents the water consumption intensity of the i-th sector (such as industry, agriculture, or domestic use), and P_i represents the scale of that sector. As W_{limit} remains relatively constant or even decreases due to climate change and ecological restoration needs, the optimization of industrial structures and the improvement of water-use efficiency become the primary mechanisms for decoupling economic growth from water consumption.

Furthermore, water resource constraints are not merely quantitative but also spatial and temporal. The mismatch between the spatial distribution of water resources and the location of productive forces often necessitates inter-basin water transfer projects or the implementation of water-sensitive urban designs. Failure to adhere to these constraints can lead to groundwater over-exploitation, land subsidence, and the degradation of aquatic ecosystems, ultimately undermining the sustainability of regional development.

The implementation of the "Plan (2016–2030)" is closely related to these developments. This plan provides a comprehensive framework for strategic growth and scientific advancement over the specified fifteen-year period. Through the systematic execution of this roadmap, the integration of emerging technologies and academic research is expected to reach new milestones, ensuring that long-term objectives in innovation and infrastructure are met with technical precision and institutional support.

In the formula: A_{2023} represents the volume of agricultural irrigation water consumption in the Hexi inland river basin.

According to the agricultural functional zoning plan for Gansu Province, the Hexi Inland River region is prioritizing the industrial upgrading of the maize seed production sector while systematically developing an intensive facility-based agricultural and livestock production system. As of 2023, maize (26.13×10^8 m^3), Arid Regions

These areas represent the primary regions for agricultural water use within the basin, collectively accounting for 68.7% of the agricultural water footprint in the Hexi inland river basin. Furthermore, this footprint exhibits a consistent upward trend. Specifically, the agricultural water footprint in Wuwei City increased from 22.36×10^8 m^3 in 2011 to 35.75×10^8 m^3 in 2023.

···increased to 108×10^8 m^3, while Zhangye City grew from 24.64×10^8 m^3 to 33.98×10^8 m^3. This upward trend has become the dominant factor shaping the overall spatial and temporal patterns of the agricultural water footprint within the river basin.

This indicates that the agricultural water footprint of the Hexi inland river basin is primarily influenced by the cities of Wuwei and Zhangye. Furthermore, the agricultural water footprint of Jiuquan City increased significantly, rising from 12.39×10^8 m^3 in 2011 to 20.71×10^8 m^3 in 2023.

Facing the increasingly severe problem of water resource over-exploitation in the Hexi inland river basin, there is an urgent need to prioritize the implementation of high-efficiency water-saving irrigation projects in key areas such as Wuwei and Zhangye. Simultaneously, it is essential to promote high-value-added···

Value-added water-saving agriculture is essential to achieving the sustainable utilization of regional water resources.

2 Changes in AWF in the Hexi Inland River Basin

The Agricultural Water Footprint (AWF) serves as a critical indicator for assessing the total volume of water consumed during crop production, encompassing both "blue water" (surface and groundwater) and "green water" (effective rainfall). In the Hexi inland river basin, the spatio-temporal dynamics of the AWF have undergone significant shifts due to climate change and evolving agricultural practices.

Recent data indicates that while the total area under cultivation has expanded, the implementation of advanced irrigation technologies and the optimization of crop patterns have led to fluctuations in water use efficiency. The blue water footprint remains the dominant component in this arid region, reflecting a high dependency on irrigation. However, the increasing scarcity of water resources necessitates a transition toward value-added water-saving agriculture. This approach focuses not only on reducing the physical volume of water used but also on maximizing the economic and nutritional output per unit of water consumed.

Analyzing the historical trends of AWF in the Hexi region reveals that structural adjustments in the agricultural sector—such as shifting from low-value, high-water-consumption grains to high-value, water-efficient cash crops—are vital for mitigating regional water stress. Furthermore, the integration of precision agriculture and digital monitoring systems has begun to show promise in reducing the overall water footprint, thereby supporting the long-term sustainability of the basin’ s hydrological cycle.

3.2 作物种植结构优化

According to the *Gansu Province “14th Five-Year Plan” for Water-Saving Society Construction*, the region is committed to advancing a comprehensive strategy for sustainable water management. This strategic framework emphasizes the integration of water conservation into all aspects of socio-economic development, aiming to address the inherent challenges of water scarcity in the province. The plan outlines specific targets for improving water use efficiency across various sectors, including agriculture, industry, and urban domestic use, while promoting the adoption of advanced water-saving technologies and management practices. By prioritizing the protection of water resources and the restoration of aquatic ecosystems, the initiative seeks to ensure long-term water security and support the high-quality development of Gansu’ s economy and environment.

basin 2011 to 2023

Agricultural water conservation and efficiency enhancement have been listed as primary tasks. The planning explicitly states that

The water footprints of mutton (12.32×10^8 m^3) and dairy products (13.00×10^8 m^3)

it is necessary to follow the fundamental principles of “optimizing structure, reducing water consumption, and increasing efficiency”

As shown in Figure 3 [Figure 3: see original paper], the agricultural water footprints of various cities within the basin exhibit significant

multi-objective optimization methods, which involve simultaneously optimizing multiple interrelated objective functions under the premise of satisfying specific constraints [?]. Based on

footprint fluctuated between 0.53×10^8 and 1.51×10^8 m^3 during the research period, with an average annual value of

Using data from the typical year of 2023 and employing Matlab R2024b software, the

The agricultural water footprint of Jiayuguan City is significantly lower than the basin average; Jinchang

problem is solved. This study focuses on the Hexi inland river basin, selecting wheat,

City maintained a level between 6×10^8 and 8×10^8 m^3 from 2011 to 2019, which then surged to 11.50×10^8 m^3 in 2023.

closely related to rapid development. Meanwhile, Wuwei City and Zhangye City, as

footprint accounts for as much as 77.2%, representing the primary source of water resource consumption in the basin.

all showed significant growth.

spatial differentiation and temporal variation characteristics. The annual average agricultural water footprint of Jiayuguan City is 0.88×10^8 m^3, accounting for only 1.1% of the basin total, indicating

The sudden increase in 2023 to 11.50×10^8 m^3 is closely linked to the development of its 10-billion-yuan "vegetable-fodder-livestock" agricultural industry.

principles to comprehensively optimize the agricultural industrial structure. Therefore, this study adopts the weighted sum method to transform the multi-objective optimization problem into a single-objective optimization

typical crop types as optimization objects. The agricultural water footprints of these crops

3 Shows the distribution of AWF in the Hexi inland river basin in 2011, 2015, 2019 and 2023

Evolution of Agricultural Water Footprint and Optimization of Planting Structures in the Hexi Inland River Basin

By adjusting the planting structure, this study aims to achieve the highly efficient utilization of water resources.

Through the implementation of water-efficient technologies, the region continues to reduce total planting areas while significantly increasing yields per unit area.

This approach addresses the dual objectives of agricultural sustainability and regional food security.

The goal is to realize a strategy of "reducing area while enhancing efficiency." Concurrently, medicinal herbal crops have played a role in this transition.

The optimization of the planting structure has yielded significant results, with the total area increasing to 7.59×10^4 hm^2 and production levels rising accordingly.

3.2.1 种植结构优化分析在河西内陆河流域，以

Based on the crop cultivation area of 2023, through technological upgrades and optimization of agricultural management practices, it is possible to further enhance regional food security and resource utilization efficiency. By integrating advanced machine learning algorithms with multi-source remote sensing data, researchers can more accurately monitor crop growth dynamics and predict yield fluctuations. These technological advancements facilitate the precise application of fertilizers and irrigation, thereby reducing environmental impact while maintaining high productivity levels. Furthermore, the integration of deep learning models allows for the early detection of pests and diseases, providing a robust framework for sustainable agricultural development in the coming years.

The total volume increased from 30.92×10^4 t to 40.19×10^4 t. This trend is consistent with the observations recorded in Zhangye City.

The strategic planning direction focuses on the prioritized development of medicinal herbs such as *Isatis indigotica* (Banlangen), *Glycyrrhiza uralensis* (Licorice), and *Lycium barbarum* (Goji berry). This initiative aims to leverage regional ecological advantages to establish standardized cultivation bases, ensuring the consistent quality and supply of these essential traditional Chinese medicines. By integrating modern agricultural technologies with traditional pharmacological expertise, the plan seeks to enhance the value chain of these specific botanical resources, supporting both clinical efficacy and the sustainable growth of the pharmaceutical industry.

investment, and other factors, aiming to maximize the optimization of the total planting area. In

The Gansu inland river basins are slated for prioritized development during the "14th Five-Year Plan" period. This strategic focus aligns with regional ecological and economic goals, emphasizing sustainable water resource management and the enhancement of ecological security barriers. The development framework aims to balance the protection of fragile desert-oasis ecosystems with the promotion of high-quality agricultural and industrial growth, ensuring that water utilization remains within the limits of environmental carrying capacity.

Under the premise of considering constraints such as planting area and water resources, this paper proposes a multi-objective optimization model for agricultural resource allocation. By integrating machine learning algorithms with traditional optimization techniques, we aim to maximize crop yields while minimizing environmental impact. The model accounts for the stochastic nature of precipitation and the varying water requirements of different crop varieties across distinct growth stages. Furthermore, we incorporate spatial constraints to ensure that the total allocated planting area does not exceed the available arable land. Through this approach, we provide a decision-support framework for sustainable agricultural management that balances economic benefits with ecological preservation.

Gobi ecological agriculture and vegetable production bases supplying Hong Kong and the Greater Bay Area have significantly promoted the development of the vegetable industry. By leveraging unique local environmental conditions and modern agricultural technologies, these initiatives have transformed previously arid regions into productive hubs for high-quality produce.

The development of Gobi ecological agriculture focuses on maximizing resource efficiency in challenging terrains. Through the implementation of advanced greenhouse technologies, precision irrigation, and soil-less cultivation techniques, these regions can produce a stable supply of premium vegetables. This approach not only addresses food security concerns but also ensures that the produce meets the rigorous quality and safety standards required for export to highly regulated markets like Hong Kong and the broader Greater Bay Area.

Furthermore, the establishment of dedicated supply bases has streamlined the agricultural value chain. By integrating production, processing, and cold-chain logistics, these bases minimize post-harvest losses and maintain the nutritional integrity of the vegetables. This systematic integration supports the regional economy by creating jobs and fostering technological innovation within the agricultural sector, while simultaneously providing urban centers with a reliable source of fresh, sustainable, and high-quality food products.

aims to balance regional economy and water security. The optimization results are compared with···

The vegetable planting area increased significantly (4.77×10^4 hm^2), with a corresponding increase in yield.

Compared to the situation in 2023, the current landscape exhibits significant changes. In contrast to the conditions observed in 2023,

Compared to the original crop planting area (73.80×10^4 hm^2), the optimized planting area···

The planting area decreased by 4.61×10^4 hm^2. To a certain extent, this adjustment···

reached 240.93×10^4 t. Furthermore, the planting area for orchard fruits expanded, with production increasing to 67.67×10^4 t.

3.2.2 目标函数值优化分析在河西内陆河流域这

···mitigated the water resource pressure in the inland river basins of the Hexi region. At the same time, crop···

Against the backdrop of unique geographical locations and resource constraints, this study explores the optimization of resource allocation and system performance through advanced computational frameworks. In such environments, traditional infrastructure often faces significant challenges, necessitating the development of more resilient and efficient methodologies. By integrating machine learning techniques with robust mathematical modeling, we aim to address the inherent limitations of data transmission and processing in isolated or resource-scarce regions.

The primary objective of this research is to establish a comprehensive theoretical framework that accounts for both environmental variables and technical constraints. We utilize a series of optimization algorithms to enhance the reliability of the system, ensuring that performance metrics remain stable even under fluctuating conditions. Furthermore, this study investigates the trade-offs between computational complexity and energy efficiency, a critical consideration for systems operating in remote areas with limited power supplies.

Through rigorous empirical analysis and simulation, we demonstrate the effectiveness of the proposed approach. Our findings suggest that by leveraging adaptive strategies and intelligent resource management, it is possible to significantly mitigate the negative impacts of geographical isolation. This research provides valuable insights for the design and implementation of future technological solutions in similar challenging environments, contributing to the broader field of sustainable and resilient engineering.

The production volume increased from 1256.04×10^4 t to 1432.14×10^4 t, representing a growth of⋯

The optimization of crop planting structures is essential for minimizing water resource consumption and maximizing agricultural productivity. By strategically adjusting the spatial distribution and variety of crops, it is possible to significantly enhance water-use efficiency while ensuring food security. This process involves a complex interplay of hydrological constraints, soil characteristics, and climatic variables.

Advanced modeling techniques, including machine learning and deep learning, are increasingly employed to analyze these multi-dimensional datasets. These models allow researchers to simulate various scenarios and identify the most sustainable planting configurations. Furthermore, integrating remote sensing data with ground-based observations provides a robust framework for monitoring real-time water requirements and crop health.

Ultimately, the goal of optimizing planting structures is to achieve a balance between economic returns for farmers and the preservation of vital water ecosystems. Such efforts are critical in the context of global climate change and the increasing scarcity of freshwater resources, necessitating a transition toward more resilient and water-efficient agricultural systems.

Increasing agricultural yields while simultaneously reducing the total area under cultivation is a critical objective for modern sustainable agriculture. Achieving this goal requires the integration of advanced technologies and optimized management strategies to maximize the efficiency of existing land resources. By leveraging innovations in machine learning and deep learning, researchers can develop precision agriculture techniques that enhance crop productivity through data-driven insights.

[Figure 1: see original paper]

The implementation of these technologies allows for more precise monitoring of soil health, moisture levels, and nutrient requirements, ensuring that resources are applied only where and when they are most needed. This targeted approach not only boosts overall output but also minimizes the environmental footprint of farming operations. Furthermore, the adoption of high-yield crop varieties and improved irrigation systems plays a vital role in decoupling production growth from land expansion, thereby preserving natural ecosystems and biodiversity.

The results of the study indicate ([Figure 5: see original paper]) that through the implementation of optimization measures, the Hexi inland river basin has achieved significant improvements in water resource management and ecological stability. The analysis demonstrates that these strategic interventions have effectively mitigated the previous trends of environmental degradation. Furthermore, the data suggests that the integration of localized water allocation policies with modern agricultural techniques has enhanced the overall resilience of the regional ecosystem against climate variability.

176.10 $\times 10^4$ t. This indicates that through the reasonable optimization of planting structures,

The maximization of economic benefits is pursued with the ultimate goal of achieving a win-win situation for both the economy and the ecology.

thereby achieving the efficient utilization of water resources and the enhancement of economic benefits.

The economic objective function value of the river basin increased by 6.75×10^8 yuan. This

The Hexi Corridor no longer serves as a national commercial grain production base. Instead, it has transitioned into the largest corn seed production base in China, as well as an important regional production center for characteristic agricultural products such as dehydrated vegetables, hops, and wolfberries.

[Figure 1: see original paper]

The Hexi Corridor is located in the arid region of Northwest China, characterized by a typical temperate continental climate. The region features long hours of sunshine, high cumulative temperatures, and a significant diurnal temperature range. These unique climatic conditions provide an ideal environment for the accumulation of dry matter and the prevention of pests and diseases in crops. However, the scarcity of water resources remains the primary limiting factor for agricultural development in this area.

In recent years, the agricultural structure of the Hexi Corridor has undergone profound transformations. Driven by market demand and national strategic adjustments, local farmers have shifted from traditional grain cultivation to high-value-added economic crops. This shift has not only increased rural incomes but also promoted the efficient use of limited water resources through the adoption of modern irrigation technologies and specialized farming practices. As shown in (eq:water_{efficiency}), the optimization of crop patterns has significantly improved the water-use efficiency (η) across the oasis agricultural zones.

$$\eta = \frac{Y}{ET}$$

Where Y represents the crop yield per unit area and ET denotes the total evapotranspiration during the growing season. Research indicates that the η value for seed corn is substantially higher than that of traditional wheat varieties in this region. Furthermore, the integration of machine learning algorithms in precision agriculture has allowed for better prediction of soil moisture levels, further stabilizing yields in the face of climate variability.

[Figure 2: see original paper]

Despite these advancements, the ecological pressure on the Hexi Corridor continues to mount. The over-extraction of groundwater for irrigation has led to the shrinkage of terminal lakes and the degradation of desert-edge vegetation. Future agricultural strategies must balance economic output with ecological sustainability to ensure the long-term viability of this vital agricultural corridor. Consistent with the findings of [**?**], sustainable water management remains the cornerstone of regional development.

The growth is attributed to the improvement of economic benefits derived from certain low-water-consumption and high-efficiency crops.

functions, current agricultural development is oriented toward ensuring regional self-sufficiency. In the face of

Specifically, the production of Chinese medicinal materials in Gansu Province ranks second in the nation.

To address the challenges of water scarcity, it is imperative to adhere to the development of modern agriculture characterized by water conservation and high efficiency.

The adjustment of the planting structure resulted in an additional economic benefit of 12.06×10^8 yuan. Compared with⋯

Guided by industry trends, the planting structure of grain and industrial crops has been scientifically adjusted. During the optimization process of crop cultivation in the Hexi inland river basin [Figure 4: see original paper], the planting area of wheat—a high water-consumption crop—decreased from 12.97×10^4 hm^2 to⋯

decreased to 9.08×10^4 hm^2, representing a reduction of 3.89×10^4 hm^2; maize cultivation

The strategic objective proposed in 2022 to transition from a "major province of medicinal materials" to a "strong province of Traditional Chinese Medicine (TCM)" underscores the critical importance of modernizing the TCM industry. A fundamental requirement for achieving this high-quality development is the establishment of a robust and standardized quality evaluation system for Chinese medicinal materials.

1. Introduction

The quality of Chinese medicinal materials is the cornerstone of clinical efficacy and safety in TCM. However, traditional identification methods often rely on subjective sensory experiences, which lack the precision required for modern industrial standards. To address these challenges, researchers have increasingly turned to advanced analytical techniques and computational intelligence.

[Figure 1: see original paper]

Recent advancements in machine learning and deep learning offer transformative potential for the automated identification and quality assessment of medicinal herbs. By integrating high-throughput data—such as hyperspectral imaging, chromatographic profiles, and molecular markers—with sophisticated algorithms, it is now possible to achieve objective, reproducible, and rapid quality control. This technological shift is essential for the digital transformation of the TCM industry, ensuring that the transition to a "strong province" is supported by rigorous scientific methodologies and standardized production practices.

alignment; the plan aims for the total output value of the entire traditional Chinese medicine (TCM) industry chain in the province to strive to exceed 1000×10^8 yuan by the end of 2025. Furthermore, the "Fourteenth Five-Year Plan of Gansu Province···"

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

Source: ChinaXiv —Machine translation. Verify with original.