

Dynamic Evolution and Driving Mechanisms of Green GDP: Provincial Evidence from China

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Abstract. This study constructs a comprehensive Green GDP accounting framework encompassing economic, resource, and environmental dimensions. Based on data from 2010–2022 for 31 provinces in mainland China and using an entropy weighting method to determine indicator weights, provincial Green GDP values are calculated. The results indicate that Green GDP and conventional GDP rise in tandem, with the former expanding at a marginally faster rate; meanwhile, the environmental-cost component exhibits a gradual decline over time. A structural inflection is observed around 2015–2016, after which growth patterns shift, and significant regional disparities in Green GDP are apparent. An ARIMA model forecast shows the gap between Green GDP and conventional GDP narrowing gradually from 17.4% in 2022 to 12.9% in 2028. Panel fixed-effects analysis reveals that economic scale is the primary driver of Green GDP growth; industrial structure upgrading exhibits a short-term “decline-then-rise” effect on Green GDP, and rapid urbanisation exerts additional environmental pressure. By integrating economic, resource, and environmental factors, this research offers a holistic and innovative approach to evaluating sustainable development. The entropy-based weighting and the combination of time-series forecasting with panel analysis represent methodological advances, and the findings not only enrich the theoretical understanding of Green GDP dynamics but also carry practical implications.

Keywords: Green GDP, Entropy Weight Method, Environmental Benefits, Regional Heterogeneity, Fixed-Effects Model.

1. Introduction

Rapid economic growth often incurs environmental degradation and resource depletion, which traditional GDP fails to reflect. Green GDP has emerged as a more comprehensive indicator by adjusting GDP to account for ecological costs and benefits.

The construction of a Green GDP accounting framework and its methodological refinement are core issues in the field of sustainable development. Domestic and international scholars have undertaken multi-dimensional explorations based on the UN’s System of Environmental-Economic Accounting (SEEA). For example, Xu Jiayin (2024) proposed a revised model on the basis of traditional GDP that incorporates natural resource depletion (water resources, energy, minerals), environmental pollution losses (treatment costs, environmental degradation), and positive resource-environment benefits (waste reuse) [1]. Zhou Yuting (2023), based on the SEEA framework and focusing on Jiangxi Province, designed a customised indicator system that refines resource depletion into energy, minerals (such as copper and pyrite), and land resources; includes environmental governance inputs covering urban infrastructure and industrial pollution controls; and innovatively adds ecological protection benefits (such as forestry investment and solid waste recycling) [2]. Duan Ling (2023), taking Sichuan Province as a sample, used a resource-environment value loss method to build an accounting model focusing on cultivated land and water resource depletion, dividing pollution losses into actual treatment costs and implicit costs (such as health losses from air pollution), and for the first time included “life-extension benefits” in the environmental improvement account [3]. Yang Kaili (2022), targeting the resource-based city of Datong, refined accounting methods for

energy depletion (converted to standard coal equivalent), changes in cultivated land, and water resource depletion within the SEEA-2012 framework, and proposed a model $\text{Green GDP} = \text{Traditional GDP} - \text{Resource Depletion} - \text{Environmental Loss} + \text{Ecological Improvement Benefit}$ [4]. Dong Han (2024) adopted an international comparative perspective, selecting data from China, the US, Japan, and others, and applied principal component analysis (PCA) to reduce the dimensionality of natural resource depletion indicators (such as forest rent, cultivated land area), constructing a cross-country Green GDP accounting model [5]. In summary, existing research has followed a progressive path of “theoretical framework – regional adaptation – methodological innovation,” but breakthroughs are still needed in monetising ecological service values and ensuring cross-regional comparability of indicators. It is necessary to combine big data technologies and policy tools to promote the standardisation and practical implementation of Green GDP accounting.

In China, growing emphasis on sustainable development has renewed interest in such measures. This study constructs a five-dimensional Green GDP accounting system for 31 provinces from 2010 to 2022, integrating economic, resource, and environmental data. It examines temporal trends, regional disparities, and the role of industrial transformation, providing empirical insights for green policy-making.

2. Theoretical Foundation

2.1. Construction of Accounting System

For the construction of the green GDP accounting system, this study selects five first-level indicators, with multiple specific second-level indicators under each, covering the economic, resource, and environmental systems, providing a basic framework for green GDP accounting. The specific accounting system is shown in Table 1:

Table 1. Green GDP Accounting Indicators and Data Source

Category of Accounting Indicators	Data Indicators for Accounting
Traditional National Economy	GDP of each province
Natural Resource Depletion Value	Cultivated land area of each province Forest resources of each province Energy consumption of each region Total water consumption of each region
Environmental Degradation Cost	Emission cost of waste gas pollutants in each province Cost of wastewater pollutants in each province Emission cost of industrial solid waste in each region Investment in environmental infrastructure construction in each region
Environmental Governance Investment	Investment in environmental pollution control in each region Investment in forestry construction and management in each region Investment in geological disaster prevention and control in each region
Environmental Benefits	Output value of comprehensive utilization of "three wastes" by enterprises in each region

The traditional national economy is the core indicator of national economic accounting, reflecting the total economic output and growth of each region, with advantages of high standardization, strong international comparability, and authoritative and reliable data sources.

Natural resource depletion value corresponds to four secondary indicators: cultivated land area, forest resources, energy consumption, and total water consumption of each province. It quantifies the impact of natural resource consumption on economic development and reflects the resource and

environmental costs of economic growth, making up for the shortcomings of traditional GDP accounting by incorporating natural resources into the economic accounting system.

Indicators under environmental degradation cost include emission costs of waste gas, wastewater pollutants, and industrial solid waste, which are used to assess the economic losses caused by environmental pollution, including air, water, and soil pollution. They can quantify the economic costs of environmental damage and provide a basis for environmental governance decisions.

Environmental governance investment includes investment in environmental infrastructure construction, environmental pollution control, forestry construction and management, and geological disaster prevention and control in each region, reflecting the capital investment in environmental protection and ecological restoration, embodying the principle of "who pollutes, who governs," and quantifying the economic value of environmental protection investment.

The environmental benefit indicator is mainly the output value of comprehensive utilization of "three wastes" by enterprises, which measures the economic benefits generated by resource utilization of waste, embodies the value of circular economy, and encourages enterprises to carry out comprehensive resource utilization.

2.2. Accounting Process

Based on the constructed green GDP accounting system, the specific accounting methods are further introduced below, mainly including data collection, data preprocessing, and model construction. The specific accounting process is shown in Figure 1:

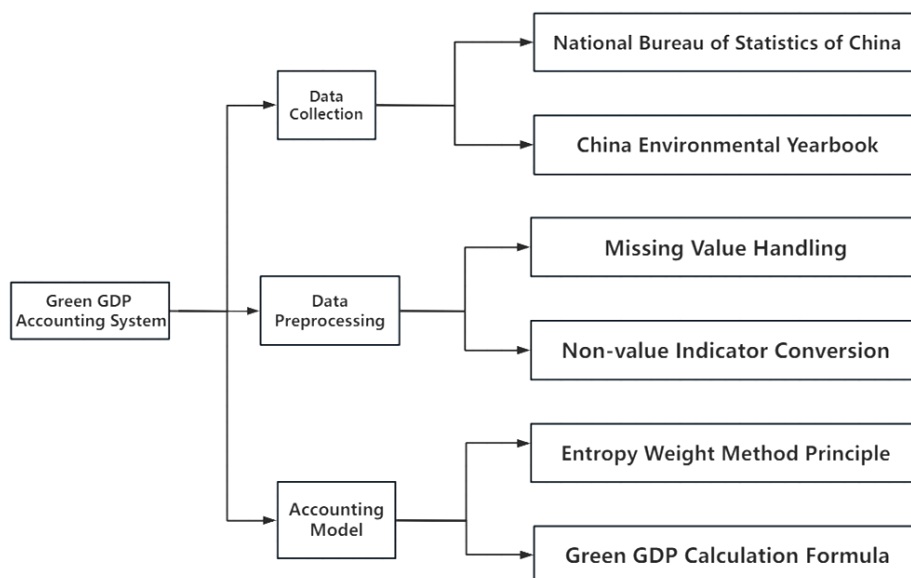


Figure 1. The accounting process of green GDP

3. Descriptive Analysis of Green GDP Accounting Results

3.1. Data Overview and Descriptive Statistics

Using Green GDP accounts for 31 provinces (2010–2022), this paper compare traditional GDP, environmental costs, and Green GDP. China's Green GDP increased by $\sim 3.17\times$ (Figure 1), above the $\sim 2.75\times$ rise in conventional GDP, implying faster growth of net output after deducting environmental costs, consistent with Yin Xiangfei [6].

The environmental-cost share in GDP declined year by year, indicating lower cost per unit of GDP and a greener growth model, in line with stronger environmental governance and ecological-civilisation policies. The World Bank once estimated pollution losses at $\sim 3.05\%$ of GDP in 2004. With higher environmental investment and technological progress, losses from degradation fell and the Green-to-total GDP share rose.

Regional differences are pronounced. In 2022, environmental costs were ~7% of GDP in Shanghai (lowest nationwide) but exceeded 30% in resource-dependent Xinjiang and Shanxi, meaning a sizable portion of output is offset by environmental losses. Accordingly, the coefficient of variation is higher for Green GDP (~0.86) than for GDP (~0.81). As noted by Shen Xiaoyan et al. (2017), divergent cost burdens widen green-output gaps [7]. Developed, service-oriented regions with greater green investment keep lower cost shares and higher Green-GDP levels and growth; resource-based, less-developed regions with pollution- and energy-intensive industries bear heavier burdens and have weaker sustainability [8].

3.2. Analysis of Green GDP Volatility

The volatility of Green GDP can be depicted by changes in its year-on-year growth rate. Figure 2 shows the trend of China’s annual Green GDP growth rates from 2011 to 2022. Year-on-year growth of Green GDP follows a “down–up–down” path: ~21.5% in 2011, easing to ~7% by 2015 with the macro downshift (“new normal”); recovering to 8–10% during 2016–2019 (around 9%); dropping to 2.6% in 2020 amid COVID-19; rebounding to ~14.1% in 2021; and easing to 6.1% in 2022. The mean is ~10.2% (SD ~4.8; CV 0.47) versus GDP’s ~8.9% (CV 0.46), indicating slightly faster net growth as environmental-cost shares fall, as also noted by Yin Xiangfei [6].

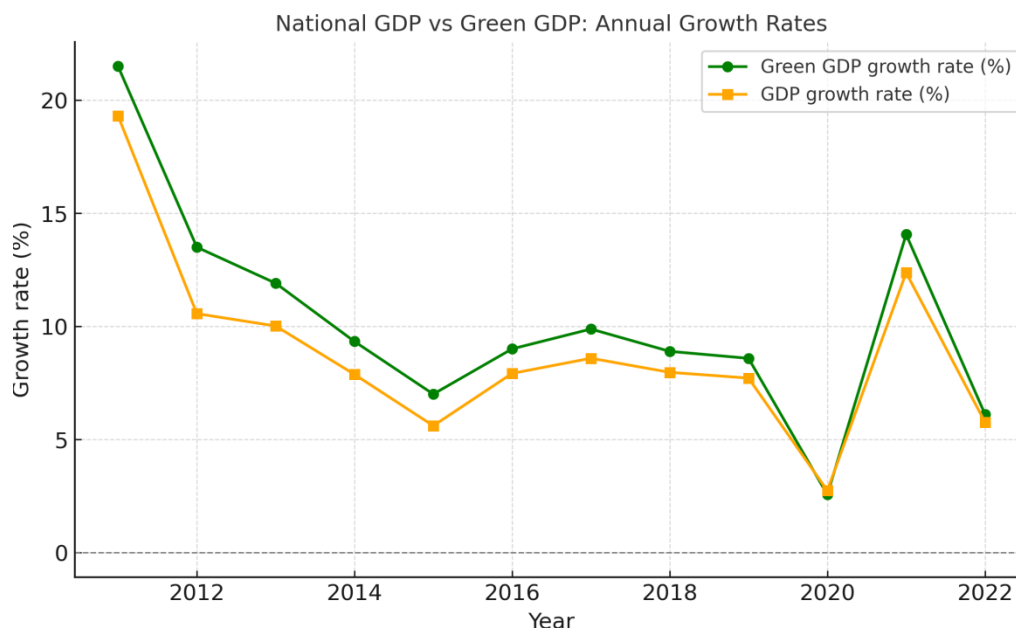


Figure 2. National GDP vs Green GDP: Annual Growth Rates (2011–2022)

Volatility is shaped by macro cycles and policy intensity. The 2014–2015 Environmental Protection Law and 13th Five-Year Plan campaigns slowed the rise of environmental costs, mechanically lifting net growth. Green-GDP growth is marginally more volatile than GDP (higher SD), but the series are highly correlated (correlation ≈1), implying macro cycles dominate while short-term cost changes play a secondary role in aggregate fluctuations.

3.3. Structural Break Test

To test whether there is a significant structural change in the Green GDP growth trend, this paper takes around 2016 as a potential structural break point and performs segmented trend fitting on the 2010–2022 Green GDP time series. As illustrated in Figure 3, the segmented trend analysis reveals average annual Green-GDP growth of ~11.2% in 2010–2015 versus ~8.1% in 2016–2022; a Chow test confirms a significant break at 2015 (5% level), and results are robust to multiple-break tests. The choice of breakpoint reflects the 2015 articulation of “innovation, coordination, green, openness, sharing” and the 2016 launch of the 13th Five-Year Plan with binding intensity targets and green initiatives.

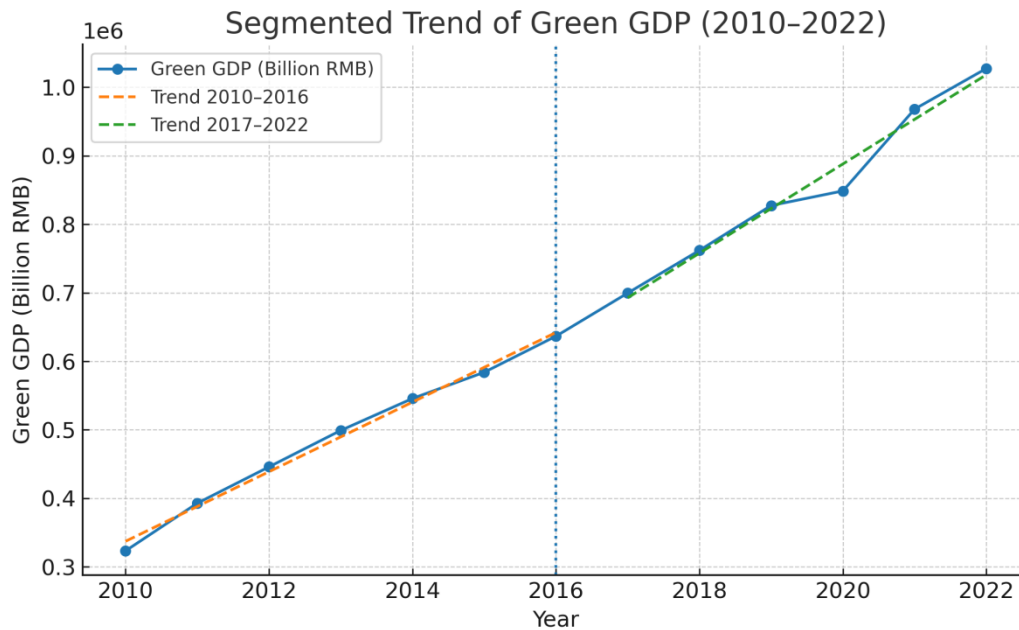


Figure 3. Segmented Trend of Green GDP (2010–2022)

The slowdown stems from dual transitions: growth shifted from high-speed to higher-quality, lowering potential growth. On the other hand, environmental regulation tightened, internalising costs and constraining high-pollution expansion. Li Jianglong and Xu Bin (2018) found that resource-rich regions saw their green economy growth notably slow in this period, corroborating the impact of tighter environmental constraints on extensive economic models [8]. In sum, The inflection cautions that environmental constraints must be built into development targets to sustain growth quality.

3.4. Regional Clustering Analysis

To examine regional heterogeneity in Green GDP, this paper conducted a clustering analysis based on 2022 data, using two variables: $\log(\text{GDP})$ (in 100 million yuan) for economic scale and environmental cost share (%) for environmental burden. Applying K-means clustering with silhouette coefficient guidance to 31 provinces, this paper identified three clusters, visualized in Figure 4. The groups are:

Low environmental cost share group (blue): Includes developed provinces (e.g., Guangdong, Jiangsu, Beijing, Shanghai) and smaller economies (e.g., Hainan, Tibet), with cost ratios of 7%–12%. These regions feature service and high-tech industries, high energy efficiency, and strong pollution control. They exhibit high absolute Green GDP—e.g., Guangdong reached RMB 11.74 trillion in 2022—benefiting from favorable natural conditions or low-pollution industrial structures.

Medium environmental cost share group (orange): Includes provinces such as Shandong, Hubei, Hebei, Sichuan, and Yunnan, with cost shares between 15% and 22%. These mid-development regions are transitioning industrially, yet traditional and resource-based sectors remain significant. Moderate environmental costs reflect ongoing governance efforts and a balance between growth and protection.

High environmental cost share group (red): Includes resource-intensive provinces (e.g., Shanxi, Xinjiang, Inner Mongolia, Guizhou), with cost shares averaging around 30% (e.g., Xinjiang 35.7%, Shanxi 31.6%). These regions experience substantial Green GDP deductions, indicating urgent need for green transformation. Notably, Chongqing has a 20% rate due to heavy industry, underscoring the influence of industrial structure and resource endowment [8]. Accelerated upgrading and clean energy adoption are critical for sustainability.

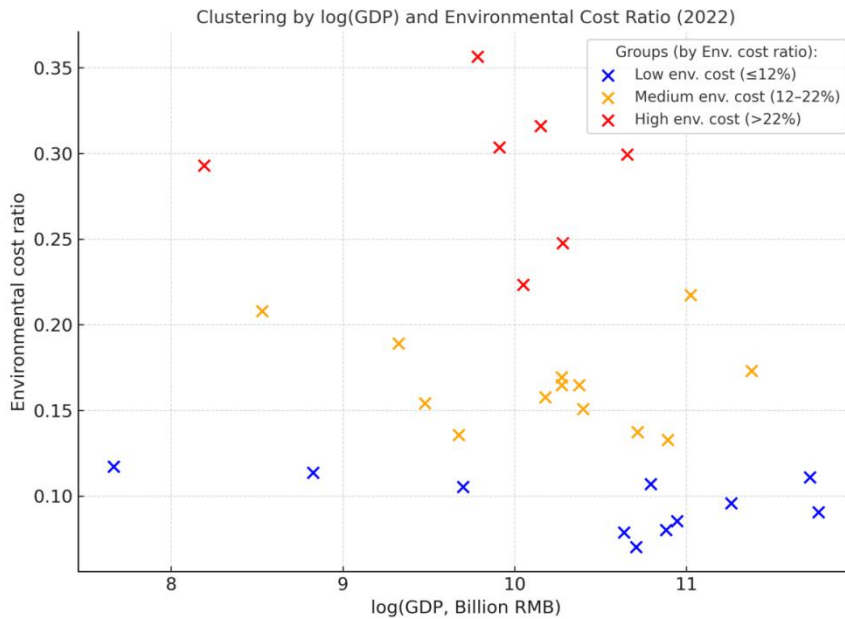


Figure 4. Clustering by log (GDP) and Environmental Cost Ratio (2022)

The clusters reflect distinct development paths: low-cost provinces achieve high-quality growth through innovation and strict regulation. Medium-cost regions are in transition, balancing growth with rising environmental investment. High-cost areas face resource dependence and “green deficits”, necessitating targeted industrial upgrading, clean energy adoption, and ecological compensation to narrow gaps and enable coordinated green transition.

4. Empirical Analysis of Green GDP

4.1. Green GDP Trends

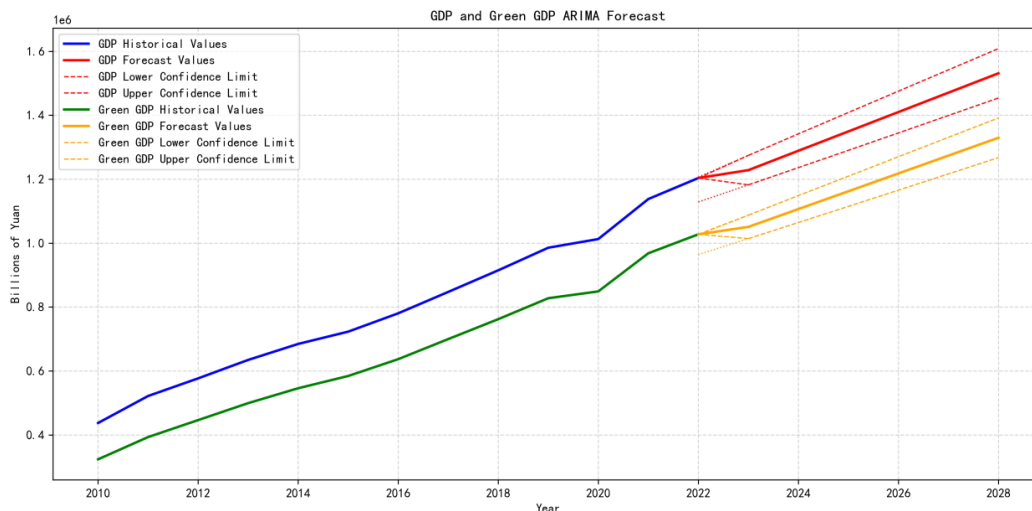


Figure 5. ARIMA Forecast of GDP and Green GDP

Figure 5 shows the ARIMA forecast of GDP and Green GDP. Within the constructed green GDP framework, the costs associated with resource depletion and environmental degradation increase rigidly and cumulatively with economic expansion. This characteristic means that the deductions for calculating green GDP cannot be easily offset by contemporaneous economic growth, maintaining a persistent gap between the two measures.

The ongoing industrial restructuring generates substantial sunk costs in the short term, such as expenses for equipment upgrades and the adoption of environmentally-friendly technologies. These costs temporarily suppress the "green added value," while the long-term benefits of such

technological advancements have not yet been fully realized. Although green GDP grows at a higher rate (7.3%) than traditional GDP (6.1%), this growth premium is insufficient for green GDP to overtake traditional GDP in absolute terms.

Investments in environmental governance are quantified as environmental benefits and added back into the total GDP calculation. However, their positive impact is significantly outweighed by the accounted negative externalities. Data limitations, such as measuring environmental benefits solely by the output value from the comprehensive utilization of the "three wastes," further contribute to the observed gap.

The econometric results indicate that green GDP's ARIMA model yields a lower AIC (197.43) than that of the traditional GDP model (202.80), suggesting its superior performance in capturing long-term trends. However, the traditional GDP model achieves a lower Mean Absolute Percentage Error (MAPE) on the test set, indicating greater sensitivity to short-term fluctuations. This introduces higher uncertainty into the green GDP model's short-term forecasts.

As shown in Figure 4, the predicted values for both traditional and green GDP exhibit a sustained upward trajectory, with green GDP consistently remaining lower. Green GDP also exhibits a narrower confidence interval around its forecasts. This corroborates the constraining factors in green GDP's growth pathway, such as the rigid accumulation of resource depletion and environmental degradation costs, the short-term sunk costs of industrial transformation, and the limitations of environmental governance investments.

In conclusion, a significant gap between green and traditional GDP is projected to persist in the coming years. Although green GDP grows at a slightly higher rate, an absolute catch-up remains unlikely in the short term. These findings highlight the need to optimize resource allocation, mitigate sunk costs, and improve the efficiency of environmental investments to foster the sustainable growth of green GDP.

4.2. Empirical Analysis of Multi-factor of Green GDP

Scholarly inquiry into green GDP has employed diverse methodologies and perspectives. Zhao Xue (2024) utilized a Structural Vector Autoregression (SVAR) model to investigate the interrelationships among sci-tech talent agglomeration, scientific output, and green GDP in the Beijing-Tianjin-Hebei region [9]. From an educational standpoint, Hao Xiaowei et al. (2025) constructed a green economic and social development index to examine the critical link between educational investment and the advancement of a green economy [10]. Qian Shuitu et al. (2019) focused on green finance, applying grey correlation analysis to data from Quzhou and Huzhou to demonstrate its promotive effect on industrial structure optimization [11]. Furthermore, the analytical approach of Xia Xiaoli et al. (2023)—who used fixed-effects models and propensity score matching (PSM) to study elderly care preferences—offers a valuable framework that could be adapted to explore green GDP's impact on industrial transformation [12].

To identify the key determinants of green GDP, this study employs a fixed-effects model. This approach effectively controls for time-invariant, province-specific heterogeneity, thereby enabling a more precise estimation of the explanatory variables' impact. Additionally, to address potential concerns of heteroscedasticity and serial correlation, the model estimates incorporate Driscoll-Kraay standard errors, which are robust to these cross-sectional dependencies.

The model is set as follows:

$$GreenGDP_{it} = \alpha_i + \beta_1 GDP_{it} + \beta_2 Structure_{it} + \beta_3 Urbanization_{it} + \gamma_{it} + \varepsilon_{it} \quad (1)$$

This study employs three distinct fixed-effects model specifications to examine the influence of key variables on green GDP from multiple angles. The model includes several explanatory variables: current regional GDP (GDP_{it} , in billion yuan), industrial structure ($Structure_{it}$, measured by the ratio of the output value of the tertiary industry to regional GDP), and urbanization level ($Urbanization_{it}$, defined as the proportion of urban population to total population). The intercept term is denoted as

α_{it} , γ_{it} captures the provincial fixed effects, and ε_{it} represents the error term. Model 1 incorporates province-specific fixed effects to assess the impacts of GDP, industrial structure transformation, and urbanization, while controlling for cross-provincial heterogeneity. Building on Model 1, Model 2 introduces time fixed effects to form a two-way fixed-effects model (see table 2). This specification accounts for unobserved time trends and cyclical fluctuations, thereby providing more accurate coefficient estimates. Model 3, also a single (province) fixed-effects model, adds the number of medical technicians as a control variable to evaluate the potential effect of healthcare service capacity on green GDP.

The construction of these models allows us to demonstrate the superiority of Model 2 in terms of both goodness-of-fit and robustness. By controlling for both unit-specific and time-specific heterogeneity, Model 2 more comprehensively captures the underlying data generation process, yielding more reliable estimates. Model 3 serves as a robustness check to determine if the inclusion of an additional relevant variable alters the core findings. Should the coefficient estimates of primary interest in Model 2 remain consistent and statistically significant even after this inclusion, it would provide strong evidence for the robustness of our baseline two-way fixed-effects model, enhancing confidence in the identified determinants of green GDP.

Table 2. Model Fitting Effect

	Model 1	Model 2	Model 3
GDP	0.953164134	0.940246086	0.953132811
structure	-1018.876755	-5571.248927	-1019.76002
urbanization	-3985.553787	-13361.27069	-4243.054783
Consideration of Time Effect	No	Yes	No
Control of Variables	No	No	Yes
Adj. R-squared	0.999	0.9991	0.999
Log-Likelihood	-3161.0759	-3135.3911	-3161.0568
AIC	6390.1517	6362.7822	6392.1136
BIC	6526.1156	6546.7332	6532.0764
BP-LM	151.344	189.883	153.100.

Model 2 is preferred due to its higher Adjusted R-squared (0.9991), lower AIC (6362.7822), and BIC (6546.7332). These metrics indicate a better balance between model complexity and explanatory power. The stability of key coefficients across all models further confirms the robustness of the findings.

GDP remains the primary driver of green GDP growth. A 100-million-yuan increase in GDP leads to an average 94-million-yuan increase in green GDP. This near 1:1 relationship underscores the strong linear pull effect of conventional economic expansion on green economic output. Industrial structure transformation has a significant short-term negative impact on green GDP. A 0.1 increase in the transformation index corresponds to a decrease of about 55.7 billion yuan. This reflects the immediate offsetting effect of sunk costs, such as investments in equipment upgrades and pollution abatement technologies. This pattern is characteristic of a J-curve development trajectory, where initial costs precede long-term gains.

The significant and negative coefficient for urbanization in Model 2 (-13,361.27) captures the associated environmental pressures and resource consumption. Urbanization involves population migration, shifts in consumption patterns, and large-scale infrastructure development, all of which exert environmental strain. Policymakers must integrate sustainability objectives into urban planning. Strategies include optimizing urban form, enhancing energy efficiency, and promoting green transportation and building standards.

Model 2 reveals significant provincial heterogeneity but insignificant time effects. This implies that policy implementation should adopt a differentiated, provincially-tailored approach within a nationally coordinated framework. Inter-provincial “environmental benefit trading” mechanisms and

a dual assessment system based on both green GDP and environmental performance could leverage these differences to drive comprehensive high-quality development.

In light of these findings, a multi-faceted policy approach is recommended. This includes fostering economic growth while incentivizing green technology R&D and deployment through subsidies and tax benefits. Addressing the short-term dislocations of industrial transformation through compensation mechanisms is also crucial. Promoting sustainable urbanization via integrated planning and green infrastructure investments is essential. Finally, harnessing provincial heterogeneity through market-based instruments like environmental trading and differentiated performance metrics can enhance overall development.

These results elucidate the direct role of GDP and the complex short-term dynamics and long-term potential of industrial restructuring and urbanization on green GDP. This analysis provides a scientific foundation for policymaking, enhancing our understanding of how to navigate the trade-offs between economic development and environmental sustainability.

5. Conclusion and Discussion

This study developed a new Green GDP indicator by integrating environmental benefits into the traditional GDP framework, aiming to provide a more comprehensive and accurate measure of environmentally adjusted economic performance at the provincial level in China. By constructing this revised accounting system and employing multiple fixed-effects models, the study offers empirical insights into the determinants of green economic growth and regional disparities.

Between 2010 and 2022, Green GDP grew broadly in line with traditional GDP, with a slightly higher average growth rate. Meanwhile, the share of environmental costs in GDP declined from 26% to 14.6%, reflecting improved environmental efficiency and the effectiveness of ecological protection policies.

Marked regional differences were observed. Economically advanced and service-oriented provinces generally showed lower environmental cost shares and higher Green GDP ratios, while resource-dependent regions bore heavier ecological burdens. These findings highlight the need for region-specific green development strategies. Resource-intensive areas should shift away from environmentally damaging growth models through industrial upgrading and stricter regulation. Moderately developed provinces must consolidate existing gains and further reduce environmental costs through innovation. More advanced eastern provinces can serve as benchmarks for green transformation.

The evolution of Green GDP also mirrors broader macroeconomic transitions. Around 2015–2016, under stricter environmental regulation and slower economic growth, the gap between traditional GDP and Green GDP growth narrowed—signaling a shift toward higher-quality development. Performance evaluations should therefore focus more on long-term ecological gains and sustainable growth rather than short-term output.

Model comparisons confirmed the dual fixed-effects model as the most robust specification, effectively capturing both regional and temporal heterogeneity. Results indicate that GDP remains a key driver of Green GDP, contributing approximately 0.94 billion yuan in Green GDP for each 1 billion yuan increase. Industrial structural transformation has a short-term negative effect, with a 0.1 increase in the transformation index reducing Green GDP by about 55.7 billion yuan, though a long-term rebound may emerge. Urbanization also shows a significant negative impact, highlighting the environmental challenges of rapid urban growth. Substantial provincial heterogeneity was evident, while time effects were less significant.

Policy recommendations include promoting green technologies, offering post-subsidies (15–20%) for industrial equipment renewal, and expanding green financial tools such as green bonds and interest subsidies. Sustainable urban planning, energy efficiency, and low-carbon infrastructure should be prioritized. Given regional differences, a coordinated framework of localized policies and national

oversight is essential. Tools like cross-provincial environmental benefit trading and dual-index performance assessments can turn disparities into advantages for green development.

Future research may focus on refining Green GDP accounting by incorporating sector-specific emission data, dynamic environmental efficiency metrics, and spatial econometric methods. Longitudinal studies on the interaction between green finance, policy incentives, and green innovation could further inform effective strategies for sustainable economic transformation.

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