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Research article

Measuring and decomposing natural capital use in Xinjiang from a regional-industry perspective

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ABSTRACT

Accurately portraying the mechanism of the flow of natural resource consumption between regions and its impact on ecology is of crucial value in deepening the understanding of the coordinated relationship between population, resources, environment and development. Consequently, this promotes the sustainable development of the natural economy and society. Based on a regional-industrial perspective, this study used a localized three-dimensional ecological footprint model to measure and decompose natural resources in Xinjiang from 2005 to 2020. In doing so, the study clarified the supply, demand, and flow utilization of natural capital in Xinjiang, the balance of spatial and temporal allocation of resources, the coupling between economic growth and resource consumption, and the coordination between industrial structure and ecological environment. The results showed that (1) Xinjiang's per capita ecological deficit grew from 2.096 to 11.667 in 2005–2020. Moreover, the energy footprint was a decisive part of the ecological deficit throughout the study period. Furthermore, the trend of increased ecological pressure was higher in northern and eastern Xinjiang than in southern Xinjiang. (2) The overall Gini coefficient of Xinjiang's ecological carrying capacity was at the critical value of spatial equilibrium (0.4), with differences between the groups: Northern & Southern Xinjiang > Northern & Eastern Xinjiang > Eastern & Southern Xinjiang. The reasons for this inter-regional economic disparity are related to fiscal expenditure/GDP, level of urbanization, and regional industrial output. Overall, the decoupling relationship between environmental pressures and economic growth was optimistic. (3) From an industrial perspective, the levels of industrial structural efficiency and the industrial ecological harmony index were still relatively low, but the overall trend was on the rise. (4) Resource endowment, economic development, consumption structure, and population had significant driving effects on the ecological footprint, whereas environmental protection, science, and technology could inhibit its growth to a certain extent. This study aimed to provide an in-depth analysis of the current situation and problems of natural resource use in Xinjiang and provide theoretical and practical references for sustainable development in the region.

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1. Introduction

Natural capital is a general term for natural resources and ecological services provided by ecosystems and is an essential material basis for human-social-economic development [1]. The spatial flow relationship between ecosystem service supply and demand affects regional sustainable development [2]. As the global socioeconomic system continues to expand, the demand for resources will continue to grow at a high rate, leading to a further intensification of the conflict between the health of ecosystems for goods and the expanding resource needs of human social development [3]. A series of ecological and environmental problems are induced by social development, including significant reduction of non-renewable resources, water scarcity, energy crisis, and the greenhouse effect. These environmental problems are complex in their generation and solution considering that they involve ecosystems, water cycle systems, energy development, utilization systems, and carbon source/sink systems. It is challenging to clarify the positive and negative superposition as well as the antagonistic effects of each element in the use and allocation of the composite system, making the ecological resource pressure in the region fundamentally unsolved. Energy and mineral resources are well-endowed in the Xinjiang Uyghur Autonomous Region (hereinafter denoted as Xinjiang), an essential reserve of strategic resources in China. However, Xinjiang is located in an inland arid region with scarce water resources and is in a state of heavy water ecological deficit (per capita water ecological deficit index ≤ -1.07 hm^2) [4]. Moreover, energy consumption has been increasing since 2000, and carbon emissions have increased by more than four-fold [5]. A fragile ecological environment, coupled with the rapid development of urbanization, land-use ecological orientation, and the economic and social expansion of land contradictions is prominent. Hence, the environmental pressure in Xinjiang is enormous and affects the sustainable development of the region [5]. As a critical node for maintaining the ecological barrier of the “One Belt, One Road” economic belt and a transport hub of the Overland Silk Road, Xinjiang is urgently needed to coordinate the sustainable development of the region and establish a harmonious and symbiotic ecological and economic environment [6]. In the face of the polarization of the development of the northern and southern borders, optimizing the land use pattern and coordinating the development differences between regions has become an urgent problem for the sustainable development of Xinjiang. Therefore, achieving the efficient use of resources, coping with and meeting the significant resource needs of sustainable development, and forming a benign relationship between high-quality economic development and ecological environmental protection have become urgent for regional development [7]. There is an urgent need to clarify the natural resource base, assess the current situation of natural resource consumption, and explore the degree of coordination between economic development and the use of natural capital to provide a reference for planning regional sustainable development. The ecological footprint can characterize the impacts of human activities on the natural environment in terms of the area of biologically productive land required to consume these impacts. It connects natural ecological and socioeconomic systems and achieves unified accounting of natural capital appropriation and economic externality costs [8]. The ecological footprint model has been widely used because of its scientific rationality, ease of access to data, simplicity, and intuition. It provides an effective method for evaluating the degree of sustainable development of a region, the status of resource utilization, whether the industrial structure is reasonable, and many other aspects [9]. Existing research on the ecological footprint mainly focuses on the spatial and temporal measurement of the ecological footprint and the analysis of driving factors. There is a need for more studies on the coordinated relationship between the ecological footprint and economic development. Introducing an evaluation method that reflects the relationship between ecosystems and socioeconomic factors is conducive to further exploring the state of regional sustainable development.

Currently, there are some issues with studies on the ecological footprint of Xinjiang. One major issue is the application of large-scale equivalence and yield factors to the research and evaluation of small-scale regions, which can result in errors in the results. Additionally, the research tends to focus solely on Xinjiang as a whole or on specific prefectures and municipalities, thereby lacking an analysis of the dynamic flow of natural resources among regions located at the southern, northern, and eastern borders. Furthermore, there is a lack of studies that combine natural capital accounting with economic and industrial indicators. However, a localized three-dimensional ecological footprint model replaces the global average yield selected in the traditional ecological footprint with a regional average yield at a matching scale and changes the direct borrowing of critical parameters to a local parameter scheme for the current year. This will help reduce errors in measuring natural capital status at the subnational scale. Thus, this study selected a localized three-dimensional ecological footprint model to measure the natural capital utilization status at the provincial scale in Xinjiang from 2005 to 2020 as a whole and in sub-regions to retain the differences in regional development. The coordinated relationship between ecology, economy, and society in Xinjiang and each administrative unit was analyzed using relevant sustainable development evaluation methods to provide a reference basis for categorical measurement and zonal management of natural capital. By further measuring the changes in each industry’s ecological footprint and resource use efficiency, we analyzed the drivers of the non-ideal state of sustainable development to provide decision-making references for the coordinated development of industry and ecology in Xinjiang (Fig. 1).

2. Literature review

The ecological footprint serves as a valuable tool for assessing the impact of human activities on ecosystems, thereby enabling the measurement of human ecological appropriation and the Earth’s carrying capacity. Ecological footprint quantifies the extent to which humans appropriate ecological resources by considering the balance between resource supply and demand using the basic biological production area as a metric [10]. The ecological footprint method offers an objective and succinct theoretical foundation for measuring and analyzing the sustainability of regional economic and social development [11]. Notably, both domestically and internationally, experts have conducted extensive research and proposed valuable indicators and methods to enhance the model, scale of analysis, analytical perspectives, coupling applications, identification of driving factors, and geospatial analyses.

In terms of model improvement, Niccolucci et al. [12,13] made a significant contribution by expanding the ecological footprint model from a two-dimensional to a three-dimensional (3D) framework, thereby enabling a more nuanced measurement of both capital flow and stocks. Building on this work, Fang et al. [14] developed a formula to calculate the breadth and depth of regional footprints within a 3D ecological footprint model. As a result, they successfully avoided the misalignment of ecological gain/loss values during the calculation process. Furthermore, to address the limitations of single footprint indicators, a preliminary exploration of an integrated approach involving multiple footprint indicators (such as ecological, carbon, water, energy, chemical, nitrogen, and biodiversity footprints) has been conducted from a decision-making perspective to enhance the comprehensiveness of the assessment [15]. Furthermore, the standardization and localization of accounting equivalence and yield factors are pressing issues within ecological footprint assessments. The accuracy and applicability of ecological footprint models can be enhanced by implementing reasonable standardization and localization measures. Traditionally, the calculation of equivalence and yield factors has relied on biological production products, leading to potential issues with incomplete statistical data. To address this problem, Zhang et al. [16] and Li et al. [1], among others, have respectively employed the net primary productivity as the basis for calculating the local equivalence factor and yield factor, thereby overcoming this limitation. Additionally, to better capture variations in the ability of different ecosystems to provide ecological services, Li et al. [17] and Guo et al. [18] based their calculations on equivalence factor and yield factor measurements of ecosystem service value. Moreover, Liu et al. [19] have used an energy-value method, employing a "one area, one value per year" parameter, specifically for the northern border, resulting in more realistic and grounded outcomes.

Regarding research scales, the scope of ecological footprint analysis has expanded from the macro to the micro level. It has gradually become more refined and specific, encompassing global, national, provincial, and urban agglomerations; watersheds; economic zones; ecologically fragile areas; municipalities; counties; households; and individuals. For instance, Fang et al. [20] explored the environmental footprints of 65 countries involved in the "Belt and Road" Initiative, while investigating the flow generated by international trade with other economies. Xu et al. [21] used an improved ecological footprint model to estimate the potential ecological carrying capacity of each province in China and compared the results with the actual situation. Li et al. [22] studied urban agglomerations on a regional scale to reveal the patterns of natural capital utilization. Furthermore, Guo et al. [23] and Wang et al. [24] conducted scientific assessments of the ecological sustainability of the Upper Yellow River and East Liaohe River Basin, respectively, focusing on the watershed scale.

From an analytical perspective, consumption prevails in most cases. For instance, Zheng et al. [25] assessed the current status of the sustainable utilization of natural capital in Chinese provinces, cities, and autonomous regions from a consumer standpoint. Similarly, other researchers focused on production perspectives. Fang et al. [26] developed a calculation method to determine the land footprint and carrying capacity from a production-oriented viewpoint. However, the profound relationship between the ecological footprint and

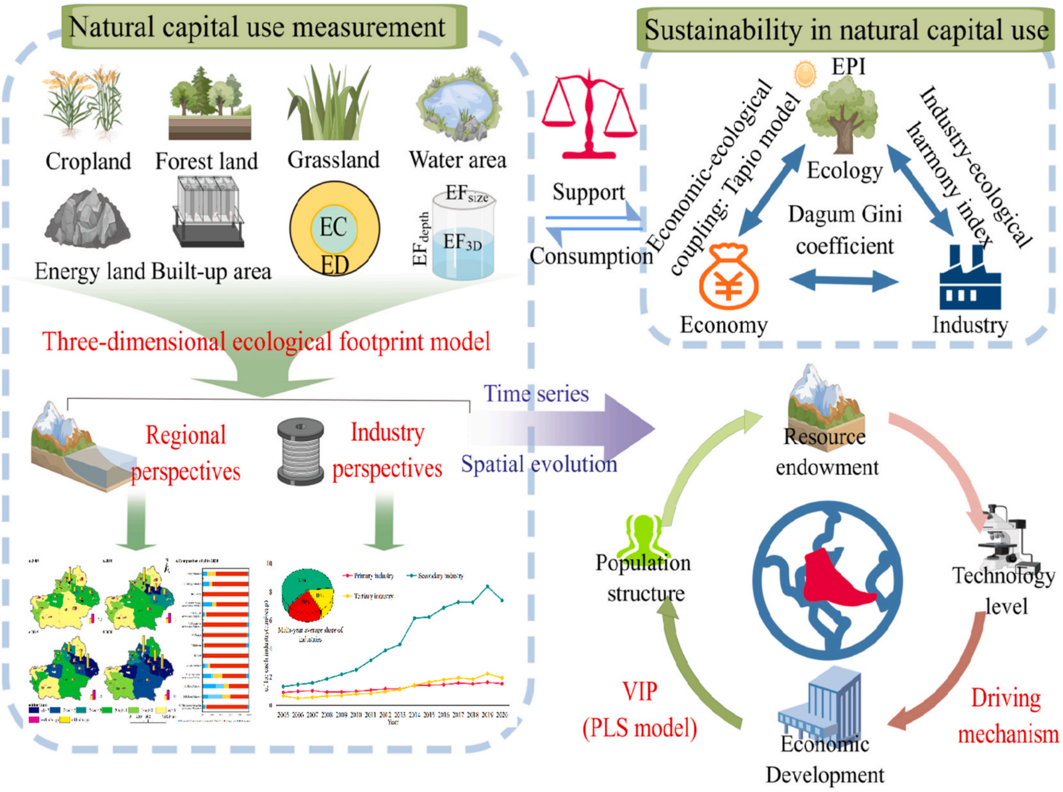


Fig. 1. Research framework (Some material provided under license by Figdraw).

ecological carrying capacity tends to be overlooked. To address this gap, Wang et al. [27] investigated the ecological sustainability of arable land in the Yangtze River Economic Zone from a "consumption-output" perspective. Additionally, innovative studies have emerged from both microanalysis perspectives, such as exploring the mechanisms of inter-factor interaction and coordination, and macroanalysis perspectives involving adjustments to boundaries. For example, Huang et al. [28] explored the changing characteristics of the synergistic effect between the regional ecological footprint and ecosystem service function from the perspective of the coupling between the intensity of human activities and ecosystem service function. Furthermore, Yue et al. [29] integrated the planetary boundary theory with the concept of ecological footprint to extend the maximum range of human activity impacts to a global scale, thereby providing a new perspective for evaluating ecological sustainability.

In the coupling application of the model, resource efficiency, urbanization, human capital, and technological progress are combined with the ecological footprint to analyze the specific performance of the relationship between the ecological footprint and economic development [30–32]. Currently, the methods used to reflect the relationship between ecological and environmental systems and socioeconomics include the environmental Kuznets curve [33], system dynamics model [34], Gini coefficient [35,36], coupled coordination degree model [37], and Tapio decoupling model. Among these, the Tapio model makes a fine distinction between decoupled states and has become one of the most widely used decoupling methods [38].

In terms of drivers, the main research methods for ecological footprint drivers are Partial Least Squares (PLS), Multi-scale Geographically Weighted Regression, Quantile-Quantile Regression, Quantile Regression, Drivers, Pressure, State, Impact, Response, correlation analysis, and Stochastic Impacts by Regression on Population, Affluence, and Technology models [39]. Among them, PLS solves the problem of multiple correlations of variables in multiple regression analysis, adequately explains the intensity of the effect of each independent variable on the dependent variable and has been widely used by scholars [40].

In terms of geospatial analysis, in recent years, some researchers have proposed innovative approaches such as multi-spatial scenario analysis, ecological networks, and AI high-precision ecological footprint mapping. For example, Tu et al. [41] used the ecological footprint as an essential indicator for ecological network analysis and optimized the regional ecological network using high spatial and temporal resolution location data to map the digital footprint. Tang et al. [42] combined the concepts of a 3D ecological footprint model with spatial scenarios and established a framework for ecological footprint evaluation using positional geographic coordinate units. Ye et al. [43] presented a high-resolution ecological footprint mapping, a novel AI model that provides a new method for revealing the spatial heterogeneity of ecological footprints and fine-scale spatiotemporal analyses.

In summary, the ecological footprint accounting system has continuously improved, broadening the scope of research by integrating other models. The research scale has gradually become more refined and specific, and incorporating geospatial concepts into the model has enhanced the visual representation of the results, making them more intuitive and detailed. In addition, the perspectives

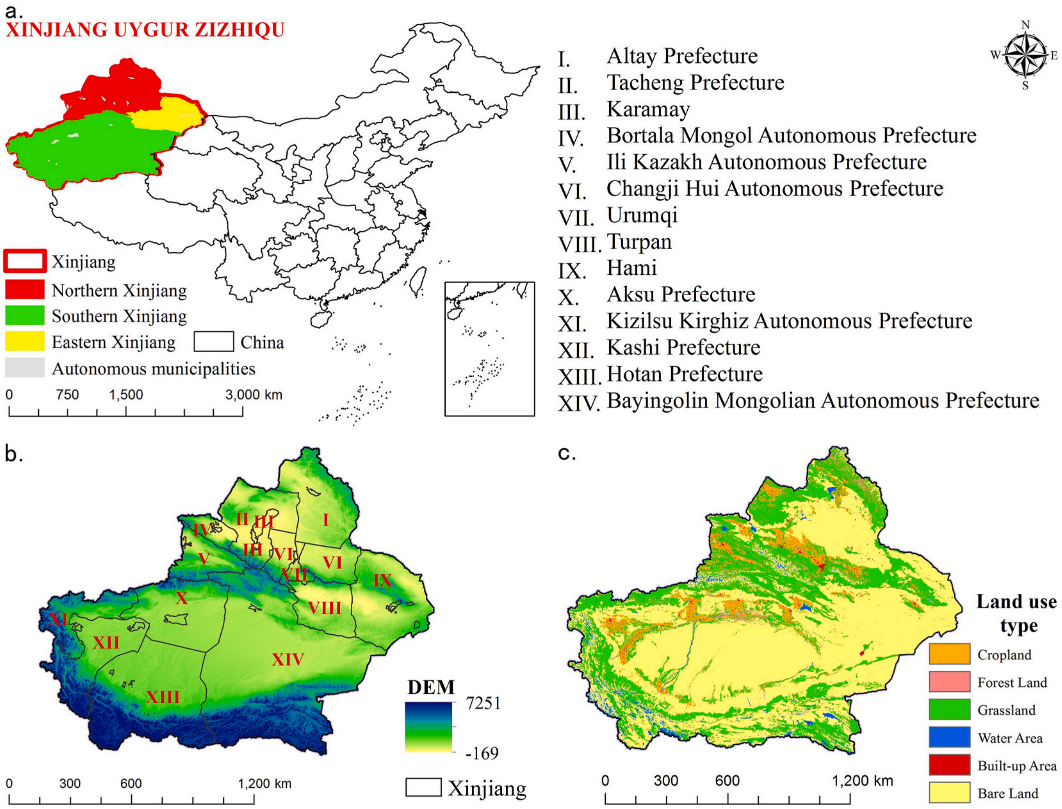


Fig. 2. Study zoning (a), its DEM (b) and land use type (c).

and levels of analysis have become more diverse. However, despite the increasing maturity of the ecological footprint concept, some issues still merit further investigation: (1) The critical parameters of the ecological footprint, namely the equivalence and yield factors, do not fully consider the research scale, time, and actual circumstances. Instead, they were borrowed directly from the empirical values of previous studies. (2) There is a scarcity of studies examining the sustainability of natural capital from multiple scales and perspectives and analyzing its connections and compatibility with socioeconomic development. However, this research gap must be addressed. (3) The scale and structure of industrial development mirror economic advancements. It is crucial to further investigate the impact of industrial structure on eco-efficiency and quantify the level of coordination between industrial growth and the ecological environment. Therefore, this paper focuses on localized ecological footprint parameters, considering the “heterogeneity” among different regions and industries. It aims to analyze the interrelationships among ecology, economy, and society to provide a reference for promoting the coordinated development of ecology, economy, and industry.

3. Research methods

3.1. Study area

Xinjiang is located deeply inland on the north-western border of China (73°40′-96°18′ E, 34°25′-48°10′ N) (Fig. 2a). It accounts for one-sixth of China’s land area, is rich in land resources (Fig. 2c), and is the main body of China’s arid zone [44]. Xinjiang has 14 regions, states, and cities (Fig. 2b). The geomorphological description of Xinjiang is “three mountains sandwiched between two basins, ”; the north of the Tianshan Mountains is divided into Northern Xinjiang, the eastern part of the Tianshan Mountains is called Eastern Xinjiang, and the south of the Tianshan Mountains is divided into Southern Xinjiang, which forms a three-patterned style of regional delineation (Fig. 2a). Eastern Xinjiang covers less area than Northern and Southern Xinjiang but is the throat of the Silk Road. Southern Xinjiang has a vast area and complex terrain with abundant light and mineral resources, and minerals account for more than 70% of the minerals in the entire territory. However, it has many deserts, including the Gobi, drought, little rain, and harsh natural conditions. The land area available in Northern Xinjiang was much larger than that in Southern Xinjiang, accounting for 83.9% of the total land area in Northern Xinjiang. Historically, there has been a significant difference in population between Northern and Southern Xinjiang, with the population of Southern Xinjiang accounting for more than two-thirds of the total population of Xinjiang. With the development of the economy and society, the population distribution of Northern and Southern Xinjiang tends to be balanced. In 2020, Southern Xinjiang accounted for 48.5% of the total population of Xinjiang, but its gross domestic product (GDP) only accounted for 29.9% of the total GDP of Xinjiang. Compared with Northern Xinjiang, the resource endowment of Southern Xinjiang is disadvantaged, and its economic base is fragile; hence, economic development shows a different pattern of high and fast in the north, low and slow in the south.

3.2. Data sources

The data required for this study were divided into three categories: social statistics data, land use data, and driver data (Table 1). Statistical data are mainly used to account for the ecological footprint and select indicators for impact factor analysis of the ecological footprint. The biological resources account uses production statistics for 30 products, including agricultural, forest, livestock, and aquaculture products. The energy consumption account was based on the consumption of 10 types of energy, including coke, raw coal, and electricity. The ecological footprint drivers were analyzed using statistics from the corresponding years involving economic development, consumption structure, population, environmental protection, science, and technology. Land-use data were mainly used to extract the areas of various types of biologically productive land (cropland, forest land, grassland, water area, energy land, and built-up area) in Xinjiang in 2005, 2008, 2010, 2013, 2015, 2018, and 2020 to further calculate the ecological carrying capacity. For the missing land use data between 2005 and 2020, considering that short-term land data changes would not be significant, the average value method was used for estimation (i.e., the average annual area change was added to the annual data one by one) [45]. Due to data availability, Xinjiang municipality was not included in this study for the time being. Moreover, the average production during the study period was used for missing production data in the statistical yearbook.

Table 1
Data description.

Data classification	Data use	Data sources
Social statistics	Biological resource accounts, accounting for energy consumption accounts, analysis of ecological footprint impact factors, calculation of regional economic differences	Xinjiang Statistical Yearbook (2004–2021) China Energy Statistics Yearbook (2020)
Land use	Extraction of biologically productive land area for each category for ecological carrying capacity calculations	Centre for Resource and Environmental Sciences and Data, Chinese Academy of Sciences (http://www.resdc.cn/) Resolution: 1 × 1 km Year: 2005, 2008, 2010, 2013, 2015, 2018, 2020
Driving factors	Data on the independent variables of the Partial Least Squares (PLS) model	Xinjiang Statistical Yearbook (2004–2021)

Table 2
Ecological footprint accounts, composition, and critical parameters.

Account Type	Biologically productive land				Non-living productive land	
Land use type	Cropland	Forest land	Grassland	Water area	Built-up area	Energy land
Account composition	Rice, wheat, maize, barley, beans, potatoes, cotton, oilseed rape, caraway, sunflower, sugar beet, vegetables, fruiting melons, alfalfa, pork, poultry eggs, poultry meat	Apples, pears, grapes, peaches, apricots, dates, nuts	Beef, horsemeat, camel meat, mutton, cow's milk, goat's milk, sheep's wool, goat's fleece	Fishery product	Electricity land	Raw coal, washed coal, coke, coke oven gas, natural gas, crude oil, petrol, diesel, liquefied petroleum gas, refinery dry gas
Equivalent factors	1.339	2.065	0.687	0.353	1.339	2.065
Yield factors	0.405	0.336	0.471	0.184	0.405	0

3.3. Improved three-dimensional ecological footprint modelling

Niccolucci et al. [13] introduced two new indicators, footprint depth and footprint breadth, based on a classical two-dimensional model (Equations (1)–(3)). They developed a three-dimensional ecological footprint model that allowed for spatial analysis and distinguished between capital stocks and flows. This enhanced model transforms the representation of ecological footprints from two-dimensional surface areas to three-dimensional cylindrical volumes, thereby explaining human appropriation of natural resource flows and stocks. However, the computation of the basic three-dimensional ecological footprint model does not accurately express ecological gain or loss and only applies to a single land type experiencing an ecological deficit. Thus the depth of ecological footprints when different types of land are accumulated is underestimated. To address this, Fang et al. [14] improved and optimized a basic three-dimensional model (Equations (4)–(6)) and derived the following formulas for calculating the breadth and depth of ecological footprints at a regional scale:

$$EF = N \times ef = N \times \sum_{i=1}^{n} \left(r_j \times a_i\right) = N \times \sum_{i=1}^{n} r_j \left(\frac{c_i}{p_i}\right) \tag{1}$$

$$EC = N \times \mathrm{ec} = N \times \sum_{j=1}^{6} A_j \times r_j \times y_j \tag{2}$$

$$\mathrm{ED} = \mathrm{EF\text{-}EC} \tag{3}$$

$$EF_{\mathrm{size}} = \sum_{i=1}^{n} min\{EF_i, EC_i\} \tag{4}$$

$$\mathrm{EF_{depth}} = 1 + \frac{\sum_{i=1}^{n} \max\{\mathrm{EF_i\text{-}EC_i}, 0\}}{\sum_{i=1}^{n} \mathrm{EC_i}} \tag{5}$$

$$EF_{\mathrm{3D}} = EF_{\mathrm{size}} \times EF_{\mathrm{depth}} \tag{6}$$

where i is the type of commodity consumed; j denotes the type of land use; p_i is the average production capacity of the commodity i; c_i is the per capita consumption of the commodity i; a_i is the land area (hm^2) per capita converted to the commodity i; N is the total number of people; A_j is the actual per capita area (hm^2) of productive land of the category available j; r_j and y_j are the equivalent and yield factors, respectively; EF and EC are the total ecological footprint and carrying capacity of the region (hm^2), respectively; ef and ec are the ecological footprint and carrying capacity per capita (hm^2/cap), respectively. Moreover, EF_{size} is the regional footprint breadth (hm^2); EC_i is the ecological carrying capacity of land type i; EF_i is the ecological footprint of land type i; n is the number of land types; EF_{depth} is the depth of the regional footprint (dimensionless), EF_{3D} characterizes the regional three-dimensional ecological footprint. When $EF_{\mathrm{depth}} = 1$, the flow capital needed by human beings is utilized, and there is no need to use the stock capital; when $EF_{\mathrm{depth}} > 1$, it means that the stock capital needs to be consumed to make up for the lack of flow capital; the higher the value of EF_{depth}, the more the natural capital stock is consumed, showing an unsustainable development situation.

It should be noted that the *EC* calculations also require a reduction of 12% for biodiversity conservation. Energy land use was discounted for fossil-energy consumption projects using energy conversion coefficients with various energy conversion reference coefficients obtained from the China Energy Statistics Yearbook 2020. In addition, at the provincial scale, the national equivalent factor and provincial yield factor are required [14]. Therefore, in this study, r_j and y_j are referred to as the multi-year averages of r_j in China and y_j in Xinjiang based on NPP measurements by Li et al. [1]. Furthermore, r_j is energy land being replaced by forest land, and r_j and y_j are the construction land being replaced by cropland (Table 2).

3.4. Indicators related to sustainability evaluation of natural capital use

3.4.1. Stock flow utilization ratio

When capital flows are fully utilized ($EF > EC$), stock capital is consumed gradually. The stock flow utilization ratio (R) characterizes the magnitude of the relationship between stocks and flows in the human utilization of natural capital (Equation (7)) [46]. R is calculated as follows:

$$R = \frac{EF - EF_{\text{size}}}{EF_{\text{size}}} = EF_{\text{depth}} - 1 \ (EF > EC) \tag{7}$$

3.4.2. Ecological pressure index

The Ecological Pressure Index (*EPI*) characterizes the sustainability of regional ecosystems and is the ratio of the ecological footprint to the biological carrying capacity of a given region (Equation (8)) [47]. The *EPI* formula is as follows:

$$EPI = \frac{EF}{EC} \tag{8}$$

In ecological surplus areas, $0 < EPI \leq 1$. In ecological deficit areas, when $1 < EPI \leq \frac{\overline{EPI}}{2}$, the region is in mild overload; when $\frac{\overline{EPI}}{2} < EPI \leq \overline{EPI}$, the region is in moderate overload; and when $EPI \geq \overline{EPI}$, the region is in high overload [48].

3.4.3. Dagum Gini coefficient

The Gini coefficient is an indicator for measuring the level of interregional differences, and the Gini coefficient of ecological carrying capacity reflects the fairness of natural resource distribution [49]. The Dagum Gini coefficient (*DG*) is an upgrade of the traditional Gini coefficient, which can be divided into the Gini coefficient within a group (G_w), the Gini coefficient between groups (G_b), and coefficients of hypervariable density (G_h). In this study, we use the per capita ecological carrying capacity indicators that characterize the natural resource endowment of Xinjiang cities and towns from 2005 to 2020 and apply *DG* to measure the differences in natural resource endowment and the degree of contribution of Xinjiang regions and inter-regions. G_w reflects the gap in the level of ecological carrying capacity within regions, G_b reflects the gap in the level of ecological carrying capacity between regions, and G_h reflects the difference in the level of cross-overlap of ecological carrying capacity between regions, reflecting the relative gap. *DG* compensates for the shortcomings of other methods used to measure regional gaps because they cannot solve the overlapping phenomenon of examination data and can better identify the sources of regional gaps (Equation (9)) [50].

$$DG = \frac{1}{2n^2\overline{y}} \sum_{j=1}^{k} \sum_{h=1}^{k} \sum_{i=1}^{n_j} \sum_{r=1}^{n_h} \left| y_{ji} - y_{hr} \right| \tag{9}$$

where y_{ji} and y_{hr} are the per capita ecological footprints of each prefecture-level city within subregions j and h, respectively; $\overline{y}$ is the average per capita footprint breadth in Xinjiang; n is the number of prefectures; k is the number of dividing districts; and $n_j(n_h)$ denotes the number of cities and municipalities in the interior of the *j(h)* region. The warning line for the Gini coefficient is 0.4 as which is the inequitable-state threshold. The smaller the value, the higher the spatial balance, and vice versa, and the lower the balance [51].

3.4.4. Tapio model

The Tapio model can be used to study the coupled relationship between economic growth and resource consumption or environmental pollution. This model comprehensively reflects the sensitivity of economic changes to changes in resources and environ-

Table 3
Criteria for determining the degree of decoupling.

Degree of decoupling (sustainable level)	ΔTE	ΔTG	E_t
Strong decoupling (ideal)	<0	>0	$E_t < 0$
Weak decoupling (general)	>0	>0	$0 \leq E_t \leq 0.8$
Recession decoupling (worse)	<0	<0	$E_t > 1.2$
Expansion link (general)	>0	>0	$0.8 \leq E_t \leq 1.2$
Recession link (poorer)	<0	<0	$0.8 \leq E_t \leq 1.2$
Weak negative decoupling (worse)	<0	<0	$0 \leq E_t \leq 0.8$
Strong negative decoupling (least desirable)	>0	<0	$E_t < 0$
Expansion negative decoupling (general)	>0	>0	$E_t > 1.2$

mental pressures (Equation (10)) [52]. In this study, the Tapio model ratio method was used to calculate the ecological footprint decoupling index in Xinjiang, and GDP was selected as an indicator of economic development to study the decoupling relationship between regional economic development and ecological footprint. The calculation formula is as follows:

$$E_t = \frac{\Delta \mathrm{TE}}{\Delta \mathrm{TG}} = \frac{\frac{\mathrm{TE}_t - \mathrm{TE}_{t-1}}{\mathrm{TE}_{t-1}}}{\frac{\mathrm{TG}_t - \mathrm{TG}_{t-1}}{\mathrm{TG}_{t-1}}} \tag{10}$$

where E_t is the decoupling index; ΔTE and ΔTG are the rates of change of footprint and GDP; TE_t and TG_t are the footprint and GDP values in year t, respectively; and the criteria for determining E_t are shown in Table 3 [53].

3.5. Industry-ecology harmony index

The Industry-Ecology Harmony Index (*IEHI*) can further describe the sustainable development status of Xinjiang's industrial structure in the process of development in harmony with the ecological environment. Moreover, the *IEHI* (Equation (11)) indicates the benefits of the industrial structure per unit of ecological capacity (carrying capacity) [54]. The formula is as follows:

$$IEHI = \frac{ISB}{ec} = \frac{X_1/X_2}{ec} = \frac{y_1/l_1}{y_2/l_2} \times \frac{1}{ec} \tag{11}$$

where *IEHI* is the industry-ecological harmony index; *ISB* is the industrial structure benefit; *ec* is the per capita ecological carrying capacity; X_1 is the comparative labor productivity of the primary industry; and X_2 is the comparative labor productivity of the secondary and tertiary industries; y_1 and l_1 denote the proportion of the primary industry's national income and the proportion of the workforce, respectively; y_2 and l_2 denote the proportion of the secondary and tertiary industries' national income and the proportion of the workforce, respectively.

3.6. Partial least squares regression

3.6.1. Principles and methods

PLS regression finds the fundamental relationship between two matrices (*X* and *Y*). It explains the multidimensional direction with the highest variance in the Y space by finding the multidimensional direction in the X space. This solves the problem of multiple correlations of variables in multiple regression analysis and explains the strength of the effect of each independent variable on the

Table 4
Ecological footprint driver indicators.

Impact factor	Indicators	Unit	Definition
Resource endowment (A)	*ec* (X_1)	hm^2/cap	Total biologically productive land area that the Earth can provide for each human being.
Economic development (B)	Value added of primary industry (X_2)	100 million yuan	The value of growth in the current clearing cycle (generally measured in years) over the previous clearing cycle for sectors whose products are derived directly from nature (including plantations, forestry, pastoralism, and fisheries).
	Value added of the secondary sector (X_3)	100 million yuan	The value of additions and transfers of fixed assets created in the production process by production units and sectors in the secondary sector (including industry and construction).
	Tertiary value added (X_4)	100 million yuan	Value of over-the-cycle (generally annual) growth in the distribution and services sector over the previous liquidation cycle.
	Per capita GDP (X_5)	Yuan/person	Impact (increase/decrease) of regional ecological pressures.
	Total investment in fixed assets (X_6)	100 million yuan	Monetary expression of the level of integrated socio-economic development.
	Daily average energy consumption (X_7)	Million tonnes of standard coal/day	Total daily consumption of non-renewable energy.
Consumption structure (C)	Total retail sales of consumer goods (X_8)	100 million yuan	Expression of regional consumer demand.
	Per capita disposable income of rural households (X_9)	Yuan/person	Measuring rural affluence.
	Per Capita disposable income of urban households (X_{10})	Yuan/person	Measuring urban affluence.
Population (D)	Population at the Year-end (X_{11})	10000 persons	Characterizing the scale of resource consumption.
	Urbanization rate (X_{12})	%	Characterizing the level of social development.
Environmental Protection (E)	Afforestation area (X_{13})	10^4 hm^2	Soil and water conservation and wind and sand control capacity.
	Energy saving and environmental protection expenditure (X_{14})	100 million yuan	Pollution control intensity.
Science and Technology (F)	Expenditures on research and development (X_{15})	10000 yuan	Expenditure on basic research, applied research and experimental development in real terms by society as a whole.
	Volume of transaction in technical markets (X_{16})	10000 yuan	Reflecting the actual situation of a region in terms of technology transfer, technological progress, etc.

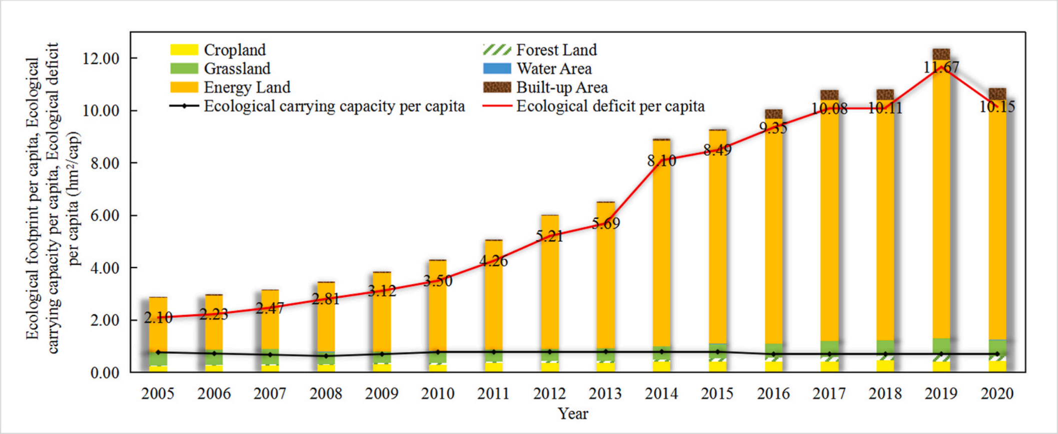


Fig. 3. Per capita ecological footprint (composition), ecological carrying capacity, and ecological deficit in Xinjiang.

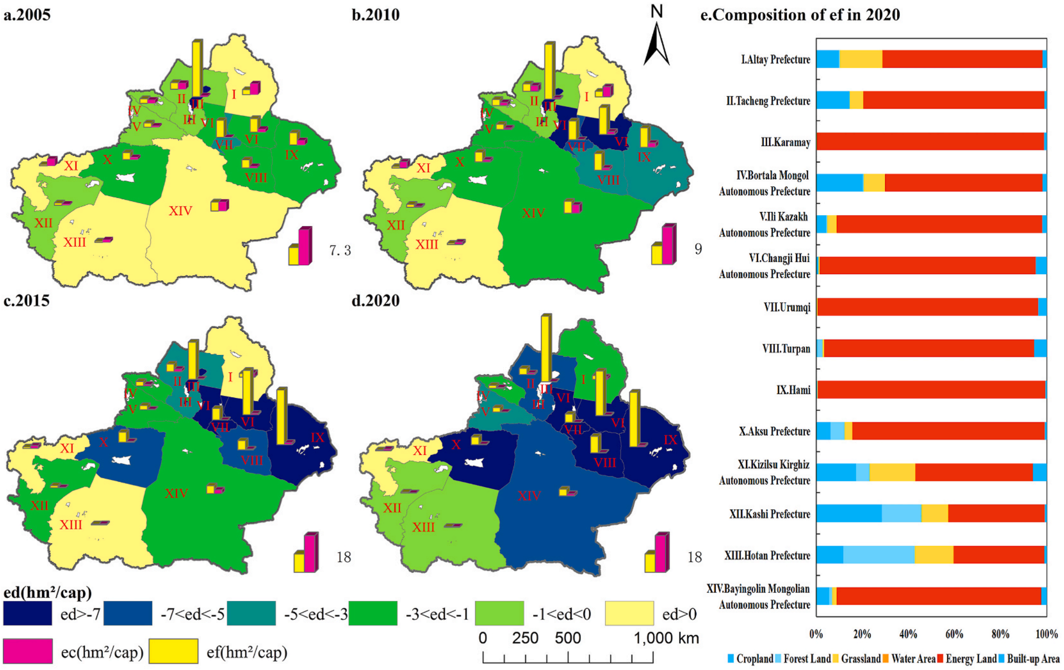


Fig. 4. Per capita ecological footprint (ef), ecological carrying capacity (ec), ecological deficit (ed), and ecological footprint composition in Xinjiang.

dependent variable. Therefore, the PLS model is often used to explore drivers of ecological footprint change [40]. The variable importance projection (VIP) in PLS is often applied to identify the degree of influence of each indicator on the ecological footprint. In general, indicators with a value of 1 or more are considered to be significantly influential, indicators with a VIP value between 0.8 and 1 are considered generally essential, and indicators with a VIP value of 0.8 or less are considered highly unimportant.

3.6.2. *Selection of indicators*

Indicators were selected based on the actual situation in Xinjiang from 2005 to 2020 and the availability of data (Table 4). The direct or indirect relationship of society, population, and economy with the local area was considered, and a previous method for selecting factors that influence ecological footprint was consulted.

4. Results and analysis

4.1. Analysis of the spatial and temporal evolution of natural capital utilization in Xinjiang from a regional perspective

4.1.1. Analysis of the temporal evolution of the ecological footprint in Xinjiang

Xinjiang's *ef* grew from 2.862 hm^2/cap in 2005 to 12.369 hm^2/cap in 2019 and declined in 2020. The reason for this may be that 2020 was affected by the corona virus disease-19 pandemic, which changed economic and social consumption habits, thus leading to a decrease in *ef* [55]. The *ec* fluctuated slightly, remaining essentially constant at approximately 0.7 hm^2/cap, which means that available biologically productive land for per capita consumption was only 0.7 hm^2/cap (Fig. 3). The *ef* was roughly 9.5 times the *ec*, implying that at least 9.5 spatially biologically productive areas of Xinjiang are needed to sustain socioeconomic activities at current consumption levels. Xinjiang experienced an ecological deficit during the study period, with the *ed* increasing from 2.096 hm^2/cap in 2005 to 11.667 hm^2 in 2019, a nearly 5.6-fold increase, and a decrease of 10.146 hm^2/cap in 2020. Evidently, ecological pressures are increasing and they are in a state of ecologically unsustainable development. The contribution of each type of biologically productive land to the ecological footprint ranks as follows: energy land > grassland > cropland > forest land > construction land > water. Furthermore, the energy footprint has always been a decisive part of the ecological footprint during the study period, rising from a share of approximately 73% in 2005 to 86% in 2019.

4.1.2. Characteristics of spatial evolution of ecological footprint in Xinjiang

The ecological deficits in cities and towns in Xinjiang showed an increasing trend of varying degrees. The high-value areas are economic zones on the northern slope of the Tianshan Mountains and the cities of Turpan and Hami on the eastern border. In contrast, the medium-to low-value areas were located in the Altay Prefecture and northern Xinjiang. Except for Kizilsu Kyrgyz Autonomous Prefecture, all other regions entered the ecological deficit stage in 2020 (Fig. 4a–d). First, from 2005 to 2020, the ecological deficit situation in various cities and towns in Xinjiang showed different degrees of growth trends, with significant differences between the regions, and the ecological pressure in the north and east of Xinjiang gradually aggravated more than that in the south of Xinjiang. Second, from 2005 to 2015, Altay, Hotan, and Kizilsu Kyrgyz Autonomous Prefectures were in a state of ecological surplus. However, there was a gradual downward trend, and only Kizilsu Kyrgyz Autonomous Prefecture did not enter the ecological deficit stage in 2020. Third, Karamay has been a high-pressure ecological zone for 15 years, whereas the cities of Urumqi, Changji Hui Autonomous Prefecture, Turpan, Hami, and Aksu regions gradually developed into high-pressure ecological zones during this period. Karamay is a resource-rich city surrounded by the Gobi Desert. The high demand for mineral resources in this area and strong exploitation of these resources has led to a massive depletion of natural capital stock, resulting in a severe ecological deficit. Urumqi is the economic center of the entire territory, and the city's construction, industrial development, and high demand for resources have made the already fragile ecological environment face even more significant challenges. The Changji Hui Autonomous Prefecture is an essential part of the economic belt on the northern slope of the Tianshan Mountains and occupies an important position in the economic development of the entire territory. Each of the eight counties in the prefecture has advantages in terms of resources. However, with rapid growth and population increase, resource consumption is increasing daily and gradually increasing the pressure on the ecological environment. Turpan City is known as the "fire state" and "wind reservoir." Hami is a vital node city in the Silk Road Economic Belt, rich in resources and energy, and one of the wealthiest areas in the country in terms of sunshine hours. However, the southern part of the mountain is dry and hot with little precipitation. The oil and gas in Aksu Prefecture are very considerable as it provides approximately 96.32% of the gas of the "West-East Gas Pipeline" project. The resource endowment of these areas, coupled with the rapid development of their fragile ecological environments, is gradually becoming high-pressure. To alleviate high-pressure situations, it is necessary to strengthen the restoration and protection of the ecological environment, impose rigid constraints on policies and systems, and reduce energy consumption.

In terms of the composition of the per capita ecological footprint in each city and prefecture, energy land is almost the main contributing land to the per capita ecological footprint in most regions (Fig. 4e). This is especially true in Karamay, Urumqi, Changji Hui Autonomous Prefecture, Hami, Turpan, Aksu Prefecture, and Bayinguoleng Mongol Autonomous Prefecture. Built-up land and watersheds contributed less to per capita ecological footprint in each region. Forestland contributed to the per capita ecological footprint of Hotan Prefecture to a greater extent than it does in other regions. Cultivated land contributes more to the per capita

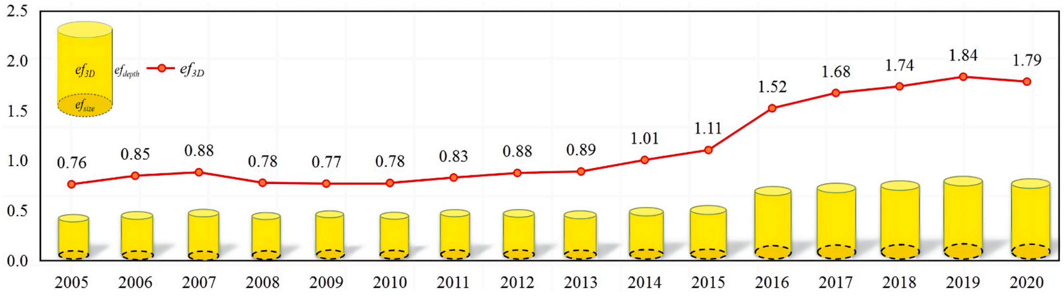


Fig. 5. Per capita ecological footprint size, ecological footprint depth, and three-dimensional (3D) ecological footprint in Xinjiang.

ecological footprint in the Kashi Prefecture than it does in other regions. Grassland contributed more to Altay Prefecture and Kizilsu Kyrgyz Autonomous Prefecture than to other regions.

4.2. Sustainability analysis of natural capital utilization in Xinjiang from a regional perspective

4.2.1. Analysis of regional footprint size and footprint depth in Xinjiang

The ef_{size} in Xinjiang during the study period generally showed a steady upward trend (Fig. 5) from 0.695 hm^2/cap in 2005 to 0.903 hm^2/cap in 2020, with a growth rate maintained within 6%; the trend was basically in line with the ef_{3D}. This shows that the occupancy level of capital flow in Xinjiang slowly increased during the study period. This is due to the fueling effect of the implementation of the Western development strategy on the economic development of Xinjiang and the continuous improvement of the economic field. Moreover, Xinjiang's commitment to social stability and long-term peace and security, and its pursuit of development in the midst of stability also contributed.

The ef_{depth} in Xinjiang from 2005 to 2020 showed an overall fluctuating upward trend, increasing from 1.099 to 1.252 in 2007, decreasing to 1.181 in 2008, and gradually increasing to 2.038 in 2019. The ef_{depth} in the study period exceeded the original length of 1 m, and the population would need approximately 2.5 m^2 of spatially biologically productive land in Xinjiang to sustainably meet the resource consumption during this period. The regional footprints in the study period were all deeper than the original length of 1, and residents needed approximately 2 x spatially biologically productive land in Xinjiang to sustainably meet resource consumption during the study period. It is evident that Xinjiang is overdrawing its capital stock year by year to meet the demands of various developments. In addition, the 2022 Xinjiang Ecological and Environmental Conditions Bulletin indicates that the ecological quality grade of the entire Xinjiang region is Category III (the proportion of natural ecosystem coverage is average). Furthermore, 35.4 percent of the county area has poor natural ecological background conditions. The capacity and level of ecological and environmental management must be continuously upgraded to alleviate ecological pressures and risks.

4.2.2. Ecological sustainability analysis of natural capital utilization in Xinjiang

The per capita stock flow utilization ratio (R) increased slowly and fluctuated from 2005 to 2015, and began to increase rapidly in 2016, reaching a maximum value of 1.04 in 2019 (Fig. 6). This shows that flow capital can no longer meet the needs of production and life. The situation of gradually increasing stock capital to compensate for the lack of flow capital has become the norm in Xinjiang, and the natural capital provided by ecology gradually tends to become saturated. However, except for 2019, the R of the other years has not yet exceeded 1, and the consumption of stock capital has not yet completely replaced the capital flow. As a province rich in natural resources, it is imperative for Xinjiang to improve the efficiency of resource utilization and ensure ecological security.

The trend of the *EPI* in Xinjiang from 2005 to 2020 was consistent with the trend of R, and 2016 was a critical point in the change in ecological stress in Xinjiang. Thus, the entire study period is ecologically unsustainable. Among them, 2005–2007 had mild ecological overload, 2008–2013 had moderate ecological overload, and 2014–2020 had high ecological overload. In 2016, a qualitative change in the land economy of Xinjiang, and the accelerated rate of ecological imbalance in 2016–2020 may be related to the construction of the

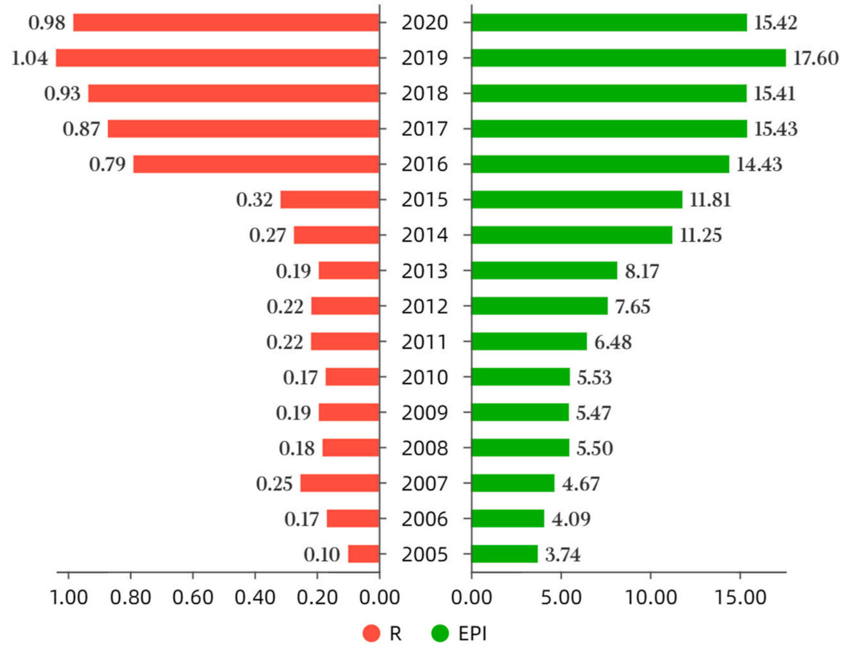


Fig. 6. Inter-annual variation in per capita stock flow utilization ratios and per capita ecological pressure indexes.

Table 5
Dagum Gini coefficient (*DG*), Gini coefficient within (G_w), and between groups (G_b), and coefficients of hypervariable density (G_h) and their contributions.

Year	*DG*				Contribution rate(%)		
	Overall	G_w	G_b	G_h	G_w	G_b	G_h
2005	0.415	0.166	0.055	0.194	39.998%	13.215%	46.786%
2008	0.412	0.169	0.050	0.194	40.938%	12.067%	46.995%
2010	0.399	0.161	0.038	0.200	40.332%	9.506%	50.162%
2013	0.403	0.161	0.031	0.211	39.937%	7.731%	52.332%
2015	0.409	0.164	0.047	0.198	40.181%	11.433%	48.385%
2018	0.406	0.162	0.034	0.211	39.882%	8.273%	51.845%
2020	0.400	0.160	0.036	0.204	39.921%	9.036%	51.042%

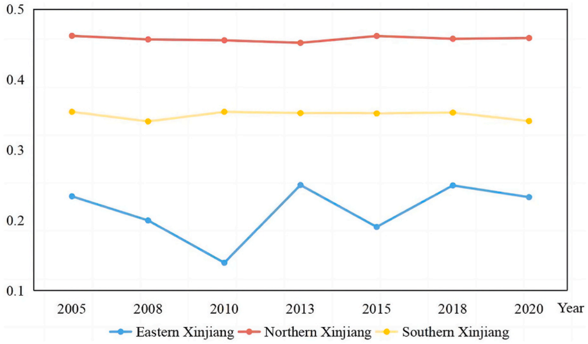
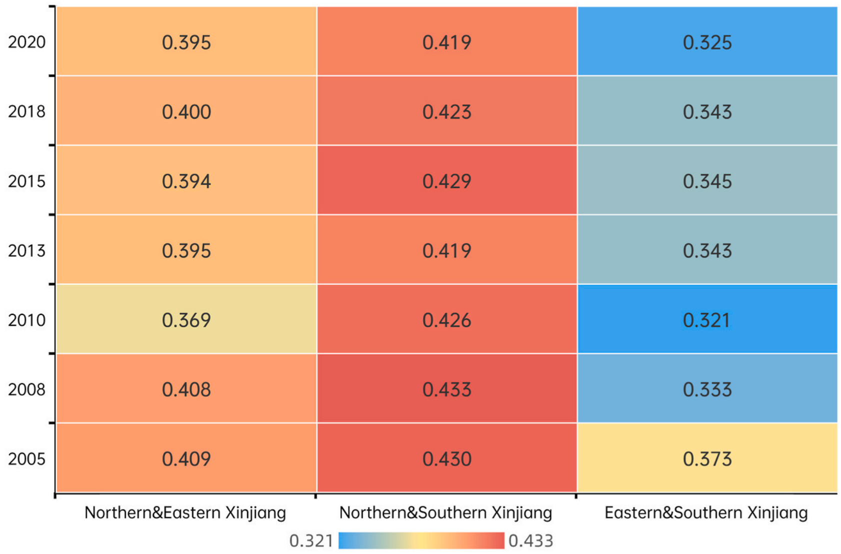


Fig. 7. Differential evolution of regional resource endowment/Gini coefficient within (G_w) in Xinjiang.



	Northern&Eastern Xinjiang	Northern&Southern Xinjiang	Eastern&Southern Xinjiang
2020	0.395	0.419	0.325
2018	0.400	0.423	0.343
2015	0.394	0.429	0.345
2013	0.395	0.419	0.343
2010	0.369	0.426	0.321
2008	0.408	0.433	0.333
2005	0.409	0.430	0.373

Fig. 8. Differential evolution of regional resource endowment/Gini coefficient within (G_b) in Xinjiang.

core area of the Silk Road Economic Belt, which is rapidly developing.

4.2.3. Equity analysis of natural capital utilization in Xinjiang

As shown in Table 5, *DG* changes in Xinjiang during the study period were subtle, approximately 0.4, which is at the critical value of spatial equilibrium. This indicates a significant gap in the use of natural resources in Xinjiang. The degrees of contribution were in the following order: $G_h > G_w > G_b$. From the trend of the evolution of intra-group differences (Fig. 7), the intra-group coefficient of variation in Southern and Northern Xinjiang has not fluctuated much, whereas the overall intra-group coefficient of variation in eastern Xinjiang mimics a “W" shape where it reaches a low point in 2010 and 2015 and then rises again. The intra-group Gini

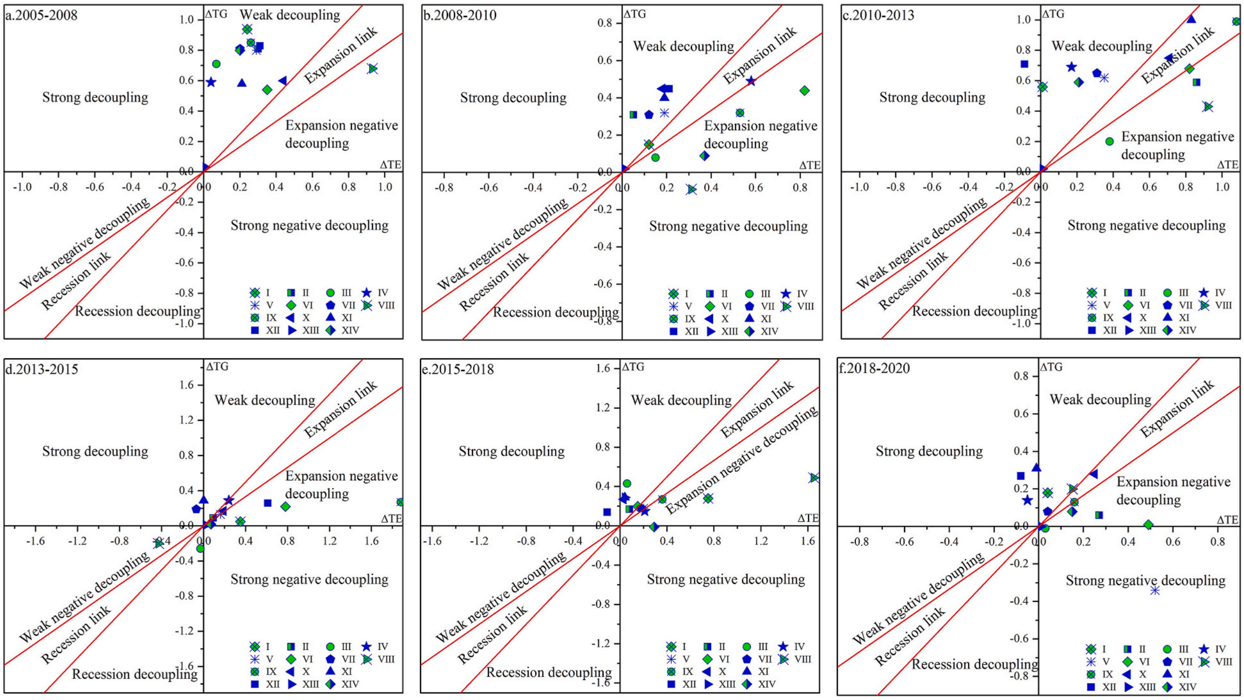


Fig. 9. Decoupling effects of natural capital utilization in Xinjiang (2005–2020).

coefficient of Northern Xinjiang was significantly higher than that of Southern and Eastern Xinjiang; therefore, the intra-group variation in Northern Xinjiang was more obvious. In terms of the trend of the evolution of the differences between groups (Fig. 8), the differences between the groups of Northern Xinjiang and Eastern Xinjiang were between 0.369 and 0.409, the differences between the groups of Northern Xinjiang and Southern Xinjiang were between 0.419 and 0.430, and the differences between the groups of Eastern Xinjiang and Southern Xinjiang were between 0.321 and 0.373, with relatively obvious and clear numerical gaps. The largest differences were between Northern and Southern Xinjiang, followed by Northern and Eastern Xinjiang. The smallest differences were observed between the Eastern and Southern Xinjiang groups. The reasons for this inter-regional economic disparity are related to fiscal expenditure/GDP, level of urbanization, and regional industrial output [56].

4.2.4. Decoupling effects of natural capital utilization in Xinjiang

Regarding the time-series changes, the decoupling status of natural capital utilization and economic growth effects in Xinjiang's cities and towns showed apparent changes over the six periods (Fig. 9). The overall decoupling relationship between environmental pressures and economic growth was relatively optimistic. The decoupling types in the six periods were dominated by weak decoupling, expansion links, and expansion negative decoupling, with the number of expansion links, expansion negative decoupling, and strong

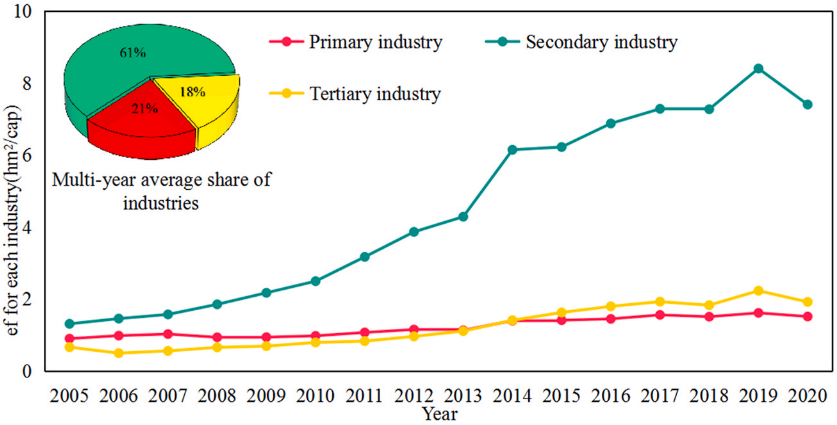


Fig. 10. Changes in the ecological footprint of each industry in Xinjiang and its share.

decoupling regions gradually increasing. Although these regions consume many resources, they are still experiencing economic growth. Some regions have reached the ideal state of strong decoupling. From 2008 to 2010 (Fig. 9b), the weak decoupling state changed more obviously, decreasing from 13 regions in the previous period (2005–2008) to eight regions (Fig. 9a), whereas the expansion of negative decoupling increased from one region to four regions. Xinjiang's ecological footprint expanded from 2013 to 2015 (Fig. 9d). In 2018–2020 (Fig. 9f), excessive economic growth brought about large-scale resource consumption, ecological pressure increased dramatically, and the expansion-negative decoupling status reappeared.

Regarding spatial change, from 2005 to 2008 (Fig. 9a), only Turpan (VIII) experienced expansionary negative decoupling, with the GDP growing at a lower rate than the *EF*. From 2008 to 2010 (Fig. 9b), only Turpan showed strong negative decoupling, with declining GDP whereas *EF* increased. This indicates that Turpan had the worst resource utilization during this period, with economic decline but increased ecological pressure. From 2010 to 2013 (Fig. 9c), Turpan turned to expansion-negative decoupling, and Kashi Prefecture (XII) turned to strong decoupling. This indicates that the ecological pressure in Turpan decreased slightly during this period. The development of the Kashi Prefecture's economy has a very low dependence on ecological pressure, and resources have reached sustainable utilization. From 2013 to 2015 (Fig. 9d), Turpan turned to weak negative decoupling and Karamay (III) turned to recession decoupling. This indicates that the two regions did not achieve sustainable resource utilization during this period. In contrast, Kizilsu Kyrgyz Autonomous Prefecture (XI) and Urumqi (VII) became strongly decoupled, achieving ideal economic development and resource utilization. From 2015 to 2018 (Fig. 9e), the difference in the decoupling index of most regions in Xinjiang gradually narrowed, with Kashi Prefecture returning to strong decoupling. From 2018 to 2020 (Fig. 9f), Kashi Prefecture, Kizilsu Kyrgyz Autonomous Prefecture, and Bortalla Mongol Autonomous Prefecture (IV) were in a state of strong decoupling, and sustained economic development was not at the expense of causing more ecological pressure. The Ili Kazakh Autonomous Prefecture (V) has experienced strong negative decoupling, with economic development and resource use in an undesirable state. There is a need to further optimize the structure of resource use to achieve an ideal decoupling state.

4.3. Analysis of ecological footprint evolution in Xinjiang from an industrial perspective

4.3.1. Decomposition of the industrial footprint in Xinjiang

As industries grow, their ecological costs also increase. Considering the variability in the ecological footprints of different industries, the proportion of total consumption of that type of land by industry becomes a valid basis for allocation. Therefore, this cost can be measured by different industries' occupation of ecological land resources. The primary industry mainly covers agriculture, forestry, animal husbandry, and fishery (excluding agriculture, forestry, animal husbandry, and fishery professional and auxiliary activities), directly occupying arable land, forest land, grassland, and water resources, and indirectly occupying energy. Secondary industries mainly include mining, manufacturing, electricity, heat, gas, and water production and supply, and construction. The tertiary sector is the service sector. Energy and construction land footprints are the major footprints of the secondary and tertiary industries. However, energy and construction land footprints involve major industries and need to be further disaggregated and calculated based on the proportion of resources consumed by each industry [54].

4.3.2. Analysis of changes in the ecological footprint of three major industries in Xinjiang

From 2005 to 2020, the multiyear average shares of the three major industries in Xinjiang were 21%, 61%, and 18%, respectively (Fig. 10). The ecological footprint of secondary industries accounts for the highest proportion, which is mainly reflected in industry-led activities. Primary industries have the second-highest ecological footprint share, whereas tertiary industries have the lowest. In other words, the secondary industry is the main contradiction affecting the ecological efficiency of industries in Xinjiang. From the dynamic changes in the ecological footprint of each industry, there were different degrees of increase. Among these, the ecological footprint of the secondary industry increased the most. The tertiary industry had the second largest increase at 188.9%. The primary industry showed a relatively small increase of 68%, consistent with the development speed of each industry. After 2013, the ecological footprint

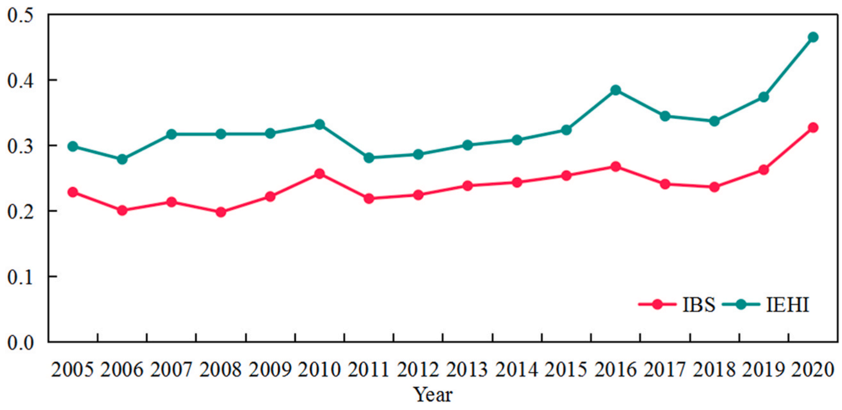


Fig. 11. Index of industrial structure efficiency and industrial-ecological harmony in Xinjiang.

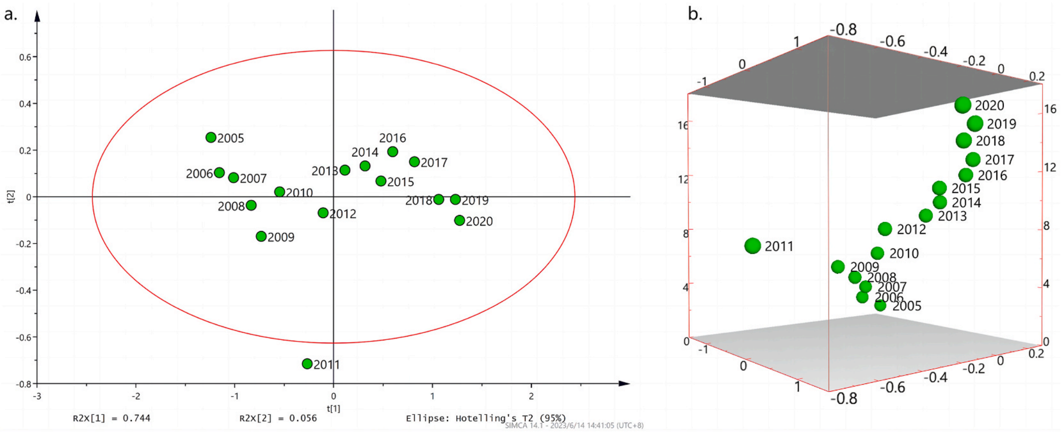


Fig. 12. T^2 tolerance ellipsoids (a) and three-dimensional (3D) distributions (b).

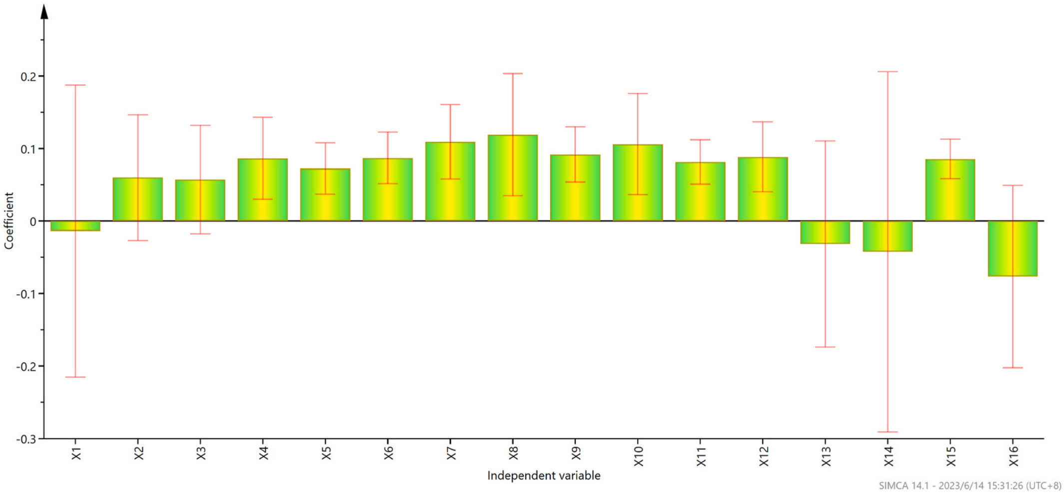


Fig. 13. Regression coefficients for the Partial Least Squares (PLS) model.

of the tertiary industry gradually became higher than that of the primary industry, becoming the second most dominant industry in Xinjiang, mainly dominated by the tourism industry. The footprint of the primary industry gradually became the smallest, indicating that the intensity of the resource pressure from the vigorous development of this industry was small, which is conducive to the protection of resources and the environment compared to other industries.

4.3.3. Analysis of the coordination between industrial structure and ecological environment in Xinjiang

Fig. 11 shows the trends in *ISB* and *IEHI* in Xinjiang from 2005 to 2020. The levels of *ISB* and *IEHI* in Xinjiang are still relatively low. However, the efficiency of industrial structures and ecological and environmental coordination are generally increasing. The *IBS* rose from 0.23 in 2005 to 0.33 in 2020, indicating that the degree of difference in labor productivity between industries gradually decreased. The leading industries in the region's current economic development are still concentrated in the secondary and tertiary industries, and the labor productivity gap between the primary, secondary, and tertiary industries gradually decreased. The rise in the *IEHI* indicates that Xinjiang's industrial development is gradually taking advantage of the region's ecological and environmental carrying potential and that the tendency of industrial development to exceed the carrying capacity of the ecological and environmental environment is weakening.

4.4. Drivers affecting natural capital utilization in Xinjiang

Considering the EF in Xinjiang during the study period as the dependent variable and the 16 indicators selected above as the independent variables, the data were entered into SIMCA 14.1 software for PLS analysis. First, the outliers were eliminated, except for 2011, which is located in the ellipse (Fig. 12a); the distribution of the remaining sample points is more concentrated (Fig. 12b), and all of them are located inside the ellipse. After eliminating the outliers and constructing the model again, the PLS regression model fitted

Table 6
Ranking of ecological footprint drivers.

Fact-ors	X_8	X_{10}	X_7	X_9	X_{11}	X_6	X_{12}	X_5	X_{15}	X_4	X_3	X_2	X_1	X_{14}	X_{13}	X_{16}
VIP value	1.14	1.14	1.13	1.12	1.12	1.12	1.12	1.11	1.11	1.11	1.09	1.09	1.01	0.93	0.34	0.25

well, and the results were highly reliable. As can be seen in Fig. 13, afforestation area (X_{13}), energy-saving and environmental protection expenditures (X_{14}), and technology market turnover (X_{16}) show a negative correlation with the ecological footprint. This indicates that they have an inverse driving effect on the ecological footprint, and the outputs confirm that, theoretically, resource endowment, environmental protection, and scientific and technological upgrades inhibit the growth of the ecological footprint.

The VIP value measures the strength of the influence of the driving factors on the ecological footprint. According to the analysis results of SIMCA 14.1, the VIP value of the model was obtained (Table 6). The total retail sales of consumer goods (X_8), per capita disposable income of urban households (X_{10}), daily average energy consumption (X_7), per capita disposable income of rural households (X_9), population at the year-end (X_{11}), total investment in fixed assets (X_6), urbanization rate (X_{12}), per capita GDP (X_5), expenditures on research and development (X_{15}), tertiary value added (X_4), value added of the secondary sector (X_3), value added of primary industry (X_2), and per capita ecological carrying capacity (X_1) all had VIP values greater than 1, which are significant drivers. The VIP value of energy conservation and environmental protection expenditure (X_{14}) was between 0.8 and 1, which is a generally important factor. The afforestation area (X_{13}) and volume of transactions in technical markets (X_{16}) was less than 0.8, which are unimportant factors. Overall, resource endowment, economic development, consumption structure, and population had significant driving effects on the ecological footprint, reflecting the significant influence of human activities on the ecological footprint. Environmental protection and improving science and technology, as effective ways to alleviate ecological pressure, can inhibit the growth of ecological footprint to a certain extent. However, the degree of input must be continuously increased.

5. Conclusion

Combined with the actual situation of Xinjiang's resource endowment, location, environment, and industrial structure, it is urgent to coordinate the region's sustainable development and establish an ecological and economic environment with harmonious coexistence. Based on regional, industrial, and economic differences, this study quantitatively analyzes the degree of natural capital utilization in Xinjiang using a localized 3D ecological footprint model. On this basis, we constructed a comprehensive evaluation model of regional "ecological-social-economic" sustainability and discussed the coordination relationship between different factors. The results showed that the *ef* of Xinjiang exhibits an overall fluctuating trend from 2005 to 2020, with energy land contributing the most. Moreover, economic development, consumption structure, and population expansion contribute to the growth of EF. Furthermore, environmental protection, science, and technology can inhibit the growth of the *ef* to a certain extent. Regarding the spatial distribution pattern, the multiyear *ef* of Northern and Eastern Xinjiang were generally higher than those of Southern Xinjiang. The equity in natural capital utilization results revealed that the intra-group Gini coefficient is significantly higher in Northern Xinjiang than in Southern and Eastern Xinjiang. High-value areas of *ed* occur in the economic zone on the northern slopes of the Tianshan Mountains and in the cities of Turpan and Hami in Eastern Xinjiang. In contrast, the medium- and low-value areas were located in Southern Xinjiang and the Altay region in Northern Xinjiang, respectively. By 2020, only Kizilsu Kyrgyz Autonomous Prefecture was in ecological surplus. In terms of interannual and cumulative impacts, the state of ecological sustainability gradually shifted from mild to high ecological overload. However, the overall decoupling of environmental pressures from economic growth was more positive. It is worth noting that the Turpan region experienced economic decline but increased ecological stress. Economic development and resource use in the Karamay and Ili Kazakh Autonomous Prefectures were suboptimal in some years. From an industrial perspective, the degree of coordination between industrial structure and resource pressure was low, but the overall trend was upward. Xinjiang's industrial structure has been continuously adjusted and is developing steadily and favorably; however, the intensity of the adjustment is low.

6. Discussion

The development of the ecological footprint method has been the direction of model optimization to more accurately quantify the actual status of regional natural capital utilization and flow [57]. Therefore, this paper quantifies the degree of natural capital utilization through the regional-industrial perspective and constructs a sustainability analysis of the coordinated development of "ecology-economy-society" based on the background of uneven development in Xinjiang. By comparing the results of this paper with those of related research in Xinjiang, it is found that the results of this paper have less deviation or the overall trend of increase or decrease in the *ef*, *ec*, and the *ed* of Xinjiang as a whole or of prefectural and municipal cities in the same period as those of Li et al. [1], Yue et al. [29], Zhang et al. [58], and Xu et al. [59]. The overall trend of increase and decrease is basically the same. Some of the deviations may be due to the different selection of equivalence and yield factors and the differences in the accounting items of biological accounts. In addition, due to data availability, Xinjiang municipalities have been excluded from the calculation of administrative units for the time being. This may overlook the special ecological problems and challenges of these regions. Therefore, there is a great need to explore the ecological footprint methodology to account for natural capital more applicable to Xinjiang and unified accounts in later studies. As far as possible, all relevant factors should be considered to ensure the study results' accuracy and comprehensiveness. Furthermore, fossil energy is a dominant resource that Xinjiang is self-sufficient in, and the energy footprint has consistently been a decisive part of the ecological footprint over the study period, accounting for approximately 86% of the ecological footprint share in 2019. This paper has only explored the extent to which various types of biologically productive land use contribute to the ecological footprint, whereas Xinjiang itself is rich in resources, and as an energy outflow region, the resources themselves can be considered as a means to offset the ecological deficit, and to some extent Xinjiang's fossil energy sources can be regarded as a kind of ecological capacity, so deeper research is yet to be carried out from this perspective.

As a resource-based province and in a critical period of economic development transition, Xinjiang still has a significant, rigid demand for economic output [19]. Overall, the environmental value consumed in Xinjiang is hardly equal to the economic value it creates, and the ecological deficit tends to increase further. In the long run, a large amount of consumption of ecosystems will be formed, leading to decreased ecological use efficiency. In turn, it is bound to be constrained by the resource environment in industrial development. Therefore, strong measures must be taken to alleviate the pressure on the ecology caused by human activities and achieve the coordinated development of Xinjiang's economy, ecology, and society. Some studies have shown that high-intensity environmental regulation in Xinjiang can optimize industrial structure and promote high-quality economic growth by forcing enterprises to innovate [60]. Therefore, in view of the existing problems, the industrial structure can be adjusted by combining the relevant regional policies and the market, improving the industrial technology efficiency and energy consumption threshold, and increasing the capital investment in environmental protection. In addition, as an essential energy production base in China, Xinjiang's energy footprint is also a significant contributor to its ecological footprint. Energy is a driving force for economic and social development and a source of environmental pollution. It can have a profound impact on the environment and climate. Currently, the focus of slowing down the energy footprint growth is to promote the continuous decline of energy intensity through technological progress [61]. At the same time, changing the energy structure dominated by coal, increasing the use of clean energy, and developing low-carbon renewable energy, inhibiting the energy footprint growth. When promoting urbanization, it is also necessary to moderately control the size of the population in line with the ecologically suitable population and rationally distribute the population. This will narrow the regional development gap and effectively alleviate the pressure of population growth on the ecological environment.

Data availability

Data will be made available on request. The data used in this study are all publicly available and are detailed in the data description.

Ethics declarations

Review and/or approval by an ethics committee was not needed for this study because all participants are not involved in ethical research.

CRediT authorship contribution statement

Mengting Jin: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Peng Guo:** Supervision, Project administration, Funding acquisition. **Quan Xu:** Writing – review & editing, Supervision, Software. **Yanjun Ba:** Software, Data curation. **Xuan Wang:** Software, Resources.

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.

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