ASSESSING ECONOMY–ENVIRONMENT COUPLING COORDINATION THROUGH GREY RELATIONAL ANALYSIS WITH DECOUPLING AND SPATIAL HETEROGENEITY IN JILIN PROVINCE, CHINA (2004-2017)

QI, P.

Chongqing Electromechanical Vocational and Technical University, Bishan, Chongqing 404000, China
(e-mail: pangqi016@hotmail.com)

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Abstract. Economic expansion often imposes disproportionate pressures on air, water, and land. To systematically evaluate the interaction between economic development and the ecological environment, this study examines Jilin Province, China, over the period 2004–2017, thereby ensuring a consistent temporal framework. To provide a reproducible metric for aligning development with ecological protection, we integrate grey relational analysis into a quantitative framework that measures the coupling and coordination between economic growth and ecological sustainability. Specifically, we construct indicator systems for the economy and the eco-environment, normalize all variables, and apply grey relational analysis to estimate relational degrees and derive data-driven weights. Time-varying subsystem scores are then synthesized to compute coupling and coordination indices and to classify development stages from severe imbalance to high-level coordination. We further assess growth–pressure decoupling elasticities and, where data permit, explore spatial heterogeneity and driving factors related to industrial structure, energy efficiency, and pollution control. This framework identifies key leverage indicators—such as energy and carbon intensity, wastewater and air-pollution loads, and vegetation or land conditions—and enables transparent comparison across jurisdictions and over time. It contributes to biometrical and quantitative ecological assessment by explicitly linking economic upgrading with biodiversity conservation, environmental quality, and climate objectives.
Keywords: *composite indicators; entropy weighting; decoupling elasticity; spatial heterogeneity; socio-ecological systems*

Introduction

Since the initiation of reform and opening up, China has undergone a period of remarkable economic development, leading to significant growth and a substantial enhancement of its overall national strength. However, this rapid expansion has also given rise to pressing issues of unbalanced, uncoordinated, and unsustainable development that demand urgent attention. The challenge is particularly evident in the assessment of environmental carrying capacity for sustainable development (Yang, et al., 2015), the imperative to foster green development models (Wang, et al., 2021), and the complex coordination between green finance and the green economy (Liu, et al., 2020). Achieving a harmonious balance requires a comprehensive approach to managing the intricate relationships of economic activities, logistics, and the ecological environment (Zhang, et al., 2020).

The multifaceted and multi-level ecological and environmental problems are deeply intertwined with economic progress. Scholars have extensively explored the spatial coupling between regional economic development and environmental pollution (Ma, et al., 2013), the nexus between urbanization and pollutant emissions (Yu, et al., 2018), and the evaluation of ecological carrying capacity within rapidly developing economic zones (Wu, et al., 2021). These issues span across diverse sectors, highlighting the need to

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coordinate new urbanization patterns with the agro-ecological environment (Cai, et al., 2021) and to manage the environmental impacts of foundational economic activities, such as resource exploration in sedimentary basins (Cheng, et al., 2022b). Consequently, the comprehensive management and accelerated improvement of the ecological environment have become principal themes in China's contemporary development narrative.

The three northeastern provinces, renowned as "the birthplace of industry" in China, occupy a pivotal position in the nation's economic landscape. Jilin Province, as one of these old industrial bases, made historic contributions to the national economic construction, especially in the early days of the People's Republic of China. Studies focusing on this region have analyzed its economy-wide material inputs and outputs (Li, et al., 2010), the coupling relationship between its urbanization and eco-environment (Liu, et al., 2018), and its overall green development efficiency (Li, et al., 2020). However, at the beginning of the reform and opening up, while Jilin experienced new opportunities, its economic standing has consistently lagged behind that of more dynamic regions like the Pearl River Delta.

In response, the Jilin provincial government and related institutions have actively implemented national policies. Yet, the path to industrial revitalization remains challenging. For a prolonged period, Jilin's economic growth has depended on an inefficient large-scale development model characterized by high consumption and high investment. This model, often reliant on the exploitation of resources like tight gas reservoirs (Zhang, et al., 2021), has amplified ecological and environmental stress (Yao, et al., 2019) and necessitates a deeper understanding of the coupling between core systems like the regional economy and transportation (Du, et al., 2022). This historical reliance on a resource-dependent industrial structure (Cheng, et al., 2022a) has led to a significant waste of ecological resources, polluting water, air, and soil. The decoupling effects of industrial carbon emissions (Han, et al., 2018) and the uncoordinated relationship between sectors such as tourism, urbanization, and the ecological environment (Zhang, et al., 2021; Ma and Tang, 2022) exemplify this conflict. The legacy of past resource extraction technologies (Hanlie, et al., 2012) complicates the relationship between environmental quality and the financial economy , underscoring the need for a reproducible, quantitative framework to analyze the coupling coordination within these complex socio-ecological systems (Jiang, et al., 2022).

To quantitatively diagnose these interdependencies, scholars increasingly use composite indicators within a coupling coordination framework. This approach, often enhanced by methods such as grey relational analysis to explore factor relationships (Hu and Xie, 2025), has been widely applied to assess the synergy between grain production and economic development (Zhang and Li, 2023) and between urbanization and the eco-environment in less-developed regions (Chen, et al., 2022). The scope of these studies is broad, encompassing the evaluation of coupling between ecosystem resilience and regional economies (Liu, et al., 2025), tourism and environmental protection (Zhao and Li, 2017), and the identification of driving factors influencing social-ecological resilience (Zhu, et al., 2024). The methodology's utility has been proven in analyzing the coupling mechanisms between technology service agglomeration and regional innovation (Xu, et al., 2019), the tourism industry and ecological civilization (Yuan and Jang, 2022), and the interconnected development of the socioeconomy, ecological environment, and tourism (Zhang, et al., 2025). Methodologically, Grey Relational Analysis (GRA) is a valuable tool for such sustainability research (Hu and Liu, 2022; Jayant, et al., 2018), particularly for deriving data-driven weights that, like entropy weighting, can overcome the

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subjectivity of traditional methods. It is increasingly applied to explore the driving factors of regional sustainable development (Liu and Xin, 2022) and to develop new analytical models (Li, et al., 2018).

While extensive research has investigated coupling coordination in various contexts, such as between regional economies and logistics systems (Liang, et al., 2025), a gap remains for a comprehensive framework that not only measures coordination but also assesses decoupling elasticity and spatial heterogeneity in old industrial bases. These regions, analogous to resource-exhausted cities and villages (Luo, et al., 2025; Zhao, et al., 2022), require targeted analysis to guide their sustainable transformation. Therefore, this study aims to develop and apply a quantitative framework that integrates a coupling coordination degree model with Grey Relational Analysis (GRA) to evaluate the economy-environment system in Jilin Province. Specifically, this paper will construct comprehensive indicator subsystems, use GRA to derive data-driven weights, and compute time-varying coupling and coordination indices to classify the province’s development stage. Furthermore, the analysis will extend to assessing growth-pressure decoupling elasticities and exploring the drivers of spatial heterogeneity, such as industrial structure and pollution control. Ultimately, this work seeks to provide a transparent and reproducible metric that pinpoints leverage indicators—like energy intensity and pollution loads—to better align economic upgrading with biodiversity maintenance, environmental quality, and climate objectives.

Economic and ecological environment of Jilin province

Present situation of economic development in Jilin Province

Jilin Province, endowed with rich natural resources, holds a crucial role as both a heavy industrial base and a major grain production hub in China. In the early stages of the reform and opening-up period, Jilin Province leveraged its resource advantages and industrial capacity to join the ranks of rapidly developing regions. However, with the acceleration of national economic growth, Jilin’s economic expansion began to lag behind other regions in the 1990s. This disparity has prompted the state to propose the revitalization strategy for the Northeast, with Jilin Province actively responding by implementing various countermeasures. While some progress has been made, significant gaps remain in achieving the provincial and national developmental goals.

Jilin Province is divided into nine administrative regions: Changchun City, Jilin City, Siping City, Songyuan City, Baicheng City, Tonghua City, Baishan City, Liaoyuan City, and Yanbian Autonomous Prefecture. These regions exhibit uneven levels of economic development, which is primarily assessed through two indicators: regional GDP and local fiscal revenue. The specific values of regional GDP and fiscal revenue for all nine cities are presented in *Table 1,* which illustrates the magnitude of inter-city disparities and the growth-rate differences observed in 2017. Despite the overall resource-rich status of the province, regional disparities in economic development persist, further emphasizing the need for targeted revitalization efforts.

In this context, improving the coordination between economic development and ecological sustainability has become a critical issue for Jilin. The province’s reliance on an industrial development model characterized by high resource consumption and investment has led to serious ecological degradation, including the pollution of water, air, and soil. As a result, the challenge of balancing economic growth with environmental preservation remains a key focus for policymakers, in line with national strategies aimed

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at improving ecological carrying capacity and advancing green development initiatives. This challenge is especially apparent in the province's economic growth, where heavy industry and agriculture dominate but require urgent reforms to align with sustainable development goals.

Table 1. *Economic situation of nine cities and counties in Jilin Province in 2017*

Ranking	Region	Gross regional product (100 million yuan)	Growth rate	Local fiscal revenue	Growth rate
1	Changchun	6328	8.00%	450.00	8.30%
2	Jilin (Province)	2640	5.00%	105.00	-22.50%
3	Songyuan	1706	1.00%	47.90	-5.50%
4	Siping	1276	5.00%	56.60	-10.70%
5	Yanbian	935	3.70%	69.50	-24.00%
6	Tonghua	900	-15.10%	61.90	-25.20%
7	Liaoyuan	810	4.00%	18.30	-24.40%
8	Baicheng	742	6.00%	41.50	-1.20%
9	Baishan	730	5.50%	27.00	-42.60%

The growth rates for regional GDP and local fiscal revenue in *Table 1* are calculated using the previous year as the reference point, allowing the indicators to reflect changes in economic expansion and fiscal conditions relative to the immediately preceding period.

The region under study is endowed with abundant natural resources, functioning both as a major heavy-industry base and an important grain-producing area. During the early years of China's reform and opening-up, it capitalized on these resource advantages and became one of the country's rapidly developing regions. However, as China's overall economic growth entered a period of accelerated expansion, this region began to fall behind, particularly from the 1990s onward. Despite the implementation of national strategies such as the Revitalization of Northeast China, it continues to face difficulties in achieving its development objectives, especially in terms of economic balance and ecological sustainability.

Administratively, the region comprises multiple jurisdictions with markedly different levels of economic development. Economic statistics from 2017 reveal pronounced disparities among cities and prefectures. For example, Changchun—the provincial capital—recorded a GDP growth rate of approximately 8%, significantly higher than the provincial average of 5.3%. In sharp contrast, Tonghua experienced a dramatic economic downturn, with GDP contracting by 15.1% and local fiscal revenue decreasing by 25.2%. Meanwhile, cities such as Yanbian and Liaoyuan registered modest yet positive growth of 3.7%, rebounding from previous negative trends. Despite these fluctuations, the central urban area, led by Changchun and Jilin, continues to dominate the regional economic landscape, contributing more than half of the total GDP, while the eastern forested zone and the western ecological zone remain comparatively underdeveloped.

Fiscal revenue data further illustrates the regional imbalance. In 2017, Changchun was the only city to exhibit positive growth in local fiscal revenue—an increase of 8.3%—at a time when provincial-level fiscal revenue declined overall by 4.1%. Jilin City, in contrast, suffered a sharp 22.5% decrease in fiscal revenue despite achieving a modest GDP increase of 5%. This mismatch reflects inefficiencies in economic output as well as political and fiscal challenges, including the "water-squeezing" policy that has constrained fiscal expansion. Moreover, the financial capacity of local governments varies considerably: Changchun's GDP is 2.4 times that of Jilin, while its fiscal revenue exceeds Jilin's by more than fourfold.

These disparities highlight an urgent need for more coordinated economic planning and ecological stewardship. Accelerating the development of the eastern and western regions—particularly the forested and ecological zones—offers important opportunities for revitalization and sustainable growth. However, achieving this requires reconciling industrial advancement with ecological protection, as the region's historical reliance on high-consumption growth models has resulted in resource inefficiency, environmental degradation, and constraints on long-term competitiveness.

Overall status of ecological environment in Jilin province

The region in question is located in the northeastern part of China, covering an area of approximately 187,400 km^2, or about 2% of the country's total land area. According to the 2017 Statistical Yearbook, the permanent population of the region was 27.3 million, and the built-up industrial land area reached 314.2 km^2. Rich in natural resources, this area has historically served as an important strategic base for China's early industrial development. However, despite its resource abundance, the region faces significant challenges related to industrial inefficiency, outdated production technologies, and environmental degradation. Much of the industrial activity in the area is still characterized by resource wastefulness, uncontrolled emissions of industrial waste gases, and low utilization rates of both wastewater and circulating water. During 2004 to 2017, the permanent population decreased from 28.4 million to 27.3 million, while the urbanization rate increased from 48.1 percent to 59.6 percent. These inefficiencies, compounded by the continuous expansion of the population, have exacerbated ecological damage and pollution, which now pose a serious threat to the region's long-term sustainability.

The destruction and pollution of the ecological environment, driven largely by human production and survival activities, have become increasingly critical issues. Environmental hazards such as acid rain, the greenhouse effect, ozone layer depletion, land desertification, and rising sea levels are all contributing to the decline in ecological health. In particular, the region has faced significant challenges in managing industrial emissions, which have played a central role in exacerbating air pollution.

Human production and livelihood activities have accelerated ecological risks—including acid deposition, greenhouse forcing, stratospheric ozone depletion, and land degradation—that collectively undermine ecological health. A central pressure in the study area is industrial air pollution: exhaust gases contain high levels of nitrogen oxides (NOx), sulfur dioxide (SO_2), and soot/smoke particulates. From 2011 to 2017, the total industrial exhaust gas emissions averaged 138 million m^3 per year, with coal-fired sources contributing 67.4 percent. A province-wide inventory (2011–2017) indicates sustained reductions in SO_2 and NOx after 2014, while smoke/dust shows greater inter-annual volatility, consistent with sectoral shifts and end-of-pipe retrofits (*Table 2*; *Fig. 1*).

The region in question, located in the northeastern part of China, is endowed with rich natural resources and has historically served as a critical industrial base. However, despite its resource advantages, the region faces significant environmental challenges, particularly related to outdated production technologies, inefficient resource utilization, and widespread pollution. Industrial waste emissions and wastewater discharge are two of the primary contributors to the region's ecological degradation.

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Table 2. *Emission of main pollutants in exhaust gas of Jilin Province from 2011 to 2017*

Age	Sulfur dioxide (10,000 tons)	Nitrogen oxides (10,000 tons)	Smoke (powder) dust (ten thousand tons)
2011	41.32	60.47	43.22
2012	40.35	57.59	26.48
2013	38.15	56.05	32.02
2014	37.23	54.92	47.51
2015	36.29	50.17	44.73
2016	18.8	30.07	21.87
2017	16.61	25.54	19.57
Average value	32.68	47.83	33.63

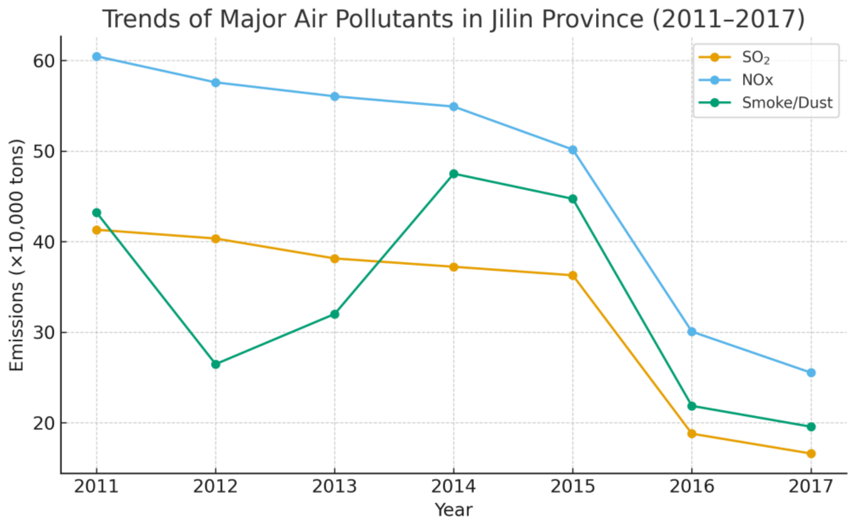

Figure 1. *Trends of major air pollutants in Jilin Province (2011–2017). SO_2 and NOx show sustained decreases after 2014, consistent with strengthened emission controls; smoke/dust exhibits larger inter-annual variability, reflecting sectoral shifts and end-of-pipe retrofits*

According to data from 2011 to 2017, nitrogen oxides, the main pollutant in the industrial waste gases of this region, have remained the highest, with an average annual emission of 478,300 tons. Coal dust emissions, which experienced the greatest fluctuations over the years, averaged 336,300 tons annually, reaching a low of 195,700 tons in 2017. Sulfur dioxide emissions showed a steady decrease, from 413,200 tons in 2011 to 166,100 tons in 2017, with an average annual emission of 326,800 tons. Despite this reduction, the overall total pollutant emissions, including sulfur dioxide, remain significantly high, posing serious risks to the environment, agriculture, climate, and natural resources, such as water and soil. The persistent presence of these pollutants not only harms the environment but also threatens public health and the region's sustainable development.

In addition to air pollution, wastewater discharge presents another major environmental challenge. Due to outdated technology and insufficient resource utilization, industrial wastewater in the region contains high levels of metal pollutants, including lead, mercury, cadmium, and hexavalent chromium. Monitoring records from

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2011 to 2017 show that lead concentrations ranged from 0.013 to 0.019 mg L^{-1}, while cadmium concentrations ranged from 0.002 to 0.006 mg L^{-1}. The random discharge of this wastewater not only contributes to river pollution but also affects agricultural irrigation, damages fishery and aquaculture systems, and increases water quality contamination. This polluted water also causes soil degradation, impacting crop yields and further harming the agricultural economy. The pollution levels are typically measured by the concentration of these heavy metals in the wastewater, and data from 2011 to 2017 indicate that the levels of these pollutants are still significant, as shown in *Table 3*.

Table 3. *Discharge of main heavy metal pollutants in wastewater of Jilin Province from 2011 to 2017*

Age	Total amount of wastewater discharged (10,000 tons)	Lead (kg)	Mercury (kg)	Cadmium (Cd) (kg)	Hexavalent chromium (kg)
2011	116162	267.80	7.70	35.30	131.50
2012	119509	198.90	5.40	26.60	109.70
2013	117703	161.60	5.90	28.90	59.50
2014	122171	165.10	6.30	30.20	135.00
2015	126908	204.00	4.30	28.40	75.60
2016	97073	219.43	5.40	70.93	64.13
2017	121464	203.34	6.66	77.53	94.97
Average value	117284	202.88	5.96	42.56	95.76

The spatial pattern of ammonia-nitrogen discharge across the nine cities in 2011 and 2017 is depicted in *Figure 2,* which visually highlights the substantial declines in major industrial centers.

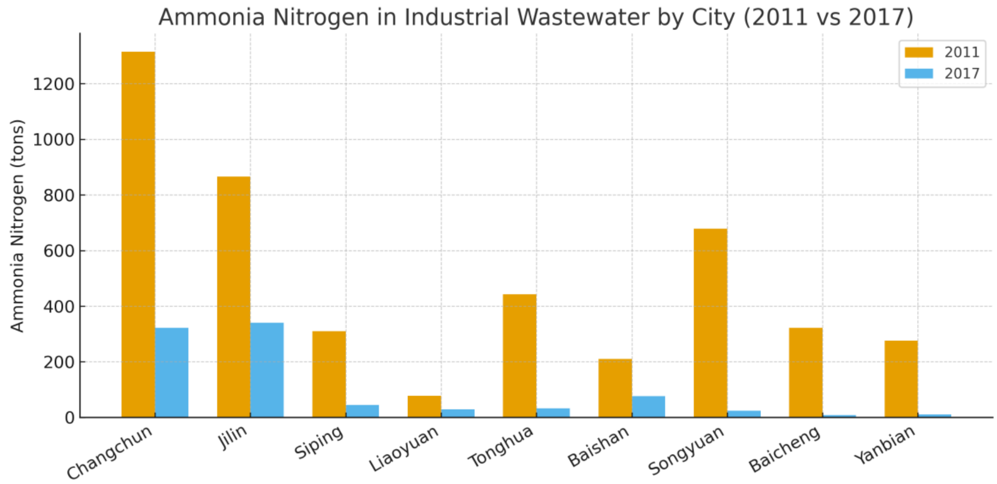

Figure 2. *Ammonia nitrogen in industrial wastewater by city: 2011 vs 2017. Most cities show pronounced declines by 2017, suggesting improved wastewater management; residual loads in key hubs call for sector-targeted upgrades*

The region in question, located in northeastern China, is endowed with abundant natural resources and has played a crucial role as an industrial base. However, despite its

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resource wealth, the region faces significant environmental challenges due to outdated production technologies and inefficient resource utilization. These challenges are particularly evident in the management of industrial waste emissions and wastewater discharge, which are major contributors to the region's ecological degradation.

According to data from 2011 to 2017, industrial wastewater discharge in the region has generally shown an increasing trend, with a slight decrease observed in 2013, lasting until 2014. The analysis of heavy metal pollutants in the wastewater indicates a high concentration of lead, with an average annual discharge of 202.88 kg. Mercury content, by contrast, remains relatively low, averaging 5.96 kg annually. Notably, mercury content has exhibited the smallest fluctuation, with a standard deviation of only 1.08, suggesting that its discharge levels have remained relatively stable in recent years. Cadmium emissions have shown minimal fluctuation, while hexavalent chromium levels have fluctuated significantly. Lead, however, has seen the greatest variability, with total emissions decreasing from 267.8 kg in 2011 to 161.6 kg in 2013, before rising again to 203.34 kg in 2017.

In terms of total emissions of heavy metal pollutants, lead remains the most significant contributor, though its fluctuations are concerning. While the discharge of hexavalent chromium was at its lowest in 2013, it still represents a notable environmental challenge. These heavy metals, particularly lead, cadmium, and hexavalent chromium, pose severe risks to water quality, soil health, and public health, exacerbating the region's environmental issues. Between 2014 and 2017, the province invested 5.6 billion yuan in wastewater-treatment upgrades, completed 36 industrial end-of-pipe retrofits, and added 11 flue-gas desulfurization units, which jointly contributed to the observed decline in ammonia-nitrogen discharge and SO2 emissions. The industrial discharge of these pollutants not only harms water resources and ecosystems but also poses long-term risks to agriculture and human health.

Present situation of ecological environment in nine cities and prefectures of Jilin Province

In 2017, the province's air quality improved, and the number of days with good weather also increased significantly compared with the previous year. Monitoring records show that PM10 declined from 116 μg m^{-3} in 2011 to 72 μg m^{-3} in 2017, while PM2.5 declined from 62 μg m^{-3} in 2013 to 38 μg m^{-3} in 2017. The emission standards of particulate matter (PM10), ozone, fine particulate matter, carbon monoxide, nitrogen dioxide and six other pollutants have met the requirements of the State Environmental Protection Agency. Among them, the concentrations of harmful substances such as inhaled particulate matter (PM10) and particulate matter (PM2.5) have dropped significantly. The industrial smoke dust emissions (10,000 tons) from 2011 to 2017 are shown in *Table 4*.

The distribution of smoke-dust emissions in 2017 is further illustrated in *Figure 3,* showing the concentration of emissions in the provincial capital and other heavy-industry zones.

(1) Analysis of industrial tail gas emissions in Jilin Province: By analyzing the data changes of sulfur dioxide concentration (μg m^{-3}) and factory soot emissions (10,000 tons) in 9 cities and counties in Jilin Province from 2011 to 2017, the impact on the industry is compared. Exhaust gas and development changes in different regions. Comparative analysis of sulfur dioxide concentration in 9 cities and counties of Jilin Province: Since there is no data of Yanbian Autonomous Prefecture from 2011 to 2017, the data of Yanji

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City is used instead. The concentration of sulfur dioxide in the air from 2011 to 2017 (μg m^{-3}) is shown in *Table 5*.

***Table 4.** Emissions of industrial smoke dust from 2011 to 2017 (10,000 tons)*

Region	2011	2012	2013	2014	2015	2016	2017
Changchun	11.62	4.08	7.30	7.09	8.08	2.45	1.83
Jilin (Province)	12.09	3.57	3.41	6.76	8.92	4.76	3.96
Siping	2.34	2.43	3.50	5.97	3.46	0.70	0.85
Liaoyuan	0.84	0.85	0.96	2.40	1.85	0.49	0.60
Tonghua	2.09	1.76	1.85	4.21	2.54	1.70	1.69
Baishan	1.19	1.14	1.06	2.36	1.42	0.87	0.87
Songyuan	2.99	2.98	3.99	3.16	2.86	0.41	0.64
Baicheng	0.98	0.82	0.85	1.19	1.02	0.60	0.57
Yanbian	1.99	1.89	2.12	3.57	3.57	1.81	0.99

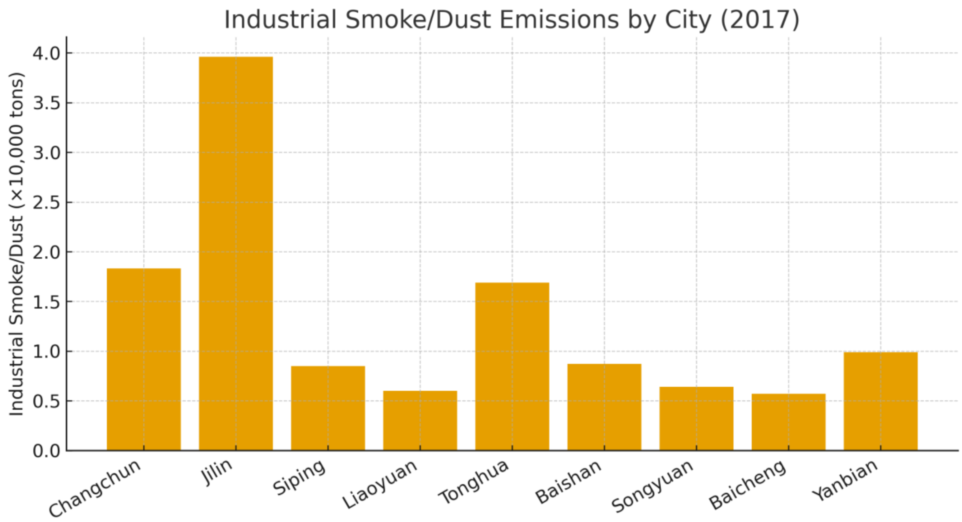

***Figure 3.** Industrial smoke/dust emissions by city in 2017. The provincial capital (Changchun) and Jilin City remain relatively higher than western municipalities, indicating differentiated abatement priorities*

***Table 5.** 2011-2017 concentration of sulfur dioxide in the air (μg m^{-3})*

Region	2011	2012	2013	2015	2016	2017
Changchun City	26	31	55	36	28	26
Jilin City	23	24	26	30	23	18
Siping City	22	27	30	27	22	26
Liaoyuan City	27	36	45	26	25	18
Tonghua City	26	33	26	39	29	26
Baishan City	15	29	27	26	35	29
Songyuan City	27	23	32	21	15	14
Baicheng City	35	22	21	20	12	11
Yanji city	27	30	29	18	14	15

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(2) Analysis of industrial wastewater discharge in Jilin Province. Industrial drainage has a great impact on environmental pollution. The ammonia nitrogen emission in wastewater is used to reflect the impact of Philippine water on ecological environment. Meanwhile, the data law of ammonia nitrogen emission in industrial wastewater from 9 cities and counties in Jilin Province from 2011 to 2017 is analyzed, and the differences and changes are compared. The discharge amount of ammonia nitrogen in industrial wastewater from 2011 to 2017 (tons) is shown in *Table 6*.

Table 6. *2011-2017 ammonia nitrogen emissions in industrial wastewater (tons)*

Region	2011	2012	2013	2014	2015	2016	2017
Changchun	1314.87	1334	1383.77	1405.85	1199.69	474.01	322.60
Jilin (Province)	866.54	879	823.43	890.74	850.92	430.81	340.22
Siping	309.57	276	285.61	296.35	302.04	49.22	44.34
Liaoyuan	78.00	89	85.38	5333.00	59.43	35.73	28.88
Tonghua	442.89	510	476.07	334.30	351.62	36.94	33.31
Baishan	210.80	185	201.29	212.26	208.04	83.31	76.03
Songyuan	678.40	598	560.71	476.31	468.73	43.20	24.61
Baicheng	321.68	256	128.79	128.46	130.61	11.35	8.96
Yanbian	276.37	260	276.88	284.77	270.56	28.45	10.80

The region in question, located in northeastern China, is rich in natural resources and has historically been an important industrial base. However, despite its resource wealth, the region faces significant environmental challenges, particularly due to outdated production technologies and inefficient resource utilization. These issues are notably apparent in the management of industrial waste emissions and wastewater discharge, which contribute significantly to the region's ecological degradation.

According to data from 2011 to 2017, industrial wastewater discharge in the region has generally increased, with a slight decrease observed in 2013, continuing until 2014.

The reduction in ammonia nitrogen discharge reflects positive trends in wastewater treatment and environmental protection efforts, contributing to a cleaner ecological environment. However, despite these improvements, the overall levels of industrial pollution, including heavy metals and other contaminants, remain high, posing ongoing challenges to sustainable development and the protection of natural resources. The reduction in ammonia nitrogen discharge is a step forward, but continued efforts are needed to address other environmental hazards and to promote further ecological restoration.

Status quo and analysis of sustainable development and coupling coordinated development

Theory of sustainable development and coupled development

Sustainable development is a fundamental principle in the scientific concept of development, emphasizing the need for balance between social, economic, and environmental factors. The theory of sustainable development advocates for the coordinated development of nature, society, and the economy, with a primary focus on equity between current and future generations. It stresses the importance of fostering

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harmonious coexistence between humans and nature, while recognizing that social and economic growth should not surpass the carrying capacity of available resources and the environment.

International organizations, governments, and researchers all reflect this evolving development theory through their policies and strategies. The International Union for Conservation of Nature (IUCN) has emphasized key areas for sustainable development, such as controlling population growth, protecting existing resources, and advancing the use of sustainable, renewable resources. In defining sustainable development, the World Commission has stated, "Development that can meet the needs of the present generation without compromising the ability of future generations to meet their own needs."

This definition underscores the need for balanced development that accounts for both the present and the future. Sustainable development, therefore, requires an integrated approach that promotes responsible resource use, environmental protection, and equitable social progress, while ensuring that the actions of today do not undermine the ability of future generations to thrive.

Coupling and coordinated development degree of economy and ecological environment in Jilin Province

Sustainable development requires a harmonious balance between economic growth and ecological preservation, and understanding the interaction between these two systems is crucial for achieving long-term sustainability. The coupling degree, while useful for reflecting the interaction between systems, does not account for the level or performance of each individual system. In contrast, the coupling coordination degree not only measures the interaction between systems but also incorporates the level of development within each system. This makes it a more comprehensive tool for assessing the balance and coordination between economic and ecological systems.

In this paper, an empirical analysis is conducted to explore the relationship between economic development and the ecological environment in the region, with a particular focus on Jilin Province and its nine cities and prefectures. The coupling coordination degree model is employed to evaluate how economic development and ecological systems mutually restrict and influence each other. The model consists of an economic subsystem index T_1 and an eco-environmental subsystem index T_2, each constructed from the standardized indicators described in the previous section. The two subsystem indices are used as inputs to the coupling function C, which is defined to capture the interaction intensity between the economic and environmental dimensions. The coordination degree D is then obtained by combining C with the composite development index T, where T is calculated as the weighted sum of T_1 and T_2. This structure allows the model to reflect both subsystem performance and interaction strength in a unified framework. If the ecological environment deteriorates beyond a certain threshold, it directly restricts economic development, creating a feedback loop that hinders further growth. Conversely, unsustainable economic practices can lead to further environmental degradation.

The coupling coordination degree of economic development and ecological environment in Jilin Province, as calculated by the model, provides insights into the current state of coordination between these two crucial systems. The results, shown in *Table 7,* highlight the degree of balance and the areas where improvements are needed to foster more sustainable development in the region.

Achieving sustainable development requires the harmonious integration of economic and ecological systems, where the balance between the two plays a crucial role in shaping

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long-term growth. In this study, the coupling degree (C) and coupling coordination degree (D) models are employed to analyze the relationship between economic development and ecological environment in Jilin Province. These models provide a comprehensive understanding of how the two systems interact and how their development levels have evolved over time.

Table 7. *Coordinated development degree of economic development and ecological environment in Jilin Province*

	C	T	D	Coordinated development type
2004	0.9999	0.2618	0.5116	Reluctantly coordinate
2005	0.9970	0.2543	0.5035	Reluctantly coordinate
2006	0.9991	0.3043	0.5514	Reluctantly coordinate
2007	0.9961	0.3758	0.6118	Primary coordination
2008	0.9999	0.3624	0.6020	Primary coordination
2009	0.9851	0.4020	0.6293	Primary coordination
2010	0.9835	0.4466	0.6628	Primary coordination
2011	0.9831	0.4601	0.6725	Primary coordination
2012	0.9668	0.4728	0.6761	Primary coordination
2013	0.9629	0.4616	0.6667	Primary coordination
2014	0.9400	0.4208	0.6289	Primary coordination
2015	0.9349	0.5051	0.6872	Primary coordination
2016	0.9435	0.5715	0.7343	Moderate coordination
2017	0.9358	0.5443	0.7137	Moderate coordination

As shown in *Table 7,* the coupling degree (C) between economic development and the ecological environment in Jilin Province during the investigation period was close to 1, indicating a coordinated relationship between the two systems. However, it is notable that the coupling degree (C) gradually decreased over time, suggesting a weakening of the interaction between economic development and ecological sustainability. This highlights a shift in the balance, pointing to the need for further integration of environmental concerns into economic planning.

The coupling coordination degree (D) reflects the degree of coordinated development between the two systems. Analysis of the degree of coordinated development (D) reveals that the relationship between economic development and the ecological environment in Jilin Province has continuously improved over the past 14 years. From 2004 to 2017, the coordination level of the economic and ecological systems evolved from mild imbalance to barely coordinated, with the ability of the two systems to develop in harmony gradually increasing. The temporal evolution of the coupling degree, composite index, and coordination degree is visualized in *Figure 4,* which clearly shows the transition from reluctant coordination to moderate coordination.

In the period from 2004 to 2006, the economic development of Jilin Province was largely uncoordinated with the ecological environment. During this time, the economic development level was relatively low, and the ecological environment remained stable, with minimal impact from economic activities. However, from 2007 to 2016, there was a significant improvement in economic development, marked by rapid industrialization, particularly in heavy industries. Despite this growth, the expansion of heavy industry

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resulted in the serious waste of natural resources and increased environmental pollution, which negatively impacted the ecological environment. This period of rapid industrial development highlighted the tension between economic growth and ecological sustainability, a challenge that requires urgent attention for future sustainable development.

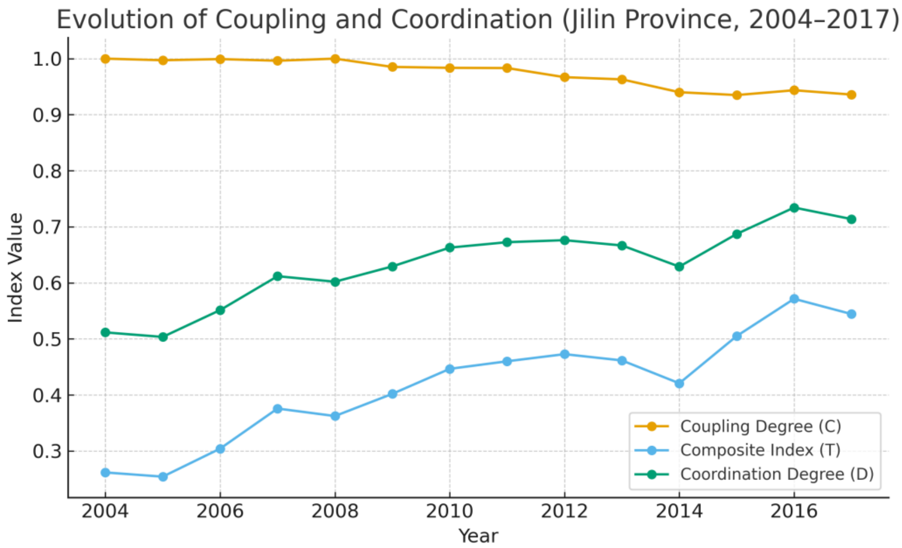

Figure 4. *Evolution of coupling degree (C), composite index (T), and coordination degree (D) between the economy and the eco-environment in Jilin (2004–2017). D improves from reluctant/primary coordination (~0.51–0.61) to moderate coordination (~0.71), while C remains high but slightly declines, indicating changing interaction strength amid structural adjustments*

The relationship between economic development and ecological environment in Jilin Province and countermeasures

Construction of index system

The economy and ecological environment are both complex systems, each with its own set of variables and interdependencies. When considered together, they form an even more intricate system, where it becomes impossible to represent either the economy or the ecological environment with a single indicator. Similarly, a single indicator cannot fully capture the relationship between the economy, society, and the environment. Therefore, it is more appropriate to use an indicator system composed of multiple variables to fully reflect the state of the economy, society, and ecological environment, and their interrelationships.

To ensure that the index system meets the research needs and accurately captures the characteristics of the economic, social, and ecological environment, the establishment of this system must adhere to several guiding principles. First, the scientific principle: The evaluation index system must be grounded in scientific thinking, seeking truth from facts and objectively measuring economic, social, and environmental factors. It should reflect the coordination of the economy, society, and environment in Jilin Province in a scientific, systematic, and comprehensive manner. Second, the systematic principle: While maintaining scientific rigor, the index system should clearly measure and reflect the overall structure and future development trends of the economic, social, and

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ecological systems. This will help ensure that all relevant indicators work together to provide a coherent understanding of the region's dynamics. Finally, the relevance principle: To ensure the organic combination of indicators, the system must be designed hierarchically, allowing for the reflection of both intra-level and inter-level relationships among indicators. This ensures the system's relevance and coherence, making it capable of addressing the complexities of economic and ecological interactions.

The economic vitality index system includes key indicators such as regional GDP, fixed asset investment rate, fiscal revenue growth rate, overseas direct investment growth rate, and total retail sales growth rate of consumers. Meanwhile, the eco-environmental index system is divided into three main aspects: eco-environmental pressure, eco-environmental state, and eco-environmental response. The components of the eco-environmental pressure index include total industrial wastewater discharge, industrial sulfur dioxide emissions, and per capita daily domestic water consumption. The ecological environment status is measured through indicators such as per capita public green space area, urban greening rate, total planting area, and urban construction land. Lastly, the ecological response indicators include the comprehensive utilization rate of solid waste in general industry and the sewage treatment rate. The complete index system for both the economic and ecological systems is shown in *Table 8*.

Table 8. *Index system of economic and social system and ecological environment system*

Two subsystems	Second-tier subsystem	Specific indicators	Index direction
Economic and social system	Economic level	Per capita GDP (10,000 yuan)	Straight
		Per capita disposable income of urban residents (10,000 yuan)	Straight
		Average wage of employees on the job (10,000 yuan)	Straight
	Economic structure	Ratio of primary industry to regional GDP (%)	Straight
		Ratio of tertiary industry to regional GDP (%)	Straight
		Regional GDP index	Straight
	Economic vitality	Investment rate of fixed assets (%)	Straight
		Growth rate of fiscal revenue (%)	Straight
		Growth rate of foreign direct investment (%)	Straight
		Growth rate of total retail sales of social consumer goods (%)	Straight
Ecological environment system	Ecological environmental pressure	Total daily discharge of industrial wastewater (10,000 tons/day)	Minus
		Daily emissions of industrial sulfur dioxide (tons/day)	Minus
	Ecological environment state	Per capita daily domestic water consumption (L)	Minus
		Per capita public green space area (m^2)	Straight
		Green coverage rate of built-up area (%)	Straight
		Sowing area (ha/10,000 people)	Straight
		Urban construction land area (km^2/10,000 people)	Straight
		Domestic garbage removal (10,000 tons)	Minus
	Ecological environmental response	Comprehensive utilization rate of general industrial solid waste (%)	Straight
		Sewage treatment rate (%)	Minus

The relationship between economic development and ecological environment in Jilin Province

The economic development and ecological environment of Jilin Province display markedly different temporal trajectories. Overall, the province's economic development

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index has maintained a long-term upward trend, albeit with notable fluctuations. Periods of decline were observed from 2004 to 2005 and 2007 to 2008, while rapid growth occurred between 2005 and 2007 and again from 2014 to 2016. In contrast, the period from 2008 to 2012 was characterized by significantly slower growth, suggesting a phase of adjustment and stabilization.

By comparison, the ecological environment index has remained relatively stable throughout the same period, except for a slight deterioration between 2011 and 2014. This divergence indicates that although economic development has advanced substantially, ecological conditions have not improved at the same pace and, in some years, have even experienced marginal decline.

From a broader perspective, the level of coordinated development between the economy and the ecological environment in Jilin Province remains relatively weak. Despite progress in both subsystems, the overall degree of coordination is still low, and pronounced spatial disparities exist among the province's nine cities and prefectures. Differences in coordination levels are particularly noticeable when comparing economically dynamic regions with those less developed. Although the general trend has shifted from uncoordinated to gradually coordinated development, substantial variation persists across both time and space.

These disparities reflect the challenges Jilin Province faces in achieving balanced, synergistic development. Some cities have made meaningful strides in integrating economic growth with ecological conservation, while others lag significantly behind. This uneven coordination highlights the need for more targeted, region-specific policies to strengthen the coupling between economic development and ecological sustainability, thereby ensuring that the province's long-term growth is both economically robust and environmentally resilient.

Relevant countermeasures and suggestions

Adhering to economic development while promoting ecological optimization is essential for ensuring the long-term sustainability of Jilin Province. The long-standing notion that "development is the last word" underscores the critical role of economic progress in elevating the province's overall competitiveness and addressing many of the structural challenges it faces—including those related to environmental protection. At present, both the economy and ecological environment of Jilin Province remain in an early stage of adjustment, with the development model still relatively underdeveloped. Therefore, while accelerating economic growth is necessary, equal emphasis must be placed on safeguarding and improving the ecological environment.

Jilin Province's economic scale remains modest, accounting for only about 1.8% of China's total GDP, which places it behind many other regions. The province is currently undergoing a pivotal phase of economic transition, providing a valuable opportunity to stimulate high-quality growth and maximize development gains. However, such progress must not come at the cost of ecological degradation. Efforts to accelerate economic development must be harmonized with strategies that protect natural resources and minimize environmental pressures.

A differentiated and region-specific approach is required to strengthen economic development across cities and prefectures, taking into consideration their unique natural endowments and industrial bases. Promoting coordinated development between the economy and ecological environment demands tailored policies. For instance, Changchun—the provincial capital—possesses a strong industrial base. To alleviate

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ecological pressures associated with rapid industrial growth, emphasis should be placed on enhancing industrial efficiency and promoting sustainable practices. In particular, the pharmaceutical sector should focus on reducing its environmental footprint while advancing production capacity, technological innovation, and brand competitiveness. More broadly, improving economic vitality and optimizing industrial structures will help reduce environmental strain.

During the process of economic expansion, it is crucial to recognize and address the negative impacts of economic activities and industrial configurations on the ecological environment. Establishing a sustainable development model is essential to ensure that long-term economic growth does not compromise ecological integrity. This entails lowering pollution from production and construction, minimizing ecological damage, and improving resource and waste utilization. The province must advance a green development pathway by prioritizing low-carbon economic growth, advocating for green consumption, and encouraging rational and efficient resource use. Only through such integrated efforts can Jilin Province achieve a future in which economic development and ecological protection progress in tandem.

Conclusion

Sustainable development has become the shared goal of nations in the 21st century, with ecological security now at the forefront of global attention. As global economic development accelerates, countries worldwide are increasingly focusing on sustainable development research and the protection of their national ecological environments.

For China, strengthening the ecological system and maintaining ecological security are fundamental to ensuring the sustainable economic and social development of the nation. In this context, transforming Jilin Province into an “ecological province” and developing an “eco-environment-friendly economy” are key objectives. Achieving this requires not only the protection of ecological resources but also fostering a balance between economic growth and environmental preservation. As a major agricultural province, ensuring ecological security and promoting sustainable ecological development are paramount tasks for Jilin Province.

Given the current ecological challenges and the various factors influencing the sustainable development of the province’s environment, this paper proposes several strategies to ensure ecological security and achieve long-term sustainability in Jilin. These recommendations focus on the following key areas: the implementation of industrial policies that prioritize environmental protection, the establishment of a capital investment support system for ecological environmental protection, and the creation and enhancement of a supervision and incentive mechanism to safeguard ecological resources. By addressing these aspects, Jilin Province can make significant strides toward balancing economic growth with environmental sustainability, ultimately securing its ecological future.

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