Postprint: Driving Factors of Ecological Footprint Change in the Guanzhong-Tianshui Economic Zone

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Abstract

Revealing the driving factors that influence changes in the ecological footprint of the Guanzhong-Tianshui Economic Zone is of significant importance for establishing an energy-efficient industrial structure and pursuing coordinated development among economy, environment, ecology, and society. Employing the ecological footprint method and partial least squares (PLS) method, and based on the calculated ecological footprint of the Guanzhong-Tianshui Economic Zone from 2005 to 2014, the variable importance in projection (VIP) and standardized coefficients of PLS were determined to compare the relative importance of various driving factors. The results indicate that the more significant driving factors affecting ecological footprint changes include the added value of the tertiary industry, gross domestic product (GDP), and total retail sales of consumer goods. By contrast, cultivated land area and total regional population exert no significant driving effect on the ecological footprint of the Guanzhong-Tianshui Economic Zone. Accordingly, policy recommendations are proposed, including the organic integration of industrial structure optimization with energy structure optimization, transformation of energy utilization modes, improvement of energy utilization efficiency, enhancement of land use efficiency, strengthening of land protection, increase of land ecological carrying capacity, guidance of low-carbon consumption behaviors, and promotion of low-carbon lifestyles.

Full Text

Preamble

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Driving Factors of Ecological Footprint Changes in the Guanzhong-Tianshui Economic Zone

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Abstract

Identifying the driving factors behind ecological footprint changes in the Guanzhong-Tianshui Economic Zone is crucial for establishing an energy-efficient industrial structure and promoting coordinated development among economy, environment, ecology, and society. Based on ecological footprint data for the zone from 2005 to 2014, this study employs ecological footprint analysis and partial least squares (PLS) regression to determine variable importance in projection (VIP) and standardized PLS coefficients, thereby comparing the relative importance of various driving factors. The results indicate that the most significant drivers of ecological footprint change are tertiary industry added value, gross domestic product (GDP), and total retail sales of consumer goods, while cultivated land area and total population show less pronounced effects. Accordingly, we propose integrating industrial structure optimization with energy structure optimization, transforming energy utilization patterns, improving energy efficiency, strengthening land protection, enhancing land ecological carrying capacity, and promoting low-carbon consumption behaviors and lifestyles.

Keywords: ecological footprint; driving factors; partial least squares; Guanzhong-Tianshui Economic Zone

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1. Introduction

As a quantitative method for reflecting human utilization of natural resources, ecological footprint analysis converts regional resource and energy consumption into the biologically productive land area required to support these material flows [1-2] and has been widely applied in studies of ecological status and sustainable development [3-4]. Analyzing the driving factors of ecological footprint change helps us understand the extent to which socioeconomic development impacts the ecological environment. From a national perspective, China' s rapid industrialization and heavy chemical industrialization between 2000 and 2010 made industry the dominant driver of ecological footprint change [5]. In terms of energy consumption alone, industrial energy use is generally considered to far exceed that of other sectors, leading to the proposition that industries with large output value or energy consumption proportions contribute most to driving ecological footprint changes. However, research findings present a more nuanced picture. Jia Junsong' s study of Henan Province showed that the tertiary sector dominated ecological footprint changes from 2000 to 2013, with transportation activities having a particularly significant driving effect—growth in unnecessary and inefficient transport substantially increased the ecological footprint [6]. Similarly, Ma Mingde et al. found that in Ningxia, a resource-based heavy industry province, the primary industry had higher elasticity in ecological resource occupation than other sectors from 1995 to 2010 [7]. Both Henan and Ningxia are industry-dominated provinces, yet the industries driving ecological footprint change were not the industrial sectors themselves. The rapid development of the tertiary industry not only significantly drives transportation carbon emissions and energy consumption [8] but also promotes energy consumption growth in the construction sector [9], both of which significantly impact ecological footprint changes.

In practice, while the secondary industry exceeds the tertiary industry in both output value and total energy consumption, it is important to note that China promulgated its first industrial emission trial standard in 1973, and industrial environmental protection has remained a focus of domestic environmental policy [10]. In recent years, policies such as the *Industrial Energy Conservation Management Measures*, industry-specific eco-industrial park standards, comprehensive eco-industrial park standards, clean production standards for the semi-coke industry, and the *Industrial Green Development Plan (2016-2020)* have effectively constrained the ecological occupation of the secondary industry, reducing its role in driving ecological footprint increases to some extent. Nevertheless, ecological security risks arising from environmental problems in the tertiary industry cannot be ignored. According to the National Bureau of Statistics' *2013 National Economic and Social Development Statistical Bulletin*, the secondary and tertiary industries accounted for 43.9% and 46.1% of GDP, respectively. By 2015, this shifted to 40.5% and 50.5%, with the tertiary industry' s share exceeding the secondary industry' s for the first time. Will this industrial structural transformation bring changes in ecological footprint driving factors?

Compared with the secondary industry, the tertiary industry has lower resource demand and generates fewer waste products, making it a resource-saving and environmentally friendly industry [11]. The low-carbon development of the tertiary industry helps reduce regional ecological footprints [12]. The Guanzhong-Tianshui Economic Zone is a national-level economic zone in northwest China supported by secondary industry clusters. The added value of the secondary industry has consistently accounted for 51.39% of the zone' s GDP, remaining the dominant force in economic and social development. Does the secondary industry also dominate ecological footprint changes? What are the driving effects of other factors on the ecological footprint? This study combines the industrial structure and socioeconomic development status of the Guanzhong-Tianshui Economic Zone, applying ecological footprint analysis and partial least squares regression to investigate the driving factors affecting ecological footprint changes.

2. Study Area Overview

The Guanzhong-Tianshui Economic Zone occupies a strategically important location connecting eastern and western China and linking north and south. The zone covers an area of 79,600 km^2, encompassing Xi' an, Baoji, Xianyang, Weinan, Tongchuan, and Shangzhou districts in Shaanxi Province, as well as Zhashui and other counties and districts and Tianshui City in Gansu Province. The region has a warm temperate semi-arid or semi-humid climate, with the Wei River valley as its central axis. To the north lies the loess plateau hilly region of northern Shaanxi, while the Qinling Mountains form the southern boundary. North of the Qinling Mountains are the Wei River tributaries of the Yellow River basin, while to the south are the Jialing, Dan, and Han River tributaries of the Yangtze River basin.

Since the implementation of the Western Development Strategy, industrialization in the zone has achieved remarkable results. In 2015, the Guanzhong-Tianshui Economic Zone realized a GDP of 432.28 billion yuan and total social fixed asset investment of 229.1 billion yuan. However, rapid economic growth has brought environmental protection and resource consumption challenges. From 2005 to 2015, energy consumption grew at an average annual rate of 7.59%. The coal-dominated energy structure and heavy chemical industry trend will likely persist for a considerable period [13]. Urbanization has directly stimulated demand for urban construction land, while land reserve resources show a declining trend. Wetlands around the Wei River have experienced large-scale shrinkage, and water quality in some tributaries remains inferior to Class V standards. The zone' s cultivated land area decreased from 2,095.09 thousand hectares in 2005 to 2,052.90 thousand hectares in 2015, and biodiversity has been compromised. The region' s ecological carrying capacity situation is not optimistic.

Existing studies have employed methods such as STIRPAT and general multiple linear regression to analyze ecological footprint driving factors [14-15]. However, traditional regression models cannot overcome the problem of multicollinearity among variables [16], lack research on the internal mechanisms affecting ecological footprints, and include relatively few impact factors in the models, failing to comprehensively reflect the mutual influence between ecological footprints and socioeconomic indicators [17-18]. The PLS model overcomes limitations such as multicollinearity and insufficient sample points by identifying and filtering noise in data information and extracting variables with stronger explanatory power for dependent variables [19-20].

3. Research Methods

3.1 Partial Least Squares Regression

In multiple linear regression, we construct data matrices where the independent variable set X and dependent variable set Y are n×p and n×m matrices, respectively, assuming p dependent variables y ···y and m independent variables x ··· x . The basic PLS method first extracts the first component t from the independent variable set X and the first component u from the dependent variable set Y. These components are linear combinations of their respective variables that carry the variation information in data matrices X and Y. Simultaneously, t must have strong explanatory power for u —the stronger the explanatory power of the independent variable' s linear component t for the dependent variable' s component u , the stronger the model' s explanatory capacity.

Model accuracy is often tested using cross-validation. After extracting the first component t to establish the regression of X on t and Y on u , if the regression equation meets the accuracy requirement (Q^2 0.0975), the algorithm terminates. Otherwise, the process continues by calculating and refining the unexplained parts of the variables until the extracted components can significantly explain the variable variation in regression analysis. Ultimately, r components t ···t are extracted from data matrix X, and the model establishes regression equations between y and t ···t , then between y and x ···x .

Variable importance in projection (VIP) is commonly used to measure the importance of each independent variable' s effect on the dependent variable. VIP represents an indirect relationship calculated through principal components and weights, reflecting an independent variable' s explanatory power. The larger the weight of an independent variable in the principal component and the larger the variance ratio, the stronger its influence on the dependent variable. When a variable' s VIP > 1, it can be considered a significant influencing factor with strong driving effect; when $0.5 <$ VIP < 1, the factor has moderate importance; and when VIP < 0.5, the independent variable is considered relatively unimportant with weak driving capacity [21].

3.2 Model Indicator Selection

Xu Zhongmin et al. introduced the indicator of ecological footprint per 10,000 yuan GDP when evaluating sustainable ecological carrying capacity [22]. Liu Jianxing et al., taking the ecological footprints of primary, secondary, and tertiary industries as research objects, concluded that industrial structure has a certain impact on ecological footprint [23]. Li Yiqiong et al. selected socioeconomic variables such as resident consumption level, proportion of secondary industry, industrial profits above designated size, and total social fixed asset investment as factors influencing ecological footprint change [24-25]. Wang et al., from a spatial difference perspective, found that due to regional characteristics, China' s eastern coastal areas generally have larger ecological footprints [26].

Regarding selected driving factors in existing research, GDP, as a macro indicator reflecting overall regional economic development status, has a strong impact on ecological footprint. Industrial structure can reflect the relationship between regional economic development and ecological resource utilization, land occupation, and other ecological conditions, demonstrating ecological resource supply and demand. Total social fixed asset investment can reflect regional industrial structure characteristics to some extent. Gross industrial output value above designated size mainly reflects local industrial enterprises' consumption of ecological resources. Total population can be used to study the impact of regional population size on ecological resource consumption [27]. The urbanization rate can reflect how changes in regional population composition affect the ecological environment [28]. Rural per capita consumption expenditure can reflect how consumption by different social groups impacts the regional ecological environment. Total import and export volume shows how trade level changes affect the ecological environment. Cultivated land area considers land use impacts.

Given data availability and statistical consistency, this study selects indicators across three dimensions: economic, social, and land use. Economic indicators include added values of the three industries, total social fixed asset investment, and gross industrial output value above designated size as structural indicators, with total retail sales of consumer goods as a quantity indicator. Regarding population data, the ratio of urban to rural population only exists in census years and cannot form time series data reflecting regional population structure changes, so this ratio was excluded, retaining only total population. Municipal statistics lack detailed consumption expenditure data for urban and rural residents, so per capita net income of urban and rural residents was used as a substitute, with total retail sales of consumer goods reflecting regional consumption status. For land use, cultivated land area was selected as the indicator reflecting land structure. Since regional import and export trade adjustments were not made in the ecological footprint calculation, indicators such as total import and export volume were not included in the ecological footprint driving factor model. The total regional ecological footprint was used as the dependent variable Y, with the indicators listed in Table 1 as independent variables.

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4. Data Sources and Processing

Research data were obtained from the *Shaanxi Statistical Yearbook* (2006-2015), *Gansu Statistical Yearbook* (2006-2015), and the *National Economic and Social Development Statistical Bulletins* of various cities and counties in the Guanzhong-Tianshui Economic Zone (2006-2015). Zhen' an, Shangnan, and Shanyang counties in Shangluo City do not belong to the Guanzhong-Tianshui Economic Zone, but given their relatively small economic aggregate and resource consumption, Shangluo City data were used to represent these three counties and Shangzhou district. Crop production data were used as substitutes for agricultural product consumption to ensure consistent statistical 口径.

shows the selected indicators for ecological footprint driving factors.

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5. Ecological Footprint Calculation and Analysis

The ecological footprint calculation results for the Guanzhong-Tianshui Economic Zone show that from 2005 to 2014, per capita ecological footprint exhibited a growth trend, increasing from 1.796 hm^2 to 3.117 hm^2, with a growth rate of 73.55% and an average annual growth rate of 6.32% (Figure 1). During 2005-2015, the proportion of secondary industry added value remained at 51.39%, higher than other industries. With advancing urbanization and industrialization, the intensity of resource occupation and pollution emissions further increased, leading to a corresponding rise in ecological footprint.

[Figure 1: see original paper] shows the changing trend of per capita ecological footprint in the Guanzhong-Tianshui Economic Zone from 2005 to 2014.

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6. Results Analysis

6.1 Model Results and Analysis

The per capita ecological footprint calculation results for various accounts in the Guanzhong-Tianshui Economic Zone from 2005 to 2014 show that fossil energy land has the largest mean per capita ecological footprint at 1.271 hm^2, followed by arable land ecological footprint at 0.353 hm^2, construction land at 0.040 hm^2, water areas at 0.274 hm^2, and pollution absorption land at 0.017 hm^2 (Table 2). Fossil energy accounts constitute the main component of ecological footprint, with pollution absorption land accounting for 51.39% of the total and showing an upward trend, indicating unbalanced ecological footprint distribution.

Cross-validation Q^2 = 0.9604 > 0.0975, indicating that extracting one component t significantly improves model precision. The PLS model' s explanatory power for the dependent variable is 97.26%. Therefore, the calculation extracts one component t . Cross-validation Q^2 = -0.4484 < 0.0975, so the algorithm terminates after extracting component t .

shows the per capita ecological footprint by account category in the Guanzhong-Tianshui Economic Zone from 2005 to 2014.

Outlier analysis was conducted to further confirm model reliability. According to the outlier identification principle, the t /t ellipse plot was drawn to identify outliers. All sample points were distributed inside the ellipse, indicating no outliers and ensuring sample quality. Therefore, the selected independent variables require no modification.

6.2 Variable Importance Analysis

VIP values were used to measure the importance of each driving factor for ecological footprint change. Figure 3 shows the VIP values for ecological footprint impact factors obtained from the model, arranged in descending order of importance: tertiary industry added value, total retail sales of consumer goods, GDP, per capita disposable income of urban residents, gross industrial output value above designated size, secondary industry added value, total social fixed asset investment, primary industry added value, per capita net income of rural residents, cultivated land area, and total population. All driving factors except cultivated land area and total population have VIP values greater than 1, indicating they are significant influencing factors with strong driving effects. The remaining indicators have relatively similar driving effects on ecological footprint change.

[Figure 2: see original paper] shows the t /t ellipse plot.
[Figure 3: see original paper] shows the variable importance in projection output.

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7. Conclusions

The driving factors affecting ecological footprint change in the Guanzhong-Tianshui Economic Zone, in order of importance, are: tertiary industry added value, total retail sales of consumer goods, GDP, per capita disposable income of urban residents, gross industrial output value above designated size, secondary industry added value, total social fixed asset investment, primary industry added value, per capita net income of rural residents, cultivated land area, and total population.

Regarding economic indicators, tertiary industry added value has the most significant driving effect on ecological footprint, while secondary industry added value' s driving effect is less than that of the tertiary industry but still significantly impacts ecological footprint change. The secondary industry accounts for 51.39% of GDP and continues to rise. The rapid socioeconomic development of cities within the Guanzhong-Tianshui Economic Zone benefits from industrial enterprises' operations, which consume large amounts of energy resources and emit substantial pollutants, causing significant increases in fossil energy accounts and pollution emission accounts. However, as the leading industry, the secondary industry' s driving effect on ecological footprint is surpassed by the tertiary industry, creating a phenomenon where the dominant economic sector does not dominate ecological footprint driving factors. More importantly, policies such as the Wei River comprehensive management and elimination of backward production capacities have played crucial roles in constraining the secondary industry' s ecological occupation.

In terms of population and land, total population is positively correlated with ecological footprint change, reflecting that ecological footprints primarily originate from human activities. The driving effect of cultivated land area on ecological footprint is not strong. On one hand, urban development occupies considerable cultivated land, reducing its area and thus the ecological footprint from agriculture. On the other hand, urban expansion increases construction land, raising its ecological footprint. These two effects offset each other, resulting in no substantial change in total ecological footprint.

Regarding social consumption, urban consumption has a stronger driving effect than rural consumption. As income levels rise, consumption structures for products such as meat, eggs, milk, and other goods and services are changing, with consumption quantities gradually increasing. High-income groups have lower dependence on public transportation, and the proportion of private vehicles is relatively high, leading to increased energy consumption. With improving quality of life, the number of household appliances such as refrigerators is also rising synchronously, increasing carbon consumption.

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8. Countermeasures and Suggestions

8.1 Integrate Industrial and Energy Structure Optimization

We should organically combine industrial structure optimization with energy structure optimization, strengthen policy supervision and energy management for the tertiary industry' s ecological environment, and conduct energy audits and energy conservation actions in the service sector. Taking the construction of low-carbon tourism scenic areas and development of low-carbon tourism as objectives, we should integrate tourism resources, optimize tourism routes, and form a Silk Road tourism corridor combining historical culture with natural ecology. We should promote energy-efficient buildings, reduce building operation energy consumption, carry out energy-saving renovations of energy systems for large public buildings and public institution offices (including heating, air conditioning, and hot water systems), and promote large-scale application of distributed solar and geothermal energy.

8.2 Improve Energy Utilization Efficiency and Transform Energy Use Patterns

Fossil energy accounts constitute 51.39% of the ecological footprint in the Guanzhong-Tianshui Economic Zone, with the coal proportion consistently maintained at 70%-80%. We should strictly control coal increments, implement comprehensive regional resource and energy management, establish and improve the "dual control" system of energy consumption intensity and total energy consumption, and reduce the consumption proportion of high-carbon fossil energy such as coal. Focusing on key industries such as Xi' an and Tianshi as industrial concentration areas, we should promote industrial boiler energy efficiency testing, residual heat and pressure utilization, motor system energy-saving renovation, and energy system optimization projects. We should vigorously develop and utilize clean energy such as geothermal and wind power, focusing on developing modern wind power equipment components and industrialization projects.

8.3 Strengthen Land Protection and Enhance Land Ecological Carrying Capacity

In promoting new urbanization in the Guanzhong-Tianshui Economic Zone, we should demarcate ecological protection red lines based on ecological function importance and ecological environment sensitivity/vulnerability, using these red lines as the foundation for spatial planning. We should clarify management responsibilities, strengthen use regulation, and enhance monitoring and supervision. To avoid encroaching on high-quality cultivated land and ensure existing productive land is not abandoned or encroached upon by urban construction, we should improve the utilization efficiency of biologically productive land. We should adhere to mountain closure for grazing bans and afforestation, strengthen farmland water conservancy facility construction, convert wasteland to arable land through irrigation, and focus on maintaining and improving the health of forest and grassland ecosystems, using the Loess Plateau as an ecological barrier.

8.4 Guide Low-Carbon Consumption Behavior and Promote Low-Carbon Lifestyles

We should guide the development of green transportation in the Guanzhong-Tianshui Economic Zone, taking the lead in planning and constructing public bicycle transportation networks in the Guanzhong urban agglomeration, and strengthening the construction of non-motorized vehicle lanes and sidewalks. Based on the three-year action plan for Wei River basin water pollution prevention and control, we should improve domestic sewage treatment capacity, ensure the treatment rate of urban sewage treatment plants, and prioritize sewage recycling and reuse. We should establish domestic waste and other waste recycling systems and promote pilot construction for resource utilization and harmless treatment of kitchen waste.

It should be noted that accurately calculating energy account ecological footprints according to the energy consumption status of primary, secondary, and tertiary industries would help deepen understanding of energy-saving industrial structures. However, due to limitations in China' s current energy statistics system, which cannot yet reflect energy consumption status by industry type, the precision of research results is constrained by data source limitations.

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