sustainability

MDPI

Article

Green Innovation and Biodiversity Conservation: Evidence from the Yangtze River Economic Belt

Jiawei Liu [1,*] and Yonghong Tu [2]

[1] School of Finance, Renmin University of China, Beijing 100872, China
[2] Yangtze River Economic Belt Research Institute, Renmin University of China, Yibin 644000, China; tuyh1966@ruc.edu.cn
* Correspondence: liujw0412@163.com; Tel.: +86-15600230621

Abstract

Green innovation has been widely regarded as an important driver of sustainable development; however, its implications for biodiversity conservation remain insufficiently explored. Existing studies primarily focus on the roles of green innovation in pollution control and energy efficiency, leaving its relationship with biodiversity outcomes largely understudied. This gap is particularly pronounced in regions experiencing intense ecological pressure, such as the Yangtze River Economic Belt (YREB), where rapid industrialization and human activities have substantially altered ecosystems. Using panel data from 11 provinces in the YREB over the period 2017–2020, this study examines the impact of green innovation development on biodiversity. Employing a two-way fixed-effects model, the results indicate that green innovation development is positively associated with biodiversity conservation, and this association remains robust to a range of endogeneity checks and robustness tests. To further explore potential transmission channels, we conduct a mechanism analysis. The findings provide indicative evidence that green innovation is associated with biodiversity outcomes through carbon emission reduction and improvements in environmental governance. Overall, this study contributes to the literature by shedding light on the biodiversity implications of green innovation and offers policy-relevant insights for regions seeking to balance innovation-driven growth with ecological protection.

Keywords: biodiversity; Natural Capital Index; green innovation; green finance; Yangtze River Economic Belt

1. Introduction

Biodiversity underpins ecosystem functioning, resilience, and the provision of essential ecosystem services that sustain human societies. Yet a large body of global assessments has documented persistent and widespread declines in species abundance, habitat extent, and ecological integrity despite decades of conservation efforts. For example, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services warns that more than one million species are currently threatened with extinction, driven by land-use change, overexploitation, pollution, invasive species, and climate change [1]. Similarly, global biodiversity indicators compiled by Butchart et al. (2010) show ongoing deterioration across multiple taxonomic and ecosystem-level dimensions [2]. These trends underscore the urgency of identifying effective pathways for reconciling economic development with biodiversity conservation.

Check for updates

Academic Editor: Tim Gray

Received: 20 November 2025
Revised: 21 January 2026
Accepted: 5 February 2026
Published: 12 February 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

In recent years, green innovation has increasingly been promoted as a means of achieving environmental improvements while maintaining economic growth. Green innovation—ranging from clean production processes to renewable energy technologies—has been shown to reduce environmental footprints and emissions, thereby improving environmental performance in both developed and developing economies [3,4]. However, empirical evidence on the relationship between green innovation and biodiversity conservation remains limited, particularly at the subnational level.

China provides a unique opportunity to examine this relationship. Large river basins represent both ecological hotspots and centres of human activity, making them particularly susceptible to biodiversity loss. The Yangtze River basin—central to the Yangtze River Economic Belt (YREB)—supports diverse mountain, forest, wetland and freshwater ecosystems, and harbours numerous endemic species. At the same time, it contains some of China's most rapidly urbanizing and industrialized regions, with extensive agricultural production and heavy infrastructure development. Pressures similar to those observed in other major river basins worldwide, such as the Mekong, Danube, and Mississippi, including hydrological alteration, land conversion, and pollution, have increasingly contributed to habitat degradation and ecological fragmentation within the Yangtze River Economic Belt (YREB) [5]. While these challenges are common across large river basins, the YREB is characterized by distinctive development patterns shaped by rapid industrialization, dense population distribution, and strong policy-driven economic integration. Understanding how emerging development models—particularly innovation-driven growth—affect biodiversity outcomes in this complex socio-ecological system is therefore of critical importance.

The YREB has been a major focal area for national ecological initiatives and experimentation with green innovation policies. In parallel, biodiversity pressures within the region—urban expansion, agricultural intensification, reservoir-induced hydrological changes—remain substantial. Existing studies on the YREB have tended to focus on environmental pollution, carbon emissions or economic sustainability, with relatively less attention given to biodiversity as a measurable ecological outcome. Moreover, biodiversity metrics in the Chinese research context often rely on either micro-scale species diversity indices or coarse ecological indicators, which present challenges for inter-provincial comparative research.

Against this background, this study has three closely related objectives, which also constitute its main contributions. First, we explicitly introduce green innovation as a driver of biodiversity in the Yangtze River Economic Belt. Using the provincial Green Innovation Development Index, we quantitatively examine how green innovation is associated with variations in a province-level biodiversity indicator. Second, we adapt and implement a Natural Capital Index framework to construct a macro-scale, province-level measure of biodiversity [2,6]. Instead of relying on traditional micro-level measures of α, β and γ diversity that require detailed plot-based species inventories [7,8], our approach provides a scientifically grounded yet cost-efficient indicator system suitable for regional policy analysis. Third, we assemble and empirically test a comprehensive set of anthropogenic drivers—including urbanization, cropland expansion, hydrological regulation, agrochemical use, aquaculture and protected areas—and offer an integrated assessment of how these factors jointly shape biodiversity in the YREB. In addition to examining the relationship between green innovation development and biodiversity conservation, this study further explores the potential pathways through which green innovation may influence biodiversity outcomes. By considering both technological and governance-related channels, this paper provides a more comprehensive understanding of how innovation-driven development is associated with ecological sustainability. In doing so, the study provides a systematic evidence base for basin-scale biodiversity conservation and sustainable management.

2. Literature Review

2.1. Biodiversity

Biodiversity is a cornerstone of ecosystem resilience and human well-being, offering critical services such as climate regulation, water purification, soil fertility, and cultural benefits [9]. However, biodiversity has been increasingly threatened by anthropogenic activities, resulting in widespread ecosystem degradation and species loss [10]. Understanding the drivers of biodiversity loss is crucial for developing effective conservation strategies, especially in regions undergoing rapid urbanization and industrialization, where human pressures on ecosystems are more intense.

Land-use change, driven primarily by agricultural expansion and urbanization, is one of the most significant factors contributing to biodiversity loss. The conversion of natural habitats into agricultural land or built environments results in habitat destruction and fragmentation, which directly impacts species richness and ecosystem functions [11,12]. Urbanization, for example, leads to the reduction in green spaces, disrupting the continuity of habitats and isolating species populations, thereby decreasing ecological connectivity. The intensification of agriculture, through practices such as monoculture farming and increased pesticide and fertilizer use, further exacerbates the loss of biodiversity by altering soil quality and ecosystem structure [13–15]. The shift from diverse natural landscapes to uniform agricultural fields diminishes species diversity and disrupts local food webs.

Infrastructure development, including roads, dams, and reservoirs, is another major driver of biodiversity loss. Infrastructure projects fragment ecosystems, isolate habitats, and restrict species migration, leading to the degradation of ecosystem services [16]. Roads, for instance, not only act as physical barriers but also increase roadkill, disrupt migration routes, and introduce pollutants into surrounding ecosystems. Dams and reservoirs affect the natural flow of rivers and alter aquatic habitats, further limiting biodiversity and ecosystem stability. Studies have shown that habitat fragmentation due to infrastructure development reduces biodiversity by impeding species movement and disrupting ecological networks [5]. These findings underscore the importance of considering infrastructure development as a key factor influencing biodiversity.

Additionally, the human footprint, which reflects the cumulative impacts of urbanization, agriculture, and industrial activities, has been identified as a critical factor affecting biodiversity. The human footprint quantifies the intensity of human pressures on ecosystems, with indicators such as urban built-up areas, agricultural land use, and aquaculture practices capturing the extent of human influence on natural environments [17]. Urbanization leads to habitat loss and fragmentation, while agricultural activities, particularly in intensive farming systems, degrade ecosystems by altering soil structure and introducing harmful chemicals into the environment. Aquaculture also poses a threat to aquatic biodiversity by disrupting ecosystems, changing nutrient cycles, and introducing contaminants [18]. These anthropogenic pressures have led to a decline in species richness and ecosystem integrity, especially in regions where human activity is concentrated.

In recent years, green finance has gained increasing attention as an important factor influencing biodiversity conservation. Green finance refers to financial activities that support the transition towards environmentally sustainable development, including the financing of green technologies, renewable energy, pollution control, and conservation efforts. While green finance is primarily associated with climate change mitigation and pollution reduction, its role in biodiversity conservation is equally significant. Green financial instruments, such as green bonds, provide essential capital for environmental projects, including those aimed at protecting and restoring biodiversity. By directing investment into conservation projects, habitat restoration, and sustainable land-use practices, green finance can help mitigate the negative impacts of human activities on biodiversity [19]. Green finance

can also drive innovation in environmental technologies, further enhancing biodiversity conservation efforts. By providing financial incentives for sustainable practices, such as green agriculture and eco-friendly infrastructure, green finance encourages companies and governments to adopt innovative solutions that reduce environmental impact and improve biodiversity outcomes [20]. This creates a positive feedback loop, where financial support for sustainable practices leads to innovation in green technologies, which in turn helps conserve biodiversity.

Finally, ecological conservation measures, such as the establishment of nature reserves and protected areas, play a crucial role in biodiversity conservation. Nature reserves provide critical refuges for species, helping to preserve biodiversity in the face of human-induced pressures. However, the effectiveness of these reserves depends on their size, connectivity, and the quality of their management [21]. Properly designed and well-managed reserves can help mitigate biodiversity loss by providing safe habitats for species and maintaining important ecosystem services. Despite their importance, however, conservation interventions are not always sufficient to counterbalance the pressures from urbanization, agriculture, and infrastructure development, making it essential to integrate conservation efforts into broader land-use planning and development strategies.

2.2. Green Innovation

Green innovation, defined as the development and application of technologies that reduce environmental harm and improve resource efficiency, has become a key strategy for addressing the global environmental crisis. The concept of green innovation encompasses a broad range of technologies, from renewable energy solutions and energy-efficient industrial processes to eco-friendly product designs and waste management systems [22,23]. Green innovation aims not only to mitigate environmental damage but also to promote long-term sustainability by optimizing resource use and reducing ecological footprints.

Empirical studies have shown that green innovation has significant positive impacts on environmental sustainability. For instance, green technologies in renewable energy, such as wind, solar, and hydroelectric power, help reduce dependence on fossil fuels and lower carbon emissions [24]. These innovations contribute to cleaner air, reduced water consumption, and more sustainable energy systems. Similarly, innovations in waste management, such as recycling technologies and circular economy practices, help reduce the amount of waste sent to landfills, further minimizing environmental pollution [4]. Green innovation, therefore, plays a crucial role in achieving environmental sustainability by decreasing pollution and promoting the efficient use of natural resources.

In addition to environmental benefits, green innovation also contributes to economic sustainability. By fostering the development of green technologies, countries and businesses can create new markets, generate employment opportunities, and increase competitiveness in the global economy. For example, the clean energy sector, which includes technologies such as solar and wind energy, has become a major source of employment, particularly in emerging economies [25]. Moreover, the development of green technologies can lead to cost savings for businesses through increased energy efficiency and reduced resource consumption. As a result, green innovation not only benefits the environment but also promotes economic growth and job creation, particularly in sectors related to renewable energy, energy efficiency, and sustainable agriculture [26,27].

While green innovation is widely recognized for its contributions to environmental and economic sustainability, its direct impact on biodiversity remains underexplored. Most studies have focused on green innovation's ability to reduce emissions and improve resource efficiency, but there is limited research on how these innovations affect biodiversity outcomes. Green innovation, particularly in the areas of energy production, sustainable

agriculture, and pollution control, has the potential to directly benefit biodiversity by reducing habitat destruction, limiting pollution, and enhancing ecosystem resilience.

One important area where green innovation can influence biodiversity is in sustainable agriculture. Traditional farming practices, including monoculture cropping and the extensive use of pesticides and fertilizers, have contributed to significant biodiversity loss by degrading ecosystems and reducing species richness [28]. However, innovations in agricultural technologies, such as precision farming, organic fertilizers, and integrated pest management, can reduce the environmental impact of agriculture and enhance biodiversity. For example, precision farming techniques optimize the use of water, fertilizers, and pesticides, minimizing waste and reducing environmental harm [29]. These innovations can help preserve habitats, protect soil biodiversity, and increase the sustainability of agricultural practices.

Similarly, green innovation can contribute to biodiversity conservation by promoting clean energy technologies that reduce reliance on fossil fuels. The transition to renewable energy sources, such as solar, wind, and hydroelectric power, can reduce the negative impacts of energy production on ecosystems and biodiversity. Traditional energy production methods, such as coal and oil extraction, have been linked to habitat destruction, air and water pollution, and climate change, all of which threaten biodiversity. By adopting clean energy technologies, green innovation can help mitigate these impacts and support biodiversity conservation by reducing the environmental footprint of energy production [30].

The literature reviewed above highlights the growing role of green innovation in reshaping production patterns, environmental governance, and ecological outcomes. Despite the potential of green innovation to support biodiversity, there remains a significant gap in the literature concerning its direct effects on biodiversity outcomes. While many studies focus on green innovation's role in pollution reduction and energy efficiency, the relationship between innovation-driven development and biodiversity remains understudied. This is particularly true in regions where biodiversity is most at risk, such as the Yangtze River Economic Belt (YREB), where human activities and industrial development have placed significant pressure on ecosystems. Moreover, existing studies rarely explore the specific channels through which green innovation may influence biodiversity outcomes. Although improvements in environmental performance and governance are often discussed in related contexts, the mechanisms linking innovation-driven development to biodiversity conservation have not been systematically examined. This study aims to fill this gap by examining the role of green innovation development (GIDI) in promoting biodiversity conservation in the YREB, and by further exploring the potential pathways through which green innovation may affect biodiversity, providing a more comprehensive understanding of how innovation-driven development can contribute to ecological sustainability.

Building on this literature, this study posits that green innovation development can contribute to biodiversity conservation by fostering cleaner production processes and facilitating a transition toward less resource- and pollution-intensive economic structures. Accordingly, we propose the following hypotheses:

H1: *Green innovation development is positively associated with biodiversity outcomes in the Yangtze River Economic Belt.*

Beyond this baseline relationship, the literature also suggests that green innovation may influence biodiversity indirectly through multiple channels. First, green innovation can alleviate environmental pressure by reducing emissions intensity and pollution-related stress. Second, green innovation can promote industrial upgrading and structural transformation, thereby reducing biodiversity loss associated with heavy and resource-intensive industries. Accordingly, we propose the following hypotheses:

H2 (Pollution mitigation channel)**:** *Green innovation development contributes to biodiversity conservation by reducing environmental pressure, particularly through lowering carbon emission intensity.*

H3 (Structural transformation channel)**:** *Green innovation development promotes biodiversity by facilitating industrial upgrading toward less resource- and pollution-intensive economic activities.*

These hypotheses are empirically examined in the subsequent sections using regression-based analyses at the provincial level. Specifically, the baseline specification captures the aggregate prediction that greater green innovation enhances biodiversity performance, while the choice of control variables reflects the pressures identified in the theoretical mechanisms. Moreover, the mechanism tests in Section 4.5 are explicitly designed to correspond to the theoretical channels outlined above.

3. Materials and Methods

The empirical strategy follows directly from the theoretical mechanisms summarized in Section 2. Specifically, green innovation is predicted to affect biodiversity performance. To capture the aggregate implication, we estimate a reduced-form two-way fixed-effects model in which biodiversity outcomes (NCI) are regressed on green innovation (GIDI) and a set of theoretically motivated covariates. This approach allows us to test the core theoretical prediction while controlling for observable sources of ecological variation.

3.1. Study Area

This study focuses on the Yangtze River Economic Belt (YREB), which encompasses 11 provincial-level regions spanning the upper, middle, and lower reaches of the Yangtze River. The region is ecologically diverse, ranging from mountainous forests and karst systems in the upper reaches to more intensive agricultural and urbanized areas in the middle and lower reaches. It represents one of China's most dynamic socio-ecological systems. The YREB is characterized by significant heterogeneity in ecosystem conditions, anthropogenic pressures, industrial structure, and innovation capacity, making it an ideal case for exploring the interactions between biodiversity, green innovation, and green finance.

3.2. Variables and Measurements

3.2.1. Biodiversity: Natural Capital Index (NCI)

Biodiversity represents the observable diversity at various levels, including genes, species, populations, ecosystems (habitats), and landscapes. It encompasses measures of quantity and richness, among others [31]. The Convention on Biological Diversity (CBD) provides a more comprehensive concept of biodiversity, which includes "the variability among living organisms from all sources, including terrestrial, marine, and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems." Therefore, biodiversity assessment involves systematically collecting information on biodiversity status, pressures, drivers, impacts, and responses and analyzing it to make quantitative or qualitative judgments about biodiversity status and changes, providing foundations for decision-making.

Biodiversity is measured using the Natural Capital Index (NCI), a habitat-based indicator that integrates both habitat quantity and habitat quality [2,6]. Biodiversity reflects the diversity of species, populations, ecosystems, and landscapes, as well as the ecological processes that sustain them. This study uses NCI to reflect the proportion of natural and semi-natural ecosystems remaining relative to a baseline condition, adjusted for the intensity of anthropogenic pressures.

1. Habitat Area

Habitat area for each province is derived from land-cover maps, capturing the area of forests, grasslands, wetlands and other natural ecosystems. The area component is defined as:

$$area_{i,t} = \frac{A_{i,t}}{A_{i,0}} \quad (1)$$

where $A_{i,t}$ is the natural-habitat area of province i in year t, and $A_{i,0}$ is the corresponding area in the baseline year (2016). For the construction of the Natural Capital Index (NCI), the year of policy implementation is chosen as the baseline, following the idea that the choice of reference year carries important interpretative value in assessing changes in natural capital [6]. In this study, 2016 is selected as the baseline year, corresponding to the implementation of the Development Plan for the Yangtze River Economic Belt. This plan marks the beginning of a new phase in biodiversity conservation and the promotion of a new development pattern in the region, and therefore provides a meaningful reference point for evaluating subsequent changes in biodiversity.

2. Habitat Quality

Habitat quality is measured using a pressure-based approach consistent with the original design of the study [32]. The method assumes that human activities exert negative ecological pressure on natural habitats, and that the cumulative level of these pressures determines the overall ecological condition of a province in a given year. Following this framework, seven pressure factors are used: climate change, population density, GDP intensity (GDP per km^2), habitat fragmentation, acidification, eutrophication and ozone exposure. Each factor is transformed into a standardized pressure magnitude ranging from 0 to 1000, where 0 represents the minimum pressure (optimal ecological state) and 1000 represents the maximum pressure (highly degraded state). The Pressures on Biodiversity are shown in Table 1.

Table 1. Pressures on Biodiversity.

Indicator	High Ecosystem Quality Pressure = 0	Low Ecosystem Quality Pressure = 1000
Rate of Temperature Change	20-year change < 0.2 °C	20-year change > 0.2 °C
Population Density	<10 people per square kilometer	>150 people per square kilometer
GDP	0 RMB per square kilometer	>38 million RMB per square kilometer
Fragmentation	Natural area > 64%	Natural area < 1%
Acidification	Deposition < critical load	Deposition > 5× critical load
Eutrophication	Deposition < critical load	Deposition > 5× critical load
Ozone Exposure	AOT40 < critical level	AOT40 > 5× critical level

For each pressure factor j, the normalized pressure magnitude is calculated as:

$$pressure_{j,i,t} = \frac{value_{j,i,t} - value_j^{(0)}}{value_j^{(1000)} - value_j^{(0)}} \times 1000 \quad (2)$$

where $value_{j,i,t}$ is the observed value of pressure j in province i and year t, $value_j^{(0)}$ corresponds to the lower bound of the "0-pressure state", and $value_j^{(1000)}$ corresponds to the upper bound of the "1000-pressure state".

The composite index reflects the total anthropogenic pressure exerted on natural habitats. The composite pressure state for province i is then:

$$state_{i,t} = \sum_j pressure_{j,i,t} \quad (3)$$

To ensure comparability across years, the composite pressure state is normalized relative to the baseline year. The relative habitat-quality index is defined as:

$$quality_{i,t} = \frac{state_{i,t}}{state_{i,0}} \quad (4)$$

where $state_{i,0}$ denotes the composite pressure state of province i in the baseline year. This formulation preserves the logic and scaling used in the original method while providing a transparent and replicable quality metric that aligns with ecological-pressure modelling practices.

3. Natural Capital Index

The final NCI for province i in year t is calculated as:

$$NCI_{i,t} = area_{i,t} \times quality_{i,t} \quad (5)$$

$NCI_{i,t}$ represents the relative biodiversity status compared to the baseline year and is a relative value rather than an absolute value. A higher NCI value indicates a higher level of biodiversity in the region.

3.2.2. Green Innovation Development (GIDI)

The level of green innovation development is measured using the Green Innovation Development Index (GIDI), constructed following the official framework of the Yangtze River Economic Belt Green Innovation Development Index Report. The GIDI consists of two primary dimensions—green innovation input and green innovation output—operationalized through eight secondary indicators and 25 tertiary indicators. Indicator weights are determined using confirmatory factor analysis (CFA) and normalized to ensure comparability across provinces. A complete description of indicator definitions, data sources, and weighting procedures is provided in Appendix A.

3.3. Model Design

To evaluate the relationship between green innovation and biodiversity, the following panel regression model is estimated:

$$NCI_{i,t} = \alpha + \beta_1 GIDI_{i,t} + \beta_2 X_{i,t} + \sigma_i + \mu_t + \varepsilon_{i,t} \quad (6)$$

where $NCI_{i,t}$ represents the level of biodiversity, i denotes the province, t represents the year, $GIDI_{i,t}$ is the key independent variable in this study representing the level of green innovation development, $X_{i,t}$ represents a range of control variables related to biodiversity conservation, σ_i represents the fixed effect of province, μ_t represents the fixed effect of year, and ε_{it} is the disturbance term.

Based on relative research, control variables including natural and human-driven pressures [5,10,14,17]. Because natural ecological conditions are already embedded in the NCI measure, only human activity factors are included to avoid endogeneity. Four primary categories of anthropogenic pressures are considered: (1) Ecosystem fragmentation, represented by highway density and reservoir capacity, reflecting habitat division caused by infrastructure [16,33]. (2) Human footprint, capturing land-use intensity via urban built-up area ratio, agricultural land ratio, fertilizer and pesticide use, and aquaculture area [17].

(3) Green financial activity, measured by green bond balance, reflecting the role of financial instruments in supporting biodiversity-related investment. (4) Ecological construction, represented by the proportion of nature reserve area, indicating conservation efforts that mitigate biodiversity loss [21].

These indicators comprehensively capture human pressures related to land conversion, agricultural inputs, infrastructure expansion, financial activity, and conservation investment. The final set includes eight indicators, summarized in Table 2. Importantly, to reduce mechanical overlap with the dependent variable, our baseline specifications do not include socio-economic covariates that replicate the NCI subcomponents. The control set focuses on innovation- and policy-relevant factors that are not used in the construction of the NCI.

Table 2. Variable Definitions.

Indicator	Meaning
density	Total length of highways per 100 square kilometers
capacity	Sum of reservoir water storage capacity in the region
town	Ratio of urban built-up area to total land area in the region
cropland	Ratio of agricultural land to total land area in the region
pesticide	Total amount of pesticide and fertilizer usage adjusted for pure content
aquaculture	Ratio of aquaculture land to total land area in the region
bond	Total balance of green bonds issued from the start to the end of the year
reserve	Ratio of nature reserve area to total land area in the region

It is important to note that the panel used in this study consists of a relatively small number of observations (11 provinces over four years). This limitation mainly reflects data availability constraints for constructing consistent province-level biodiversity indicators in China. Nevertheless, the two-way fixed-effects (TWFE) model remains appropriate for the present analysis for several reasons.

First, biodiversity outcomes are characterized by strong structural persistence and substantial unobserved heterogeneity across provinces. The TWFE framework effectively controls for time-invariant provincial characteristics (e.g., geomorphology, baseline ecosystem endowment) as well as common time shocks, allowing identification to rely on within-province variation over time. Second, the panel is fully balanced, which improves estimation efficiency even in small-N settings. Third, the primary objective of this study is not large-sample prediction, but mechanism-oriented inference regarding how changes in green innovation capacity relate to biodiversity dynamics within a highly regulated ecological corridor.

To further mitigate small-sample concerns, we conduct a series of robustness checks. The consistency of results across these specifications supports the reliability of the baseline estimates.

To explore the potential mechanisms, we replace the baseline dependent variable with each mediator and estimate the same specification. This approach allows us to examine whether green innovation is systematically associated with the proposed channels.

All econometric analyses were implemented in Stata 17.0 (StataCorp LLC, College Station, TX, USA). The confirmatory factor analysis (CFA) required for constructing the GIDI index was conducted using R version 4.3.1 (R Foundation for Statistical Computing, Vienna, Austria).

3.4. Data Sources

This study uses provincial-level panel data for the 11 provinces and municipalities in the Yangtze River Economic Belt over the period 2017–2020. This spatial scope is determined by the institutional definition of the YREB, while the time window reflects the latest period for which consistent and comparable provincial-level biodiversity indicators are available. As such, the analysis focuses on structural relationships within a clearly defined regional and institutional context, rather than real-time ecological monitoring or short-term forecasting. The level of green innovation development is captured by the Green Innovation Development Index, which is taken from the Green Innovation Development Index Report of the Yangtze River Economic Belt. Biodiversity data, specifically the Natural Capital Index (NCI) for each province, are collected from the National Bureau of Statistics of China. The green financial variable, measured by the balance of green bonds, is obtained from the WIND database. All remaining socioeconomic and land-use-related indicators are sourced from the National Bureau of Statistics of China. Table 3 presents the descriptive statistics results of the variables.

Table 3. Descriptive Statistics.

Variable	N	Mean	Standard	Deviation	Minimum
NCI	44	72.9	23.5	22.8	100
GIDI	44	34.1	16.4	19.5	92.3
density	44	133.4	44.3	63.3	219.5
capacity	44	424.5	348.4	0	1263.9
town	44	4.1	8.3	0.3	30.1
cropland	44	38.5	16.9	17.7	73.6
pesticide	44	55.3	35.4	2.5	116
aquaculture	44	2.2	1.7	0.2	6.8
bond	44	309.8	284.3	14	1080
reserve	44	6.5	3.9	1.7	17.1

4. Results

4.1. Descriptive Analysis of Major Variables and NCI Components

Table 4 presents the Natural Capital Index (NCI) for all provinces in China from 2016 to 2020. Considerable spatial heterogeneity is observed across regions. Provinces such as Guangxi, Zhejiang, and Yunnan consistently exhibit high NCI values, reflecting well-preserved ecosystems with large areas of natural habitat and relatively lower ecological pressures. In contrast, Shandong, Tianjin, and Jiangsu display persistently low NCI values, indicating degraded habitat conditions and substantial anthropogenic pressures. These results align with national-scale assessments showing that coastal and urban-intensive regions face greater ecological degradation compared with southwestern provinces rich in natural ecosystems.

Temporal trends show that several provinces—most notably Shandong, Heilongjiang, and Jilin—achieved notable improvements in NCI between 2016 and 2020, suggesting positive ecological restoration outcomes. Conversely, Fujian, Hainan, and Jiangsu experienced declines in NCI during the same period, indicating that biodiversity pressures remain unresolved. These contrasting patterns highlight the importance of region-specific ecological management strategies.

Table 4. NCI of Provinces in China.

Region	2020	2019	2018	2017	2016
Beijing	73.2	73.02	74.47	73.72	74.41
Tianjin	30.03	28.63	31.09	29.98	31.41
Hebei	52.24	52.2	52.91	53.02	53.79
Shanxi	50.13	50.08	50.47	50.78	51.23
Inner Mongolia	89.16	89.11	89.15	89.06	89.18
Liaoning	65.04	64.17	64.32	64.36	65.71
Jilin	76.41	75.97	75.8	75.3	75.67
Heilongjiang	63.43	63.46	62.71	62.23	62.34
Shanghai	49.21	46.13	43.11	41.57	49.91
Jiangsu	25.67	22.84	24.26	24.39	27.21
Zhejiang	98.13	99.99	97.06	97.26	100
Anhui	46.89	43.61	45.71	46.26	49.15
Fujian	84.9	88.61	86.99	90.39	97.19
Jiangxi	94.22	95.7	93.14	95.65	98.03
Shandong	31.69	30.46	31.49	30.69	30.65
Henan	51.25	50.07	51.79	53.16	53.5
Hubei	79.31	74.99	76.68	79.12	80.81
Hunan	85.29	85.64	84.38	86.43	87.77
Guangdong	79.72	81.12	80.58	80.24	82.27
Guangxi Zhuang Autonomous Region	98.65	98.82	98.54	100	100
Hainan	91.79	91.74	96.95	96.63	100
Chongqing	75.92	74.12	75.39	77.45	78
Sichuan	83.31	83.03	83.53	83.47	83.74
Guizhou	73.77	73.24	73.01	73.65	74.08
Yunnan	97.74	97.52	98.79	99.1	99.24
Tibet Autonomous Region	80.91	80.89	80.94	80.98	80.95
Shaanxi	69.91	70.29	70.08	70.84	70.44
Gansu	52.13	51.97	52	51.82	51.67
Qinghai	57.42	57.34	57.39	57.23	57.05
Ningxia Hui Autonomous Region	70.29	70.55	70.93	71	71.36
Xinjiang Uygur Autonomous Region	40.31	40.35	40.37	40.46	40.52

To further understand spatial differences across regions, the average NCI was calculated for (1) the 11 provinces in the Yangtze River Economic Belt, (2) nine provinces in the Yellow River Basin, and (3) other provinces in China. Figure 1 plots the average values alongside fitted quadratic curves. The YREB consistently reports higher NCI levels than the Yellow River Basin and other regions throughout 2016–2020, suggesting that implementation of the Yangtze River conservation strategy has yielded substantial biodiversity benefits.

Figure 2 illustrates variation in the Green Innovation Development Index (GIDI) across the upper, middle, and lower reaches of the YREB. From 2017 to 2020, green innovation development steadily improved across the region, with the lower reaches showing no-

tably stronger performance than the upper and middle reaches. This suggests accelerating innovation-driven ecological transformation, particularly in the more developed downstream provinces.

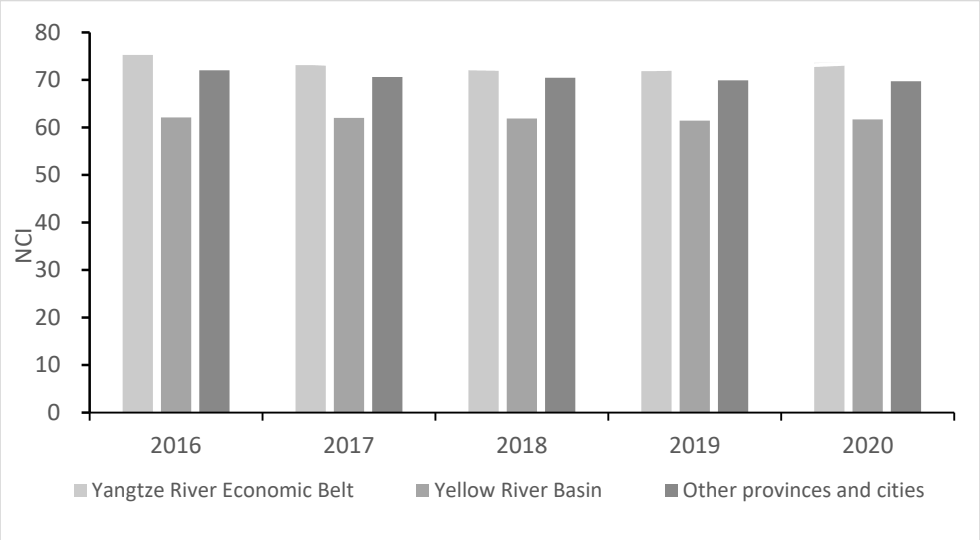

Figure 1. Average NCI of YREB, Yellow River Basin, and other provinces.

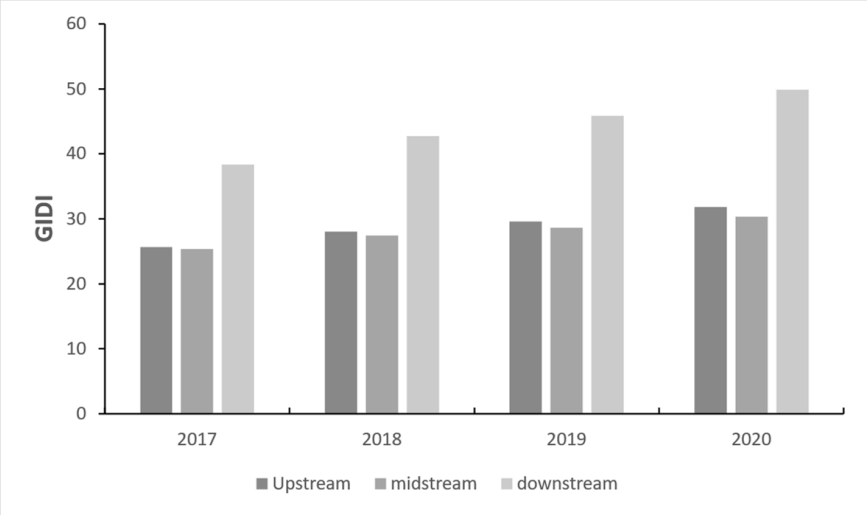

Figure 2. GIDI in the upper, middle, and lower reaches of the YREB.

To further assess the sensitivity and interpretability of the Natural Capital Index (NCI), Table 5 reports the key structural components underlying its construction for important province of China, based on the variable definitions described in Table 2. As the NCI is designed to capture relatively slow-moving land-related and ecological conditions at the provincial scale, the table focuses on cross-sectional differences using averages over 2016–2020.

A province-level examination reveals substantial heterogeneity in the underlying parameters of the NCI. Shanghai and Jiangsu exhibit high-pressure components associated with dense urban development and intensive land conversion. Zhejiang shows a similar pattern, albeit with greater landscape heterogeneity due to its coastal and hilly terrain. In Anhui and Jiangxi, agricultural land use and mixed rural–urban development play a more prominent role in shaping the pressure component. Hubei and Hunan reflect a combination of industrial activities, agricultural production, and freshwater-related land use, consistent with their central positions in the basin. Provinces in the upper reaches—namely Chongqing, Sichuan, Guizhou, and Yunnan—are characterized by mountainous

landscapes and extensive natural land coverage, where the area-related component captures structural geographic conditions, while the pressure index mainly reflects localized human activities along transportation corridors and urban clusters. Overall, although aggregate NCI values may appear comparable across provinces, the underlying parameters differ markedly, reflecting province-specific combinations of development intensity, geographic location, climate, and landscape structure.

Table 5. Structural components underlying NCI.

Province	NCI (Average 2016–2020)	Area Component (Average 2016–2020)	Pressure Index (Average 2016–2020)
Shanghai	45.984	0.462	0.999
Jiangsu	24.874	0.249	0.999
Zhejiang	98.485	0.999	0.999
Anhui	46.323	0.476	0.972
Jiangxi	95.348	0.965	0.988
Hubei	78.18	0.797	0.981
Hunan	85.903	0.871	0.986
Chongqing	76.177	0.78	0.976
Sichuan	83.415	0.841	0.991
Guizhou	73.553	0.742	0.991
Yunnan	98.478	0.991	0.994
Tibet	80.933	0.809	0.999
Qinghai	57.286	0.573	0.999

4.2. Baseline Regression Analysis

Table 6 reports the baseline regression results examining the impact of green innovation (GIDI) on biodiversity (NCI), with and without the inclusion of human-activity control variables. Across all specifications, GIDI exhibits a significantly positive coefficient, demonstrating that provinces with higher levels of green innovation tend to achieve better biodiversity outcomes. This result supports hypothesis 1 that green innovation plays a central role in reducing ecological pressures and enhancing ecological efficiency.

Table 6. Baseline Regression Results.

Variables	(1)	(2)
	NCI	NCI
GIDI	0.155 *** (2.62)	0.555 ** (0.224)
density		0.161 *** (0.036)
capacity		−7.334 *** (1.766)
town		−16.876 *** (1.689)
cropland		−1.988 *** (0.111)
pesticide		6.56 *** (1.45)

Table 6. *Cont.*

Variables	(1)	(2)
	NCI	NCI
aquaculture		8.528 *** (1.433)
bond		0.008 ** (0.004)
reserve		−1.234 *** (0.174)
Constant	67.578 *** (9.02)	144.474 *** (13.47)
N	44	44
Adjusted R^2	0.169	0.998
Year Fixed	YES	YES
Province Fixed	YES	YES

Note: 1. *** and ** denote significance at the 1% and 5% levels, respectively. Standard errors in parentheses. 2. The increase in the GIDI coefficient after adding control variables reflects a suppression effect, as several development-related pressures are negatively correlated with biodiversity but positively correlated with green innovation. 3. "YES" indicates that the corresponding fixed effects are included in the regression specification.

Column (1) reports an intentionally low-dimensional specification that includes only GIDI, province and year fixed effects. This parsimonious specification mitigates concerns about over-parameterization and limited degrees of freedom in a small panel. The positive and significant coefficient on GIDI in this setting suggests that the baseline relationship is not mechanically driven by the inclusion of a large set of controls.

When human-activity variables are included (Column 2), the coefficient of GIDI remains significant, indicating that the positive effect of green innovation is robust to the inclusion of socioeconomic and land-use factors. The coefficients of the human-activity variables yield results consistent with ecological theory. In a short panel with province and year fixed effects, the majority of the cross-sectional and temporal variation is absorbed by the fixed effects themselves. Adding control variables reallocates the remaining within-province variation rather than increasing independent identifying variation. The change in coefficient magnitude therefore reflects variation reallocation under a highly saturated FE structure.

To examine whether the increase in the GIDI coefficient after adding control variables is driven by multicollinearity, we conducted variance inflation factor (VIF) diagnostics for all control variables included in the baseline specification. The results show that all VIF values are below 6, well under conventional thresholds used to indicate serious multicollinearity concerns. This suggests that the observed change in coefficient magnitude is not mechanically driven by collinearity among the control variables.

Urbanization, agricultural land use, and reservoir capacity exhibit significantly negative effects on biodiversity, reflecting their roles in habitat conversion, fragmentation, and alteration of hydrological and ecological processes. The negative impact of cropland expansion, for example, underscores well-established mechanisms through which intensive agriculture disrupts soil health and reduces habitat heterogeneity.

Interestingly, road density displays a positive association with biodiversity at the provincial level. Although this result appears counterintuitive from a traditional ecological perspective, it can be understood in the context of recent changes in infrastructure planning and land-use governance in China. In the Yangtze River Economic Belt (YREB), transporta-

tion development has increasingly incorporated ecological restoration measures, such as roadside vegetation recovery and the integration of ecological corridors into transport networks. Existing studies in road ecology suggest that such "green infrastructure" approaches can mitigate habitat fragmentation and, in certain contexts, improve landscape-level ecological connectivity [34,35]. Moreover, road networks in the YREB are predominantly concentrated in already urbanized or heavily modified landscapes, implying that marginal expansions may generate relatively limited additional ecological pressure compared with development in ecologically intact areas.

Fertilizer and pesticide use, as well as aquaculture activity, also exhibit positive coefficients, which differ from conventional ecological expectations. Importantly, these results should not be interpreted as evidence that agricultural inputs or aquaculture expansion directly enhance biodiversity. Rather, they likely reflect the combined effects of regulatory tightening and technological upgrading in China's agricultural sector in recent years. Following the implementation of the Ministry of Agriculture's "Zero Growth Action Plan for Fertilizer and Pesticide Use," empirical research documents substantial reductions in excessive chemical inputs and improvements in input efficiency at the regional scale [36,37]. Similarly, studies on China's aquaculture sector show that strengthened environmental regulation and the adoption of more eco-friendly production systems can significantly reduce pollution intensity and ecological pressure associated with aquaculture activities [38].

These findings do not contradict the extensive ecological literature documenting the detrimental impacts of fertilizers, pesticides, and intensive aquaculture at local or ecosystem scales. Instead, they highlight the importance of scale effects, institutional context, and policy-induced technological change when interpreting aggregate relationships derived from province-level indicators. In this sense, the positive coefficients observed in the regression results reflect macro-level correlations shaped by governance and technological transitions, rather than causal ecological mechanisms. By explicitly distinguishing between core explanatory variables and contextual controls, this interpretation helps preserve the credibility of the estimated relationship between green innovation development and biodiversity outcomes.

Finally, the coefficient for green bond balance is significantly positive, suggesting that green financial instruments support biodiversity either directly (through ecological restoration and conservation projects) or indirectly (through enabling cleaner industrial processes and reducing ecological pressures). This provides empirical support for the emerging view that green finance can serve as an important complementary mechanism to ecological conservation efforts.

4.3. Endogeneity Tests

To ensure that the baseline results are not driven by reverse causality or omitted variables, two endogeneity checks were conducted.

4.3.1. Lagged Independent Variable

To address potential endogeneity, the key independent variable (GIDI) was lagged by one period. Regression results remain significantly positive (Table 7), demonstrating that the influence of green innovation on biodiversity is not driven by reverse causality or immediate feedback effects. This reinforces the robustness of the baseline findings.

Table 7. Regression Results with One-Period Lagged Key Explanatory Variable.

Variable	NCI
One-Period Lagged GIDI	0.755 *** (3.21)
density	0.133 *** (3.17)
capacity	−6.441 *** (−3.7)
town	−19.358 *** (−9.64)
cropland	−1.998 *** (−16.98)
pesticide	4.376 *** (2.6)
aquaculture	10.825 *** (6.38)
bond	0.004 (0.86)
reserve	−1.046 *** (−5.9)
Constant	142.488 *** (10.57)
N	44
Adjusted R^2	0.998
Year Fixed	YES
Province Fixed	YES

Note: 1. *** denotes significance at the 1% level, respectively. Standard errors in parentheses. 2. "YES" indicates that the corresponding fixed effects are included in the regression specification.

4.3.2. Instrumental Variable Approach

An instrumental variable (IV) approach using R&D investment as the instrument for GIDI was implemented, following established innovation-econometrics practice [39]. R&D investment is a core input to innovative activity and is closely linked to the production of new knowledge and innovation outcomes, such as patenting [40]. Moreover, regional innovation capacity is shaped by historically evolved development trajectories and path dependence, implying that long-run development patterns can condition current innovation potential [41]. Accordingly, these factors are also fundamental determinants of green innovation development, given that green technological progress relies on directed research and innovation capabilities [27]. At the same time, conditional on province and year fixed effects as well as regional controls, it is unlikely to directly affect short-term biodiversity outcomes except through its impact on green innovation. This assumption is consistent with existing studies that employ similar instruments in the innovation and environmental economics literature. As shown in Table 8, the first-stage F-statistic (139.12) exceeds the conventional threshold of 10, rejecting weak instrument concerns. The Hausman test (p = 0.01) indicates the presence of endogeneity, further justifying the IV estimation. In the second stage, the GIDI coefficient remains significantly positive, confirming that green innovation has a causal and robust positive impact on biodiversity conservation.

Table 8. Regression Results with Instrumental Variable.

Variable	First Stage	Second Stage
	GIDI	NCI
R&D	0.00000157 *** (3.98)	
GIDI		0.527 * (1.66)
density		0.165 *** (3.15)
capacity		−7.477 *** (−4.11)
town		−16.776 *** (−13.4)
cropland		−1.997 *** (−17.25)
pesticide		6.661 *** (4.93)
aquaculture		8.444 *** (7.2)
bond		0.008 * (1.84)
reserve		−1.24 *** (−9.3)
Constant		145.584 *** (10.83)
N	44	44
Adjusted R^2		0.989
F	139.12	
p	0.000	
Year Fixed	YES	YES
Province Fixed	YES	YES

Note: 1. *** and * denote significance at the 1% and 10% levels, respectively. Standard errors in parentheses. 2. "YES" indicates that the corresponding fixed effects are included in the regression specification.

4.3.3. Robustness to Potential Index Tautology

A potential concern is that the baseline NCI incorporates GDP-density and population-density proxies in its pressure dimension, which could create partial overlap with socio-economic drivers. To mitigate this concern, we construct NCI_excl, an alternative index that excludes GDP-density and population-density components from the NCI calculation and re-normalizes the remaining components. We then re-estimate the baseline models by replacing NCI with NCI_excl as the dependent variable. As shown in Table 9, the estimated effect of green innovation development remains qualitatively similar in sign and statistical relevance, indicating that our main findings are not driven by the inclusion of GDP and population components in the baseline NCI.

Table 9. Robustness: Regressions using NCI_excl.

Variables	(1)	(2)
	NCI	NCI
GIDI	0.143 *** (0.041)	0.487 ** (0.198)
density		0.158 *** (0.035)
capacity		−6.912 *** (1.702)
town		−15.633 *** (1.604)
cropland		−1.876 *** (0.108)
pesticide		5.941 *** (1.392)
aquaculture		8.214 *** (1.381)
bond		0.007 ** (0.003)
reserve		−1.108 *** (0.168)
Constant	61.224 *** (8.75)	136.887 *** (12.91)
N	44	44
Adjusted R^2	0.154	0.996
Year Fixed	YES	YES
Province Fixed	YES	YES

Note: 1. *** and ** denote significance at the 1% and 5% levels, respectively. Standard errors in parentheses. 2. "YES" indicates that the corresponding fixed effects are included in the regression specification.

4.4. Robustness Tests

4.4.1. Robustness to Time-Window Variations

To examine whether the baseline results are driven by any particular year, we re-estimate the model on two reduced time windows: 2017–2019 (excluding 2020) and 2018–2020 (excluding 2017). As reported in Table 10, the coefficient on GIDI remains positive and statistically significant in both subsamples, suggesting that the results are not driven solely by shocks in the first or last year of the sample.

Table 10. Robustness Regression Results for Different Time Intervals.

Variable	2017–2019	2018–2020
	NCI	NCI
GIDI	0.529 ** (2.55)	0.677 ** (2.44)
density	0.158 *** (4.9)	0.153 *** (3.37)
capacity	−8.012 *** (−4.04)	−6.9 *** (−3.59)

Table 10. *Cont.*

Variable	2017–2019	2018–2020
	NCI	NCI
town	−16.862 *** (−10.44)	−18.368 *** (−8.77)
cropland	−2.033 *** (−18.68)	−2.018 *** (−15.32)
pesticide	6.823 *** (4.73)	5.027 *** (2.8)
aquaculture	8.603 *** (5.94)	10.072 *** (5.66)
bond	0.011 *** (2.84)	0.003 (0.73)
reserve	−1.371 *** (−7.19)	−1.049 *** (−5.43)
Constant	149.576 *** (10.3)	144.833 *** (9.6)
N	33	33
Adjusted R^2	0.999	0.998
Year Fixed	YES	YES
Province Fixed	YES	YES

Note: 1. *** and ** denote significance at the 1% and 5% levels, respectively. Standard errors in parentheses. 2. "YES" indicates that the corresponding fixed effects are included in the regression specification.

Taken together, the robustness of these results provides strong evidence that strengthening green innovation capacity constitutes an important pathway for achieving biodiversity conservation in the Yangtze River Economic Belt. The results highlight the importance of integrating ecological protection with innovation-driven development strategies to address environmental challenges in rapidly developing regions.

4.4.2. Robustness to Provincial Influence

To further ensure that the baseline estimates are not driven by any single province, we conduct a leave-one-province-out (LOPO) robustness test. In each iteration, one of the eleven provinces in the Yangtze River Economic Belt is excluded from the sample, and the baseline regression is re-estimated using the same specification.

As reported in Table 11, the results are highly robust. Across all eleven iterations, the coefficient on GIDI remains positive and statistically significant at the 1% level. The positive effect of green innovation on biodiversity outcomes reflects a region-wide pattern within the Yangtze River Economic Belt rather than the influence of a small number of provinces.

Table 11. Robustness Regression Results of LOPO.

Dropped_Prov	β_GIDI	se_GIDI	t_GIDI
Shanghai	1.004 ***	0.339	2.960
Jiangsu	0.362 ***	0.080	4.506
Zhejiang	0.353 ***	0.075	4.728
Anhui	0.362 ***	0.080	4.535

Table 11. *Cont.*

Dropped_Prov	β_GIDI	se_GIDI	t_GIDI
Jiangxi	0.356 ***	0.080	4.442
Hubei	0.357 ***	0.076	4.721
Hunan	0.352 ***	0.082	4.307
Chongqing	0.377 ***	0.076	4.952
Sichuan	0.357 ***	0.083	4.302
Guizhou	0.359 ***	0.084	4.281
Yunnan	0.349 ***	0.083	4.205
Shanghai	1.004 ***	0.339	2.960
Jiangsu	0.362 ***	0.080	4.506

Note: 1. *** denotes significance at the 1% level, respectively. Standard errors in parentheses.

4.5. Mechanism Analysis

Following the theoretical channels outlined in Section 2, this section explores the potential mechanisms through which green innovation development affects regional sustainability outcomes. Building on the conceptual framework, we focus on two key channels: carbon emission reduction and environmental governance enhancement. To this end, we replace the baseline dependent variable with each mediator and estimate the regressions including province and year fixed effects as well as the full set of control variables.

4.5.1. Carbon Emission Reduction Channel

The first mechanism concerns the role of green innovation in reducing carbon emission intensity. As shown in Table 12, column (1) reports the regression results with carbon emission intensity as the dependent variable. The coefficient on GIDI is negative and statistically significant at the 5% level, indicating that regions with higher levels of green innovation development tend to exhibit lower carbon emission intensity. This finding provides supportive evidence for Hypothesis 2.

Table 12. Mechanism Regression Results.

Variables	(1)	(2)
	Carbon Intensity	Env. Exp. Share
GIDI	−0.020 ** (0.009)	0.012 * (0.007)
density	0.003 (0.004)	−0.001 (0.003)
capacity	−0.035 * (0.020)	0.007 (0.015)
town	0.018 (0.013)	−0.010 (0.009)
cropland	−0.014 * (0.008)	−0.002 (0.006)
pesticide	0.052 ** (0.023)	0.001 (0.007)
aquaculture	−0.010 (0.016)	0.004 (0.010)

Table 12. *Cont.*

Variables	(1)	(2)
	Carbon Intensity	**Env. Exp. Share**
bond	−0.001 (0.001)	0.003 (0.002)
reserve	−0.006 (0.005)	0.004 (0.003)
Constant	1.105 *** (0.372)	0.162 ** (0.069)
N	44	44
Adjusted R^2	0.81	0.68
Year Fixed	YES	YES
Province Fixed	YES	YES

Note: 1. ***, ** and * denote significance at the 1%, 5% and 10% levels, respectively. Standard errors in parentheses. 2. "YES" indicates that the corresponding fixed effects are included in the regression specification.

This finding is consistent with the theoretical expectation that green innovation facilitates cleaner production processes, improves energy efficiency, and accelerates the adoption of low-carbon technologies. Overall, the results provide supportive evidence that carbon emission reduction constitutes an important channel through which green innovation can promote sustainable development outcomes.

4.5.2. Environmental Governance Channel

The second mechanism examines whether green innovation operates through environmental governance, proxied by the share of environmental protection expenditure in total fiscal spending. As shown in Table 12, column (2) presents the corresponding regression results.

The estimated coefficient on GIDI is positive and statistically significant at the 10% level, implying that regions with stronger green innovation capacity allocate a larger share of fiscal resources to environmental protection. This pattern suggests that green innovation may enhance governments' environmental awareness, regulatory capacity, and willingness to support environmental initiatives through public expenditure. The mechanism analysis provides supportive evidence for Hypothesis 3.

Importantly, this result highlights a governance-related mechanism that complements the technological channel. Green innovation not only directly affects production and emissions but may also shape policy priorities and fiscal decisions, thereby reinforcing environmental protection through institutional and budgetary channels. Taken together, the evidence indicates that environmental governance improvement represents a complementary pathway through which green innovation contributes to sustainability.

5. Discussion

This study investigates the relationship between green innovation and biodiversity conservation in the Yangtze River Economic Belt (YREB). Our findings suggest that green innovation, as measured by the Green Innovation Development Index (GIDI), plays a significant positive role in enhancing biodiversity conservation. This section provides a detailed discussion of the results, compares them with existing literature, outlines the policy implications, and suggests future research directions.

5.1. Green Innovation and Biodiversity Conservation

Our results demonstrate that regions with higher levels of green innovation tend to exhibit better biodiversity outcomes, suggesting a direct link between innovation-driven development and ecological sustainability. This aligns with the theoretical framework that green innovation promotes environmentally sustainable development by reducing the environmental footprint of industries and improving ecological efficiency [22,23]. The positive relationship between GIDI and NCI (Natural Capital Index) found in this study underscores the broader environmental benefits of green innovation, specifically its capacity to mitigate biodiversity loss.

Previous studies have focused on the role of green innovation in reducing carbon emissions or improving resource efficiency, but few have explicitly linked it to biodiversity conservation [4,42]. By incorporating both green innovation input and output into the GIDI framework, our study extends this literature by showing that innovation-driven ecological solutions can directly contribute to preserving biodiversity. This finding highlights the importance of fostering a green innovation ecosystem that integrates environmental goals with economic development.

5.2. The Role of Green Finance in Biodiversity Conservation

In addition to green innovation, green finance, specifically the issuance of green bonds, plays a significant role in promoting biodiversity conservation. Our results show that green finance contributes positively to biodiversity outcomes, consistent with previous studies that highlight the potential of financial instruments in supporting environmental goals [43,44]. Green bonds can provide critical funding for biodiversity projects, including ecosystem restoration, pollution control, and sustainable resource management, thus complementing government efforts in biodiversity conservation.

The positive association between green bond balance and biodiversity further emphasizes the need to develop green financial markets to mobilize capital for large-scale ecological projects. In the context of China, where the government has increasingly promoted green finance, particularly in the Yangtze River Economic Belt, the results suggest that expanding green finance mechanisms, such as green bonds, could help address the funding gap for biodiversity conservation. This policy implication is particularly relevant in light of China's ambitious environmental goals, which include promoting green finance to support sustainable development.

However, the relationship between green finance and biodiversity is complex and requires further investigation. Future research should explore the specific mechanisms through which green finance influences biodiversity outcomes, such as by examining the types of projects funded by green bonds and their direct ecological impacts. Moreover, the effectiveness of green finance in fostering biodiversity conservation may vary depending on the institutional capacity and policy frameworks in place, which should be explored in future studies.

5.3. Human Activities and Their Impact on Biodiversity

The study also underscores the significant negative impact of human activities, such as urbanization, agriculture, and infrastructure development, on biodiversity. The interpretation of these coefficients should be understood within an aggregate, province-level framework. By explicitly accounting for institutional context, regulatory tightening, and technological upgrading, the analysis avoids attributing causal ecological mechanisms to control variables whose effects are known to operate differently at finer spatial or biological scales. As expected, urbanization leads to habitat fragmentation and the loss of green spaces, which disrupts species populations and ecological processes [11]. Agricultural

activities, particularly intensive farming practices, contribute to biodiversity loss by degrading soil quality and introducing pollutants such as pesticides and fertilizers [14]. Similarly, infrastructure development, including road building and dam construction, fragments ecosystems and restricts species migration [16,33].

Interestingly, the positive relationship observed between road density and biodiversity in this study is somewhat counterintuitive. This could be explained by the fact that infrastructure development in the YREB often integrates ecological restoration efforts, such as wildlife corridors and green infrastructure, into road construction projects. This finding highlights the importance of eco-friendly infrastructure planning, which can mitigate some of the negative impacts of roads and promote connectivity between fragmented habitats.

The human footprint metric, which incorporates indicators of urban built-up areas, agricultural land use, and aquaculture activities, further confirms the detrimental effects of human activities on biodiversity. Importantly, the assessment of these effects explicitly accounts for province-specific approaches to land-use governance, reflecting differences in development patterns, geographic location, climate conditions, and landscape characteristics. In highly urbanized downstream provinces such as Shanghai, Jiangsu, and Zhejiang, urban built-up control policies—anchored in basin-wide spatial planning frameworks—have emphasized compact urban development and intensive land-use. For instance, metropolitan regions in the Yangtze River Delta have promoted coordinated urban development and redevelopment of existing construction land to reduce incremental ecological encroachment.

In contrast, provinces in the middle and upper reaches have placed greater emphasis on aligning urban development with ecological protection redlines, particularly in mountainous and ecologically sensitive areas. Representative upstream provinces have adopted stricter constraints on urban expansion along major river corridors and reservoir zones, coupled with large-scale ecological restoration initiatives. For example, upstream provinces with complex terrain and fragile ecosystems have adopted stricter constraints on urban expansion along major river corridors and reservoir zones, coupled with large-scale ecological restoration initiatives. Agricultural land-use sustainability further differentiates provinces across the basin. While downstream and central provinces focus on high-standard farmland construction and ecological upgrading of agricultural systems, several middle and upper reach provinces promote integrated "ecology–agriculture" models that reduce soil erosion, chemical inputs, and landscape fragmentation.

5.4. Policy Implications

The findings of this study offer several important policy implications for biodiversity conservation in the Yangtze River Economic Belt and beyond. First, the results emphasize the need for green innovation to be incorporated into regional development strategies. Green innovation not only contributes to economic growth but also plays a crucial role in enhancing biodiversity outcomes. Policymakers should prioritize investments in clean technologies, eco-friendly infrastructure, and green innovation research to foster a more sustainable development path.

Second, green finance, particularly through instruments like green bonds, should be actively promoted to support biodiversity conservation efforts. Given the substantial funding requirements for large-scale ecological projects, green finance can serve as a critical tool for mobilizing private capital. Governments should incentivize the issuance of green bonds and create favorable conditions for the development of green financial markets, ensuring that funds are allocated to projects that have tangible biodiversity benefits.

Lastly, the study highlights the need for integrated land-use policies that balance development with ecological preservation. Urbanization and agricultural expansion must

be managed with careful spatial planning, ensuring that natural habitats are protected and connectivity is maintained. Policies that incentivize sustainable agriculture, limit urban sprawl, and promote ecological corridors will be essential for preserving biodiversity in rapidly developing regions.

5.5. Limitations and Future Research Directions

Several limitations of this study should be acknowledged. First, the empirical analysis relies on a relatively small provincial panel due to the limited availability of consistent biodiversity indicators at the subnational level. This scope is appropriate for examining how innovation-driven development interacts with biodiversity outcomes within a stable institutional framework. While the study does not cover the most recent years, the period analyzed corresponds to a critical phase of green development and policy implementation in China. Future research could extend this framework by employing longer time spans or finer spatial units, such as prefecture-level or remote-sensing-based biodiversity measures, to further validate and generalize the conclusions.

Second, while this study focuses on the Yangtze River Economic Belt, future research should assess the applicability of these findings to other regions with different socio-economic and ecological contexts. This would provide a more comprehensive understanding of how green innovation influences biodiversity in varying environmental settings.

Finally, there is a need for more longitudinal studies to assess the long-term impact of green innovation on biodiversity. Future research should consider the temporal dynamics of these relationships, examining the delayed effects of green innovation on biodiversity.

6. Conclusions

This study provides empirical evidence on how green innovation and green finance contribute to biodiversity conservation in the Yangtze River Economic Belt (YREB), a region of strategic ecological and economic importance. By integrating a multidimensional measure of biodiversity—the Natural Capital Index (NCI)—with a comprehensive indicator of green innovation development (GIDI) and a set of anthropogenic and financial factors, the study advances understanding of the mechanisms driving ecological outcomes in rapidly developing regions.

The empirical results indicate that green innovation exerts a significant and positive influence on biodiversity, suggesting that innovation-driven development can yield ecological co-benefits beyond its commonly studied effects on pollution reduction and energy transition. Green finance, particularly through the issuance of green bonds, also contributes to biodiversity improvement, demonstrating the potential of financial instruments to support ecological restoration and conservation. At the same time, human activities such as agricultural expansion, urbanization, and infrastructure development—captured through indicators of land-use pressure and ecosystem fragmentation—continue to pose substantial challenges to biodiversity, underscoring the need for integrated governance frameworks that balance development with ecological protection. Importantly, some control variables display associations that differ from conventional ecological expectations. These results should not be interpreted as evidence of direct ecological benefits, but rather as reflections of macro-level correlations shaped by institutional and technological transitions. This distinction reinforces the need for caution when translating province-level empirical findings into micro-level ecological or policy conclusions.

Beyond the baseline findings, this study provides further insights into the mechanisms linking green innovation and biodiversity conservation. The results suggest that green innovation may influence biodiversity outcomes through both carbon emission reduction and enhanced environmental governance, indicating that innovation-driven development

operates through multiple and interconnected channels. These findings underscore the importance of considering both technological improvements and institutional responses when assessing the ecological implications of green innovation.

The findings have several implications. First, fostering green innovation should be a priority in ecological regions, as technological upgrading offers a pathway to reduce environmental pressures while maintaining economic vitality. Second, strengthening green financial mechanisms can help address the persistent funding gap for biodiversity-related projects. Third, policies aimed at managing land-use change and human pressures must remain central to biodiversity strategies, particularly in landscapes undergoing rapid socioeconomic transformation.

Despite yielding important insights, this study is subject to limitations. The reliance on provincial-level data may mask heterogeneity within provinces, and future work could adopt finer spatial scales to capture local ecological dynamics. Additionally, the pathways linking green innovation and green finance to biodiversity deserve deeper exploration, including assessment of specific technologies or financial projects. Extending the analysis to other ecological corridors would also help determine the generalizability of the findings.

Overall, the study contributes to the growing literature on sustainability transitions by demonstrating that innovation-driven and finance-supported development can play a meaningful role in biodiversity conservation. As regions worldwide grapple with balancing economic growth and ecological integrity, the evidence presented here highlights the importance of integrating technological advancement, financial instruments, and ecological governance into cohesive policy frameworks that support long-term biodiversity resilience.

Author Contributions: Conceptualization, J.L. and Y.T.; methodology, J.L.; software, J.L.; validation, J.L.; formal analysis, J.L.; data curation, J.L.; writing—original draft preparation, J.L.; writing—review and editing, J.L.; visualization, J.L.; supervision, J.L. and Y.T.; project administration, J.L. and Y.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

NCI	Natural Capital Index
GIDI	Green Innovation Development Index
YREB	Yangtze River Economic Belt
R&D	Research and Development

Appendix A

Appendix A.1. Indicator System Design

The Green Innovation Development Index (GIDI) is constructed following the framework of the Yangtze River Economic Belt Green Innovation Development Index Report (2022) [40].

The system includes two primary dimensions, eight secondary indicators, and twenty-five tertiary indicators capturing green innovation input, innovation output, technological performance, and structural upgrading.

Appendix A.2. Data Sources

Data were obtained from the China Statistical Yearbook, China Science and Technology Statistical Yearbook, China Environmental Statistical Yearbook, energy and pollution datasets, provincial statistical reports, and patent datasets from the China National Intellectual Property Administration (CNIPA). All provincial indicators were collected for the period 2016–2020.

Appendix A.3. Data Preprocessing

Indicators were cleaned and harmonized. Outliers were winsorized at the 1% and 99% levels, missing values were linearly interpolated, and monetary indicators were converted to real terms using the provincial GDP deflator.

These steps ensure that the final dataset is consistent, complete, and suitable for factor analysis and index construction.

Appendix A.4. Indicator Normalization

Positive indicators were normalized using min–max scaling:

$$z_{i,t} = \frac{x_{i,t} - min(x)}{max(x) - min(x)} \quad \text{(A1)}$$

Negative indicators (where higher values indicate worse performance) were converted via:

$$z_{i,t} = \frac{max(x) - x_{i,t}}{max(x) - min(x)} \quad \text{(A2)}$$

This ensures that all indicators fall within [0, 1] and are directionally consistent.

Appendix A.5. Weighting Method: Confirmatory Factor Analysis (CFA)

Confirmatory Factor Analysis (CFA) was used to derive indicator weights. Factor loadings determine the contribution of secondary and tertiary indicators.

Goodness-of-fit indices ensure reliability. The resulting weights satisfy $w_k \geq 0$ and sum to 1, ensuring interpretability and statistical consistency.

Appendix A.6. Composite Index Construction

The overall GIDI score for province i in year t is constructed as:

$$GIDI_{i,t} = \Sigma w_k \times z_{k,i,t} \quad \text{(A3)}$$

where w_k is the weight for indicator k and $z_{k,i,t}$ is its normalized score.

Scores range from 0 to 1, with higher values indicating stronger green innovation capacity.

Appendix A.7. Robustness Considerations

Robustness was tested using alternative weighting methods (entropy-based weights), sensitivity checks on indicator ordering, and cross-correlation tests.

All results confirmed that the GIDI ranking is stable under alternative specifications.

Table A1. Indicator System for the Green Innovation Development Index (GIDI).

Primary Dimension	Secondary Indicator	Tertiary Indicators
Green Innovation Input	Human Capital	Higher-education share; Researchers; Talent programs
Green Innovation Input	Innovation Infrastructure	Key laboratories; Incubators; Innovation platforms

Table A1. *Cont.*

Primary Dimension	Secondary Indicator	Tertiary Indicators
Green Innovation Input	Environmental Regulation	Pollution-control investment; Environmental governance expenditure
Green Innovation Output	Green Patent Output	Green invention patents; Green utility model patents
Green Innovation Output	Industrial Green Transformation	Share of tertiary industry; Green-certified enterprises
Green Innovation Output	Resource Efficiency	Energy intensity; Water-use efficiency; Solid-waste recycling rate
Green Innovation Output	Environmental Performance	SO_2 reduction; NOx reduction; Wastewater treatment capacity

References

1. IPBES. *Global Assessment Report on Biodiversity and Ecosystem Services*; IPBES Secretariat: Bonn, Germany, 2019.
2. Butchart, S.H.M.; Walpole, M.; Collen, B.; Van Strien, A.; Scharlemann, J.P.W.; Almond, R.E.A.; Baillie, J.E.M.; Bomhard, B.; Brown, C.; Bruno, J.; et al. Global biodiversity: Indicators of recent declines. *Science* **2010**, *328*, 1164–1168. [CrossRef] [PubMed]
3. OECD. *Towards Green Growth*; OECD Publishing: Paris, France, 2011.
4. Costantini, V.; Mazzanti, M. On the green and innovative side of trade competitiveness? The impact of environmental policies and innovation on EU exports. *Res. Policy* **2012**, *41*, 132–153. [CrossRef]
5. Haddad, N.M.; Brudvig, L.A.; Clobert, J.; Davies, K.F.; Gonzalez, A.; Holt, R.D.; Lovejoy, T.E.; Sexton, J.O.; Austin, M.P.; Collins, C.D.; et al. Habitat fragmentation and its lasting impact on Earth's ecosystems. *Sci. Adv.* **2015**, *1*, e1500052. [CrossRef] [PubMed]
6. Ten Brink, P. *Biodiversity Indicators for the OECD Environmental Outlook and Strategy: A Feasibility Study*; National Institute of Public Health and the Environment: Bilthoven, The Netherlands, 2000.
7. Whittaker, R.H. Evolution and measurement of species diversity. *Taxon* **1972**, *21*, 213–251. [CrossRef]
8. Jost, L. Partitioning diversity into independent alpha and beta components. *Ecology* **2007**, *88*, 2427–2439. [CrossRef]
9. Cardinale, B.J.; Duffy, J.E.; Gonzalez, A.; Hooper, D.U.; Perrings, C.; Venail, P.; Narwani, A.; Mace, G.M.; Tilman, D.; Wardle, D.A.; et al. Biodiversity loss and its impact on humanity. *Nature* **2012**, *486*, 59–67. [CrossRef]
10. Newbold, T.; Hudson, L.N.; Hill, S.L.L.; Contu, S.; Lysenko, I.; Senior, R.A.; Börger, L.; Bennett, D.J.; Choimes, A.; Collen, B.; et al. Global effects of land use on local terrestrial biodiversity. *Nature* **2015**, *520*, 45–50. [CrossRef]
11. Seto, K.C.; Fragkias, M.; Güneralp, B.; Reilly, M.K. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. *Proc. Natl. Acad. Sci. USA* **2012**, *109*, 16083–16088. [CrossRef]
12. Ricketts, T.; Imhoff, M. Biodiversity, urban areas, and agriculture: Locating priority ecoregions for conservation. *Conserv. Ecol.* **2003**, *8*, 1. [CrossRef]
13. Phillips, R.E.; Thomas, G.W.; Blevins, R.L.; Frye, W.W.; Phillips, S.H. No-tillage agriculture. *Science* **1980**, *208*, 1108–1113. [CrossRef]
14. McLaughlin, A.; Mineau, P. The impact of agricultural practices on biodiversity. *Agric. Ecosyst. Environ.* **1995**, *55*, 201–212. [CrossRef]
15. Geiger, F.; Bengtsson, J.; Berendse, F.; Weisser, W.W.; Emmerson, M.; Morales, M.B.; Ceryngier, P.; Liira, J.; Tscharntke, T.; Winqvist, C.; et al. Persistent negative effects of pesticides on biodiversity and biological control potential on European farmland. *Basic Appl. Ecol.* **2010**, *11*, 97–105. [CrossRef]
16. Winemiller, K.O.; McIntyre, P.B.; Castello, L.; Fluet-Chouinard, E.; Giarrizzo, T.; Nam, S.; Baird, I.G.; Darwall, W.; Lujan, N.K.; Harrison, I.; et al. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science* **2016**, *351*, 128–129. [CrossRef] [PubMed]
17. Venter, O.; Sanderson, E.W.; Magrach, A.; Allan, J.R.; Beher, J.; Jones, K.R.; Possingham, H.P.; Laurance, W.F.; Wood, P.; Fekete, B.M.; et al. Global terrestrial Human Footprint maps for 1993 and 2009. *Sci. Data* **2016**, *3*, 160067. [CrossRef]
18. Naylor, R.L.; Goldburg, R.J.; Primavera, J.H.; Kautsky, N.; Beveridge, M.C.M.; Clay, J.; Folke, C.; Lubchenco, J.; Mooney, H.; Troell, M. Effect of aquaculture on world fish supplies. *Nature* **2000**, *405*, 1017–1024. [CrossRef]
19. OECD. *A Comprehensive Overview of Global Biodiversity Finance*; OECD: Paris, France, 2020.
20. Mo, Y.; Sun, D.; Zhang, Y. Green finance assists agricultural sustainable development: Evidence from China. *Sustainability* **2023**, *15*, 2056. [CrossRef]
21. Ferraro, P.J.; Pressey, R.L. Measuring the difference made by conservation initiatives: Protected areas and their environmental and social impacts. *Phil. Trans. R. Soc. B* **2015**, *370*, 20140270. [CrossRef]
22. Porter, M.E.; van der Linde, C. Toward a new conception of the environment-competitiveness relationship. *J. Econ. Perspect.* **1995**, *9*, 97–118. [CrossRef]

23. Rennings, K. Redefining innovation—Eco-innovation research and the contribution from ecological economics. *Ecol. Econ.* **2000**, *32*, 319–332. [CrossRef]
24. Popp, D.; Newell, R.G.; Jaffe, A.B. Innovation and climate policy. *Annu. Rev. Resour. Econ.* **2010**, *2*, 275–298. [CrossRef]
25. Bowen, A.; Kuralbayeva, K.; Tipoe, E. Characterising green employment: The impacts of "greening" on workforce composition. *Energy Econ.* **2018**, *72*, 263–275. [CrossRef]
26. Aghion, P.; Dechezleprêtre, A.; Hémous, D.; Martin, R.; Van Reenen, J. Carbon taxes, path dependency, and directed technical change: Evidence from the Auto Industry. *J. Polit. Econ.* **2016**, *124*, 1–51. [CrossRef]
27. Acemoglu, D.; Akcigit, U.; Hanley, D.; Kerr, W. Transition to clean technology. *J. Polit. Econ.* **2016**, *124*, 52–104. [CrossRef]
28. Tilman, D.; Clark, M.; Williams, D.R.; Kimmel, K.; Polasky, S.; Packer, C. Future threats to biodiversity and pathways to their prevention. *Nature* **2017**, *546*, 73–81. [CrossRef]
29. Popp, D. From science to technology: The value of knowledge from different energy research institutions. *Res. Policy* **2017**, *46*, 1580–1594. [CrossRef]
30. Creutzig, F.; Agoston, P.; Goldschmidt, J.C.; Luderer, G.; Nemet, G.; Pietzcker, R.C. The underestimated potential of solar energy to mitigate climate change. *Nat. Energy* **2017**, *2*, 17140. [CrossRef]
31. Hooper, D.U.; Chapin, F.S.; Ewel, J.J.; Hector, A.; Inchausti, P.; Lavorel, S.; Lawton, J.H.; Lodge, D.M.; Loreau, M.; Naeem, S.; et al. Effects of biodiversity on ecosystem functioning: A consensus of current knowledge. *Ecol. Monogr.* **2005**, *75*, 3–35. [CrossRef]
32. UNEP. *Global Biodiversity Assessment*; Cambridge University Press: Cambridge, UK, 1997.
33. Reh, W.; Seitz, A. The influence of land use on the genetic structure of populations of the common frog *Rana temporaria*. *Biol. Conserv.* **1990**, *54*, 239–249. [CrossRef]
34. Forman, R.T.T.; Sperling, D.; Bissonette, J.A.; Clevenger, A.P.; Cutshall, C.D.; Dale, V.H.; Fahrig, L.; France, R.; Goldman, C.R.; Heanue, K.; et al. *Road Ecology: Science and Solutions*; Island Press: Washington, DC, USA, 2003.
35. Ibisch, P.L.; Hoffmann, M.T.; Kreft, S.; Pe'er, G.; Kati, V.; Biber-Freudenberger, L.; DellaSala, D.A.; Vale, M.M.; Hobson, P.R.; Selva, N. A global map of roadless areas and their conservation status. *Science* **2016**, *354*, 1423–1427. [CrossRef]
36. Zhang, X.; Davidson, E.A.; Mauzerall, D.L.; Searchinger, T.D.; Dumas, P.; Shen, Y. Managing nitrogen for sustainable development. *Nature* **2015**, *528*, 51–59. [CrossRef]
37. Cui, Z.; Zhang, H.; Chen, X.; Zhang, C.; Huang, C.; Zhang, W.; Mi, G.; Miao, Y.; Li, X.; Ying, H.; et al. Pursuing sustainable productivity with millions of smallholder farmers. *Nature* **2018**, *555*, 363–366. [CrossRef] [PubMed]
38. Cao, L.; Naylor, R.; Henriksson, P.; Leadbitter, D.; Metian, M.; Troell, M.; Zhang, W. China's aquaculture and the world's wild fisheries. *Science* **2015**, *347*, 133–135. [CrossRef] [PubMed]
39. Crépon, B.; Duguet, E.; Mairesse, J. Research, innovation, and productivity: An econometric analysis at the firm level. *Econ. Innov. New Technol.* **1998**, *7*, 115–158. [CrossRef]
40. Hall, B.H.; Griliches, Z.; Hausman, J.A. Patents and R&D: Is There a Lag? *Econometrica* **1986**, *54*, 265–283.
41. Martin, R. Path dependence and regional economic evolution. *J. Econ. Geogr.* **2006**, *6*, 395–437. [CrossRef]
42. Flammer, C. Corporate green bonds. *J. Financ. Econ.* **2021**, *142*, 499–516. [CrossRef]
43. Krueger, P.; Sautner, Z.; Starks, L.T. The importance of climate risks for institutional investors. *Rev. Financ. Stud.* **2020**, *33*, 1067–1111. [CrossRef]
44. Renmin University of China. *Yangtze River Economic Belt Green Innovation Development Index Report*; Renmin University of China: Beijing, China, 2022.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.