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RESEARCH ARTICLE

# Water resource conservation promotes synergy between economy and environment in China's northern drylands

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## HIGHLIGHTS

- Considering evenness provides a more accurate assessment of sustainable development.
- Water resource conservation drives industrial transformation.
- Synergy between economic development and environmental protection is achieved.
- Regional collaboration over water could promote sustainable development in drylands.

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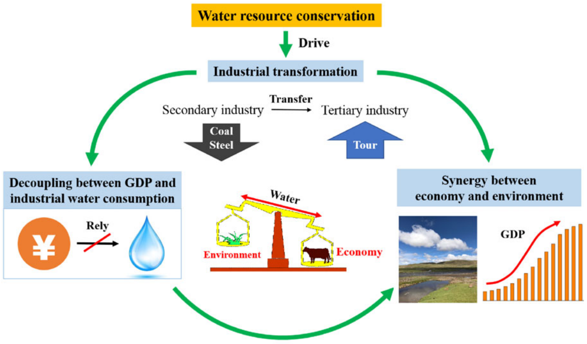
## GRAPHIC ABSTRACT



## ABSTRACT

Water resource availability is the major limiting factor for sustainable development in drylands. Climate change intensifies the conflicting water demands between people and the environment and highlights the importance of effective water resource management for achieving a balance between economic development and environmental protection. In 2008, Inner Mongolia, typical dryland in northern China, proposed strict regulations on water exploitation and utilization aimed at achieving sustainable development. Our study is the first to investigate the effectiveness and performance of these long-standing water conservation regulations. Our analyses found that the regulations drove industrial transformation, evidenced by the decreasing proportion of environmentally harmful industries such as coal and steel, and the increasing proportion of tertiary industries (especially tourism). Following industrial transformation, economic development decoupled from industrial water consumption and subsequently led to reduced negative environmental impacts. Based on these results, adaptive strategies were developed for 12 cities by revealing and integrating their development pathways and relative status in achieving sustainable development. Integration and cooperation between cities were proposed, e.g., a water trade agreement between eastern Inner Mongolia (an economically underdeveloped region with relatively abundant water resources) and central Inner Mongolia (an economically developed region with high water stress). Such an agreement may enable the holistic achievement of sustainable development across regions. By integrating the findings of our research, our study presents a reproducible framework for water-management-based sustainable development strategies in drylands.

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# 1 Introduction

Drylands occupy about 45% of the global land surface (Pravalie, 2016) and house approximately 2.5 billion people (MEA, 2005). These regions are especially sensitive and vulnerable to human activities and climate change (Dougill et al., 2010; Huang et al., 2016). Water is the major limiting factor in drylands; increased water shortages (especially in the Eurasian Steppe) due to climate change and over-exploitation of water resources (Rodell et al., 2018) are likely to affect dryland ecosystems in ways that threaten human inhabitants, such as through soil degradation and food shortages (Ghimire et al., 2018; Moreno-Jimenez et al., 2019). Moreover, water scarcity is also a major limiting factor for economic development (Distefano and Kelly, 2017). For example, given that China's social and economic development is closely related to water resources (Zhao et al., 2017; Hao et al., 2019), water scarcity largely restricts the Beijing-Tianjin-Hebei region (generally with a semi-arid climate) from being a world-class megalopolis (Zhang et al., 2021). Therefore, effective water management such as increasing water-use efficiency that can improve both ecological and social-economic systems is essential for the sustainable development of drylands (van Dijk et al., 2013; Yang et al., 2013).

The drylands of northern China contain only 19% of the country's total water resources but house one-third of the national population (Jiang, 2015), and are therefore under considerable water stress (Li et al., 2017). In particular, Inner Mongolia, which is a typical dryland province, plays an important role in maintaining ecological security in northern China (Ren et al., 2016; Bai et al., 2020). This region has been subject to increasingly severe water stress over the past decades (Li et al., 2017), mainly caused by the over-exploitation of water resources. Inner Mongolia has experienced rapid socioeconomic development (Li et al., 2018; Shang et al., 2019), which has largely depended on water resources (e.g., the coal and steel industries) (Wang et al., 2017; Lin et al., 2020). Anthropogenic water consumption has increased 4-fold, from $6.68 \times 10^9$ $m^3$ in 1987 to $27.11 \times 10^9$ $m^3$ in 2015 (Shang et al., 2019); this increase has seriously threatened regional grasslands, which also rely on water resources to sustain ecological integrity (Del Grosso et al., 2008; Wang et al., 2013; Wilcox et al., 2017). Inner Mongolia has vast grasslands that play an important role in northern China (Chen et al., 2018; Xie et al., 2019). The degradation of these grasslands due to human activities is not only a problem for Inner Mongolia but also a major threat to northern China (Hu and Nacun, 2018; Bai et al., 2020). It has resulted in a series of social and environmental problems, such as drought (Kreyling et al., 2017; Zhang et al., 2018), sandstorms (Yang et al., 2015), regression of animal husbandry (Su et al., 2005), and increased poverty (Briske et al., 2015). Moreover, the degradation of grassland in turn diminishes the soil water retention capacity (Yi et al., 2012), thereby exacerbating the tension between ecosystems and economic development. However, previous studies on water management mostly focused on one side of this conflict. There are intensive studies on managing water resources through engineering approaches (Zhou et al., 2021), generally by increasing water use efficiency in the urban area (Zhang et al., 2021; Zhou et al., 2021) or agricultural production (Qiao et al., 2009; Liu et al., 2020), or aiming at pollution control (Huang et al., 2008; Qu et al., 2019). On the other hand, some studies had also addressed the importance of ecosystem management (van Dijk et al., 2013). The conflict between ecological and social-economic systems and the actions that might relieve it have been long overlooked, thus, might lead to unexpected problems when adopting policies with only one-side focusing (Soula et al., 2021).

To alleviate water stress and promote environmental protection (particularly the restoration of grassland), strict regulations known as "Water Permit and Water Resource Fees" have been implemented in Inner Mongolia since 2008 (People's Government of Inner Mongolia Autonomous Region, 2008). These regulations force the application and evaluation of water exploitation for any purpose, excluding household use of $< 1000$ $m^3/a$. Higher water resource fees have been imposed on polluting industries, such as the metallurgical and chemical industries. For instance, 1 $m^3$ of water is charged at CNY 12, 7.5, 5, and 2 for metallurgical and chemical industries, power plants, tertiary industry, and domestic purposes, respectively. By adopting these regulations, Inner Mongolia's government aims to limit high water consumption and the expansion of polluting industries; by doing so, they aim to achieve industrial restructuring toward sustainable development. However, no systematic evaluation has been conducted to determine if and how such strict regulations on water conservation might alleviate the tension between environmental protection and economic development. Without this information, policy adjustment and the ability to achieve sustainable development are limited.

Therefore, this study quantitatively evaluated the effectiveness of the aforementioned water management policies from the following aspects: (1) whether economic development became less dependent on water consumption; and (2) whether environmental protection and economic development have jointly improved since the implementation of water conservation regulations. By doing so, we aimed to disentangle how the conflict between environmental protection and economic development can be relieved through water management actions. Furthermore, we explored the current status and development pathways at the municipal level to provide suggestions for holistic development across cities by adopting location-specific policies. Overall, our study offers a reproducible case study for sustainable development in drylands by highlighting how water management could reconcile the conflict between ecological and social-economic systems.

## 2 Methods

### 2.1 Study area

The Inner Mongolia Autonomous Region is located on the northern border of China. It has 12 major cities that collectively cover an area of 1.183 million km$^2$ and a permanent population of around 25.3 million (Table. S1). The region is characterized by a temperate climate, with uneven spatially distributed precipitation (China Meteorological Data Service Center; http://data.cma.cn/en). Almost two-thirds of the total water resources are distributed in eastern Inner Mongolia, which houses only 18% of the nation's population.

### 2.2 Data sources and analyses

Three core aspects of drylands' social-ecological system were focused on in this study, namely, water, grassland, and economy. A comprehensive water resource profile (including available water resources, water use efficiency, water usage in different industries, etc.) was obtained from the Inner Mongolia Water Resources Bulletin (Water Resources Department of Inner Mongolia, 2018), then used to investigate the direct influence of strict water resource regulations implemented in 2008 and interpret the conflict between environmental protection and economic development over water resources. Gross domestic product (GDP) was used to quantify economic development. As for the environmental aspect, we focused on the grassland which covers most of the land surface of Inner Mongolia and plays a key role in the environmental protection of northern China (Chen et al., 2018; Xie et al., 2019; Bai et al., 2020). As grassland degradation has long been an environmental problem for northern China, net primary productivity (NPP) was used to capture such an eco-environmental change. The relationship and evenness among these three aspects were analyzed before and after 2008 (2000–2008 vs. 2009–2017) to explore the influence of the aforementioned water management regulations.

Data on the GDP, population of Inner Mongolia, and its 12 cities were obtained from the Inner Mongolia Statistical Yearbook (National Bureau of Statistics, 2018). We used the 2000–2017 Chinese consumer price index (CPI) to calibrate GDP to adjust for inflation. The CPI in 2000 was set as the baseline. The calibrated GDP in a given year refers to the recorded GDP in that year divided by the ratio between the CPI in that year and the CPI in 2000. NPP was calculated based on the Carnegie–Ames–Stanford approach from MODIS data (Mu et al., 2013; Liang et al., 2015).

Relationships between water resources, GDP, NPP, and change in industry structure were tested via linear and quadratic regressions. To determine the differences in the studied variables (GDP, water resources, and NPP) before and after 2008, paired *t*-tests were used for comparisons at the provincial level (via pairwise comparisons of the average value of a given variable before and after 2008 in the same city, yielding 12 data per group). A normal *t*-test was performed for comparisons at the municipal level (by comparing the values from the first nine years with those from the subsequent nine years, resulting in nine data per group). The paired *t*-tests aimed to determine whether a holistic change occurred across all cities at the provincial level. The normal *t*-tests were performed at the municipal level to explore whether significant changes occurred in each city after 2008. Water conservation regulations were implemented in the middle of 2008; consequently, we selected the two time periods for this study (2000–2008 and 2009–2017) to reflect periods before and after regulations were in place. Therefore, each period had nine years of data. Results were deemed statistically significant at $p < 0.05$. All statistical tests were performed using SPSS v.27 (IBM Corp., Armonk, NY, USA).

### 2.3 Computation of development and evenness scores

This study aimed to understand and reconcile the conflict between economic development and the environment. Therefore, it is important to know the evenness among water resources, economic development and eco-environmental conditions in addition to their overall status. Previous assessments on sustainable development mostly used the arithmetic mean of different indicators (Sachs et al., 2018; Xu et al., 2020), which neglected the evenness among indicators and could lead to overoptimistic results (Liu et al., 2020a). This is particularly the case for the rapid economic development at the cost of the environment. Thus, this study adopted both the development score (referring to the average status of all chosen indicators) and the evenness score to study the recent status and changes of sustainable development in Inner Mongolia.

Generally, we followed the method proposed by Liu et al. (2020a), which adopted an improved radar chart method to compute the development score (DS) and evenness score (ES) (Liu et al., 2008; Liu et al., 2020b). The advantages of this method can be summarized as follows: (1) it has two dimensions, i.e. average performance and evenness among indicators, which extends its implications in sustainable development assessment; (2) it could visualize the performance of each indicator (by the radius of each sector) and their overall performance (by its total area), and also the evenness among them (by its perimeter), allowing an easy comparison over time or across space; (3) the calculation of ES was not influenced by the order of indicators (Liu et al., 2008).

GDP per capita, water resources per capita, and NPP per m$^2$ were used to represent the status of economic development, water resources, and environmental conditions, respectively; these aspects were also used to exclude the influence of population variations and differences in the spatial area on the spatial comparisons (among different cities) and temporal comparisons (2000–2008 vs. 2009–2017).

As the radar chart method required standardized inputs, we first divided all data by a selected calibration value. Taking water resources as an example, the standardized value of the water resources per capita of a certain city in a certain year ($r_{ij}$) was calculated as follows:

$$r_{ij} = WR_i / \overline{WR}, \tag{1}$$

where $i$ represents the year and city from which the data came; $j$ represents the different indexes (GDP per capita, water resources per capita, and NPP per m$^2$); $WR_i$ is the recorded value of the water resource per capita of a certain city in a certain year; and $\overline{WR}$ is the selected calibration value, e.g., the mean value of water resources per capita in China during 2000–2017.

Similar to water resources, GDP and NPP were standardized following Eq. (1) but with different calibration values. The calibration value for GDP was also the mean Chinese GDP per capita from 2000 to 2017. We used the mean values of China rather than those of Inner Mongolia to ensure that the results were comparable at the national level. In contrast, NPP per m$^2$ varies across different ecosystem types (Feng et al., 2007), and comparisons across environmental conditions using NPP should be within similar ecosystem types. We therefore used the mean NPP per m$^2$ of Inner Mongolia from 2000 to 2017 as the calibration value, because it was stable over the past 20 years (170.46±10.58, with a coefficient of variance of 6%). It was also similar to the mean value of the Eurasian Steppe (Chen et al., 2019), where Inner Mongolia locates in, and is therefore representative of the general environmental condition of the Inner Mongolia grassland.

The standardized value ($r_{ij}$) was then used as the radius of a sector in a radar chart, which comprised three sectors corresponding to the GDP, water resources, and NPP. The area ($S$) and perimeter ($L$) of the radar chart are expressed as follows:

$$S_i = \sum\nolimits_{j=1}^{n} S_j = \sum\nolimits_{j=1}^{n} \pi f_{ij} r_{ij}^2 \quad j = 1,2,\ldots,n, \tag{2}$$

$$L_i = \sum\nolimits_{j=1}^{n} L_j = 2|r_{max} - r_{min}| + \sum\nolimits_{j=1}^{n} 2\pi f_{ij} r_{ij}$$

$$j = 1,2,\ldots,n, \tag{3}$$

where $n$ represents the number of variables, namely three in the present study; $f_{ij}$ is the weight of the $j^{th}$ variable, which was set to equal weighting (1/3); *and* $r_{max}$ and $r_{min}$ represent the maximum and minimum $r_{ij}$, respectively. Notably, the doubled value of the difference between $r_{max}$ and $r_{min}$ refers to the parts of the perimeter other than the total length of all arcs (the total length of all lines between two adjacent arcs; Fig. S1). The DS and ES were calculated using $S_i$ and $L_i$:

$$DS_i = S_i / maxS_i, \tag{4}$$

$$ES_i = S_i / [\pi (L_i / 2\pi)^2] = 4\pi S_i / L_i^2. \tag{5}$$

To ensure that our results were comparable across time and space, $max\ S_i$ is the highest value among all the studied cities over the entire study period (2000–2017). DS represents the overall performance of GDP, water resources, and NPP, which can be visualized by the total area of a given radar chart. ES represents the ratio of the total area of the radar chart to that of a circle with the same perimeter (the most even status, where GDP, water resources, and NPP are similar to their calibration values or multiples of these values).

The geometric means of DS and ES were used to calculate the core sustainable development score (CSDS), which could diminish the potential overestimation of sustainable development performance by using DS only when the performances of economic development and environmental protection differed substantially. For instance, fast-growing GDP at the cost of the environment indicated unevenness, whereas a simultaneous increase in GDP and NPP indicated evenness; a similar performance might be concluded by adopting DS only, as the increased GDP may offset the decreased NPP in calculations. DS, ES, and CSDS ranged from 0 (poorest performance) to 1 (best performance). Importantly, these scores represent only the relative performances toward sustainable development based on the chosen baselines, because this study compared the performances before and after 2008 among cities rather than estimating performance toward the Sustainable Development Goals.

### 2.4 Definition of development pathway and relative development status of 12 cities

For each city, we plotted the paired average DS and ES along the x- and y- axes, respectively, for the periods before and after 2008. We visualized the development pathway by constructing a vector starting from a point before 2008 and ending at a point after 2008 (Liu et al., 2020a). The angle ($\theta$) between the vector and $x$-axis ranged from 0 to 360°, representing four types of development pathways: (1) progression ($0° \leqslant \theta \leqslant 90°$), (2) retrogression in development ($90° < \theta \leqslant 180°$), (3) retrogression in evenness ($270° \leqslant \theta < 360°$), and (4) retrogression in both development and evenness ($180° < \theta < 270°$) (Fig. S2).

To explore the different performances toward sustainable development of the 12 Inner Mongolian cities after

2008, the K-means method was used to establish thresholds for relatively high and low DS and ES values. All cities were divided into two groups (relatively high and relatively low) based on the DS or ES. By integrating both, the 12 cities were further divided into four categories in terms of their relative development status, namely relatively sustainably-developed (high DS and ES), relatively underdeveloped (low DS and high ES), relatively uneven (high DS and low ES), and relatively underdeveloped and uneven (low DS and ES). These four categories were used to depict the relative development status of the cities rather than their current performance toward the Sustainable Development Goals.

## 3 Results

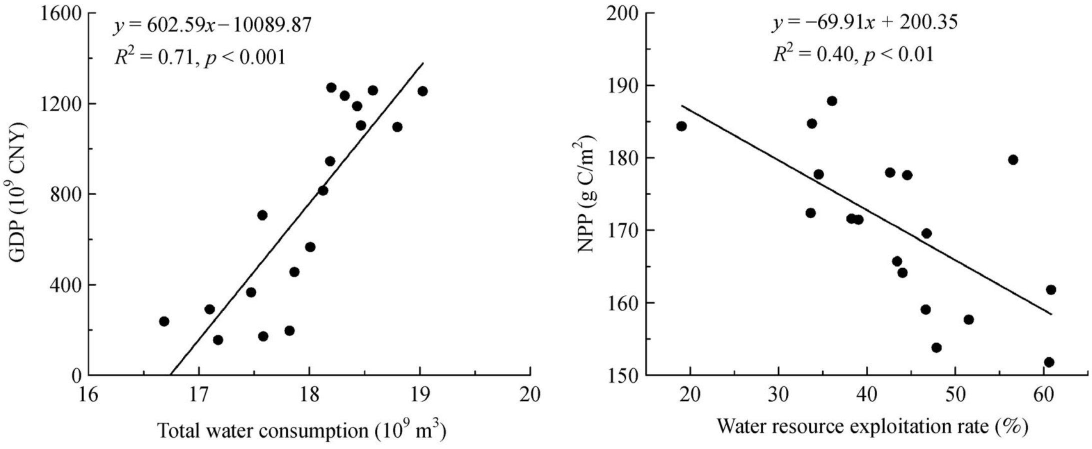
### 3.1 Conflict between economic development and environmental protection

Both the GDP and NPP of Inner Mongolia were strongly correlated with water resources in 2000–2017. GDP was highly dependent on the total water consumption ($R^2 = 0.71$, $p < 0.001$; Fig. 1(a)), whereas the exploitation of water resources decreased the average NPP ($R^2 = 0.40$, $p < 0.01$; Fig. 1(b)), thereby indicating a conflict between ecological and economic water demands.

### 3.2 Changes toward sustainable development before and after 2008

Precipitation is the major source of water recharge in Inner Mongolia; precipitation exhibited a non-significant trend from 2000 to 2017 (slope = 3.05, $R^2 = 0.14$, $p = 0.07$; Fig. S3) and was not significantly different before and after 2008 ($t = -2.01$, $p = 0.06$). The implementation of strict water resource regulations in 2008 restricted industrial water consumption and imposed high fees on water use; from 2011 onwards, Inner Mongolia's industrial structure changed from being dominated by the secondary industry to being dominated by the tertiary industry (Fig. S4). The major changes were identified as follows: (1) the decreasing proportion of the secondary industry after 2010 was largely ascribed to decreases in the coal and steel industry sectors (which account for 56% of the total reduction of the secondary industry from 2011 to 2017; Fig. 2(a)); (2) the increasing proportion of the tertiary industry after 2010 mostly stemmed from the elevated role of tourism (Fig. 2(b) and Fig. S5), which increased 15.09% from 2011 to 2017, and which surpassed the growth of the tertiary industry (13.93%); (3) industrial water consumption greatly decreased after 2010, from 2.26 $10^9$ $m^3$ in 2010 to 1.57 $10^9$ $m^3$ in 2017. Moreover, the efficiency of water usage in the region greatly improved, with a significantly decreasing trend in water consumption per unit GDP from 2000 to 2017 (slope = $-0.13$, $R^2 = 0.90$, $p < 0.001$; Fig. S6).

Four stages were identified for the transformation from coupling to decoupling between economic development (GDP) and industrial water consumption (Fig. 3(a)): (1) a slow increase in both GDP and industrial water consumption from 2000 to 2003, (2) a rapid increase in both GDP and industrial water consumption from 2003 to 2010 that is indicative of strong coupling between economic development and water consumption; (3) a continuous increase in GDP and stable industrial water consumption from 2010 to 2013; and (4) a stable GDP and decreased industrial water consumption from 2013 to 2017. A decoupling of the relationship between economic development and industrial water consumption occurred after 2010, a year after the enactment of the strict regulations on water conservation; this was similar to the change in industrial structure in



(a) (b)

**Fig. 1** Relationship between (a) total water consumption and gross domestic product (GDP) and (b) between water resource exploitation rate and net primary productivity (NPP).

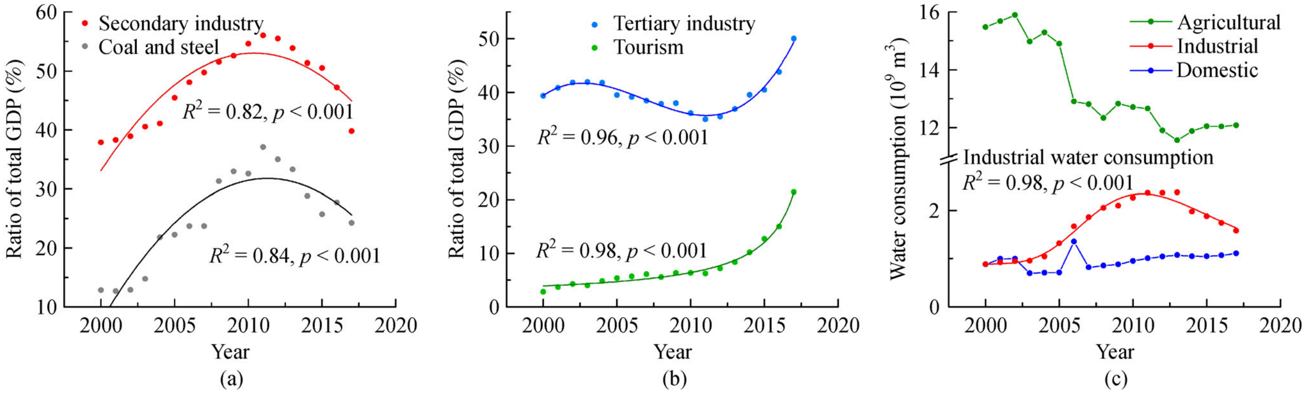
Inner Mongolia (Fig. 2). Consequently, the relationship between GDP and industrial water consumption changed from being strongly positively correlated ($R^2 = 0.97$, $p < 0.001$; Fig. 3b) to being neutral and non-significant ($R^2 = 0.11$, $p = 0.66$; Fig. 3b).

Additionally, the relationship between economic development (in terms of GDP) and environmental protection (in terms of NPP) changed after 2008. The ratio of the changing rate of GDP to NPP exhibited a unimodal shape from 2000 to 2017 ($R^2 = 0.37$, $p = 0.02$; Fig. 4(a)); the changing rate refers to the ratio of GDP/NPP in one year to its value in the previous year. ΔGDP/ΔNPP decreased since 2008, stabilized, and slightly exceeded 1 (less than 1.05) after 2014 (Fig. 4(a)). No significant relationship existed between NPP and GDP before 2008 ($R^2 = 0.07$, $p = 0.51$; Fig. 4(b)), whereas they exhibited a significant positive correlation after 2008 ($R^2 = 0.48$, $p = 0.02$; Fig. 4 (b)); this indicates a synergistic relationship between economic development and environmental protection has existed since 2009.

Overall, both GDP and NPP in Inner Mongolia significantly increased after 2008 (GDP, $p < 0.001$; NPP, $p = 0.01$; Fig. 5(a)), and GDP was almost double that of China's average in 2000–2017. Moreover, such progress did not come at the expense of water resources, as the water resource per capita was relatively stable after 2008 (Fig. 5(a)). These changes improved overall economic development, water resource conservation, and environmental protection after 2008 (Fig. 5(b)). The unchanged ES and increased DS resulted in a significantly higher CSDS after 2008 ($p = 0.001$; Fig. 5(b)).

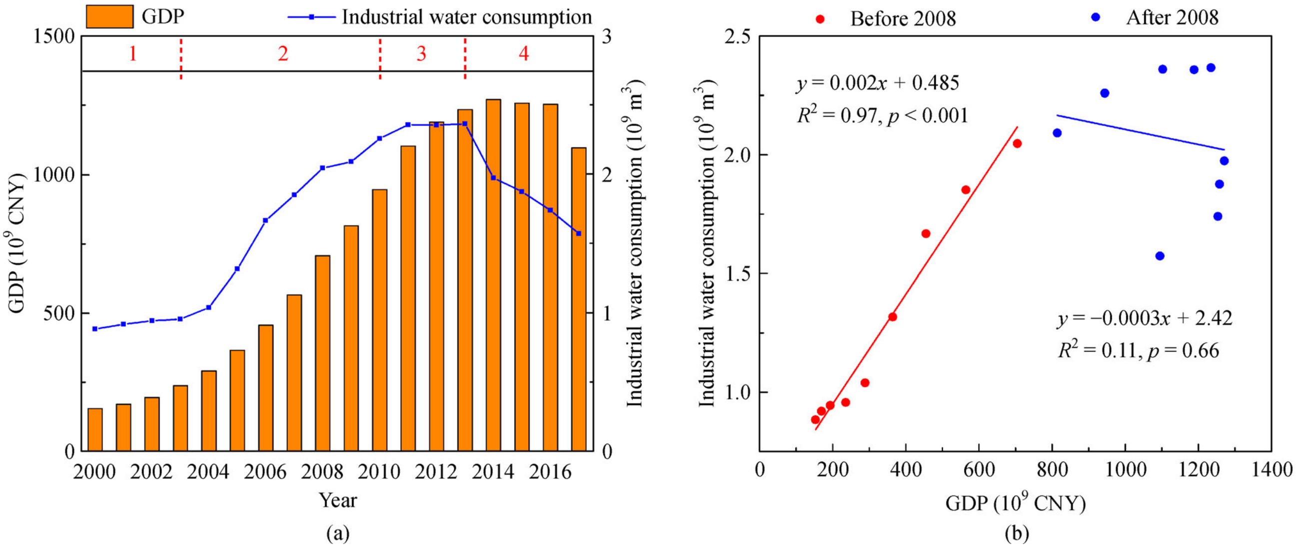
### 3.3 Development status and pathways of 12 cities

Two types of development pathways existed among the 12 studied cities; seven cities exhibited progressive pathways



(a) (b) (c)

**Fig. 2** Industry transformation from 2000 to 2017. (a) secondary industry; (b) tertiary industry; (c) change of industrial water consumption.

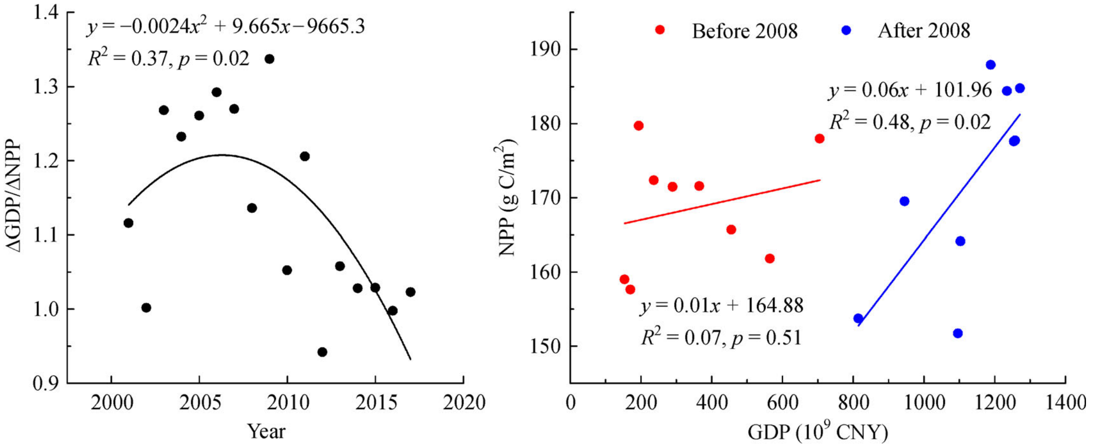


(a) (b)

**Fig. 3** Changing relationship between gross domestic product (GDP) and industrial water consumption in Inner Mongolia from 2000 to 2017. (a) Four-stage (1–4) transformation from coupling to decoupling and (b) changing relationships before and after 2008 (2000–2008 vs. 2009–2017).

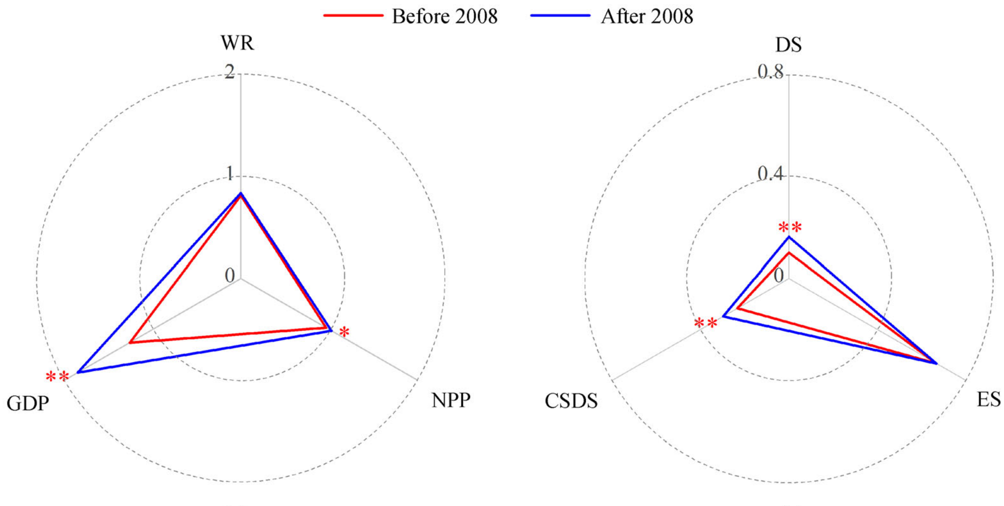
(Hulun Buir, Ordos, Baotou, Wuhai, Alxa, Tongliao, and Hinggan), and five showed a retrogression in evenness (Chifeng, Xilingol, Ulanqab, Hohhot, and Bayan Nur; Fig. 6(a); Table S2). Most of the latter cities had poor water resources ( < 620 $m^3$ per capita, or < 1/3 of the mean value of Inner Mongolia) and showed almost no progress after 2008 (except for Xilingol; Fig. 6(a); Table S3). The progressive pathways for most cities were ascribed to the fast-growing GDP at nearly no cost to water resources and NPP (e.g., Hulun Buir and Wuhai; Fig. S7); some cities also exhibited increased NPP or water resources (e.g., Hinggan and Tongliao; Fig. S7). However, Alxa developed at a high cost to water resources (Fig. S7), which is unlikely to be sustainable in the future.

The statuses of all 12 cities after 2008 were classified into four categories based on their average DS and ES from 2009 to 2017 (Section 2.4). We used the mean value of the nine years after 2008 instead of that of a single year because the water resources and NPP fluctuated over time (Fig. S8). Most of the studied cities were relatively underdeveloped, with six being underdeveloped and uneven (Fig. 6(b)). The relatively even but underdeveloped



(a) (b)

**Fig. 4** Relationships between gross domestic product (GDP) and net primary productivity (NPP) in Inner Mongolia from 2000 to 2017. (a) the ratio between ΔGDP and ΔNPP from 2000 to 2017; (b) the relationship between GDP and NPP before and after 2008 (2000–2008 vs. 2009–2017). ΔGDP/ΔNPP>1 suggests better performance in economic growth than environmental protection, whereas ΔGDP/ΔNPP = 1 indicates an equal change in GDP and NPP.



(a) (b)

**Fig. 5** Changes in water resources (WR), net primary productivity (NPP), gross domestic product (GDP), development score (DS), evenness score (ES), and core sustainable development score (CSDS) before and after 2008 at the provincial level in Inner Mongolia. (a) Changes in WR, NPP, and GDP and (b) changes in DS, ES, and CSDS. Data shown are standardized mean values of each index among 12 Inner Mongolian cities before and after 2008. The significance of differences before and after 2008 was based on paired $t$-tests of 12 cities, representing holistic changes across cities at the provincial level. * and ** indicate $p < 0.05$ and $p < 0.01$, respectively.

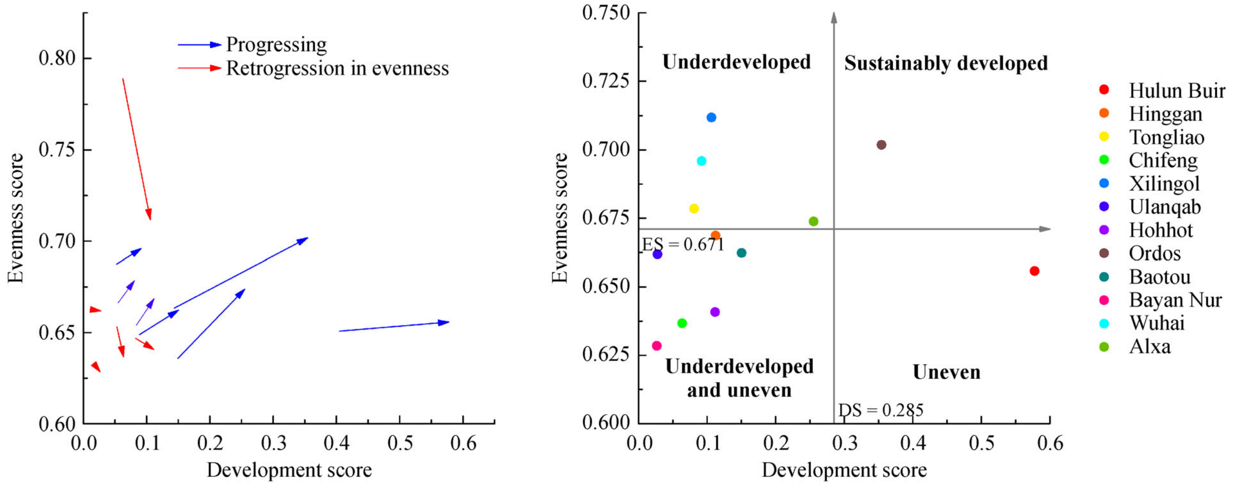
cities mostly had one deficiency in GDP, NPP, or water resources. For instance, the NPP of Xilingol was slightly lower than the provincial average (137.10 vs. 172.36 g/m$^3$), and Tongliao had lower water resources than the provincial average (1096.33 vs. 1990.76 m$^3$ per capita). Relatively underdeveloped and uneven cities experienced two main problems: some cities had stagnant economic development with much lower GDP than the provincial average (Bayan Nur, Chifeng, Ulanqab, and Hinggan; Table S3), whereas others were economically developed but lacking in water resources (Baotou and Hohhot; Table S3). The uneven status of Hulun Buir was ascribed to its deficient economic development despite its abundant water resources and high NPP (Fig. S7).

## 4 Discussion

### 4.1 Strict water resource regulation promotes sustainable development in Inner Mongolia

Since 2000, Inner Mongolia has undergone rapid economic growth that has been strongly dependent on water resources. The country's NPP also relies on water resources (Wang et al., 2013). Consequently, water resource exploitation has negatively affected regional NPP, suggesting a conflict between economic and environmental demand for water resources, which could be exacerbated by increasing water stress (Li et al., 2017). It now appears that the strict regulations on water conservation are of great importance at that time. By limiting the amount of water withdrawal and charging more for the environmentally harmful industries such as coal and steel (People's Government of Inner Mongolia Autonomous Region, 2008), the contribution of the tertiary industry (mostly ascribed to tourism, a less water-dependent industry) to the total GDP of Inner Mongolia has increased since 2011 and became the dominant contributor as of 2017. Consequently, the implementation of strict water resource regulations has contributed to the decoupling of economic development from water resources. Such increased water use efficiency resulting from industrial transformation has also been reported in other drylands in north-western China (Shi et al., 2014). The industrial transformation has enabled a synergistic relationship between economic development and environmental protection. This is ascribed to a reduction in polluting industries, namely, coal and steel, which negatively affected regional grasslands (Dai et al., 2014). The improved environmental quality could enhance the water retention capacity of dryland ecosystems (Yi et al., 2012), which may further alleviate existing water stresses.

Overall, significant progress in balancing water resource conservation, environmental protection, and economic development has been made in Inner Mongolia since the strict regulations on water conservation were implemented in 2008. Previous efforts on relieving the water stress mostly focused on improving water use efficiency (Zhang et al., 2021; Zhou et al., 2021), particularly in agricultural production (Qiao et al., 2009; Liu et al., 2020). These measures highly rely on the promotion of novel technologies and could be time-consuming. Yet, our results highlighted the strict regulations on water resources could drive the self-adjustment of industrial structure and eventually lead to a more sustainable development pathway. In this case, the local governors and businessmen came to realize that the spectacular grasslands are the reliable resources for long-term economic development instead of coal, simply under a moderately increased water cost for the traditional industry. These findings suggest that stimulating the internal motivation of industrial transformation through the regulations of water resources could



(a) (b)

**Fig. 6** Development pathway and status of 12 studied cities in Inner Mongolia. (a) Development pathway and (b) development status after 2008.

help achieve synergy between economic development and environmental protection, therefore, promote sustainable development in drylands.

### 4.2 Adaptive strategies need to be location-specific to achieve sustainable development

Despite the progress that has been achieved at the provincial level, the relative performance of Inner Mongolia's 12 cities was uneven. Most cities were relatively underdeveloped, six of which were uneven. Strategies need to be location-specific to achieve holistic sustainable development in Inner Mongolia. By considering both the development pathway and status of the studied cities, three strategies are proposed for different cities.

First, the relatively sustainably developed city, Ordos, and the most relatively underdeveloped cities (Tongliao, Wuhai, and Alxa, excluding Xilingol) exhibited progressive development pathways, which they should maintain in the future. Xilingol's uneven development pathway was ascribed to its rapid economic development, which has not decreased its water resources and NPP. Therefore, Xilingol should also maintain its development strategies. In contrast, although Alxa demonstrated a progressive pathway, its water resources decreased significantly after 2008; this may affect the local environment and impede the city's sustainable development since Alxa is a key area in the prevention of desertification in China (Feng et al., 2019). Therefore, Alxa's local government should focus on water resource conservation; national ecological compensation might be important for its sustainable development (Wei et al., 2009). Ordos exhibited the best performance toward sustainable development among the studied cities despite the negative environmental impacts of its mining industry (Yang et al., 2016; An and Lu, 2018). This finding reflects the local government's achievements toward sustainable development over the past decade (Gao et al., 2017; Zhou et al., 2019).

Second, the relatively underdeveloped and uneven cities with retrogressive development pathways, namely Bayan Nur, Chifeng, and Ulanqab (except for the capital city Hohhot) mostly lacked both water resources and economic development. Policy support from the provincial government, e.g., ecological compensation for livestock husbandry (Hu et al., 2019; Yin et al., 2019) and reasonable tax reduction (Aidt, 2010), might be important for the sustainable development of these cities. Additionally, these cities could advance economic development by growing industries that are less water-dependent. For instance, Chifeng's proximity to Beijing, one of the most economically developed cities in China, provides it the opportunity to grow its tourism sector; it is well-positioned to become a resort attraction for Beijing's urban residents who would like to experience the region's scenic grasslands.

Finally, the remaining cities exhibited the opposite characteristics. Hulun Buir and Hinggan had the most abundant natural resources (water and NPP) but lacked economic development. In contrast, Hohhot and Baotou had favorable economic conditions but high environmental stresses. These cities should implement deficiency-dependent strategies. Hulun Buir and Hinggan could use their abundant natural resources to develop their economy. Hohhot and Baotou need to reduce their intensive water-consuming industries and improve water use efficiency (Li et al., 2019; Li and Zander, 2020), e.g., by replacing coal power with low water consumption and low-carbon energy structures, such as wind power (Jiang et al., 2015). Moreover, these cities could collaborate to their mutual benefit through water trade. A water transfer project from eastern Inner Mongolia (Hulun Buir and Hinggan) to Hohhot and Baotou could alleviate water stress in these cities, and the developed economies of Hohhot and Baotou could provide ecological compensation to aid the economic development of Hulun Buir and Hinggan (see locations for all cities in Table. S1).

## 5 Conclusions and implications

This study comprehensively evaluated the effectiveness of long-standing water conservation regulations in China's northern drylands. Our results demonstrated that these strict regulations have decoupled economic development from industrial water consumption, and thus reducing negative environmental impacts. This is of great significance under the increasing global water scarcity (OECD, 2012; Wada et al., 2016). Distinct from solutions as water-saving technologies, which rely on the promotion from governments at all levels, water conservation by regulating its cost across industries seems to be a long-term solution as it could stimulate the internal motivation of industrial transformation toward a sustainable future. Tourism, a less water-dependent industry, maybe a promising and advantageous direction for the economic development of drylands. Taken together, three suggestions are proposed for sustainable development in drylands: (1) restrict the water exploitation and regulate the water cost to reconcile the conflict between economy and environment; (2) promote novel technologies to increase the water use efficiency; (3) enhance regional cooperation achieve holistic development in a mutually beneficial way.

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