



Evaluation of sustainability in northern Xinjiang based on ecological footprint-planetary boundary system framework

Zhiyang Yue^a, Hongbin Liu^b, Zhonglin Xu^{c,d,e,*}, Yao Wang^{f,*}

^a College of Geography and Remote Sensing Sciences, XinJiang University, Urumqi 830017, China

^b Henan Provincial Communications Planning & Design Institute Co., Ltd, Zhengzhou 450000, China

^c College of Ecology and Environment, XinJiang University, Urumqi 830017, China

^d Key Laboratory of Oasis Ecology, XinJiang University, Urumqi 830017, China

^e XinJiang Jinghe Observation and Research Station of Temperate Desert Ecosystem, Ministry of Education, China

^f Institute of Desert Meteorology, CMA, Urumqi, Urumqi 830002, China

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ABSTRACT

One of the core issues of sustainable development evaluation is how to precisely quantify the impact of human activities and keep it within the ecological carrying capacity. The planetary boundary theory is based on the Earth system view and measures the maximum impact of human activities on the Earth as a whole, providing a new perspective for ecological sustainability evaluation. In this study, we improved the traditional ecological footprint method and evaluated the ecological footprint of Northern Xinjiang from 2000 to 2020 based on the ecological footprint-planetary boundary system, and clarified the boundaries and status of construction land, water resources, and carbon emissions. The results show that: (1) Ecological pressures increase throughout the study area, led by industrial cities and dominated by energy footprints. (2) The state of water resources exploitation and utilization in the study area is safe, and there is greater pressure on water resources supply and demand in industrial cities. (3) The construction land in Northern Xinjiang expanded by 1.95 times, exceeded the limit by 2.75 times, and continues to rise. (4) The study area changed from a carbon sink to a carbon source, and the carbon emission rose 7.93 times. Compared with the traditional model, the improved model improved the parameter scheme, optimized the ecological account type, and constructed the water consumption footprint.

1. Introduction

The rapid development of social economy and urbanization has led to the intensification of the problems of human-land conflict, ecological dysfunction, and excessive consumption of resources, and the contradiction between ecological protection and regional economic development has become increasingly prominent (Wei et al., 2018; Liu et al., 2020). Ecological footprint transforms the ecological impact of human activities into the area of land required for consumption, uses the balance of land supply and demand to evaluate complex economic and social processes and further promote ecological sustainability evaluation (Shi et al., 2021). With the deepening understanding of ecological and environmental problems, scholars gradually realize the complexity and holistic nature of ecological problems, and a single evaluation index can no longer meet the needs of regional ecological evaluation (Fang et al., 2010). The ecological footprint began to develop from a single

concept to a system concept (Yang and Zhang, 2021; Liu et al., 2015), and a series of targeted concepts such as carbon footprint (Xia et al., 2017) and energy footprint (Fang et al., 2012) were subsequently derived. Research directions have also been deepened towards spatial-temporal variation (Yang et al., 2020; Xu et al., 2021; Xiong et al., 2022), and corresponding driving forces (Yang et al., 2017; Dong et al., 2021). The scope of the study has also gradually shifted from the national level (Li et al., 2022) to smaller scales such as provincial (Hui et al., 2021) and regional (Li et al., 2020). Although the ecological footprint method has made great progress in many fields. How to conduct ecological sustainability evaluation in a more detailed and complete way, make the evaluation results more intuitive, and provide guidance for practical production and life is still a barrier to the development of a sustainable evaluation system (Zhou et al., 2015).

Whether there is a limit to the carrying capacity of the ecological environment for human activities and whether the existing ecological

* Corresponding authors.

E-mail addresses: zyy@stu.xju.edu.cn (Z. Yue), liu@stu.xju.edu.cn (H. Liu), zlxu@xju.edu.cn (Z. Xu), wangyao@idm.cn (Y. Wang).

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pressure exceeds this limit remain key objectives pursued by the series of methods such as ecological footprint, growth limit, and carrying capacity (Meadows et al., 1972; Bishop, 1978). Planetary boundary theory considers the Earth as a system (Earth system) and advocates that the intensity and impact of human activities should be controlled within the carrying capacity of the Earth system, which is the core of sustainable development theory. The application of ecological footprint-planetary boundaries has been explored and extended by scholars in different ways. Cole et al. (Cole et al., 2014) and Dao et al. (Dao et al., 2018) all evaluated the ecological status and sustainability of the country from a national scale, reflecting the characteristics of the national resource environment and its ecological status. Fanning and O'Neill (Fanning and O'Neill, 2016), used a top-down evaluation idea to measure the relevant boundaries at the provincial scale in Canada and Spain. Dearing et al. (Dearing et al., 2014), used an approach based on the dynamic behavior of the environmental system and selected relevant indicators to be set regarding the margins in Shucheng County, Anhui Province, China. Fang proposed to integrate the ecological footprint system with the planetary boundary system to further advance regional sustainability evaluation (Fang, 2014; Fang and Duan, 2015). These studies have advanced the application of the Footprint Boundary Framework to sustainable development, enhancing its value as a scientific guide to national and regional policy setting and demonstrating the applicability of the Footprint Boundary Framework.

For global environmental issues, top-down allocation schemes are used, while water and land use issues are subject to natural backgrounds and are evaluated on a site-specific basis (Chen et al., 2020). Based on a global perspective, Planetary boundary theory sets safe boundaries for key biophysical processes in the Earth system and further sets a safe space for human activities (Steffen et al., 2015). Due to the scale effect of the planetary boundary framework, the influence of environmental boundaries and natural background constraints, and other effects gradually increase as the scale decreases, leading to the fact that relevant studies are mostly evaluated at the national level, with few studies on small-scale study areas such as watersheds, provinces, and climate

zones (Chen et al., 2020).

In this study, we measured the ecological footprint and some environmental physical boundaries in Northern Xinjiang from 2000 to 2020 based on an improved ecological footprint-planetary boundary system. Specifically, the objectives of this study are to: (1) Improve the composition of the ecological footprint accounts to make them more applicable to the ecological conditions of the study area. (2) Develop a construction land footprint to clarify the occupation of other land types by new construction land based on the inflow of construction land, which can more accurately reflect the impact of construction land expansion on the ecological environment. (3) Attempts to adopt the water-producing area method to construct a water consumption footprint that incorporates water quantity consumption into the ecological assessment, rather than just the biological output of water resources. To further improve the Ecological Footprint system. (4) Construct the model correlation factors by use data from the current year for each administrative unit, to reducing errors due to regional differences, statistical level, research scale and inter-annual variation. (5) Explore Northern Xinjiang's sustainable development and ecological status under boundary conditions. And explore the applicability of the ecological footprint-planetary boundary system at small scales in arid regions.

2. Methods and data

2.1. Study area

Northern Xinjiang refers to the northern part of the Xinjiang Uyghur Autonomous Region of China (As Fig. 1). Northern Xinjiang is far from the sea and deep inland. It has arid climate, with low rainfall and uneven distribution in space and time. The study area is rich in land resources and diverse in land use types, but the Gobi and desert areas are large, the oases are scattered, and the soil is heavily sanded and saline. In addition, the study area is rich in solar thermal and wind resources and contains abundant energy resources such as oil, natural gas, coal and other mineral resources. But the region is ecologically fragile, with a low level

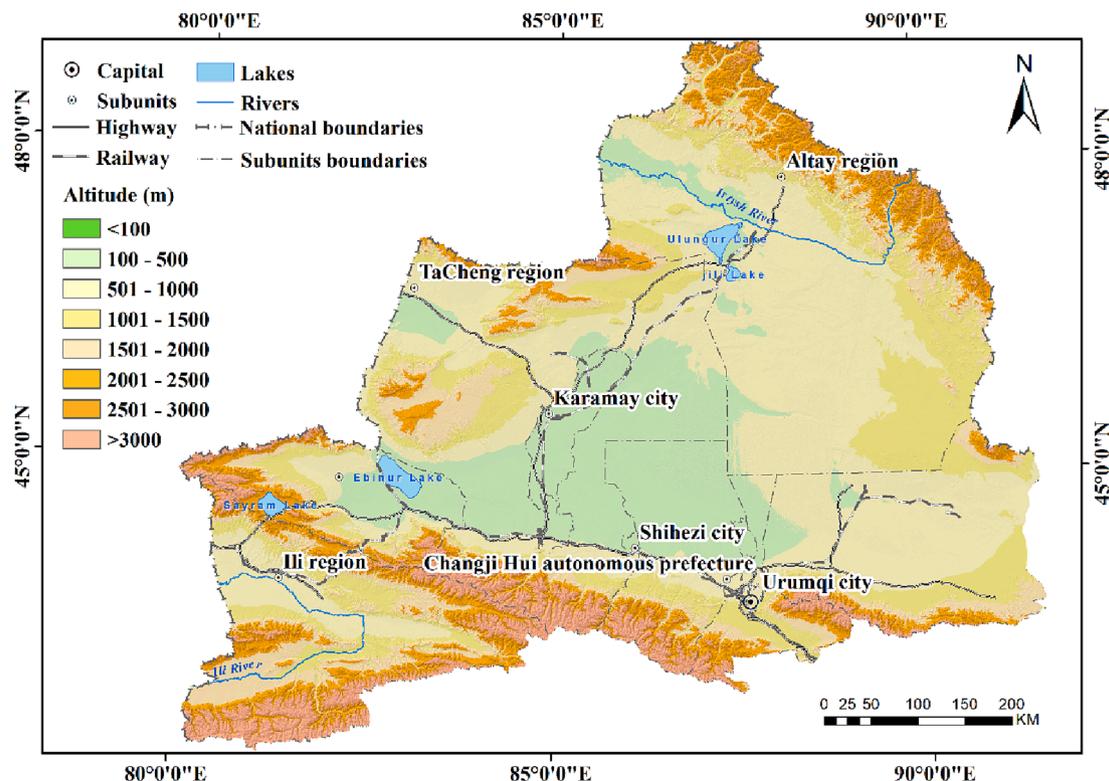


Fig. 1. Study area.

of vegetation cover and relatively high levels of drought and water scarcity. As one of the more economically developed regions of the region, Northern Xinjiang has the highest economic output and social development in Xinjiang province. However, with rapid socio-economic development and accelerated urbanization. Large-scale exploitation of land and water resources and rapid population growth have caused major changes in the surrounding natural environment, accelerating desertification, exacerbating water shortages, leading to further ecological degradation and posing a serious ecological security threat to regional development.

2.2. Methods

2.2.1. Ecological footprint account & improved ecological footprint model

The traditional ecological footprint model divides ecological accounts into energy and biological accounts (Pan et al., 2017). To reflect the territoriality and variability of footprint accounts, we expand the ecological footprint system. This study, classified the ecological accounts as biological productive and non-biological productive accounts. Biological productive accounts include arable land footprint, forest land footprint, grassland footprint and fishing footprint. Non-biological productive accounts include energy footprint, construction land footprint and water consumption footprint. The account components are shown in Table 1.

The improved ecological footprint model will contain 4 components, the equations are as follows:

$$EF = ef_{biol} + ef_{el} + r_{el} + ef_{cl} \times r_{cl} + ef_w$$

$$EC = ec_{biol} + ec_{cl} + ec_w$$

where, EF , ef_{biol} , ef_{el} , ef_{cl} and ef_w are represent the total ecological footprint, biological productive footprint, energy footprint, construction land footprint and water consumption footprint of the region respectively. r_{el} is equilibrium factor of energy footprint, r_{cl} is equilibrium factor of construction land footprint. EC , ec_{biol} , ec_{cl} and ec_w are represent total ecological carrying capacity, biological productive carrying capacity, carrying capacity of construction land and water resource respectively. The calculation methods are shown below.

2.2.2. Biological productive footprint

2.2.2.1. Equilibrium factor and yield factor. The relationship between the average productivity of each type of land and the average productivity of all raw land is represented by the equilibrium factor (r_i). The yield factor (y_i) characterize the productivity of each type of productive land to the productivity of the same type of productive land at the upper level, according to the following equations:

$$r_i = \frac{\bar{P}_i}{\bar{P}} = \frac{q_i}{\sum \frac{q_i}{s_i}}$$

$$y_i = \frac{\bar{P}_i}{\bar{P}_i} = \frac{q_i}{Q_i}$$

where \bar{P}_i , \bar{P} , q_i , s_i are average productivity of category i land, average productivity of all productive land in region, biological production of category i land and area of regional category i land respectively. \bar{P}_i , Q_i , S_i are average productivity of category i land, biological production of category i land, area of regional category i land respectively.

Biological production was calculated by the Calorific method (Zhang et al., 2009). Considering the differences in resource endowment and socio-economic development of each state, this study uses the current year data during the study period of each sub-administrative region to calculate the local model parameters, preserving the inter-regional variability and making the ecological footprint evaluation closer to the

Table 1 Ecological Footprint Account and Components.

Account Type	Biological productive account				Non-biological productive account		
	Arable land	Forest land	Grass land	Fishing	Construction land	Energy consumption	Water consumption
Account Components	Rice, wheat, corn, beans, cotton, rape, caraway, sunflower, sugar beets, potatoes, melon, pork, Poultry meat, rabbit	apples, pears, grapes, peaches, apricots, dates, nuts	beef, horse meat, camel meat, goat meat, sheep meat, alfalfa	aquatic production	construction land area, inflow of construction land by source	Coal, coke, crude oil, gasoline, kerosene, diesel, fuel oil, liquefied petroleum gas, natural gas	water consumption, total water resource

real situation.

2.2.2.2. Ecological footprint and carrying capacity. The ecological footprint is the area of biologically productive land required to produce the materials needed to satisfy human production and livelihoods in the region and to absorb the human-generated waste in the region (Wang et al., 2019; Zhou and Guan, 2012). The following equations are used for calculating the ecological footprint and carrying capacity:

$$EF = N \times ef = N \times \sum r_i(aa_i) = N \times \sum r_i \left(\frac{c_i}{p_i} \right)$$

$$EC = N \times \sum a_i r_i y_i$$

where N is the regional population, ef is ecological footprint per capita is c_i the per capita consumption of product i is the average output of product i is a_i area per capita of category i land.

2.2.3. Non-biological productive footprint

2.2.3.1. Energy footprint. The measurement of the energy footprint is calculated using the carbon absorption method (Fang et al., 2010), which is based on the idea of converting all consumed energy into carbon emissions and using the area of vegetation required to absorb the total carbon emissions for evaluation (Li et al., 2020). The formulas are expressed as follows:

$$ef_{el} = \frac{\sum m_j n_j}{k}$$

$$k = \frac{S_{al}}{S_{al} + S_{fl} + S_{gl}} \times 0.46 + \frac{S_{al}}{S_{al} + S_{fl} + S_{gl}} \times 6.44 + \frac{S_{al}}{S_{al} + S_{fl} + S_{gl}} \times 0.39$$

$$r_{el} = \frac{S_{al}}{S_{al} + S_{fl} + S_{gl}} \times r_{al} + \frac{S_{al}}{S_{al} + S_{fl} + S_{gl}} \times r_{fl} + \frac{S_{al}}{S_{al} + S_{fl} + S_{gl}} \times r_{gl}$$

where, m_j , n_j , k , are consumption of energy type j , carbon emission factor of energy type j , regional integrated carbon sequestration factor respectively. s_{al} , s_{fl} , s_{gl} are area of arable land, forest land and grass land.

2.2.3.2. Construction land footprint. The construction land footprint evaluation method is derived from ecological footprint (Rees, 1992). We improved the construction land equilibrium factor and yield factor based on the inflow and total amount of construction land in the region in the current year, which is calculated using the proportion of different land types converted into construction land. The corresponding formulas include:

$$ef_{el} = r_{cl} \times s_{cl}$$

$$r_{cl} = \frac{S_{inflow}^{al-cl}}{S_{inflow}^{cl}} \times r_{al} + \frac{S_{inflow}^{fl-cl}}{S_{inflow}^{cl}} \times r_{fl} + \frac{S_{inflow}^{gl-cl}}{S_{inflow}^{cl}} \times r_{gl}$$

$$y_{cl} = \frac{\frac{S_{inflow}^{cl}}{S_{cl}}}{\sum \frac{S_{inflow}^{cl}}{S_{cl}}}$$

where S_{cl} is the regional construction land area. S_{inflow}^{cl} is the area of regional construction land inflow in the current year. S_{inflow}^{al-cl} , S_{inflow}^{fl-cl} , S_{inflow}^{gl-cl} are the areas of arable land, forest land and grassland flowing into construction land in the region in that year respectively is $\sum S_{inflow}^{cl}$ the area of construction land inflow of Northern Xinjiang in the current year is $\sum S_{cl}$ construction land area of Northern Xinjiang in the current year.

2.2.3.3. Water consumption footprint. The water consumption footprint is derived from the idea of ecological footprint and water footprint (Ma

and Peng, 2013). The idea is to convert the regional water use into an area of water production and compare it with the regional area. If the area of the water production region is larger than the actual regional area, it means that the amount of water resources in the region can meet the requirement of regional development, and the carrying capacity of water resources is the difference between the two areas. If in contrast, the carrying capacity of water resources is 0. The formulas are expressed as follows:

$$ef_w = \sum \frac{w_i}{w_p}$$

$$w_p = \frac{w_t}{s}$$

$$ec_w = s - ef_w$$

where w_i is water consumption of industry i is w_p regional water production module is w_t total regional water resource is s area size.

2.2.4. Ecological Footprint-Planetary boundary system

The ecological footprint is a traditional method of sustainable development evaluation, which is carried out by comparing the ecological footprint of a region with its ecological carrying capacity (Cuceka et al., 2012; Martinez et al., 2019). Ecological footprint is a result-oriented approach based on a consumption perspective with a lag (Ali, 2017; Fang et al., 2016). The planetary boundary system is forward-looking and makes up for the shortcomings of the ecological footprint system. Moreover, the planetary boundary is a conservative estimate of the critical threshold, which can be used as a warning for approaching the carrying threshold of the Earth system, reducing the risk of irreversible changes that may be caused by blindly pursuing the limit (Lenton and Williams, 2013; Rockström et al., 2009; Steffen et al., 2018).

Based on the existing studies (Fang, 2014; Fang and Duan, 2015), this study locally expands and downscales the planetary boundary system and delineates the planetary boundaries as water, carbon, and productive, and construction land boundary. The ecological footprint system corresponds to the planetary boundary system is shown in Table 2.

2.2.4.1. CO₂ emission boundary. Climate change is one of the important issues facing mankind in the 21st century (Chen et al., 2021). The problem of carbon emissions is historical and global in nature, and the overall atmospheric environment is not caused by a single country or region. likewise, the catastrophic consequences are shared globally. The setting of carbon emission boundaries in planetary boundaries delineates the total amount of carbon emissions from the global scale, clarifies the balance of atmospheric emissions, and provides a direction for slowing down climate warming. Reducing the carbon emission boundary from the global scale to the regional scale is important for the adjustment of regional economic development strategy and control of carbon emission.

In this study, the cumulative per capita allocation method, which combines the “equality principle” and the “responsibility principle” is used (Guetschow et al., 2015). The regional carbon emission boundary is set based on the cumulative per capita carbon emission budget of China from 2005 to 2100, and the carbon emission scenario is discussed under the premise of 1.5 °C and 2.0 °C temperature change in the context of IPCC (Dong, 2021). The cumulative carbon budget per capita allowance is 1.74 tCO₂/cap under the 1.5 °C control target and 2.72 tCO₂/cap under the 2.0 °C control target.

The product of the population of the sub-administrative region for the year and the cumulative carbon budget allowances per capita under the control target is used as the regional carbon emission boundary. The actual carbon emissions for the year (the difference between theoretical carbon emissions and the amount of carbon sequestered by vegetation)

Table 2
Correlation between ecological footprint and planetary boundary systems.

Ecological Footprint	biological productive footprint	Arable land footprint Forest land footprint Grassland footprint Fishing footprint construction land footprint	Arable land boundary forest land boundary Grassland boundary \ construction land boundary CO ₂ emission boundary water consumption boundary	biological productive boundary	Planetary Boundary
	non-biological productive footprint	Energy footprint water consumption footprint		non-biological productive boundary	

and the carbon emission boundary are used for climate change sustainability assessment (Table 3).

Carbon emission grading concerning relevant studies and adapted to regional relevance to improve applicability in the study area. Areas with actual carbon emissions less than 0 are defined as carbon sink areas, while areas greater than 0 are defined as carbon source areas.

2.2.4.2. Construction land boundary & water consumption boundary. As the main unit for human activities, the scale of construction land is closely related to the degree of urban socio-economic development (Bruckner et al., 2015). Northern Xinjiang is a vast area with a wide variety of urban types and varying degrees of development, with large differences in the size of building land.

This study adopts a policy-oriented approach to regional construction land scale evaluation, based on the code for classification of urban land use and planning standards of development land (GB50137-2011), setting the upper limit of construction land at 150 m²/cap. Based on the above criteria, this study explores the extent of sustainable building land under the Footprint-Boundary System to provide a reference for optimizing regional spatial structure and reversing urban sprawl.

In the northwest arid regions, the limiting effects of water as a basic resource for regional production and livelihoods are particularly evident (Fang et al., 2004; Fang and Qiao, 2005). The inclusion of water consumption in ecological sustainability evaluation systems is important for regional ecological evaluation.

In this study, the water resource boundary at the regional scale is defined as the maximum amount of water that can be extracted from the total regional water resources. The study area is characterized by low water resources, concentrated precipitation periods, and significant territoriality. Based on the total water resources and water consumption of each sub-administrative region from 2000 to 2020, the low-risk threshold for the water resources boundary in the study area was set at 40% of the total regional water resources, and the high-risk threshold was set at 70% (Table 4).

2.3. Data sources

This study primarily used land-use and socio-economic data from 1995 to 2020. The land-use data were obtained from the Resources and Environment Sciences and Data Center of the Chinese Academy of Sciences (<https://www.resdc.cn/>) with a spatial resolution of 30 m. Owing to the requirements of this study, the land-use categories in the study area were reclassified as arable land, forest land, grassland, water area, construction land, and unused land (Liu et al., 2014).

The socio-economic data were from *Xinjiang Statistical Yearbook*

Table 3
Carbon Boundary Risk Category.

Carbon emission to carbon boundary ratio	Risk Category
<1	Low risk
1 ~ 2	Medium risk
>3	High risk
>5	Extremely high risk

Table 4
Water Risk category.

Percentage of water use	Risk category
<40%	Low risk
>40%	Medium risk
>70%	High risk
>90%	Extremely high risk

(1996–2021), *Xinjiang Production and Construction Corps Statistical Yearbook (1996–2021)*, *Xinjiang Water Resources Bulletin (1995–2020)*, *Xinjiang Production and Construction Corps Water Resources Bulletin (1995–2020)*. The calorific value data for agricultural, forest, and fruit products and fishery products are derived from the *Handbook of Agricultural Technology and Economics (Revised Edition 1983)*. Energy carbon emission factor and land carbon absorption factor from Tang (Tang et al., 2016).

3. Results

3.1. Biological productive boundary

3.1.1. Ecological footprint and ecological carrying capacity analysis

During the study period, the ecological footprint of Northern Xinjiang shows a significant increase: from 7.36×10^7 hm² in 2000 to 2.78×10^8 hm² in 2020, with an annual growth of 1.02×10^7 hm²/a. The energy footprint in 2020 was 10.61 times larger than in 2000, and the biological productive footprint increased by 1.04 times, with arable, forestry, fishing and grass increasing by 1.03, 2.32, 1.04, and 1.12 times respectively. The water consumption footprint increased by 1.20 times, but the construction land footprint decreased slightly. At the same time, the ecological footprint component has changed from being dominated

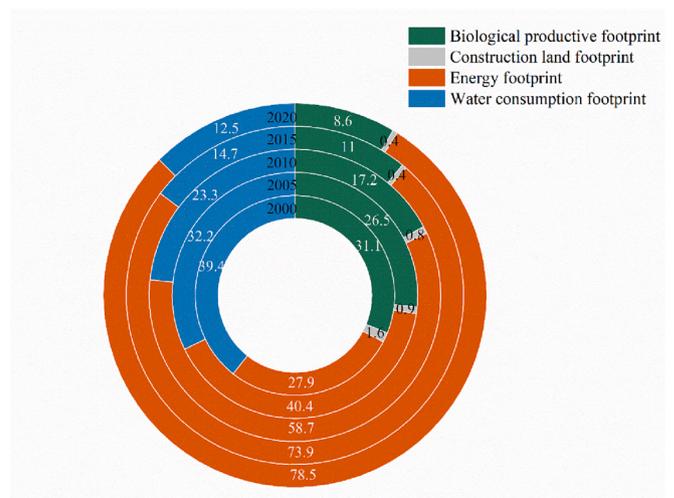


Fig. 2. Variations in ecological footprint components.

by water consumption footprint and biological productive footprint to energy footprint (Fig. 2). The per capita ecological footprint of Northern Xinjiang has increased 2.64 times, from 8.75 hm²/cap in 2000 to 23.07 hm²/cap in 2020, and all types of footprint except energy footprint show a decreasing trend.

The significant increase in the ecological footprint indicates that the socioeconomic development of Northern Xinjiang has put enormous pressure on the ecological environment, and the negative effects of human activities such as water resource sustainability expansion of construction land, and rapid Industrialization are beginning to emerge.

During the period 2000 to 2020, the area of arable land in the Northern Xinjiang increased by 45.47%, while biological output increased by 134.36%, indicating a significant increase in the efficiency of regional cultivated land use. The area of construction land has expanded by 95.09% and the intensity of human activity has increased significantly. The area of grassland increased by 4.32% and the biological output increased by 117.89%, indicating that the reversion of grazing to grass in the region has achieved some effect and the ecological damage caused by grazing has been alleviated. Significant reductions in the area of forest, water, and unused land, might negatively influence on hurt ecological restoration in the long term.

The ecological carrying capacity characterizes the ability of the ecological environment to supply the resources needed for human activities and to withstand the negative impacts of human activities. During the study period, the ecological carrying capacity of Northern Xinjiang decreased slightly: The productive land carrying capacity increased by 1.09 times, with the contribution rate increasing from 49.49% in 2000 to 56.83% in 2020. The carrying capacity of construction land decreases slightly. The carrying capacity of water resources decreases significantly due to the inability of some regions to balance

their water supply.

3.1.2. Analysis of ecological footprint and ecological carrying capacity in sub-administrative region

The sub-administrative regions of the study area were divided into different types according to the multi-year average industrial value added. Among them, agricultural prefectures sub-administrative region include Tacheng region. Industrial prefectures include Shihezi City, Karamay City, and Changji Hui autonomous prefecture. Service prefectures include Urumqi City, Bortala Mongol autonomous prefecture, Altay region, and Ili region.

From 2000 to 2020, the ecological footprint of all sub-administrative regions in the study area showed an increase (Fig. 3), with the largest increase of 619.90% in Changji Hui Autonomous Prefecture, followed by Shihezi City, Karamay City, and Urumqi City. In productive footprint, Karamay City, Bortala Mongol Autonomous Prefecture, Tacheng region, and Altay region showed varying degrees of growth. The construction land footprint has increased the most in Shihezi City. The energy footprint has increased significantly in all the prefectures. The water consumption footprint has increased less overall and has decreased in Ili region, Altay region, and Shihezi City. Due to the different natural backgrounds and the obvious differences in ecology, the sub-administrative regions should adjust their development strategies, combining their advantages and exploring economic models that would suit the natural conditions of the region.

As regards ecological carrying capacity, only Shihezi City, Altay region, and Ili region increased slightly over the period studied. All industrial cities have reduced productive land carrying capacity. Except for Urumqi City, Shihezi City, and Bortala Mongol Autonomous Prefecture, the carrying capacity of construction land in all other

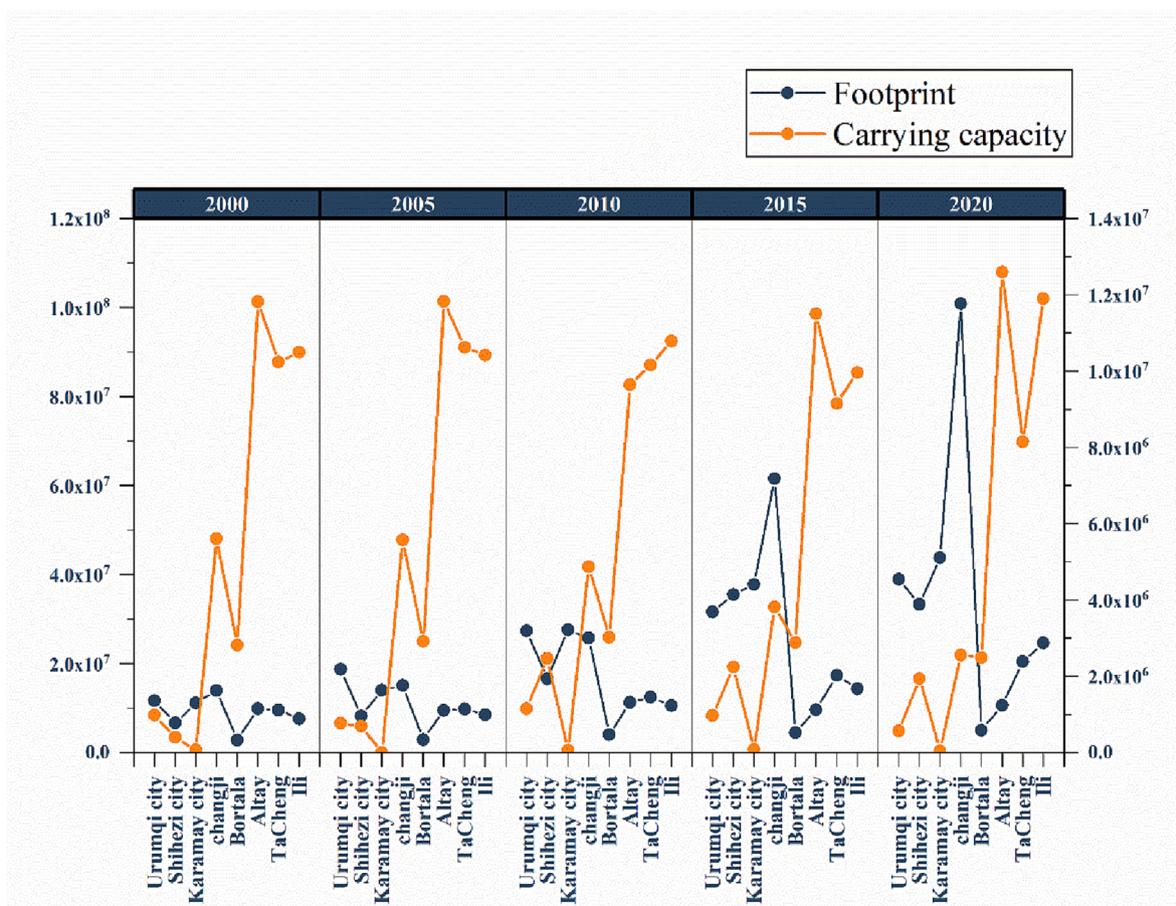


Fig. 3. Variations in Ecological Footprint and Carrying Capacity of sub-administrative regions.

prefectures decreased, indicating a slowdown in the rate of new construction land and a decrease in the occupation of productive land. Except for Shihezi City and Karamay City, water resources in the rest of the prefecture can meet the needs of social and economic development in the region, but the carrying capacity of water resources is mainly reduced. It shows that the negative effects of the irrational use and overexploitation of water resources in the early days are beginning to be felt. All sub-administrative regions should focus on developing water conservation and recycling technologies to improve the efficiency of water resource use while optimizing industrial patterns and raising public awareness of water conservation to reduce the risk of water scarcity.

3.1.3. Sustainability analysis

2000–2020, Northern Xinjiang’s ecological environment is in an unsustainable state, with an ecological footprint much larger than the ecological carrying capacity. The main driver of the long-term ecological deficit is the significant increase in the energy footprint. Among the sub-administrative regions, Urumqi City and industrial prefectures show a significant increase in ecological deficit. The Altay region is in ecological surplus except for 2015, indicating that it is a high ecological sustainability and socio-economic development is compatible with the ecological environment. Bortala Mongol autonomous prefecture was in the balance for a long time, and the ecological deficit gradually increased after 2010, while the Tacheng region and Ili region were in ecological surplus, but turned into ecological deficits in 2010 and 2015 respectively.

Overall, the large size and rapid growth of the industrial urban deficit are one of the main causes of Northern Xinjiang’s long-term ecological deficit. In contrast to the global nature of carbon emissions, land use is distinctly territorial, with differences in the natural environment of sub-administrative regions leading to different development patterns and city types. Ecological deficits indicate that the natural resources required for regional development have exceeded the number of resources that can be provided. The depletion of regional resource stocks to sustain urban development may trigger local ecosystem imbalances and increased ecological security risks. Xinjiang is at a critical stage of economic transition and should seize the opportunity of the 14th Five-Year Plan to improve its economic structure, optimize its coal-based energy structure, change its industrial-based industrial structure, develop related industries according to local conditions, improve the efficiency of resource use and consider the impact of industrial development on the ecological environment in line with relevant national and regional policies.

3.2. Water consumption boundary and analysis of water risk

Although water resources are renewable, they have a long cycle of renewal, and poor water use patterns and overexploitation can easily lead to an imbalance between regional water supply and demand. In the planetary boundary system, water use is defined as one of nine key biophysical processes, and a safe boundary is set that, if breached, could lead to regional ecosystem imbalances. Northern Xinjiang is located in a typical arid zone, and water resources are a rigid constraint on regional development. Clarifying the structure of regional water resource use and exploring the boundaries of water resources use are of great significance to ecological sustainable development.

During the study period, water use in Northern Xinjiang was within the medium risk and at the safe water boundary. Among the sub-administrative regions (Fig. 4), the Ili region and Altay region belong to low-risk category and have high sustainability of water resources, while the Tacheng region moved from the low-risk category to the medium-risk category in 2010 and continue to increase, water resource use pattern in the region should be optimized to reduce the risk of water resource imbalance (Fig. 5.).

Bortala Mongol autonomous prefecture is inmedium-risk zone for a

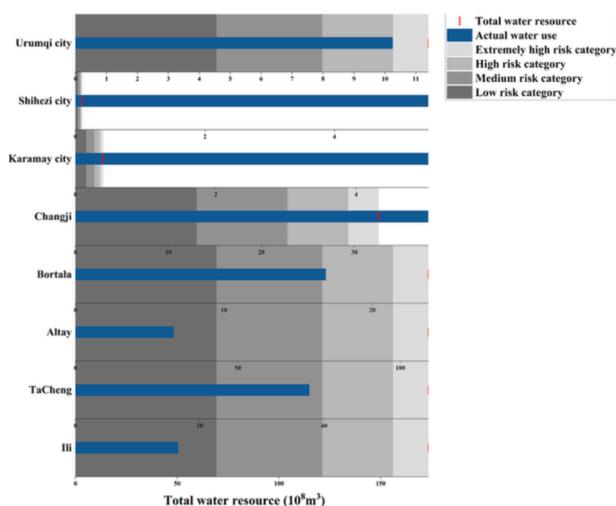


Fig. 4. Water stress for sub-administrative regions 2020.

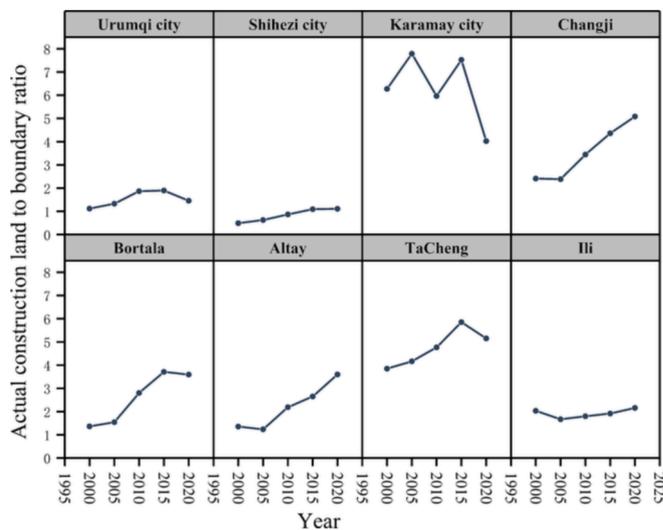


Fig. 5. Actual construction land to boundary ratio of sub-administrative regions.

long time, with water resources fulfill the development needs of the region, but reached a high risk level in 2020. Urumqi City and Changji Hui autonomous prefecture are in a high-risk category for a long time, facing high pressure on water resources, with Urumqi City meeting the water needs of the region during the study period, and Changji Hui autonomous prefecture no longer being self-sufficient after 2010. Shihezi City and Karamay City both belong to category of extremely high water risk and require water transfers to meet the region’s water balance, indicating high pressure on water resources and high ecological risk.

Water resource use in the study area is still dominated by primary industries with backward and inefficient water use patterns. Emphasis should be placed on improving the efficiency of resource use, combining resource advantages to develop leading industries. Urumqi City, Changji Hui autonomous prefecture, Shihezi City, and Karamay City belong to the core area of economic development on the north slope of Tianshan Mountains and have a high demand for water resources, but the natural endowments of the four prefectures are very different, so they should actively coordinate the state of water resources in the region, improve their use patterns and increase the efficiency of water use to reduce the environmental risks that may result from water shortages. With the opportunity for localities to develop together with the XPCC (Xinjiang

Production and Construction Corps), the Tianshan North Slope Economic Zone, as the earliest region to implement the concept of sustainable development, should build on its economic advantages and combine the experience of sustainable development to drive the neighboring regions to develop in parallel and form an integrated economic situation.

3.3. Construction land boundary and distribution analysis

As the direct recipient of human activity, the form of building land can visually reflect the scale and development of the regional economy. Since the 21st century, rapid socio-economic development and steady urbanization have led to a dramatic expansion in the scale of construction land and a continuous deterioration of urban ecology. The challenge of urban development today is to understand the relationship between urban scale and construction land and to make it the basis for quality urban development. The study area is ecologically fragile, with different types of cities at different stages of development, and it is worth thinking about how to give cities space for development while reducing new ecological pressures and ensuring reasonable environmental capacity.

The total amount of building land in the Northern Xinjiang increased by a factor of 1.95 over the study period, with the total amount of building land being 2.75 times the upper limit. Building land per capita increased from 302.31 m²/cap to 411.80 m²/cap, a 1.36-fold increase. At the same time, the scale of forest land, water, and unused land all showed varying degrees of decline, the scale of arable land rose sharply and the scale of grassland remained stable. In terms of land use change, the inflow of construction land from 1995 to 2000 and 2015–2020 is dominated by arable land, from 2005 to 2010 and 2010–2015 by grassland, and from 2000 to 2005 by unused land, while the inflow of forest land continues throughout the study period.

Considering the sub-administrative region, the largest increase in construction land was in Changji Hui autonomous prefecture, followed by Urumqi City and Tacheng region, where the inflow of construction land was mainly grassland in Urumqi City, grassland and unused land in Changji Hui Autonomous Prefecture, and arable and unused land in Tacheng region. The Altay region is dominated by unused land. Shihezi City and Ili region are dominated by arable land. Bortala Mongol autonomous prefecture is dominated by arable and unused land. and Karamay City is dominated by grassland and unused land.

The actual scale of construction land exceeded the upper limit of construction land in all sub-administrative regions, and the degree of exceeding the limit continued to rise. The prefectures that reached more than two times of the limit include Karamay City, Changji Hui Autonomous Prefecture, and Tacheng region, while the rest of the prefectures were less than two times of the limit. A large amount of development and occupation of ecological land is the main reason for the reduction of the ecological carrying capacity of the region, and the risk of ecosystem imbalance is gradually increasing with further development.

In total, the proportion of construction land to the total area of sub-administrative regions in industrial cities is significantly higher than in other types of cities: in 2020, the proportion in Urumqi and Karamay was 6.42% and 3.83% respectively, while in Shihezi City reached 25%. Changji Hui Autonomous Prefecture, Bortala Mongol autonomous prefecture, and Ili region did not exceed 2%. while the Altay region and Tacheng region were less than 1%. The proportion of built-up land in Northern Xinjiang is 1.27%, and land use types are still mainly grassland and unused land, indicating that the study area has excellent reserves of ecological resources, and attention should be paid to the protection of ecological resources in the future. Although the proportion of construction land is relatively low, as a major source of ecological pressure and a direct manifestation of human activities, certain control measures should be taken on the expansion of construction land to control the conversion of land to non-agricultural use and alleviate land conflicts. In addition, Northern Xinjiang is ecologically fragile and has a poor

resource base. Ecological damage is difficult and time-consuming to repair, and the formation of a small-scale destruction zone can lead to systemic ecological risks on a large scale, which should be given sufficient attention.

3.4. CO₂ emission boundary and carbon emission patterns

Carbon emissions are one of the main causes of the current greenhouse effect, and assessing regional carbon emissions can help research climate change issues to better combat global warming (Fang et al., 2020). Carbon emissions from a single region can have global consequences, so it is important to conduct carbon emissions-related research at small regional scales. The planetary boundary framework sets a carbon emissions target within 350 ppm, consistent with the 1 °C warming target, but atmospheric CO₂ concentrations are currently well above this target threshold (Hansen et al., 2013).

This study sets the target boundary at 1.5 °C versus 2 °C, based on the targets set in the Paris Agreement (Rogelj et al., 2020). Based on the relevant research results of Dong (Dong, 2021), we adopted a cumulative per capita equivalence method that combines the principles of equality and responsibility for carbon quota setting.

From 2000 to 2020, Northern Xinjiang gradually shifts from a carbon sink to a carbon source, with carbon emissions increasing 7.93-fold and the risk level rising from low to high (Fig. 6). In 2000, the study area was a carbon sink, could sequestering an additional 6.24 million ton of carbon while remaining carbon neutral. Since 2005, it has been a carbon source, with a 32% and 20% share of carbon emissions under the 1.5 °C and 2 °C targets respectively. after 2010, carbon emissions moved into the medium risk category and continued to increase.

During the study period, carbon emissions increased in all sub-administrative regions, with the industrial cities still dominating carbon emissions, and the dominant city shifting from Urumqi to Changji Hui autonomous prefecture (Fig. 7). Urumqi is chronically in the high-risk category for the 1.5 °C target and the medium risk category for the 2.0 °C target, which means its carbon emissions are more than twice the limit. Shihezi and Changji Hui Autonomous Prefecture both show a significantly high-risk status under both targets, with both states showing low carbon emissions before 2010 and a sharp rise after 2010 to a long-term very high-risk range, with actual carbon emissions around 10 times higher than the regional carbon limit, two regions are the developing core of northern slope economic zone of Tianshan Mountains and are also one of the largest sources of carbon emissions in Northern Xinjiang. Karamay has been in a very high-risk category. Due to its unique economic model and industrial structure dominated by heavy industry, the region's carbon emissions have remained high for a long time, and it is a new challenge to achieve a low carbon economy and adjust the industrial model under the vision of carbon peaking and carbon neutrality. The Bortala Mongol Autonomous Prefecture and the Altai region have long been carbon sinks, sequestering large amounts of additional carbon while being carbon neutral in the region. However, the additional carbon sequestration in the two states decreased significantly during the study period, from 1,169,600 ton/year and 7,026,800 ton/year to 148,900 ton/year and 4,339,300 ton/year, respectively. It shows that the rapid economic development and the increase in carbon emissions in the region pose a great challenge for ecological carbon sequestration and that the carbon sink effect in the two states may disappear without relevant mitigation interventions. In the Ili region and Tacheng region, carbon neutrality was broken by 2010 and 2020 respectively, and the region was converted from a carbon sink to a carbon source.

4. Discussion

Based on the traditional Ecological Footprint model, this study combines the idea of sustainable development, improves the Ecological Footprint account categories, sets up local parameter schemes, and

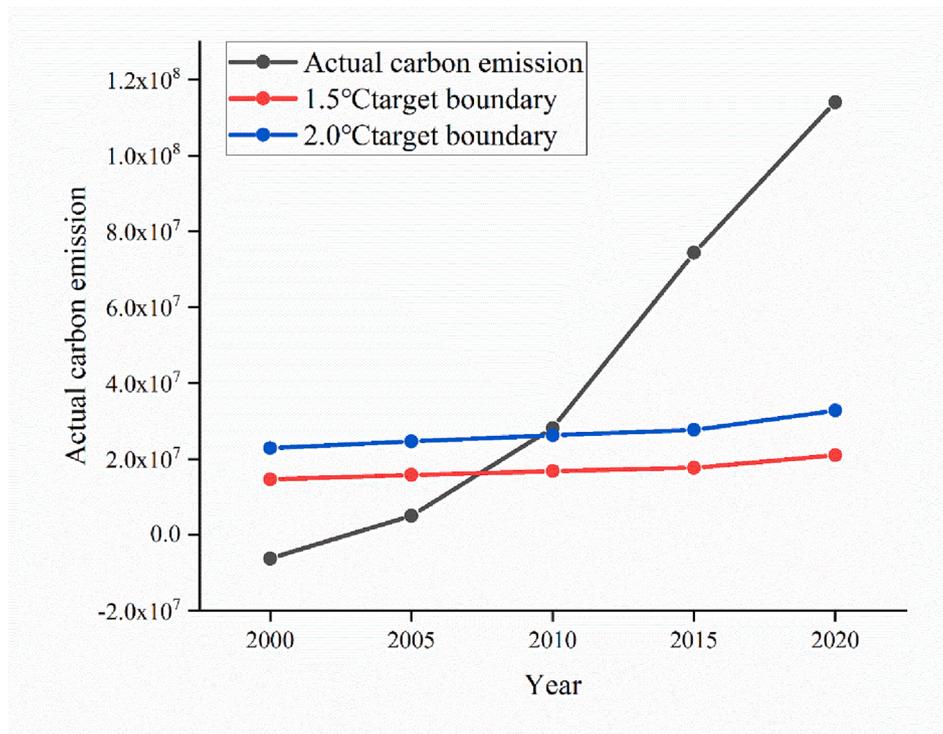


Fig. 6. Actual carbon emissions and carbon emission boundaries.

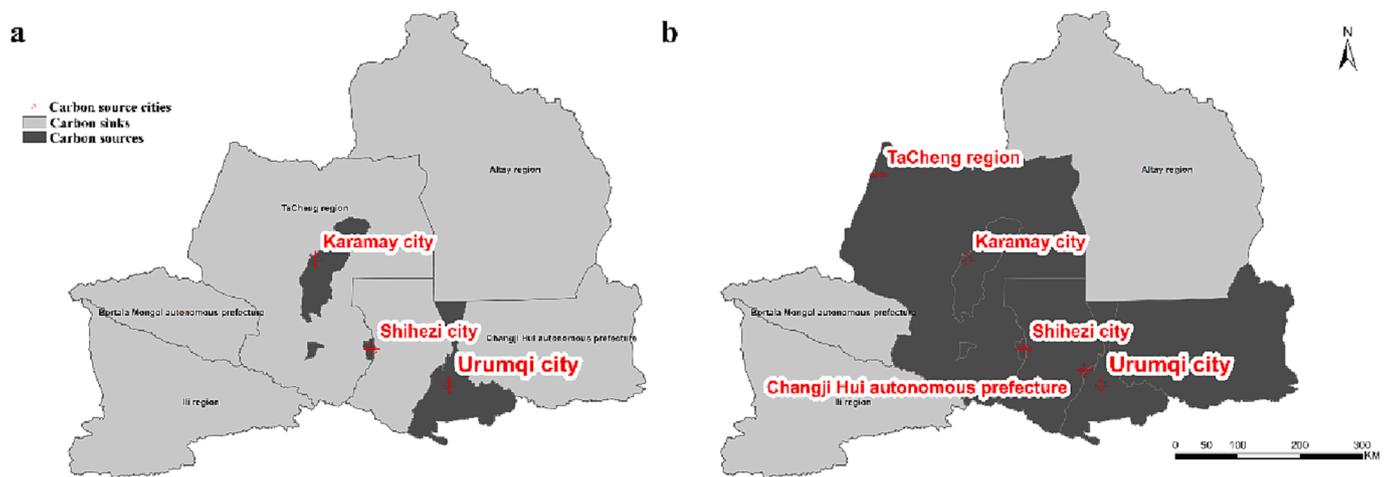


Fig. 7. Carbon Patterns in 2000 and 2020.

optimises the model composition so that it can be better used for ecological sustainability assessment in the study area. It also explores the applicability of the Footprint Boundaries System to the evaluation of small-scale regional sustainable development in drylands.

4.1. Discussion on the reasonableness of construction land boundaries

The expansion of building land is often accompanied by the large-scale loss of surrounding agricultural land, forest, and grassland, which in the long term will lead to regional ecological degradation. The territorial spatial planning and the demarcation of urban development boundaries have imposed constraints on the scale and speed of regional construction land expansion.

This study separates built-up land from land use boundaries, aiming to reflect the impact of human activity and urban expansion more accurately on regional land use and to show the differences between it

and biologically productive land. Since the 21st century, the pattern of expansion and use of construction land has shifted from an increase in size to an increase in efficiency.

During the study, the following two approaches were tried to define the upper limit of the size of construction land: (1). The land use boundary based on the per capita construction land standard. (2) the scale of urban construction that can be carried by water resources.

4.1.1. Comparison of the two approaches

Based on the *Standards of integrated quota for urban water use (SL366-2006)* (Table.5), the sub-administrative regions in the study area were graded as follows: megacities: Urumqi City, Changji Hui autonomous prefecture, Tacheng region, Ili region. Large cities: Shihezi City, Altay region. Medium cities: Karamay City, Bortala Mongol autonomous prefecture.

Based on the average water consumption of cities at all levels, the

Table 5
City size and water consumption.

City size	Unit	Mega Cities	Large cities	Medium cities	Small Cities
City Scale (Population V)	10,000 cap	$V \geq 100$	$50 \leq V < 100$	$20 \leq V < 50$	$V < 20$
Water consumption	10000 m ³ / (km ² .a)	177.2	140	120	101.4

scale of construction land that can be carried by the sub-administrative region under the two scenarios of total water resources and water resources used in the year is set as the boundary of construction land in the year (Table.6).

Under the total water resources scenario, the total water resources of the region in the current year are all classified as the amount of water available for urban development consumption, and the scale of construction land that can be carried by water resources is larger. Among them, Shihezi City and Karamay City both showed construction land exceeded the limit during the study period, and the scale of the exceeded limit continued to grow. Urumqi exceeded the construction size limit after 2015. In 2020, the actual scale of construction land in Changji Hui Autonomous Prefecture accounts for 66.86% of the bearable scale. It is below 20% in Bortala Mongol Autonomous Prefecture, below 30% in Tacheng region, and below 10% in Altay region and Ili region, which is far below the upper limit of local construction land under this scenario.

Under the water use scenario, the scale of water resources available to carry construction land is reduced. Only Urumqi City exceeds the limit in 2015 and 2020, the rest of the sub-administrative regions are below the construction land boundary, the construction scale of Karamay City and Changji Hui Autonomous Prefecture accounts for about 60% of the bearable scale. Tacheng region and Ili region account about 40%. Altay region and Bortala Mongol Autonomous Prefecture are about 20%. The study area is generally at a low-risk level and can carry a large margin of construction land.

In summary, in the evaluation of the bearable scale based on restrictive factors, the upper limit scale of construction land varies significantly under different scenarios. Compared with the stable change of population, water resources will be affected by many factors such as resource difference and exploitation level, which will also affect the scale of bearable construction land, and will weaken the reliability of the study conclusions.

Therefore, this study adopts a scheme based on per capita construction land criteria for boundary delineation and discusses the feasibility of this boundary in the footprint boundary system and its suitability in small-scale areas.

The impact of construction land on the ecological environment is not fully reflected in either the ecological footprint model or the footprint boundary evaluation system, and it is one of the priorities of the study to demonstrate this impact more comprehensively and visually. In addition, the applicability of the per capita construction land standard in the study area needs to be further explored. Northern Xinjiang is a vast area with large development differences between sub-administrative regions, and the overall per capita construction land area is about 400 m²/cap, which far exceeds the given construction land standard of 150 m²/cap.

Table 6
Maximum size of construction land under different scenarios- Urumqi as an example(hectare).

Year	Construction land per capita scenario	Total water resources scenario	Water use scenario
2000	31229.82	59762.98	47234.76
2005	29121.92	63656.88	55981.94
2010	36179.07	69300.23	68453.72
2015	40024.73	75000.00	61568.85
2020	60815.54	64334.09	57844.24

The study area is lagging in economic development and it is difficult to improve the efficiency of existing construction land use. How to reduce the scale of construction land and mitigate urban-ecological conflicts while preserving the development space of each sub-administrative region is another challenge to the sustainable development of Northern Xinjiang.

4.2. Discussion on water footprint and boundary setting

The study area is located in a typical arid zone where water resources are scarce and unevenly distributed. Traditional footprint models only consider the biological production function and footprint of water resources, while the footprint generated by water resources is evaluated by a separate water footprint system. How to evaluate regional ecological pressures and sustainability in a more comprehensive and refined way is one of the questions explored in this study. Water resource boundary thresholds, with significant geographical characteristics, and in the study area are characterized by uneven distribution, low efficiency of use, and large scale of exploitation.

The traditional ecological footprint approach converts ecological pressures into an evaluation of the area required for the region to consume those pressures. Water footprint, which converts water use to the relevant volume of water for measurement, cannot be directly integrated into the ecological footprint model. Therefore, to improve the evaluation of the ecological effects of regional water resources, this study attempts to evaluate regional water consumption and incorporate it into the ecological footprint model. The following two scenarios were tried for the evaluation of the regional water consumption footprint:

- (1) Based on the regional water resources usage, water use structure, and water production in the current year construct the equilibrium factor and yield factor for water consumption, which is used to evaluate the regional water footprint. The formulas are expressed as follows:

$$ef_w = \sum w_i \times r_i$$

$$ec_w = \sum w_i \times r_i \times y_i$$

$$r_w = \frac{w_i}{\sum w_i}$$

$$y_w = \frac{w_i}{W_i}$$

where ef_w is regional water footprint, ec_w is regional water carrying capacity, w_i is water consumption of industry i . W_i is water consumption of industry i of Northern Xinjiang. r_w is the water consumption equilibrium factor of the region, y_w is the water consumption yield factor of the region.

- (2) In this scenario, water consumption is translated into the area of water production required to meet water consumption, which is consistent with the idea of an ecological footprint system and can also be incorporated directly into the ecological footprint model. This has improved the accuracy and completeness of the evaluation of the regional ecological footprint to a certain extent. The formulas are expressed in section 2.2.3.3.

4.2.1. Comparison of the two scenarios

Based on the above two scenarios, the empirical analysis was carried out in the context of the actual situation in the study area (Table.7).

The study area is in a typical arid zone, and the distribution of water resources varies widely, so based on 2020 water resource data selected sub-administrative region with different water resource endowments,

Table 7
Comparison of the two scenarios.

Sub-administrative regions	Type	Water resources (hundred million m ³)		Water footprint		Water carrying capacity	
		Total water resources	Water consumption	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Changji Hui autonomous prefecture	Industrial prefectures	32.61	37.95	588304262.67	8572091.54	115744062.67	0
Tacheng region	Agricultural prefectures	56.77	37.63	627442966.86	6288856.58	127550015.80	3198743.42
Altay region	Service prefectures	108.6	30.31	425737281.58	3267618.95	71340614.17	8440181.05

different use efficiencies, and different types of cities for comparative analysis.

The results show that the Changji Hui Autonomous Prefecture is unable to achieve a balance between water supply and demand within the zone. Water transfers from outside the zone are particularly significant in Shihezi and Karamay, but Scenario 1 does not show significant fluctuations in values and the carrying capacity remains high.

When there is an inter-regional transfer of water, the carrying capacity of the area is overloaded, indicating that the water resources in the area cannot meet the demand, and the corresponding carrying capacity should be reduced, and the carrying capacity can be directly interpreted as the area of land in the area where the water resources can additionally meet the water demand under current water use conditions. This was well illustrated in Scenario 2.

4.2.2. Discussion on water boundary setting

The delineation of water resource boundaries has been discussed by scholars, such as Jaramillo and Destouni (Jaramillo and Destouni, 2015), who argued that the delineation of water resource boundaries should include green water in addition to blue water. Gerten et al. (Gerten et al., 2015) considered blue water under this system as only one indicator to consider some of the interactions in the water cycle and improved the method for setting water resource boundaries. Fang and Duan (Fang and Duan, 2015) consider the sustainability of water use to about both consumption and regional natural background and set the national water boundary at 40% of renewable water resources. Dong (Dong, 2021) used a freshwater boundary based on the watershed scale, and set the boundary according to the mood of river flow, reducing the influence of the time factor on the water use boundary.

The efficiency of water use in the study area varies considerably: industrial cities have high water consumption but low resources. agricultural cities have relatively high-water resources but low water use efficiency. The total amount of water resources in the study area is large but extremely unevenly distributed, with the Altay region, Tacheng region, and Ili region accounting for more than 80% of the total water resources in Northern Xinjiang, and industrial cities having fewer water resources. Water use in the north of the country accounts for about 50% of total water resources, but there are significant differences between sub-administrative regions, with utilization rates ranging from 30% in resource-rich areas to over 90% in industrial or resource-poor prefectures.

Therefore, 40% and 70% were adopted as water resource boundary thresholds in this study. Water resources, as the primary rigid resource constraint in arid zones, have an important impact on regional urban development and ecological protection. How to develop water resources more economically and intensively on the existing basis is a challenge for cities in arid zones.

4.3. Limitations and prospects

The existing system for evaluating construction land in the ecological footprint does not fully reflect the extent of its scale on the ecological environment, and how to better reflect this impact is a priority of further research. In terms of carbon emissions, this study only considers carbon

emissions from fossil fuels due to the limitation of data accuracy. Carbon emissions from carbon transfer, industrial production, and farming are not measured and should be deepened in subsequent studies.

This study considers only three of the nine important biophysical processes included in the planetary boundary system, namely water use, greenhouse gas emissions, and land use. The sustainability thresholds of the planetary boundary system cannot be fully represented. The application of the remaining biophysical processes to small-scale regions should be explored in subsequent studies.

5. Conclusions

Based on the traditional ecological footprint model, this study improves the ecological footprint account categories, sets up a local parameter scheme, and incorporates the water consumption footprint into the footprint system. Based on the planetary boundary system and the related research in the footprint-boundary system, the study analyses and evaluates the ecological land boundary, construction land boundary, water consumption boundary and carbon emission boundary in northern Xinjiang from 2000 to 2020 and explores the applicability of the footprint-boundary system in the evaluation of small-scale regional sustainable development in arid zones. The findings and conclusions of this study are as follows:

- (1) During 2000–2020, the ecological pressure on the northern Xinjiang increased significantly, with the energy footprint dominating and the ecological carrying capacity decreasing, resulting in a long-term ecological deficit and poor sustainability. Ecological pressure is increasing to varying degrees in all sub-administrative regions. With the exception of Altai region, all sub-administrative regions have ecological deficits and are consuming ecological resources to sustain urban development.
- (2) During the study period, northern Xinjiang was in the medium risk category for water resources, with a secure water boundary, significantly reflecting the constraint of water resources on the development of northern Xinjiang. Among sub-administrative regions, the capital city of Urumqi and the industrial cities face greater pressure on water resources, Changji Hui Autonomous Prefecture, Shihezi and Karamay all require water resources from outside the region to meet their own development needs. Ili region and Altay region are in the low risk category, indicating a high level of sustainability of regional water resources, while the rest of the regions are in the medium risk category. Each sub-administrative region should optimise its own water resource use patterns based on its own resource endowment to reduce water resource risks.
- (3) The scale of construction land in northern Xinjiang expanded by 1.95 times, 2.75 times the scale of the border, and the main inflow of new construction land was arable land, forest land, and grassland. Building land per capita increased from 302.31 m²/cap in 2000 to 411.80 m²/cap, a 1.36-fold increase. The actual scale of construction in the sub-administrative regions all exceeded the upper limit of construction land in that year and rose year by year. The scale of construction in industrial cities

exceeds the limit by more than two times, and the conflict between construction land and the rest of the land is pronounced. However, the overall proportion of built-up land in northern Xinjiang is 1.27%, with large land reserves, and regions should take measures to control the conversion of land to non-agricultural use to reduce potential ecological risks.

- (4) Carbon emissions in North Xinjiang rose 7.93 times, shifting from a carbon sink to a carbon source, at the risk boundary in carbon emissions. The main source of carbon is Urumqi City and industrial cities. Shihezi and Changji Hui Autonomous Prefecture are both in extremely high risk under the 1.5 °C target and the 2.0 °C target, with carbon emissions more than 10 times the regional carbon boundary. The Ili region and Tacheng region were converted from carbon sinks to carbon sources during the study period, and the amount of affluent carbon sequestration in the Bortala Mongol autonomous prefecture and Altay region was significantly reduced. In the context of carbon neutrality and carbon peaking, ecological carbon sequestration in northern Xinjiang faces a huge challenge.

Overall, the enormous environmental pressures in northern Xinjiang have far exceeded its ecological carrying capacity. The massive expansion of land for construction, the over-exploitation of water resources, and the massive emission of greenhouse gases have exacerbated the ecological imbalance, and with economic and urban development, the consumption of resources and energy is bound to increase, making the ecological environment in northern Xinjiang a serious challenge.

According to the findings above, countermeasures and recommendations for northern Xinjiang are required. First, northern Xinjiang is a typical arid zone with significant water resource constraints, and optimizing the use of water resources must be taken seriously. The government should promote water-saving technologies, increase investment and research and development in water reuse technologies, and promote the recycling of industrial and some domestic water to reduce the diversion of ecological water. In particular, the rapid development of cities, especially industrial cities, has accelerated the change of carbon patterns in northern Xinjiang, with more and more cities turning from carbon sinks to carbon sources. We should make greater efforts to develop clean energy, promote the implementation of new energy projects such as wind power and photovoltaic, restrict the entry of “high pollution, high energy consumption, and high emission” industries, promote green industries and low carbon consumption, and complement them with ecological protection and restoration measures to increase ecological carbon sinks. Finally, northern Xinjiang is so vast and sparsely populated that per capita construction land is more than double the national standard. The continued growth of construction land has led to a large loss of arable and ecological land around cities, which will pose a serious threat to regional food security and ecological safety in the long term. Along with the activation of the urban development boundary in national spatial planning, the uncontrolled expansion of cities will be curbed to some extent. Basis on preserving regional development opportunities and development space, each sub-administrative region should focus on developing unused urban land of low utility, improving land use efficiency, reducing the occupation of arable land and ecological land by urban land, and repairing ecological damage caused by urban expansion.

CRedit authorship contribution statement

Zhiyang Yue: Conceptualization, Formal analysis, Investigation, Methodology, Writing – original draft, Supervision. **Hongbin Liu:** Conceptualization, Investigation, Methodology, Writing – review & editing. **Zhonglin Xu:** Writing – review & editing, Supervision, Funding acquisition. **Yao Wang:** Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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