



UNIVERSITÀ DEGLI STUDI  
FIRENZE



UNIVERSITÀ DI SIENA



UNIVERSITÀ DI PISA

UNIVERSITIES OF  
FLORENCE - SIENA - PISA

---

---

Joint Ph.D. Program in Economics  
*Cycle 37*

DOCTORAL DISSERTATION

**Three Essays on Green Policy  
and Green Finance**

**Supervisor:**

**Prof. Silvia Tiezzi**

**Co-Supervisor:**

**Prof. Marwil J. Dávila-Fernández**

**Candidate:**

**Haomiao Niu**

**Mat. 123054**

Academic Year 2025 - 2026

# Contents

<b>Acknowledgements</b>	<b>4</b>
<b>Introduction</b>	<b>6</b>
<b>1 Environmental Policies in a Green Solow Model</b>	<b>8</b>
1.1 Introduction . . . . .	9
1.2 The model . . . . .	12
1.2.1 Brown and Green Production . . . . .	12
1.2.2 Production and Pollution . . . . .	12
1.2.3 Incorporating a Green Government . . . . .	13
1.2.4 The Three-Dimensional Dynamic System . . . . .	15
1.2.5 Propositions . . . . .	16
1.2.6 Comparative statics of polices . . . . .	18
1.3 Benchmark parametrization . . . . .	19
1.4 Numerical simulations . . . . .	21
1.4.1 BAU vs. Naive Taxation . . . . .	21
1.4.2 Alternative Green Policies . . . . .	24
1.4.3 The Optimal Policy . . . . .	30
1.4.4 Additional Analysis: The Dynamic Relationship between Pollution and Output . . . . .	33
1.5 Concluding Remarks and Policy Implications . . . . .	36
<b>2 Measuring Green Finance: A Two-Dimensional Framework and Its Appli-     cation in China</b>	<b>38</b>
2.1 Introduction . . . . .	39
2.2 Literature Review . . . . .	40
2.3 Methodology . . . . .	42
2.3.1 Coverage measurement . . . . .	42

2.3.2	Intensity measurement . . . . .	43
2.3.3	Formal Definition . . . . .	44
2.4	Case study: Chinese provincial Green finance development . . . . .	45
2.4.1	Dataset Construction . . . . .	46
2.4.2	Coverage Analysis . . . . .	51
2.4.3	Intensity Analysis . . . . .	52
2.4.4	Green Finance Index (GFI) Analysis . . . . .	55
2.4.5	Policy Implications . . . . .	58
2.5	Conclusions . . . . .	58
<b>3</b>	<b>Can Growth Be Green? Testing the Green Finance Kuznets Curve Hypothesis in China</b>	<b>60</b>
3.1	Introduction . . . . .	61
3.2	Literature Review . . . . .	63
3.2.1	The Effect of Green Finance on Economic Development . . . . .	63
3.2.2	The Effect of Green Finance on Environmental Degradation . . . . .	64
3.3	Modeling Design . . . . .	66
3.3.1	Data . . . . .	66
3.3.2	Empirical Model . . . . .	67
3.3.3	Variable Specification . . . . .	67
3.3.4	Descriptive Statistics . . . . .	69
3.3.5	Preliminary Test . . . . .	72
3.4	Empirical Results . . . . .	73
3.4.1	Main Regression Results . . . . .	73
3.4.2	Effect Decomposition of GF on EnvDeg . . . . .	76
3.4.3	Robustness and asymmetry of nonlinearity . . . . .	77
3.4.4	Current status analysis for green finance development of Chinese provinces . . . . .	79
3.4.5	Green Finance Kuznets Curve . . . . .	81
3.4.6	Mechanism Analysis for GFKC . . . . .	82
3.5	Conclusions . . . . .	86
	<b>Conclusion</b>	<b>88</b>
	<b>Appendix A</b>	<b>89</b>
A.1	Proof of the existence of Brown-Green equilibrium . . . . .	89

A.2	Proof of stability of equilibrium . . . . .	91
A.3	Proof of Pollution dominance of environmental policies . . . . .	95
A.4	Proof of output dominance of environmental policies . . . . .	96
A.5	Parameter Specification . . . . .	97
A.6	Robustness check . . . . .	99
<b>Appendix B</b>		<b>102</b>
B.1	Various Definitions of Green Finance . . . . .	102
B.2	Crucial policies and events in the Development of Green Finance in China . .	104
B.3	Log-decomposition of GFI growth (2008–2019) . . . . .	106
<b>Appendix C</b>		<b>107</b>
C.1	Variable Specification . . . . .	107
C.2	Trend of Economic Development and Environmental Degradation by Province	108
C.3	Decomposition of the Total Effect of Green Finance on Environmental Degrada- tion . . . . .	111
<b>References</b>		<b>113</b>

# Acknowledgements

As the Italian children’s rhyme says, “Dopo la pioggia viene il sereno”, the sky becomes clear again after the rain. After three years of persistent effort, this dissertation has finally come to completion. The entire research process has been a profound journey of transformation for me. From theoretical reasoning to data processing, from model construction to conclusion formulation, I have gained comprehensive academic training. More importantly, this journey has been a test and a refinement of my mind. From the initial confusion and hesitation, through moments of frustration and despair, to the final sense of achievement and serenity, the psychological challenges and growth I have experienced far outweigh the dissertation itself and will remain a lifelong treasure.

This dissertation could not have come to fruition without the invaluable guidance and support of my supervisor, Professor Silvia Tiezzi, and co-supervisor Prof. Marwil J. Dávila-Fernández. I still remember three years ago, when my English was poor, my knowledge of economics was limited, and I was uncertain about my research direction. However, Professor Tiezzi never once doubted me. With kindness and patience, she helped me build confidence and guided me forward. She always faces academia humbly but never hesitates to praise and encourage her students. Her sense of responsibility deeply moved me. Despite my clumsy drafts, she patiently read every word and offered detailed suggestions on improvements. Despite my poorly delivered presentations, she noted every audience comment and summarised them for me in follow-up emails. Despite my procrastination, she met with me weekly to check on my progress. Many times, I worried that I might disappoint her. Many times, I felt undeserving of such a wonderful mentor. She has been a warm light, guiding, comforting, and accompanying me through the long and dark nights of my PhD journey. Over these three years, her noble character, graceful personality, rigorous academic attitude, and gentle teaching style have profoundly shaped me. In the future, if I make any academic progress or learn any personal maturity, it is thanks to her influence. To have been her student will forever be my pride and honour.

When I encountered a stumbling block in my research and needed theoretical guidance,

Professor Tiezzi kindly introduced Prof. Marwil Jhonatan Davila Fernandez to me. During our first meeting, Marwil jokingly said, “I can be your co-supervisor, but be careful, I am very bossy.” Before working with him, I already knew of his remarkable academic achievements, and I worried that such a talented and sharp minded mentor might find his student too slow. However, after one year following him, I discovered that he was only bossy of himself, and endlessly patient and smiling to his students. Before knowing Marwil, I never imagined I could write a theoretical economics paper. He reassured me: “It’s okay — we’ll start from zero.” Marwil taught me step by step how to design models, perform mathematical proofs, code, read, and write academic papers. More importantly, he taught me a way of thinking like an economist that no formal course could have given me. This has been one of the most valuable lessons of my doctoral life. Perhaps, years from now, I may forget the specific equations in this dissertation, but every model I build in the future will follow traces of his guidance. Every time before meeting with him, I worried that I had made too little progress to report, but after every discussion, I always felt deeply enriched academically, intellectually, and personally. When I later heard that he had moved to the United States, I felt both happy and sad, happy that he would shine on another stage, and sad that I would have less time to learn from this wise man. I am deeply grateful for the wisdom and inspiration he has given me, and I believe fate will let our paths cross again.

Confucius once said, “Is it not a joy to have friends come from afar?” The successful completion of this dissertation is also inseparable from the power of friendship. Four years ago, when I first set foot on European soil, I was overwhelmed by uncertainty and loneliness. I thought of giving up countless times, yet the warmth and kindness of friends from around the world became the greatest source of strength that kept me going. Just as ten thousand photos in my phone cannot capture the richness of my student life abroad, one book could not record all the kindness I have received from my friends in Italy and other countries. Thank you all for being part of my youth. You colored my PhD life with joy and diversity. I get in touch with you, and then I get in touch with the world.

Now, as I complete this dissertation, my doctoral journey draws to an end. Looking back, these four years will forever remain one of the most beautiful and unforgettable periods of my life. I am profoundly grateful to the University of Siena, where I met my best mentors and dearest friends, explored the deep heritage of an ancient civilisation, and witnessed the charm of Italian culture and humanities. All these cherished memories will not be washed away by the ticking of time, instead, they will shine ever brighter, polished to be more vivid by the gentle hands of years.

# Introduction

Sustainable development has become a shared objective across economies, but a persistent and widening financing gap constrains the transition from aspiration to implementation. The annual resources required for the Sustainable Development Goals by 2030 exceed available funding by several trillion dollars, without substantial financial architecture reform and stronger alignment of incentives. In this context, the core challenge to achieve green growth is mobilising and channelling capital toward projects delivering environmental benefits while maintaining macroeconomic stability and social welfare.

Heading to sustainability requires the joint use of two complementary instruments. The first is the fiscal policy from a green government. Pollution taxes, targeted green subsidies, disclosure rules, and standards help internalise environmental externalities and create a stable fiscal and regulatory loop that supports green investment and innovation. The second is a market-led green finance system. Bonds, loans, equities, insurance, and public green expenditures provide vehicles and signals for the reallocation of capital at scale.

However, the academic literature still lacks an integrated framework that connects green policy, green finance, economic performance, and environmental quality. The dissertation aims to fill the blank and clarify how the public green policy and green financial market channels mutually reinforce and why a combined policy market approach is essential.

The first essay develops the theoretical foundation. It extends the green Solow model by distinguishing a brown sector and a green sector and by closing the fiscal loop through a pollution tax with three subsidy channels. The model establishes two core conclusions. First, introducing a pollution tax reduces pollution and lowers output relative to the no-tax economy. Second, the policy mix combining the tax with green subsidies further decreases pollution while increasing output. Numerical simulations calibrated to the Chinese economy confirm these propositions and show economic and environmental outcomes across different green subsidies. Allocating tax revenues to green finance leads to the highest steady-state green capital. Subsidising green total factor productivity maximises aggregate output, whereas abatement efficiency minimises pollution, revealing a clear economic–environmental

trade-off. Overall, the analysis confirms the critical role of a green government and its subsidy instruments in shaping the transition dynamics of a sustainable economy.

The second essay constructs a provincial level database and a macro index of green finance for China from 2008 to 2019. The framework defines two dimensions that capture different aspects of system development. Coverage tracks the diffusion of green instruments across provinces and markets. Intensity tracks the penetration of green capital within each instrument. Their product yields the Green Finance Index, and their separation permits decomposition of sources of change. National series display a steady rise in coverage with acceleration after establishing a formal policy framework and pilot zones. Intensity also rises with volatility in the early years and accelerates after 2016. Over the sample period, the index nearly doubles, with roughly three-fifths of the increase attributable to broader coverage and the remainder to deeper intensity. Spatial patterns reveal that provinces with high GF ranking are not located in coastal areas considered economically advanced, but also appear in regions with abundant renewable resources. This finding emphasises the role of ecological endowment in shaping financial greening, providing policy implications for countries that are developing a green financial system.

The third essay examines the dual impacts of green finance on economic development and environmental degradation, utilising two-way fixed effects models and provincial panel data from China (2008–2019). The empirical results reveal that, at the initial stage of green finance development, structural frictions, investment delays, and information asymmetries constrain its positive influence on both growth and environmental quality. However, once green finance surpasses critical thresholds, it simultaneously promotes economic upgrading and ecological improvement. Building on these findings, the paper proposes the Green Finance Kuznets Curve (GFKC) concept, which characterises the nonlinear relationship between green finance, economic growth, and environmental degradation. The GFKC implies that, in the long run, green finance can foster green growth once the share of green financial capital reaches a sufficiently high level. These findings align with the predictions of the theoretical model we proposed and provide quantitative guidance on the depth of financial greening required to achieve simultaneous economic and environmental gains.

The findings indicate a strategic complementarity between a capable green government and a maturing green finance market. Policy creates the rules, incentives, and public goods that enable markets to mobilise capital efficiently. Markets facilitate the restructuring and diffusion of technology that transform these incentives into measurable reductions in pollution and sustainable growth.

# Chapter 1

## Environmental Policies in a Green Solow Model

Over the past few decades, human society has achieved remarkable economic growth, but at the cost of intensive resource use and severe ecological degradation. The circular economy (CE) offers a promising pathway toward sustainability by promoting recycling, remanufacturing, and the reuse of materials. However, the CE faces a fundamental financial challenge: the massive capital required to achieve sustainability.

To address this issue, this study extends the Green Solow model by distinguishing between green and brown sectors and introducing a green government that implements environmental policies through a pollution tax and green subsidies. The model establishes a financial loop that supports the CE by endogenising the pollution tax and channelling tax revenues into green fiscal expenditure. Numerical simulations are conducted to compare different environmental policies and evaluate their impacts on output and pollution.

The results show that introducing a pollution tax reduces pollution and lowers output relative to the no-tax economy. The policy mix combining the tax with green subsidies further decreases pollution while increasing output. Allocating tax revenues to green finance leads to the highest steady-state green capital. Subsidising green total factor productivity maximises aggregate output, whereas abatement efficiency minimises pollution, revealing a clear economic–environmental trade-off. Overall, the analysis confirms the critical role of a green government and its subsidy instruments in shaping the transition dynamics of a sustainable economy.

**Keywords:** Circular Economy, Green Solow Model, Green Government, Pollution Tax, Green Subsidy

**JEL:** Q56, H23, O44.

## 1.1 Introduction

Over the past half-century, the global economy has achieved remarkable income and material growth. However, the prosperity primarily depends on massive resource consumption, threatening the planet's ecological foundations. Figure 1.1 presents the trends in global per capita GDP, fossil fuel consumption, and CO<sub>2</sub> emissions, which have remained closely aligned since the beginning of the twenty-first century. This pattern indicates that economic expansion relies heavily on natural resource exploitation, often at the cost of environmental sustainability (Choudhury et al., 2023; Krausmann et al., 2009).

While sustainable development has become a shared global aspiration in the twenty-first century, decoupling economic growth from using natural resources remains challenging. In this context, the circular economy (CE) has emerged as a promising framework for achieving sustainability. The CE emphasises reducing resource inputs and waste generation by promoting reduction, reuse, recycling, and recovery throughout production and consumption, aiming to enhance environmental quality, improve economic efficiency, and promote social well-being (Kirchherr et al., 2017).

Despite its conceptual appeal, a wide financial gap persists between the vision of the CE and its practical implementation. While the CE literature emphasises material loops, it largely overlooks the financial loop required to sustain them. Private actors also lack sufficient incentives to participate in green circular systems (Siderius & Zink, 2023), further constraining the realisation of large-scale CE projects (Uhrenholt et al., 2022). The United Nations Environment Programme Finance Initiative estimates that achieving full financial circularity would require millions to trillions of dollars globally (United Nations Environment Programme Finance Initiative, 2020). This financial unfeasibility underlines the critical role of a green-oriented government in reallocating social resources and guiding capital toward the CE (Hallegatte et al., 2012).

Environmental economics provides a theoretical foundation for addressing the financial challenge. As emissions represent negative externalities of production, internalising them through a Pigouvian tax—for example, a carbon tax—can discourage pollution and generate fiscal revenues for environmental policy (Baumol & Oates, 1988; Bovenberg & De Mooij, 1997; Nordhaus, 1993). However, research shows that taxation alone cannot effectively correct market failures, whereas a combination of instruments within a broader green policy toolbox performs better (Hallegatte et al., 2012). Such policy mixes foster directed technological change (Acemoglu et al., 2012) and support clean energy innovation (Fischer & Newell, 2008; Lim & Kim, 2012). When a green-oriented government reinvests tax revenues into green

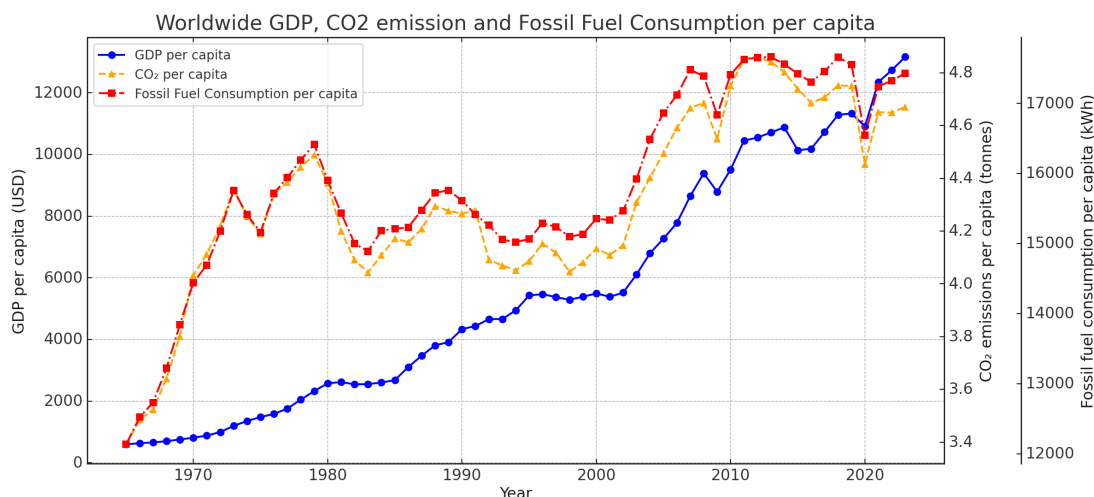


Figure 1.1: Global trends in economic growth, CO<sub>2</sub> emissions, and fossil fuel consumption. Author’s compilation with data from World Bank and Global Carbon Budget (2024).

subsidies, it can maintain fiscal neutrality while achieving both economic and environmental goals, thereby establishing a virtuous cycle: pollution  $\rightarrow$  taxation  $\rightarrow$  green subsidies  $\rightarrow$  green production  $\rightarrow$  pollution abatement. This loop resolves the problem of capital sourcing and allocation within the CE framework.

A key question is how these green subsidies should be allocated. In practice, subsidy channels vary widely across countries. For example, green finance subsidies—such as green bonds and preferential loans—are prevalent in China (Climate Bonds Initiative, 2024). Japan’s Green Transformation Fund dedicates JPY 20 trillion to green R&D and transition technologies (International Energy Agency, 2023). Germany’s National Climate Initiative has provided substantial funding for emission-reduction and pollution-abatement projects (National Climate Initiative, 2021). Nevertheless, the optimal redistribution of pollution tax revenues remains theoretically ambiguous, as few studies systematically compare the impacts of different subsidy channels—this is the core question examined in this paper.

In addition, existing analyses typically assess green policies based solely on emission outcomes, neglecting the dynamic balance between environmental protection and economic growth. In practice, countries at different stages of development exhibit distinct growth–environment preferences. Even within a single economy, such preferences evolve as development progresses. Therefore, a framework that enables comparative policy evaluation and allows policy instruments to adapt dynamically to shifting national priorities can fill the existing gap in the literature.

This paper develops a macro-dynamic model that integrates a green-oriented government, pollution taxation, and environmental subsidies into a unified analytical framework to ad-

dress the above issues. Building on the Green Solow Model (GSM) proposed by Brock and Taylor (2010), which incorporates pollution dynamics into the classical Solow framework (Solow, 1956), we extend it toward a circular-economy (CE) perspective through two main innovations.

First, we model an economy with two production sectors: green and brown. The brown sector generates output but also pollution, whereas the green sector produces output while creating positive environmental externalities.

Second, we introduce a green-oriented government that connects the two sectors. The government levies a pollution tax on the brown sector. It recycles the revenues as subsidies to the green sector under a balanced-budget condition, forming a closed financial loop consistent with CE principles. Three subsidy channels are designed for comparative analysis: (i) green finance subsidies to accelerate green capital accumulation; (ii) green total factor productivity (TFP) subsidies to enhance production efficiency; and (iii) pollution-abatement technology subsidies to strengthen emission reduction capacity. The government may implement any single channel or a combination of them.

Using parameters calibrated to the Chinese economy, we simulate the model to examine how alternative subsidy schemes affect economic output and pollution, and to identify the optimal policy configuration under different growth–environment preferences. The simulation results confirm that introducing a pollution tax reduces pollution and lowers output relative to the no-tax scenario. The policy mix combining pollution tax with green subsidies leads to an equilibrium with higher output and lower pollution. Allocating tax revenues to green finance leads to the highest steady-state green capital. Subsidising green total factor productivity maximises aggregate output, whereas subsidising abatement efficiency minimises pollution. This pattern reveals a fundamental trade-off between economic growth and environmental protection. The optimal policy choice depends on the government’s preference structure. Growth-oriented governments favour green TFP support, while environmentally oriented governments prioritise abatement subsidies. Our results also verify the existence of an inverted-U-shaped Environmental Kuznets Curve (EKC) relationship (Grossman & Krueger, 1995), as well as a U-shaped effect of the green capital share on output and an inverted-U-shaped effect on pollution, providing a theoretical foundation for future empirical investigations.

The remainder of this paper is organised as follows. Section 1.2 presents the theoretical framework and dynamic equations. Section 1.3 describes the parameter calibration and simulation setup. Section 1.4 presents the comparative policy results and discusses optimal policy

combinations under alternative growth–environment preferences. Section 1.5 concludes with policy implications and directions for future research.

## 1.2 The model

### 1.2.1 Brown and Green Production

The economy consists of two types of production: green and brown. Brown production refers to economic activities that generate negative environmental externalities through pollutant emissions. Its opposite concept is green production. However, no unified definition of green production exists in the academic literature. After reviewing various interpretations, Baines et al. (2012) defines green production as the application of environmentally and socially responsible practices that reduce the negative impact of manufacturing activities while simultaneously harmonising the pursuit of economic benefits.

Most existing studies define green production as optimising production processes and upgrading green technologies to reduce firms' emissions. This definition highlights the reduction of negative environmental externalities rather than the creation of positive ones. If so, even if green production is widely adopted, the aggregate pollution level in the economy would continue to rise, with only a decline in the growth rate of pollution. This definition offers a limited contribution to the realisation of a CE, as it merely slows, rather than reverses, environmental degradation. From a CE perspective, a proper closed-loop system requires specific sectors to undertake pollution reduction actively.

Accordingly, we adopt a stricter definition of green production: a production activity that reduces the current total level of social pollution while generating economic benefits. In other words, the environmental externality of green output is positive, rather than a mitigation of negative externalities.

There are two extra clarifications. First, it is important to note that we are distinguishing production activities rather than the companies themselves. Therefore, a company can simultaneously engage in green and brown production. Second, green production and brown production are not substitutable categories. Any given production must be unequivocally classified into one and only one of the two.

### 1.2.2 Production and Pollution

The production functions for brown and green companies are:

$$Y_B = AK_B^\alpha \tag{1.1}$$

$$Y_G = AK_G^\alpha \quad (1.2)$$

where  $Y_B$  and  $Y_G$  denote brown and green output, respectively, and  $K_B$  and  $K_G$  are the corresponding capital stocks. Consistent with the production structure, the two forms of capital are assumed to be non-substitutable. The parameters  $A$  and  $\alpha$  denote total factor productivity and output elasticity concerning capital, respectively.

To keep the expression as simple as possible, we abstracted it from the labour market and excluded it from the production function. Also, we assume relative prices are constant and normalise them to one. The capital accumulation functions are subject to Solow's form:

$$\dot{K}_B = sY_B - \delta K_B \quad (1.3)$$

$$\dot{K}_G = sY_G - \delta K_G \quad (1.4)$$

where  $s$  is saving rate and  $\delta$  is depreciation rate. They are assumed to be equal across activities. A dotted variable denotes its derivative with respect to time<sup>1</sup>.

Based on our definition, brown and green production will generate and reduce pollution.

$$\dot{P} = \Omega Y_B - \phi Y_G \quad (1.5)$$

where  $P$  is pollution,  $\Omega$  is the pollution generating coefficient of brown production, and  $\phi$  is pollution abatement coefficient of the green sector.

### 1.2.3 Incorporating a Green Government

We assume the government is green-oriented, meaning it levies a pollution tax rate  $\tau$  on brown production. Accordingly, the brown production function is modified as in equation (1.6).

$$Y_B = (1 - \tau)AK_B^\alpha \quad (1.6)$$

The pollution tax rate is determined by a function  $f$  of pollution  $P$ :

$$\tau = f(P) \quad (1.7)$$

---

<sup>1</sup>For a generic variable  $x$ , we denote its time derivative as  $\dot{x} = \frac{dx}{dt}$ .

We assume that  $f(x)$  is a monotonically increasing function bounded within  $[0, 1]$ , implying that the pollution tax rises with the pollution level but never exceeds unity.

The government collects  $\tau Y_B$  units of tax revenue from the brown sector and reallocates them as green subsidies. These subsidies serve three purposes: (i) promoting green capital accumulation ( $K_G$ ); (ii) enhancing the total factor productivity of green production ( $A$ ); and (iii) improving the pollution abatement efficiency ( $\Phi$ ). The corresponding shares  $\theta_1$ ,  $\theta_2$ , and  $\theta_3$  lie within  $[0, 1]$  and satisfy  $\theta_1 + \theta_2 + \theta_3 = 1$ . The vector  $\theta = \{\theta_1, \theta_2, \theta_3\}$ , termed a “green-policy combination,” represents the government’s allocation strategy across subsidy channels.

Each subsidy channel affects the economy differently. The share  $\theta_1$  devoted to green capital accumulation raises the effective saving rate according to:

$$s_G = (1 + \theta_1\tau)s \quad (1.8)$$

A higher pollution tax and a larger subsidy share strengthen green capital formation. Two mechanisms can account for this increase: households respond to higher risk-adjusted returns on green assets, while firms reinvest more due to lower user costs of green capital. In both cases, the saving rate rises from  $s$  to  $(1 + \theta_1\tau)s$ , accelerating green capital accumulation.

Subsidies directed toward green total factor productivity (GTFP) enhance  $A$  through increased government R&D investment in green industries. Higher research expenditure improves production technology, thereby raising output per unit of green capital:

$$A_G = A + \theta_2\tau \quad (1.9)$$

Similarly, subsidies allocated to pollution abatement improve  $\phi$  by supporting cleaner technologies such as waste recycling and wastewater treatment. It reflects the government’s efforts to strengthen environmental efficiency and expand the economy’s overall abatement capacity:

$$\phi_G = \phi + \theta_3\tau \quad (1.10)$$

After introducing pollution taxes and green subsidies, equations (3.2), (1.4), and (1.5) are updated as follows:

$$Y_G = A(1 + \theta_2\tau)K_G^\alpha \quad (1.11)$$

$$\dot{K}_G = s(1 + \theta_1\tau)Y_G - \delta K_G \quad (1.12)$$

$$\dot{P} = \Omega Y_B - (\phi + \theta_3\tau)Y_G \quad (1.13)$$

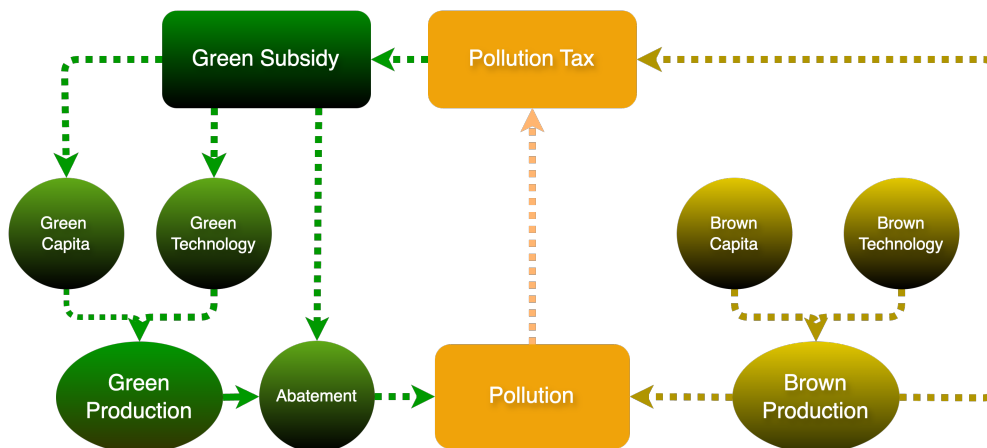


Figure 1.2: Outline of the model

Finally, we introduce one additional realistic assumption:

$$\phi < \Omega \quad (1.14)$$

The assumption suggests that the environmental positive externality efficiency of green output is lower than the environmental negative externality efficiency of brown output. As International Energy Agency (2023) and Friedlingstein et al. (2022) observe, pollution concentrations continue to rise, underscoring that emitting pollutants is easy, whereas abatement remains difficult due to the persistent imbalance between emissions and absorptive capacity. Figure 1.2 presents the model's basic structure.

#### 1.2.4 The Three-Dimensional Dynamic System

Three dynamic variables characterise the economy: brown capital  $K_B$ , green capital  $K_G$ , and pollution  $P$ . We now formulate the dynamic equations for the three variables based on the preceding formulas.

(i) **Brown capital dynamics.** Substituting the brown production function (Eq. 1.6) and the tax rule (Eq. 1.7) into the capital accumulation equation (Eq. 1.3), we obtain:

$$\dot{K}_B = sY_B - \delta K_B = [s(1 - f(P))AK_B^{\alpha-1} - \delta] K_B = f_1(K_B, P) \quad (1.15)$$

(ii) **Green capital dynamics.** Similarly, substituting the green output function (Eq. 1.11) and the tax rule (Eq. 1.7) into the accumulation equation for green capital

(Eq. 1.12), we obtain:

$$\dot{K}_G = s(1 + \theta_1 f(P))Y_G - \delta K_G = [s(1 + \theta_1 f(P))(A + \theta_2 f(P))K_G^{\alpha-1} - \delta] K_G = f_2(K_G, P) \quad (1.16)$$

**(iii) Pollution dynamics.** Finally, substituting Eqs. 1.6, 1.11, and 1.7 into the pollution equation (Eq. 1.13), the pollution dynamics are expressed as:

$$\dot{P} = \Omega A K_B^\alpha (1 - f(P)) - (\phi + \theta_3 f(P))(A + \theta_2 f(P))K_G^\alpha = f_3(K_B, K_G, P) \quad (1.17)$$

Equations (1.15)–(1.17) jointly define the three-dimensional dynamic system of the model, where  $f_1$ ,  $f_2$ , and  $f_3$  denote the corresponding dynamic functions for  $K_B$ ,  $K_G$ , and  $P$ , respectively.

**Steady-state equilibrium.** Setting the dynamic system to its steady state, i.e.,  $\dot{K}_B = \dot{K}_G = \dot{P} = 0$ , yields the equilibrium conditions:

$$\begin{aligned} 0 &= [s(1 - f(P))AK_B^{\alpha-1} - \delta] K_B \\ 0 &= [s(1 + \theta_1 f(P))(A + \theta_2 f(P))K_G^{\alpha-1} - \delta] K_G \\ 0 &= \Omega A K_B^\alpha (1 - f(P)) - (\phi + \theta_3 f(P))(A + \theta_2 f(P))K_G^\alpha \end{aligned} \quad (1.18)$$

### 1.2.5 Propositions

We can state and prove the following propositions based on the Eq.1.18.

**Proposition 1:** There is no equilibrium solution at the *corner Brown* case ( $K_G = 0$ ).

**Proof:** If  $K_G = 0$ , according to the third equation in system 1.18, the second term becomes zero. Hence,

$$\Omega A K_B^\alpha (1 - f(P)) = 0.$$

Since  $(1 - f(P))$ ,  $\Omega$ , and  $A$  are all nonzero, it follows that  $K_B = 0$ . In this case,  $P$  can take any arbitrary value, meaning no economically meaningful equilibrium exists at  $K_G = 0$ .  $\square$

This proposition implies that an economy relying solely on brown production cannot reach a steady state once green capital is absent. Pollution keeps evolving and grows explosively because the production structure lacks an endogenous mechanism for abatement, making equilibrium infeasible.

**Proposition 2:** There is no equilibrium solution at the *corner Green* case ( $K_B = 0$ ).

**Proof:** If  $K_B = 0$ , the first term in the third equation of system 1.18 equals zero, yielding

$$0 = -(\phi + \theta_3 f(P))(A + \theta_2 f(P))K_G^\alpha.$$

Since  $(\phi + \theta_3 f(P))$ ,  $(A + \theta_2 f(P))$ , and  $K_G$  are all positive, this equality cannot hold unless  $K_G = 0$ , which contradicts the initial condition of the corner Green case. Therefore, there is no equilibrium at  $K_B = 0$ .

This result shows that a purely green economy cannot sustain equilibrium under the current structure. Even though green production reduces pollution, the lack of brown output eliminates the source of tax revenue used to fund green subsidies, breaking the policy loop.

**Proposition 3:** The three-dimensional system admits one unique and economically meaningful interior equilibrium point with coordinates  $(K_B, K_G, P) = (K_B^*, K_G^*, P^*)$ .

**Proof:** See Appendix A.1.

The existence of a positive and stable interior equilibrium implies the green sector's essential role in realising a circular economy. In practical terms, this insight resonates with contemporary carbon-neutrality strategies: merely reducing emissions from polluting activities is insufficient to meet net-zero goals. Instead, what is truly required is the expansion of green production that generates positive environmental externalities, which limit pollution, lead to an economic-environmental equilibrium, and eventually create an engine for sustainable growth.

**Proposition 4:** The interior Brown–Green equilibrium point  $(K_B^*, K_G^*, P^*)$  is locally stable.

**Proof:** See Appendix A.2.

This proposition indicates that minor deviations from the interior equilibrium in capital or pollution levels will diminish over time, leading the system to converge to its steady state. A unique and locally stable equilibrium suggests long-term dynamics will inevitably stabilise at a balanced Brown–Green configuration regardless of the economy's initial conditions, structural characteristics, or the specific mix of green policies adopted. This implies that the transition toward sustainability is path-independent once a consistent policy framework is in place, providing theoretical support for achieving carbon neutrality through stable endogenous adjustments.

### 1.2.6 Comparative statics of policies

The previous propositions show that the existence and stability of the steady state do not depend on the functional form of the pollution tax or on the specific configuration of green subsidies. Nevertheless, the steady-state levels of output and pollution do respond to policy variations. We therefore turn to a comparative policy analysis.

Let  $\mathcal{F}$  denote the admissible set of pollution-tax functions:

$$\mathcal{F} = \left\{ f : \mathbb{R}_+ \rightarrow [0, 1] \mid f(0) = 0, f'(P) > 0, \lim_{P \rightarrow \infty} f(P) = 1 \right\},$$

Moreover, let  $\Theta$  denote the admissible set of green-subsidy combinations:

$$\Theta = \left\{ \boldsymbol{\theta} = (\theta_1, \theta_2, \theta_3) \in [0, 1]^3 \mid \theta_1 + \theta_2 + \theta_3 = 1 \right\}.$$

For any pair  $(f, \boldsymbol{\theta}) \in \mathcal{F} \times \Theta$ , The dynamic system admits (under standard regularity assumptions) a unique interior steady state  $(K_B^*, K_G^*, P^*)$ , from which we define the steady-state output and pollution mappings:

$$Y^* : \mathcal{F} \times \Theta \rightarrow \mathbb{R}_+, \quad P^* : \mathcal{F} \times \Theta \rightarrow \mathbb{R}_+.$$

Specifically,

$$Y^*(f, \boldsymbol{\theta}) = A(1 - f(P^*)) [K_B^*(f)]^\alpha + (A + \theta_2 f(P^*)) [K_G^*(f, \boldsymbol{\theta})]^\alpha,$$

$$P^* = P^*(f, \boldsymbol{\theta}) \text{ s.t. } \Omega A(1 - f(P^*)) [K_B^*]^\alpha = (\phi + \theta_3 f(P^*)) [K_G^*]^\alpha.$$

To simplify notation, we represent the steady-state pollution and output under each policy configuration as a bivariate mapping of the tax rule  $f$  and the subsidy vector  $\boldsymbol{\theta}$ :

$$(Y^*, P^*) = (Y^*(f, \boldsymbol{\theta}), P^*(f, \boldsymbol{\theta})).$$

We then define three benchmark configurations:

$$(Y_{0,0}^*, P_{0,0}^*) \equiv (Y^*(f \equiv 0, \mathbf{0}), P^*(f \equiv 0, \mathbf{0})), \quad (\text{no-tax economy}),$$

$$(Y_{f,0}^*, P_{f,0}^*) \equiv (Y^*(f, \mathbf{0}), P^*(f, \mathbf{0})), \quad (\text{tax-only economy}),$$

$$(Y_{f,1}^*, P_{f,1}^*) \equiv (Y^*(f, \mathbf{1}), P^*(f, \mathbf{1})), \quad (\text{tax-plus-subsidy economy}).$$

These notations will be used henceforth to compare steady-state outcomes across policy

regimes.

**Proposition 5: Pollution dominance of environmental policies.** The steady-state pollution levels satisfy:

$$P_{0,0}^* > P_{f,0}^* > P_{f,1}^*.$$

This proposition indicates that a pollution-tax policy stabilises emissions at a finite level relative to the no-tax case, and the inclusion of green subsidies further reduces steady-state pollution beyond the tax-only equilibrium.

**Proof:** See Appendix A.3.

**Proposition 6: Output dominance of environmental policies.** The steady-state outputs satisfy:

$$Y_{0,0}^* > Y_{f,0}^* \quad \text{and} \quad Y_{f,1}^* > Y_{f,0}^*.$$

This proposition suggests that introducing a pollution tax (without subsidies) lowers aggregate steady-state output relative to the no-tax case. This reflects the classical trade-off effect of environmental taxation. While the tax internalises environmental externalities and curbs emissions, it restrains brown production and reduces aggregate output. By contrast, recycling tax revenues into green subsidies raises output relative to the tax-only equilibrium, as the subsidy component offsets the distortionary burden of taxation by stimulating green investment and technological progress. Consequently, the combined policy achieves lower pollution and enhances steady-state productive efficiency compared with a pure tax regime.

**Proof:** See Appendix A.4.

### 1.3 Benchmark parametrization

To provide a more concrete and intuitive view of the above propositions and properties, we report a set of numerical examinations in Section 1.4. Before that, this section clarifies the benchmark parameter specifications that serve as the foundation for the subsequent analysis. It is organised into four parts: the calibration of model parameters, the specification of the pollution tax function, the setting of initial conditions, and the definition of green policy scenarios.

First, our parameterisation is calibrated to the Chinese economy for two main reasons. First, as one of the world's fastest-growing economies, China faces severe environmental challenges arising from decades of resource-intensive expansion. This makes it an ideal empirical context for studying the trade-offs between economic growth and environmental degrada-

Parameter Name	Symbol	Value	Source
Saving rate	$s$	0.45	(CEIC Data, 2023)
Total Factor Productivity	$A$	1	Assumed
Output elasticity of capital	$\alpha$	0.55	(Lin & Liu, 2017)
Depreciation rate	$\delta$	0.06	(Holz, 2006)
Pollution coefficient	$\Omega$	0.01	Assumed according to carbon emission
Abatement coefficient	$\phi$	0.005	Assumed

Table 1.1: Parameter settings calibrated to the Chinese economy.

tion. Second, China’s ”top-down” green transition—characterised by decisive government intervention combined with active market participation—offers a representative case for examining how a green government can coordinate economic development with environmental protection. The coexistence of centralised policy design and decentralised implementation makes China particularly suitable for exploring the effectiveness of mixed instruments such as pollution taxes and green subsidies.

Table 1.1 reports the numerical parameters that reflect empirical characteristics of the Chinese economy. Appendix A.5 provides detailed explanations and data sources.

In addition, we specify the functional form of the pollution tax function  $f(\cdot)$ . As discussed previously,  $f(\cdot)$  satisfies three basic conditions:  $f(0) = 0$ ,  $f(+\infty) = 1$ , and  $f'(x) > 0$ . In the numerical simulations, we adopt a simple functional form:

$$f(P) = \frac{P}{1 + P}.$$

Proposition 3 has demonstrated that the uniqueness of the steady-state equilibrium is not affected by the specific functional form of the pollution tax, as long as it satisfies the above properties. See Appendix A.6 for robustness checks with alternative functional specifications.

Finally, we consider six distinct policy scenarios to investigate how alternative environmental policies affect the economy’s dynamic evolution. These scenarios differ in whether the government imposes a pollution tax and how the resulting revenues are allocated across three subsidy channels—green capital accumulation ( $\theta_1$ ), green total factor productivity enhancement ( $\theta_2$ ), and pollution abatement efficiency improvement ( $\theta_3$ ). These scenarios allow us to assess the macro-dynamic implications of different fiscal recycling schemes within the same policy framework.

Specifically, the six cases are defined as follows: (i) the Business-as-Usual (BAU) case without any taxation or subsidies; (ii) the Naive Tax (NT) policy, where the government levies

Parameter / Policy	BAU	Naive	Baseline	GF	GTFP	PAC
Pollution tax imposed	No	Yes	Yes	Yes	Yes	Yes
$\theta_1$ (Green capital accumulation)	0	0	1/3	1	0	0
$\theta_2$ (Green TFP enhancement)	0	0	1/3	0	1	0
$\theta_3$ (Pollution abatement efficiency)	0	0	1/3	0	0	1

Table 1.2: Policy scenarios and corresponding parameter configurations

a pollution tax but provides no subsidies ( $\theta_{NT} = (0, 0, 0)$ ); (iii) the Baseline (BASE) policy, where revenues are equally distributed among the three channels ( $\theta_{BASE} = (1/3, 1/3, 1/3)$ ); (iv) the Green Finance (GF) subsidy policy, which fully supports green capital accumulation ( $\theta_{GF} = (1, 0, 0)$ ); (v) the Green Total Factor Productivity (GTFP) subsidy policy, which targets technological improvements in green production ( $\theta_{GTFP} = (0, 1, 0)$ ); and (vi) the Pollution Abatement Coefficient (PAC) subsidy policy, which directs all funds to emission-abatement technologies ( $\theta_{PAC} = (0, 0, 1)$ ). Table 1.2 summarises these six scenarios and their associated parameter settings.

These policy settings provide the foundation for the subsequent comparative simulations discussed in the next section.

## 1.4 Numerical simulations

This section presents the numerical simulations of the dynamic model based on the above parameter calibration. The structure of this section is organised into four parts. First, we compare the results of the BAU and Naive Tax scenarios to analyse the impact of the pollution tax on economic equilibrium. Second, we examine the outcomes of three alternative green-subsidy schemes to explore how different subsidy policies affect the economy. Third, we investigate the existence of an optimal subsidy configuration. Finally, based on the model framework, we test the Environmental Kuznets Curve (EKC) hypothesis and analyse the effects of the green capital share on output and environmental degradation.

### 1.4.1 BAU vs. Naive Taxation

#### Capital and Pollution Dynamics

Figure 1.3 illustrates the dynamic evolution of brown capital ( $K_B$ ), green capital ( $K_G$ ), and pollution ( $P$ ) under the BAU and Naive Tax policies. Panels (a)–(c) correspond to  $\Delta K_B$ ,  $\Delta K_G$ , and  $\Delta P$ , respectively, all expressed as percentage deviations from the baseline

equilibrium.<sup>2</sup>For more precise comparison across variables, the initial values of the economy are set at the baseline steady state,  $(K_{B0}, K_{G0}, P_0) = [85.37, 89.81, 0.001]$ . Accordingly, the baseline appears in the figures as a horizontal line along the  $x$ -axis, while the other curves represent percentage deviations relative to this equilibrium.

Panel (a) shows that, relative to the baseline, brown capital in the BAU economy is about 3% higher, while under Naive Tax it is roughly 48% lower. Hence,  $K_B$  under Naive Tax is approximately 51% lower than in BAU. Economically, this reflects the reduction in the marginal profitability of brown production once pollution is taxed, which slows brown capital accumulation and leads to a smaller steady-state  $K_B$ . This outcome is consistent with Proposition 5, which establishes that  $P_{0,0}^* > P_{f,0}^*$ : the imposition of a pollution tax curbs emissions by restraining the expansion of brown capital.

Panel (b) shows that green capital remains almost unchanged across the two regimes. Both trajectories lie about 0.002% below the baseline level, implying that the presence or absence of a pollution tax has almost no effect on  $K_G$ . This occurs because, without any green subsidies, the tax does not directly affect the accumulation equation of  $K_G$ .

Panel (c) presents the dynamics of pollution. Under BAU, pollution grows without bound, indicating the absence of a finite steady state. Instead, pollution converges to a stable level with a pollution tax. This dynamic pattern provides numerical confirmation of Proposition 5 ( $P_{0,0}^* > P_{f,0}^*$ ), showing that the introduction of a positive pollution tax stabilises the system by internalising the environmental externality. Pollution taxation effectively reduces emissions by indirectly affecting brown capital, transforming an otherwise divergent pollution path into a bounded steady state.

## Output Dynamics

Figure 1.4 shows the corresponding evolution of total output ( $Y$ ), brown output ( $Y_B$ ), green output ( $Y_G$ ), and the green-output share ( $Y_G/Y$ ). All variables are measured as percentage deviations from the baseline equilibrium, while the green-output share is expressed in percentage points.

Panel (a) indicates that total output under BAU is about 1Hence, relative to BAU, introducing a pollution tax lowers total output by about 25%. This decline reflects the contractionary effect of environmental taxation on aggregate production, consistent with Proposition 6, which states that  $Y_{0,0}^* > Y_{f,0}^*$ . Economically, the reduced profitability of brown capital diminishes investment and aggregate output, highlighting the growth–environment

<sup>2</sup>Since the vertical scales of the panels differ, all results are interpreted in percentage form for consistency.

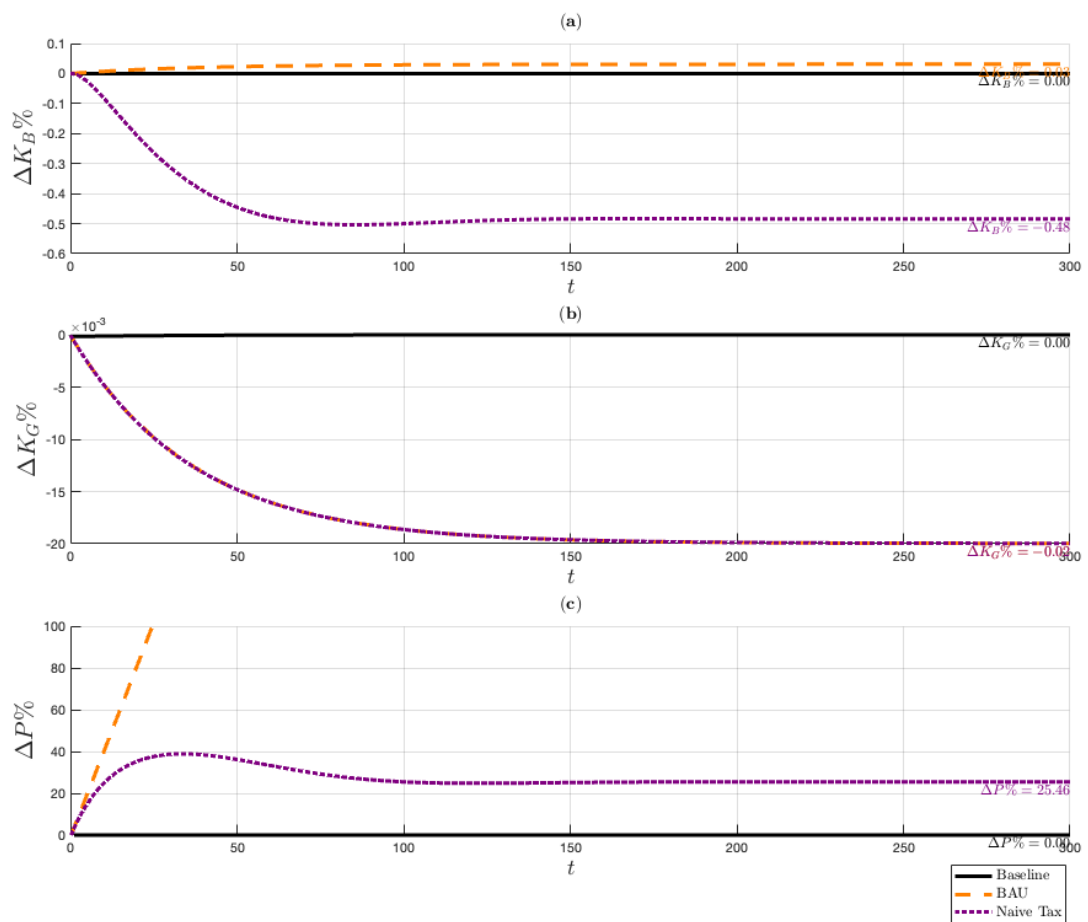


Figure 1.3: Capital stock and pollution under BAU and Naive Tax scenarios. The horizontal axis represents time, while the vertical axis ( $\Delta x$ ) indicates the percentage deviation of each variable from its baseline equilibrium. Orange and purple curves represent the BAU and Naive Tax policies, respectively.

trade-off embedded in the model.

Panel (b) shows that brown output is about 3% higher than the baseline in BAU and 48% lower under Naive Tax. The difference of roughly 51% confirms that the reduction in total output primarily originates from the contraction of the brown sector. Panel (c) shows that green output remains unchanged across the two regimes, with deviations around -0.002%. This invariance indicates that the pollution tax affects output composition entirely through the brown channel rather than by altering green production.

Panel (d) shows that the green-output share rises from about 50% in BAU to about 67% under Naive Tax, an increase of 17 percentage points. This pattern indicates that although the pollution tax does not directly enhance green output, it effectively suppresses brown output, thereby increasing the relative importance of the green sector and achieving a modest but clear structural greening. In short, the pollution tax policy attains a higher green-output proportion and lower pollution at the cost of reduced aggregate production, in line with Proposition 6 ( $Y_{0,0}^* > Y_{f,0}^*$ ).

### Mechanism Analysis

In summary, introducing a pollution tax generates three main effects: lower pollution, lower total output, and a higher share of green production. The mechanism underlying these results is illustrated in Figure 1.5. The pollution tax raises the production cost of the brown sector, reducing its marginal profitability and slowing capital accumulation. As brown capital contracts, emissions decline and pollution dynamics converge to a finite steady state, confirming the stability mechanism implied by Proposition 5. At the same time, since the tax does not directly stimulate green investment, the reduction in brown output is not offset by an expansion of green production, leading to a lower aggregate steady-state output as described in Proposition 6. Nevertheless, the effective suppression of brown activity results in a higher proportion of green output, marking a structural shift toward a greener economy despite the decline in total production.

#### 1.4.2 Alternative Green Policies

We now extend the analysis by introducing three green subsidy schemes—GF, GTFP, and PAC—and comparing their dynamic implications. Also, all variables are expressed as percentage deviations from the baseline, as we did for the BAU and Naive Tax comparison. This section maintains the same structure as the previous one: first, it examines capital and pollution dynamics, then output dynamics, and finally, it discusses the transmission

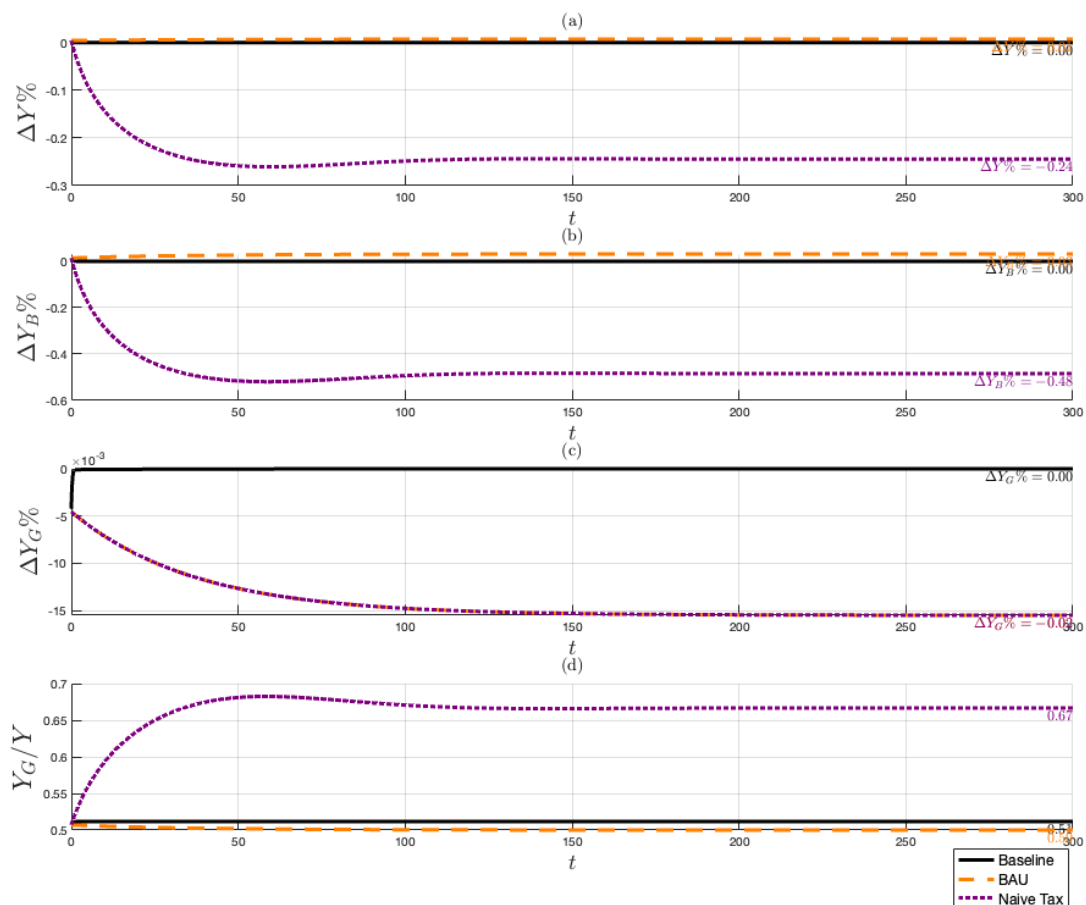


Figure 1.4: Total, brown, and green output under BAU and Naive Tax scenarios. Panels (a)-(c) show the percentage deviations of total, brown, and green output from the baseline equilibrium. Panel (d) reports the evolution of the green-output share  $Y_G/Y$ . Orange and purple curves represent the BAU and Naive Tax policies, respectively.

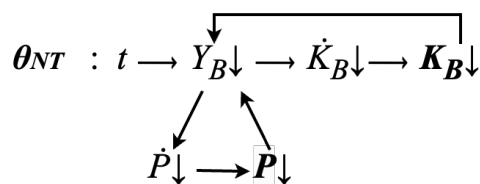


Figure 1.5: Mechanism through which pollution taxes affect capital, output, and pollution.

mechanisms.

### Capital and Pollution Dynamics

Figure 1.6 illustrates the steady-state deviations of brown capital ( $K_B$ ), green capital ( $K_G$ ), and pollution ( $P$ ) under the three subsidy policies. Panels (a)–(c) correspond to  $\Delta K_B$ ,  $\Delta K_G$ , and  $\Delta P$ , respectively.

Panel (a) shows that, relative to the baseline, the GF policy lowers brown capital by about 35%, the GTFP policy by 28%, and PAC slightly increases  $K_B$  by 2%. Panel (b) shows the opposite trend for green capital: GF raises  $K_G$  by 44%, GTFP by 34%, and PAC slightly reduces it by 2%. These patterns reveal a systematic substitution between  $K_G$  and  $K_B$ , where more substantial green accumulation coincides with a contraction of brown capital. This result also shows that channelling pollution-tax revenues into green finance effectively enhances green capital's saving rate and accumulation efficiency, achieving the most substantial increase in steady-state  $K_G$  and the sharpest reduction in  $K_B$ .

Panel (c) compares steady-state pollution levels. In all three green subsidy cases, pollution is substantially lower than under the Naive Tax policy, where the deviation reached about 2.5 times compared to the baseline. In contrast, GF and GTFP increase pollution to about 1.5 and 1.2 times, respectively, while PAC reduces it slightly (-2%) relative to the baseline, reaching the lowest pollution among all scenarios. This ranking confirms Proposition 5, which states that  $P_{f,0}^* > P_{f,1}^*$ : Introducing green subsidies alongside pollution taxation effectively, whatever the subsidy path it is, reduces emissions relative to a tax-only policy. A further finding is that PAC delivers the lowest steady-state pollution level, despite its green capital being lower than that under GF and GTFP. This seemingly counterintuitive result will be explained in the subsequent mechanism analysis following the discussion of output dynamics.

### Output Dynamics

Figure 1.7 presents the dynamics of total output ( $Y$ ), brown output ( $Y_B$ ), green output ( $Y_G$ ), and the share of green output ( $Y_G/Y$ ) across the three subsidy regimes. All variables are measured as deviations from the baseline equilibrium, with the green share reported in percentage points.

Panel (a) shows that introducing any green subsidy leads to higher total output than with the Naive Tax policy, where  $Y$  was about -24% relative to the baseline. With the GF subsidy, total output stands at -6%, almost identical in PAC, and rises to +4% in GTFP. Hence, all subsidy policies exceed the output compared to pure taxation, confirming Proposition 6

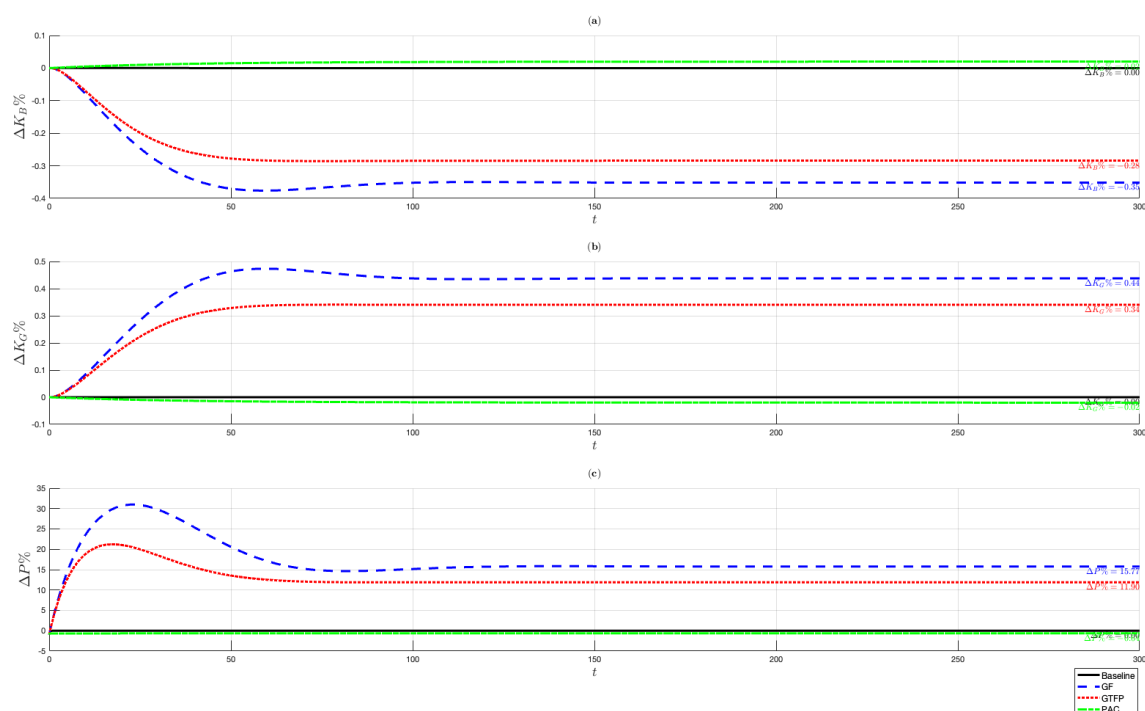


Figure 1.6: Capital stock and pollution under alternative green-policy scenarios. Panels (a)–(c) show the percentage deviations of  $K_B$ ,  $K_G$ , and  $P$  from the baseline equilibrium. Blue, green, and red curves represent the GF, GTFP, and PAC policies.

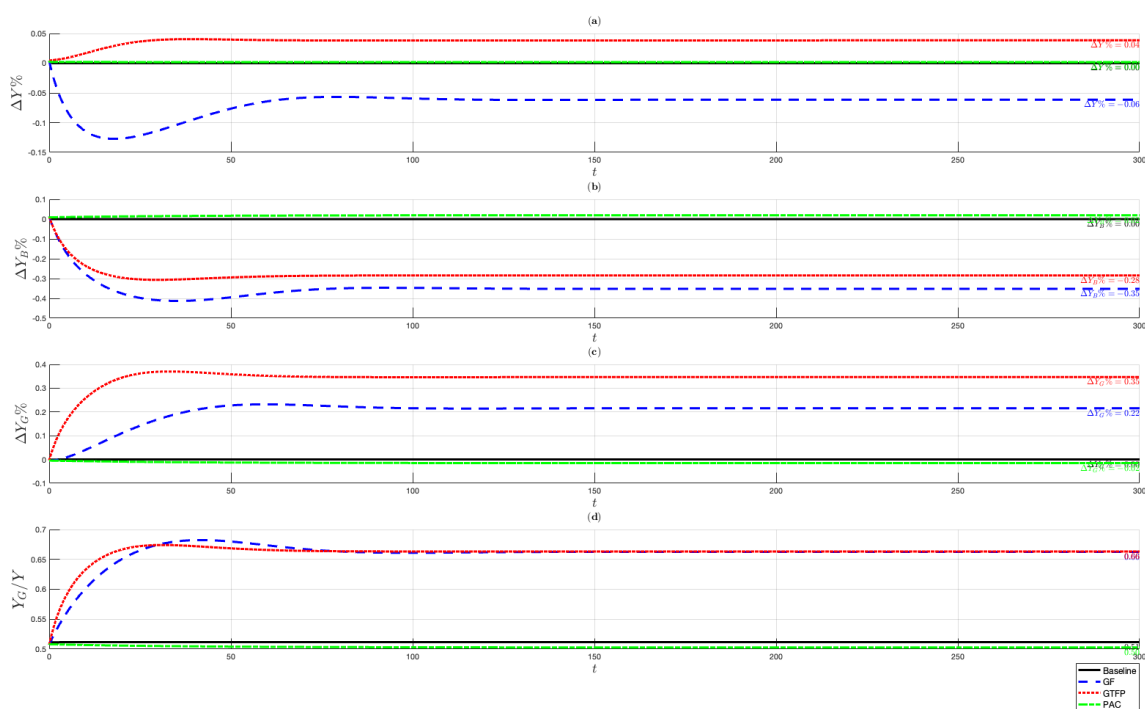


Figure 1.7: Output dynamics under alternative green-policy scenarios. Panels (a)–(c) show the percentage deviations of total, brown, and green output from the baseline equilibrium. Panel (d) reports the evolution of the green-output share  $Y_G/Y$ . Blue, green, and red curves represent the GF, GTFP, and PAC policies.

( $Y_{f,1}^* > Y_{f,0}^*$ ). Among them, GTFP achieves the highest steady-state output.

Panels (b) and (c) show the decomposition of this aggregate result. In GTFP, brown output  $Y_B$  decreases by 28% and green output  $Y_G$  increases by 35%. This indicates that the GTFP policy increases total output by expanding green production while restraining brown production. In the GF scenario,  $Y_B$  decreases by 35%, while  $Y_G$  increases by 22%, leading to a decline in total output. PAC yields minimal changes in  $Y_B$  and  $Y_G$ , maintaining output stability near the baseline. A further, seemingly counterintuitive finding emerges when comparing Panel (b) of Figure 1.6: although the GF policy achieves the highest level of green capital, it does not generate the highest green output. We will return to this issue in the mechanism analysis section.

Panel (d) reports the steady-state share of green output. GF and GTFP raise  $Y_G/Y$  to approximately 66%, almost identical to the Naive Tax economy (67%), but they do so while achieving much higher total output. In other words, GF and GTFP maintain a high degree of production greenness without the severe output losses observed under pure taxation, suggesting the effectiveness of green subsidies in output growth. While delivering the smallest green share, PAC attains the cleanest environment and a balanced output. These outcomes illustrate the policy trade-offs between environmental quality and economic expansion.

### Mechanism Analysis

The distinct performance of the three green subsidy policies can be interpreted through the transmission channels summarised in Table 1.3 and Figure 1.8. Table 1.3 reports the changes in the green saving rate, green productivity, and abatement efficiency under the three subsidy paths, capturing how each policy reallocates fiscal resources within the green sector. Figure 1.8 illustrates how these subsidy channels affect capital accumulation, pollution dynamics, and output performance.<sup>3</sup>

The GF policy channels all fiscal resources into the green saving rate  $s_G$ , raising it by 18.8%. However, this increase does not translate into the highest green output or the lowest pollution.

First, consider green output. By comparing Panel (b) of Figure 1.6 with Panel (c) of Figure 1.7, we find that although GTFP results in a minor increase in green capital than GF, it achieves a higher level of green output. The reason is that GTFP directly enhances the green production function (Eq. 1.11) by raising the productivity parameter  $A_G$ , whereas GF indirectly stimulates green output by increasing capital accumulation through Eq. 1.12.

<sup>3</sup>The upward and downward arrows in the figure indicate changes relative to the Naive Tax scenario without subsidies.

Therefore, although GTFP generates a smaller expansion in  $K_G$ , its higher factor productivity leads to a greater overall  $Y_G$ . Next, consider pollution. Since the GF policy allocates all subsidies to green capital accumulation while leaving the abatement efficiency  $\phi_G$  unchanged—and  $\phi_G$  is the parameter most directly affecting pollution mitigation—its improvement in green capital does not translate into lower pollution. This explains why GF yields the highest green capital but fails to deliver the lowest pollution.

The GTFP policy operates through the productivity channel by increasing  $A_G$  by 15.1%. Enhanced  $A_G$  improves the efficiency of green production, raises  $Y_G$ , and further leads to the highest total output. Like the GF scenario, GTFP has no subsidy in pollution abatement, leaving  $\phi_G$  unaffected, so its effectiveness in pollution mitigation is less than that of the PAC policy.

PAC enhances  $\phi_G$  by 0.5%, but the most significant improvement is in pollution-abatement efficiency. However, as shown in Panels (b)–(d) of Figure 1.7, PAC exhibits the highest brown output, the lowest green output, and the smallest green-output share. This phenomenon occurs because it does not allocate subsidies to green-capital accumulation or green-sector productivity. Nevertheless, PAC delivers the lowest steady-state pollution level, as it maximises the environmental cleaning efficiency of green production. This finding carries an important policy implication: effective green policy design must be guided by environmental objectives, and the most active and direct forms of intervention should prioritise enhancing the green sector’s abatement efficiency.

Policy	$s_G$	$A_G$	$\phi_G$
Initial	0.4500	1.0000	$5.000 \times 10^{-3}$
GF	0.5347 (18.81%)	1.0001 (0.01%)	$5.0005 \times 10^{-3}$ (0.01%)
GTFP	0.4500 (0.00%)	1.1513 (15.13%)	$5.0005 \times 10^{-3}$ (0.01%)
PAC	0.4500 (0.00%)	1.0000 (0.00%)	$5.0245 \times 10^{-3}$ (0.49%)

Table 1.3: Equilibrium changes in key green channels under alternative subsidy schemes (percentage changes relative to the initial condition in parentheses).

In summary, the comparative simulations confirm that adding green subsidies to pollution taxation consistently improves environmental and economic performance relative to a tax-only scenario. This finding numerically validates the second part of Proposition 5 ( $P_{f,0}^* > P_{f,1}^*$ ) and Proposition 6 ( $Y_{f,1}^* > Y_{f,0}^*$ ). The comparative analysis of the three green-subsidy policies shows that GF achieves the highest level of green capital, GTFP yields the highest green and total output, and PAC results in the lowest pollution.

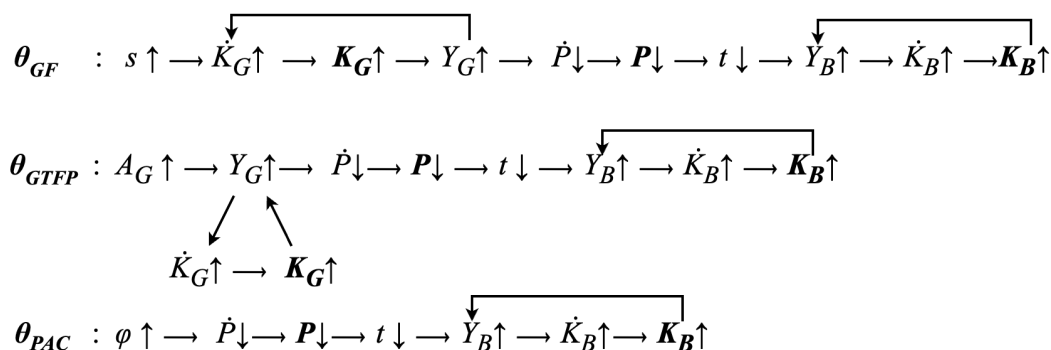


Figure 1.8: Transmission mechanisms of the three green policies.

### 1.4.3 The Optimal Policy

The analyses above examined a limited set of fixed policy vectors  $\theta$  and showed how different allocations of pollution tax revenues influence equilibrium outcomes. However, these examples represent only a few discrete combinations. We must explore the space of feasible  $\theta$  values to identify a truly optimal policy.

From the economic growth perspective, an optimal policy maximises steady-state total output. From the environmental perspective, it minimises steady-state pollution. These two goals are both desirable but may not be jointly attainable. This section investigates whether a single policy configuration that achieves both or whether a trade-off between them inevitably arises.

To visualise the entire policy space, we simulate equilibrium outcomes for all feasible combinations of  $\theta = (\theta_1, \theta_2, \theta_3)$  subject to the constraint  $\theta_1 + \theta_2 + \theta_3 = 1$ . This constraint leaves two degrees of freedom. Accordingly,  $\theta_2$  and  $\theta_3$  are varied from 0 to 1 in increments of 0.01, with  $\theta_1$  determined residually. The initial values of the three state variables are set as follows:  $(K_{B0}, K_{G0}, P_0) = [100, 1, 0.01]$ . These values represent an economy dominated by brown capital in the early stage, with a small share of green capital and moderate initial pollution. Appendix ?? provides detailed explanations of the initial settings. All other parameters are identical to table 1.1. Each combination is simulated for 300 periods, and the final observation is recorded as the steady-state values of output  $Y_{eq}$  and pollution  $P_{eq}$ .

The results are plotted in Figure 1.9, which displays the corresponding equilibrium surfaces. The left panel of Figure 1.9 shows that minimum pollution occurs near  $(\theta_2, \theta_3) \approx (0.01, 0.98)$ . The right Panel shows that maximum output appears around  $(\theta_2, \theta_3) \approx$

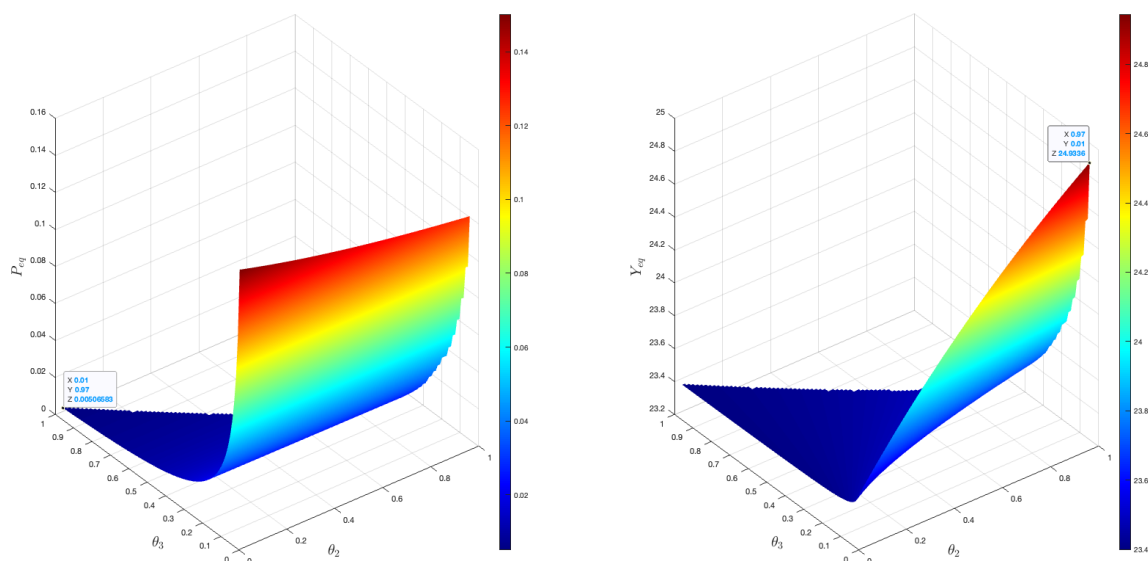


Figure 1.9: Equilibrium pollution and output across policy configurations<sup>4</sup>

The left surface shows equilibrium pollution  $P_{eq}$  and the right surface shows total output  $Y_{eq}$ . The horizontal axes represent  $\theta_2$  and  $\theta_3$ , and the colour gradient (from blue to red) denotes increasing values. Labelled points indicate the combinations that minimise pollution and maximise output.

(0.98, 0.01). The two points are far apart, indicating a clear trade-off between environmental quality and economic expansion.

Under the current calibration, the policy maximising output is approximately  $(\theta_1, \theta_2, \theta_3) = (0.01, 0.98, 0.01)$ , which corresponds to the GTFP configuration where all pollution tax revenues enhance the total factor productivity of green production. The policy minimising pollution is  $(\theta_1, \theta_2, \theta_3) = (0.01, 0.01, 0.98)$ , corresponding to the PAC policy that allocates nearly all revenues to pollution-abatement efficiency. Hence, higher output entails higher pollution, indicating that the two objectives cannot be attained simultaneously. Under the current calibration, the policy maximising output is approximately  $(\theta_1, \theta_2, \theta_3) = (0.01, 0.98, 0.01)$ , which corresponds to the GTFP configuration where all pollution tax revenues enhance the total factor productivity of green production. The pollution-minimising policy is  $(\theta_1, \theta_2, \theta_3) = (0.01, 0.01, 0.98)$ , corresponding to the PAC policy that allocates nearly all revenues to pollution-abatement efficiency. Hence, higher output entails higher pollution, indicating that the two objectives cannot be attained simultaneously.<sup>5</sup>

From an environmental perspective, the PAC policy performs best because it directly raises the abatement coefficient  $\phi$ , which reflects the efficiency of technologies such as recycling, waste treatment, and emission filtration. From a growth perspective, the GTFP policy

<sup>5</sup>The optimal points are not exactly located at  $\theta = (0, 1, 0)$  and  $\theta = (0, 0, 1)$  due to the precision setting in the numerical search algorithm. With finer grid resolution, the output-maximising and pollution-minimising configurations would converge increasingly close to these boundary points.

is superior because it improves  $A_G$ , the productivity of green capital, thereby increasing green and total output. Examples include subsidies for green patents, research on low-carbon technologies, and financial support for green enterprises.

The results indicate a clear trade-off between the two objectives. However, searching for a balanced policy that performs well in both dimensions remains possible, even if neither is individually optimal. To identify such a balance, we reformulate the problem as a multiple-criteria decision-making (MCDM) exercise using the Simple Additive Weighting (SAW) method (Tzeng & Huang, 2011). The technique assigns explicit weights to output and pollution and aggregates their normalised values into a single performance score:

$$p_i = \sum_{j=1}^m w_j r_{ij}, \quad (1.19)$$

where  $p_i$  is the overall performance of policy  $i$ ,  $r_{ij}$  is its normalized score for criterion  $j$ , and  $w_j$  is the corresponding weight.

Normalisation is required because output and pollution differ in scale (in our simulations,  $P$  ranges between 0 and 0.15 while  $Y$  ranges between 23 and 25). We use the standard min-max normalisation, distinguishing between benefit-type and cost-type indicators:

$$\begin{aligned} Y_{\text{norm}} &= \frac{Y - Y_{\min}}{Y_{\max} - Y_{\min}}, \\ P_{\text{norm}} &= \frac{P_{\max} - P}{P_{\max} - P_{\min}}. \end{aligned} \quad (1.20)$$

We assign a weight  $w_{gp}$  to output, interpreted as the growth preference, and  $1 - w_{gp}$  to pollution. A higher  $w_{gp}$  indicates a stronger preference for economic growth. Since this preference varies across economies and development stages,  $w_{gp}$  is treated as a parameter ranging from 0 to 1. The comprehensive policy index is then given by

$$\begin{aligned} I(\boldsymbol{\theta}) &= w_{gp} Y_{\text{norm}}(\boldsymbol{\theta}) + (1 - w_{gp}) P_{\text{norm}}(\boldsymbol{\theta}), \\ \boldsymbol{\theta}^* &= \arg \max_{\boldsymbol{\theta}} I(\boldsymbol{\theta}). \end{aligned} \quad (1.21)$$

Equation (16) summarises the optimisation procedure for identifying the policy that best balances output and pollution under a given preference  $w_{gp}$ .

The results in Table 1.4 reveal a clear threshold pattern. When  $w_{gp} < 0.5$ , the government emphasises environmental quality, and the optimal policy allocates nearly all tax revenues to  $\theta_3$ , corresponding to the PAC policy. When  $w_{gp} > 0.5$ , the priority shifts to economic growth, and the optimal configuration converges to  $\theta_2 \approx 0.99$ , consistent with the GTFP policy. The

model therefore predicts a distinct transition from environmental to growth orientation once the weight on output exceeds one-half.

Parameters \ $w_{gp}$	0.1	0.4	0.5	0.6	1.0
$\theta_1$	0	0	0	0	0
$\theta_2$	0.01	0.01	0.99	0.99	0.99
$\theta_3$	0.99	0.99	0.01	0.01	0.01

Table 1.4: Optimal policy configurations under different growth preferences ( $w_{gp}$ )

Together, these results provide continuous policy mapping that links developmental preferences to optimal subsidy design within the green tax–subsidy framework.

#### 1.4.4 Additional Analysis: The Dynamic Relationship between Pollution and Output

In the previous sections, we focused on the temporal evolution of key variables under different policy settings. This subsection examines the dynamic relationships among these variables during the transition process.

Figure 1.10 illustrates the relationship between pollution and output. The colour of each curve corresponds to the policy scenarios discussed earlier. Unlike the previous figures that compared values relative to the baseline, this figure presents the absolute levels of pollution and output. All curves start from a common initial state but follow distinct evolutionary paths that converge to different steady states<sup>6</sup>.

Across all policy scenarios, pollution rises before gradually declining, while output follows the opposite trajectory—falling initially and recovering over time. This pattern arises because the pollution tax takes effect immediately at  $t = 0$ , suppressing brown-sector production. As the brown sector dominates early, aggregate output falls on impact. Over time, however, capital accumulation in both sectors accelerates, driving a recovery and eventual expansion of total production.

These dynamics reveal the delayed effects of green policies. At the early stage of implementation, green sectors such as clean production and pollution treatment remain too small to offset the contraction in brown output, resulting in a short adjustment phase during which both output and environmental performance appear weak. As green investment continues

<sup>6</sup>The initial values of the three state variables are set as  $(K_{B0}, K_{G0}, P_0) = [100, 1, 0.01]$ . All other parameters are identical to Table 1.1.

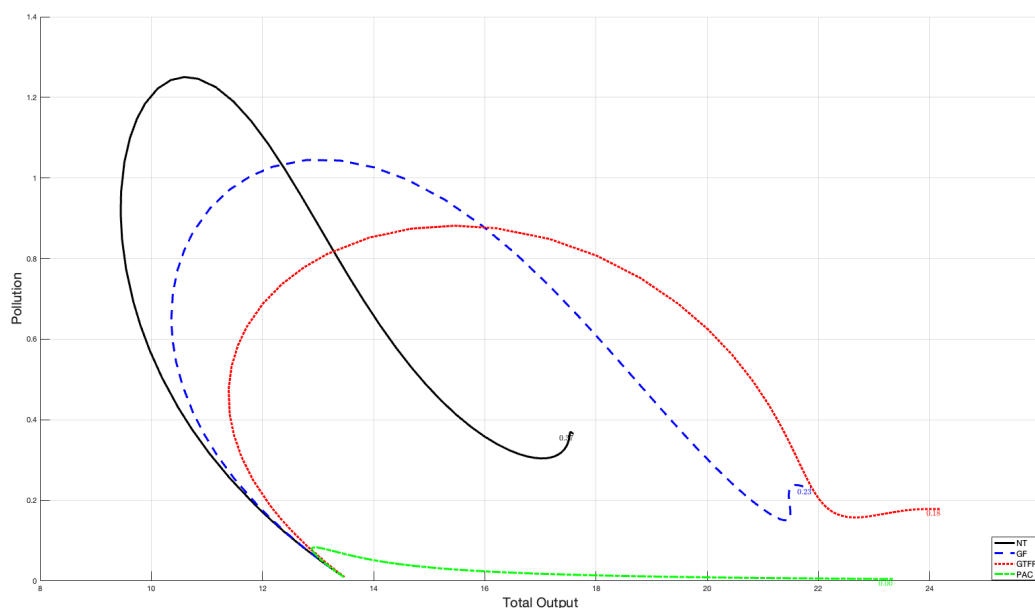


Figure 1.10: Dynamic relationship between pollution and output under different policies

and capital reallocates toward cleaner activities, the positive effects of the transition emerge: output rises steadily while pollution declines.

Overall, the economy moves toward its sustainable steady state along a nonlinear path. This finding carries clear policy implications—short-term stagnation in output or pollution reduction should not be misinterpreted as policy failure. Sustained green reforms will ultimately bring about both economic expansion and environmental improvement.

When pollution and output are examined jointly, their relationship exhibits an inverted U-shape: at lower output levels, growth is accompanied by higher pollution, while beyond the turning point, further expansion leads to pollution reduction. This provides theoretical support for the Environmental Kuznets Curve hypothesis (Grossman & Krueger, 1995).

Our model further suggests that the structural composition of capital plays a central role in shaping these outcomes. To explore this mechanism, we express green capital in relative rather than absolute terms, using the share of green capital in total capital,  $K_G/(K_G + K_B)$ , as the primary variable of interest.

The results are presented in Figure 1.11, where the horizontal axis represents the green capital share and the vertical axes in the upper and lower panels correspond to pollution and output. The share of green capital increases steadily, and its relationship with pollution and output is distinctly nonlinear in all policy scenarios. Pollution follows an inverted U-shaped pattern as the green capital share rises. It initially increases and subsequently declines, with a gentler slope before the turning point and a steeper drop afterwards. Output exhibits the

opposite trajectory, forming a U-shaped curve.

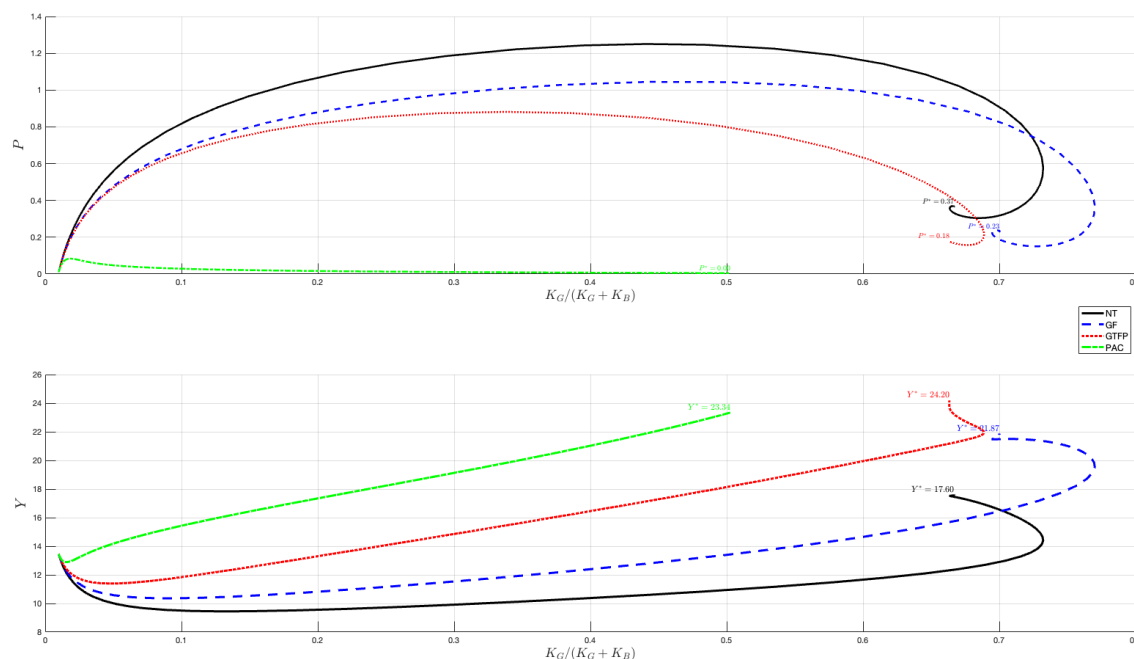


Figure 1.11: Share of Green Capital vs Pollution and Output

The nonlinear relationships in Figure 3.5 arise from the changing dominance of green and brown production over the transition. The brown industry dominates the economy at low levels of the green capital share. Imposing the pollution tax at  $t = 0$  reduces brown production and aggregate output. However, pollution does not immediately decline because green production and abatement capacity are still too small to offset ongoing emissions from the brown sector. As a result, output falls while pollution rises in the early phase.

As the green subsidy is applied, the scale of the green sector expands and its abatement effect strengthens, gradually offsetting emissions from brown production. The subsequent decline in pollution reduces the effective tax burden and allows part of the brown sector to recover. In this later phase, total output rises while pollution falls. This dynamic process leads to an inverted U-shaped relationship between the green capital share and pollution and a U-shaped relationship between the green capital share and output, providing a theoretical foundation for future empirical research.

## 1.5 Concluding Remarks and Policy Implications

This study develops a dynamic green–brown growth framework that integrates environmental taxation, fiscal recycling, and technological feedback within a unified macroeconomic model. By distinguishing between green and brown capital and introducing endogenous pollution and abatement channels, the model clarifies how different policy instruments jointly determine the long–run equilibrium of output and emissions. The theoretical analysis and numerical simulations together yield a set of coherent and policy–relevant conclusions.

First, the comparison between the BAU and Naive Tax economies confirms that pollution taxation alone stabilises emissions, but at the cost of lower output. Specifically, relative to the no–tax case, introducing a pollution tax dramatically reduces steady–state pollution while decreasing aggregate output by roughly one quarter. The tax curbs brown production and capital accumulation, yielding a cleaner but smaller economy. At the same time, the green share of total output increases because the contraction of the brown sector exceeds the adjustment in green production. Hence, the pollution tax is necessary for dynamic stability, yet it induces a classical growth–environment trade-off.

Second, the introduction of green subsidies fundamentally alters the equilibrium outcomes. All three fiscal recycling schemes—GF, GTFP, and PAC—reduce pollution and increase total output relative to the tax-only policy. Specifically, the GF policy achieves the highest level of green capital by channelling all tax revenues into the green saving rate. The GTFP policy enhances the productivity parameter  $A_G$ , generating the highest green and total output but delivering only moderate environmental improvements. In contrast, the PAC policy yields the lowest steady-state pollution. These results underscore the inherent trade-off between output expansion and environmental quality.

Third, the mechanism analysis clarifies the transmission channels behind these outcomes. The GF and GTFP schemes strengthen green accumulation and productivity, yet because they leave the abatement coefficient  $\phi_G$  unchanged, their additional green output does not fully offset the induced emissions. PAC follows a distinct path: directly improving  $\phi_G$  lowers the effective tax burden on the brown sector and stabilises total output even with a minor green component. These results reveal that the marginal effectiveness of green investment depends on the scale of green capital and its environmental efficiency.

From a policy perspective, the analysis carries three key implications. First, pollution taxation alone is effective in controlling emissions but insufficient to sustain growth. The policy mix combining pollution tax with fiscal subsidy toward the green sector is doubly effective in the environment and the economy. Second, the choice of subsidy design should reflect

government priorities. Growth-oriented governments may favour productivity-enhancing instruments such as GTFP, which maximise aggregate output. In contrast, environmentally oriented governments should prioritise abatement-based instruments such as PAC, which achieve the cleanest equilibrium without reducing output. Third, the model underscores the importance of coordination between financial and environmental policies: directing tax revenues to the most efficient abatement or productivity channels can reconcile the traditional trade-off between economic expansion and ecological sustainability.

In conclusion, the extended Green Solow framework provides a consistent theoretical foundation for evaluating the macroeconomic effects of environmental taxation and green fiscal recycling. It shows that well-designed combinations of taxes and subsidies can simultaneously reduce pollution and sustain output growth. Future research could extend the model to include international spillovers, heterogeneous firms, or adaptive technological transitions, offering a richer understanding of the financial pathways toward a circular and low-carbon economy.

## Chapter 2

# Measuring Green Finance: A Two-Dimensional Framework and Its Application in China

A persistent financing gap continues to hinder progress toward the Sustainable Development Goals (SDGs). Green finance has become a cornerstone of the global response to climate change. However, it still lacks a transparent and scalable framework to assess how extensively and intensively green finance has developed.

This study introduces a two-dimensional Green Finance Index (GFI) to measure green finance: Intensity and Coverage. *Intensity* measures the degree of greenisation in the financial market by the average market share of green financial products. *Coverage* captures the degree of spread of green financial markets by calculating the proportion of active green financial markets. Furthermore, it constructs China's provincial green finance dataset, covering the period from 2008 to 2019, based on this methodology. The dataset reveals a steady upward trend in China's green finance development, particularly after 2016. Approximately 62% of the overall increase in the national GFI is attributable to the broader application of new green instruments, while the remaining 38% stems from deeper greening within existing markets. Provincial disparities are evident, as higher GFI values are found mainly in regions rich in natural and ecological resources rather than in economically advanced coastal areas, underscoring the importance of natural endowments in driving green finance expansion.

**Keywords:** Green Finance Index, Measurement methodology, Chinese provincial green finance dataset

**JEL:** G18, Q56, Q58

## 2.1 Introduction

Sustainable development has garnered broad political and academic support and is widely recognised as one of the defining challenges of the twenty-first century. However, translating this vision into tangible outcomes faces a persistent obstacle—a global shortage of capital. According to OECD projections, without structural reforms to the global financial architecture, the worldwide shortfall could reach US\$6.4 trillion per year by 2030 (Organisation for Economic Co-operation and Development, 2025) (see Figure 2.1). Climate finance illustrates the magnitude of the challenge: average annual flows amounted to approximately US\$1.3 trillion in 2021–2022, far below the US\$8–9 trillion required each year through 2030 (Climate Policy Initiative, 2023).

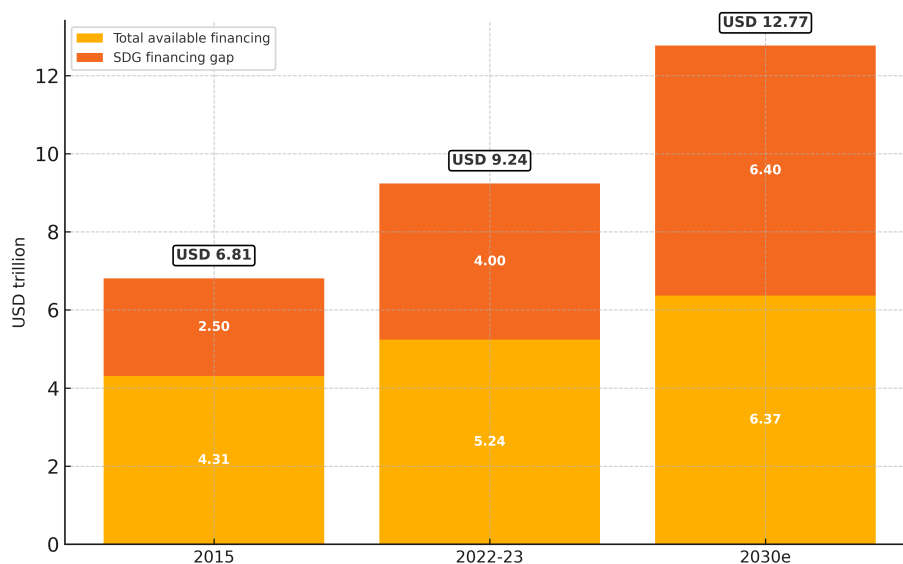


Figure 2.1: SDG Financing Gap. Data source: Organisation for Economic Co-operation and Development (2025)

Closing this gap requires mobilising both public and private capital toward projects that deliver environmental benefits and support low-carbon development. A growing set of financial instruments and policies—including green bonds, green loans, carbon markets, fiscal incentives, green central banking, financial technologies, and community-based green funds—collectively constitute what is broadly referred to as green finance (Sachs et al., 2019). Green finance offers a pragmatic pathway for narrowing the SDG funding gap (Flammer, 2021). By mobilising social capital—especially from the private sector—it supports renewable and clean energy investment, mitigates carbon emissions, strengthens urban climate resilience, and promotes overall environmental sustainability (Taghizadeh-Hesary & Yoshino, 2019).

Although a unified definition has yet to emerge, green finance is generally understood as

the mobilisation of public and private capital into activities that generate measurable environmental benefits while reducing climate-related risks. Lindenberg (2014) defines it broadly as any investment, policy, or financial system that explicitly incorporates environmental criteria to enhance sustainability. A summary of representative definitions from international institutions, national authorities, and scholars is provided in Appendix B.1.

Despite its rapid global expansion, academic research on green finance still faces major empirical challenges—particularly in measurement. The absence of a transparent and standardised framework for quantifying regional levels of green finance development has constrained comparative research and limited systematic evaluation of its economic and environmental impacts.

To address this gap, the present study develops a comprehensive yet computationally tractable methodology for constructing a Green Finance Index (GFI), enabling interregional and temporal comparison. Using this framework, we compile a provincial-level GFI dataset for China covering 2008–2019 and analyse the main features of regional green finance development. The findings enrich the methodological foundations of green finance assessment and offer policy insights for designing strategies to better align financial systems with sustainable development goals.

## 2.2 Literature Review

Currently, the measurement approaches for green finance can be broadly categorised into two types: single-indicator proxy methods and composite multi-indicator evaluation methods. The former refers to using a single indicator within the green finance market as a representative measure of the entire sector, such as green bonds (K.-H. Wang et al., 2022) or green loans (Z. Wang & Wang, 2022; Zhu et al., 2024). Several research institutions have developed market-based indices (e.g., S&P Global Green Bond Index; Bloomberg Global Aggregate Green Social Sustainability Bond Index (Bloomberg Index Services Limited, 2022)), which have subsequently been adopted in academic research (Kartal et al., 2025). While this approach is simple and easy to implement, its major limitation lies in its inability to capture the complexity of the green finance system comprehensively.

An increasing number of scholars and research institutions have shifted toward multi-indicator construction methods, which incorporate various segments of the green finance market into a unified assessment framework. Essentially, this methodological approach belongs to the framework of multiple-factor analysis (MFA) (Tzeng & Huang, 2011). These methods can be further divided into two subtypes. First is the subjective evaluation systems,

which rely primarily on expert scoring or survey questionnaires (Z/Yen Group & Finance Watch, 2025). Second is the objective evaluation systems, which are based on observable market-scale data. The core procedure of the objective composite index method typically involves three steps. First, it quantifies the development level of different sub-markets within the green finance sector, including green bonds, loans, and stocks, among others<sup>1</sup>. Then, normalise the data to eliminate the error caused by the difference in units of measurement. Second, it applies an appropriate weighting scheme to assign relative importance to each sub-market. Third, it aggregates the weighted indicators to construct a comprehensive index of green finance development. This approach currently represents the mainstream methodology for developing green finance indices in academia. Some use subjective weighting by expert consultants (Lee & Lee, 2022). The majority of research adopts the objective method, which means the weighting is derived from the statistical characteristics of the data. For example, Zhou et al. (2020) adopted an improved Principal Component Analysis (PCA) approach. The entropy weighting method is most commonly used, especially among Chinese scholars (Lv et al., 2021).

The multi-indicator approach has become a widely adopted method for measuring green finance indices in both academic research and institutional practice. This method enables straightforward cross-regional comparisons by normalising heterogeneous indicators from various segments of the financial market. However, several notable limitations remain.

First, the normalisation process removes the original scale and units of the raw data, thereby stripping away much of the inherent informational content and retaining only the comparative value. For example, in the case of green bonds, the original market data may refer to the absolute issuance volume or the proportion of green bonds relative to total bond issuance. However, once these values are normalised, the substantive meaning embedded in the raw figures is effectively erased. The resulting indicators serve merely to illustrate relative differences across time or regions rather than conveying the actual scale or structural significance of green bond development.

Second, many scholars have adopted the min–max normalisation method, which renders the standardisation process highly dependent on the integrity of the whole data range. The inclusion of new data points can alter the maximum and minimum values of the dataset, necessitating a recalibration of the entire normalisation procedure. This not only increases computational complexity but also undermines the temporal stability of the index over time.

Last but not least, in the process of indicator selection, many scholars include both positive

---

<sup>1</sup>Some also consider political, environmental, and economic indicators in the measuring framework (International Finance Forum (IFF), 2024).

and negative indicators—likely due to constraints in data availability. However, this practice introduces a potential neutralisation effect, whereby it becomes unclear whether an observed increase in the final green finance index is driven by improvements in positive indicators or by the reduction of negative ones. This ambiguity may obscure the interpretation of the underlying drivers of green finance performance.

Our objective is to construct a new composite multi-indicator framework for green finance index development. This framework aims to provide a comprehensive assessment of the overall performance of the green finance market, similar to existing indices, while simultaneously preserving the interpretability of the original data. Such a design facilitates disaggregated analysis of individual sub-markets. The proposed index can support both cross-regional comparisons and temporal trend analyses. Moreover, it enables researchers and policymakers to distinguish whether variations in green finance development are driven by the deepening of specific sub-markets or by the broader expansion of green capital across different segments of the financial system.

## 2.3 Methodology

This paper measures green finance along two complementary dimensions: *Coverage* and *Intensity*. *Coverage* captures the diffusion and application of green finance—that is, how many types of green financial instruments are employed to support the green transition (its horizontal reach). *Intensity*, in contrast, measures the degree of greening within the financial system—how strongly financial capital has been directed toward environmentally sustainable activities (its vertical strength). Together, these two dimensions form the *Green Finance Index* (GFI), which provides a comprehensive measure of both the diversity of green financial participation and the strength of green capital allocation.

### 2.3.1 Coverage measurement

*Coverage* quantifies how widely green financial instruments are adopted within a region. A simple count of green financial instruments provides an intuitive indicator, but it fails to account for cross-regional differences in financial system maturity. Therefore, a relative measure is more appropriate. Defining *Coverage* as a proportion enables consistent comparison across economies with differing financial structures. Accordingly, the *Coverage* of green finance is measured as the proportion of green financial instrument categories currently active relative to the total number of potential categories in the financial system. Since green finance constitutes a subset of the overall financial system, *Coverage* naturally lies within

[0, 1].

Incorporating *Coverage* into the GFI framework offers three main advantages. First, it captures the horizontal diffusion of green finance—how widely different types of green financial instruments are adopted within a region—thereby complementing *Intensity*, which reflects the vertical penetration of green capital within each instrument category. Second, analysing *Coverage* and *Intensity* both separately and jointly within the GFI allows decomposition of overall progress into two distinct sources: expansion in instrument adoption (higher *Coverage*) and deepening of green capital within instruments already in use (higher *Intensity*). Third, *Coverage* facilitates fairer comparison across economies with varying levels of financial development. Economies with more sophisticated financial systems have greater potential to adopt multiple green financial instruments; thus, low *Coverage* in such cases indicates underutilised capacity and acts as a penalty term within the composite index.

### 2.3.2 Intensity measurement

*Intensity* captures the degree of greening within financial markets. There are two general approaches to measuring this dimension. The first uses the absolute size of green financial activities—such as the total volume of green loans, bond issuance, or fund assets—as an indicator of greening. However, this measure is problematic because absolute amounts are not comparable across regions of different economic scales and may also rise simply alongside faster growth in non-green finance, giving a distorted view of green progress. Empirical evidence confirms this: while global green finance volumes increased more than a hundredfold between 2012 and 2021, their share in total financial activity rose only modestly (TheCityUK, 2022).

The second approach defines overall *Intensity* as the ratio of total green capital to total financial capital, summing across all markets. Although this adjusts for scale differences, it is still dominated by the largest market segments. For example, if market sizes are  $T_1, T_2, T_3$  with corresponding green capital  $G_1, G_2, G_3$ , the ratio  $(G_1 + G_2 + G_3)/(T_1 + T_2 + T_3)$  mainly reflects  $G_3/T_3$  when  $T_3$  is much larger, even if the smaller markets are substantially greener. This aggregation bias can lead jurisdictions to focus on greening their largest markets while neglecting others.

To overcome these limitations, we treat the measurement of *Intensity* as a Multiple Criteria Decision-Making (MCDM) problem and apply the Simple Additive Weighting (SAW) method with equal weights across markets (Tzeng & Huang, 2011). Specifically, we first compute the share of green capital within each financial market, referred to as the *Sub-Intensity*,

and then take their simple average to obtain the overall *Intensity* of green finance. Equal weighting eliminates the influence of market size and ensures that each market contributes symmetrically to the composite indicator. As an averaged ratio, *Intensity* naturally lies within  $[0, 1]$ .

### 2.3.3 Formal Definition

Bringing the two dimensions together, the *Green Finance Index* (GFI) combines *Coverage* and *Intensity* into a single composite measure. Conceptually, it can be interpreted as a coverage-adjusted average share of green financial capital.

For a given region at a specific time,<sup>2</sup> suppose there are  $n$  potential categories of green financial instruments,

$$\mathbf{GF} = \{GF_1, GF_2, \dots, GF_n\},$$

among which  $m$  categories ( $m \leq n$ ) are actively utilised in practice. Each green instrument  $GF_j$  corresponds to a conventional financial market (for example, green bonds to the bond market, green loans to the credit market). Let the total size of the corresponding market be  $S_j$ , and the size of its green component be  $GS_j$ .

**Definition 1. Coverage.**

$$\text{Coverage} = \frac{m}{n},$$

which represents the proportion of potential green financial instruments that are currently in use within the region.

**Definition 2. Sub-Intensity.**

$$SI_j = \frac{GS_j}{S_j}, \quad j = 1, 2, \dots, m,$$

where  $SI_j$  measures the share of green capital within the corresponding market associated with instrument  $j$ .

**Definition 3. Intensity.**

$$\text{Intensity} = \frac{1}{m} \sum_{j=1}^m SI_j,$$

that is, the arithmetic mean of sub-intensities across all active green financial instruments.

**Definition 4. Green Finance Index.**

$$\text{GFI} = \text{Intensity} \times \text{Coverage}.$$

---

<sup>2</sup>For simplicity, we present the index for a single economy at a single point in time. Panel notation (e.g.,  $i$  for region and  $t$  for time) can be added straightforwardly.

By construction, both *Coverage* and *Intensity* lie within  $[0, 1]$ , and so does the resulting *GFI*.

The multiplicative form of the GFI captures the joint contribution of two complementary dimensions—how widely green finance has expanded across markets and how deeply it has taken root within them. An increase in either dimension raises the GFI, yet the interaction between them highlights the structural importance of expanding green financial coverage: the diffusion of new instruments amplifies the aggregate impact of financial greening. At the same time, the formulation preserves analytical transparency, as *Coverage* and *Intensity* remain separately interpretable. This allows decomposition of overall performance into extensive (instrument adoption) and intensive (capital penetration) margins, offering policymakers a diagnostic tool to trace whether progress in green finance stems from diversification across instruments or from deepening within existing markets.

## 2.4 Case study: Chinese provincial Green finance development

This section applies the proposed methodology to China, one of the world’s most dynamic laboratories for green finance. In recent years, China has emerged as a global leader in this field: Chinese issuers placed about USD 131 billion of labelled green bonds in 2023—the largest national total worldwide (Climate Bonds Initiative, 2024)—while outstanding green loans accounted for 13% of all bank lending by the end of 2024 (Yue & Nedopil, 2025).

China’s experience combines strong government direction with active market participation, reflecting the institutional characteristics of a socialist market economy. The government has progressively steered capital flows toward low-carbon and environmentally sustainable sectors through strategic policy documents and regulatory frameworks. Appendix B.2 summarises the major milestones of China’s green finance policy framework and its engagement in international initiatives. An analysis of China’s green finance system illuminates the institutional and policy mechanisms through which state-led financial governance can advance environmental sustainability, offering a comparative reference for other developing economies seeking to align financial systems with low-carbon development goals.

In what follows, we construct a provincial dataset covering China’s green finance development between 2008 and 2019 and summarise its spatial and temporal characteristics.

### 2.4.1 Dataset Construction

#### Span and Region

The dataset covers 30 provincial-level administrative units in mainland China, including four municipalities directly under the central government, over the period 2008–2019. Although China’s formal green-finance framework was only established in 2016 with the publication of the *Guidelines for Establishing a Green Financial System*, both public and private green financing activities had already been developing before this point.

The year 2008 is chosen as the starting point for two reasons. First, it marks the year when the Industrial Bank of China became the first Chinese financial institution to adopt the *Equator Principles*, signalling the country’s initial participation in international environmental and social risk-management practices. Second, 2008 also witnessed institutional coordination between the former Ministry of Environmental Protection and the China Banking Regulatory Commission through an information-sharing agreement, which enabled banks to access firms’ environmental compliance records. These milestones collectively symbolise the beginning of China’s integration of environmental governance with financial supervision. The end year, 2019, is selected to avoid distortions associated with the COVID-19 pandemic and to ensure data consistency prior to the major reforms in China’s green finance disclosure and carbon market systems initiated in 2020.

#### Scope of Green Finance System

Green finance in China operates through the interaction between market mechanisms and policy guidance. The provincial green-finance database developed in this study therefore integrates both tradable green financial instruments and government-led fiscal activities.

In the market dimension, contemporary China possesses a wide range of tradable green financial products, including loans, bonds, equities, insurance, funds, trusts, and carbon-finance instruments. However, due to data availability and intertemporal consistency, this study focuses on four representative markets—green loans, green bonds, green stocks, and green insurance—as measurable components of the tradable green-finance system. For analytical purposes, these four categories are treated as the complete set of tradable green financial instruments.

In addition to market-based mechanisms, public policy constitutes an equally important pillar of China’s green-finance architecture, particularly in a system where financial development is promoted through top-down institutional design. Public green finance refers to fiscal activities in which the government guides or supplements market mechanisms to channel

funds toward sustainable sectors. Despite their diverse forms—green subsidies, tax incentives, public investment, and state green funds—their essence lies in fiscal expenditure on green development. Accordingly, we measure the public component of green finance through a single indicator that is green fiscal expenditure (GFE).

Together, these five components—four market-based and one fiscal—define the overall structure of the green-finance system. When calculating *Coverage*, the denominator is therefore set to five, representing the total number of green finance domains included in this framework.

### Criteria of Green Finance Items

A key challenge in quantifying green finance lies in distinguishing between green and non-green financial products. According to the *Guidelines for Establishing a Green Financial System* (2016), green finance includes all economic activities that promote environmental improvement, climate change mitigation, and efficient resource use across sectors such as environmental protection, clean energy, and green transportation. Translating this broad definition into measurable indicators remains challenging.

First, there is no unified standard for classifying “green” versus “non-green” projects across different financial instruments. Although policy documents such as the *Green Bond Principles (China)* and the *Green Credit Guidelines* offer partial guidance, consistent definitions for products like equities or insurance remain lacking, especially in our time span that is the early stage of Chinese green financial development. Second, most green instruments target specific projects rather than entire enterprises, creating ambiguity when a single firm undertakes both green and conventional activities. Third, data constraints limit the measurement. Reliable provincial statistics, especially for green credit, are not publicly available.

Given these challenges, this study establishes identification criteria for each category of green financial instrument as follows:

#### Green Loans

*Definition.* Green loans are commonly understood as loans made primarily or wholly to fund or refinance projects with clear environmental benefits. The most widely accepted framework is the *Green Loan Principles (GLP)*, developed by the LMA (in coordination with ICMA and others). In China, the classification of green loans follows the “Green Credit Guidelines” issued by the China Banking and Insurance Regulatory Commission (CBIRC) in 2016, which defines green credit as loans supporting environmental protection, energy saving, and resource-efficient industries.

*Measurement.* Due to the unavailability of officially published provincial-level green credit data from commercial banks in China, we resort to an alternative proxy. Green loans are measured by the total amount of loans obtained by all green-listed companies in China.<sup>3</sup> Data are derived from the EastMoney Choice Database. Green-listed companies are defined as those classified under the stock market sectors of “ecological protection” and “environmental governance.”<sup>4</sup>

This identification standard is based on the following considerations. First, the unavailability of data from unlisted companies necessitates their exclusion from the analysis. This may lead to an underestimation of the Coverage and Intensity of green finance, as some regions may have numerous green enterprises that are not publicly listed. Second, using companies categorised under the sectors of “ecological protection” and “environmental governance” as the definition of green companies may also lead to an undercount. In reality, sectors related to green industries may also encompass manufacturing, energy, agriculture, and other related fields. However, companies in these sectors often engage in both green and non-green activities, making it difficult to identify them as purely green enterprises. Therefore, their loans cannot be accurately classified as green loans. In contrast, companies under ecological protection and environmental governance are characterised by production activities whose primary purpose is environmental protection, therefore can be reasonably classified as green enterprises. As of the 2023 revision of the CSRC industry classification, a total of 88 listed companies fall within the ecological protection and environmental governance category, forming the empirical basis for the measurement of provincial green loans.

### **Green Stocks**

*Definition.* Green stocks represent equity financing instruments issued by companies whose core business activities directly contribute to environmental improvement or resource efficiency. In most studies, the classification of green-listed companies follows stock exchange or regulatory sector definitions related to environmental protection or renewable energy.

*Measurement.* Green stocks are measured as the total market capitalisation of all green-listed companies in China. The identification criteria for green-listed companies are identical to those used for green loans. Market capitalisation is calculated as the product of the number of shares and share price, based on annual average values to smooth daily price volatility. Data are derived from the EastMoney Choice Database.

<sup>3</sup>Total loans = short-term loans + long-term loans.

<sup>4</sup>The sector classification is based on the industry classification standards issued by the China Securities Regulatory Commission (CSRC). The industry code for ecological protection and environmental governance is 77, which falls under the broader category of “Water Conservancy, Environment and Public Facilities Management (N)”.

### Green Insurance

*Definition.* Internationally, green insurance refers to insurance products that transfer or mitigate environmental and climate-related risks, thereby supporting sustainable development. It is generally guided by the United Nations Environment Programme’s *Principles for Sustainable Insurance (PSI)*, which advocate integrating ESG factors into underwriting and risk management.

In China, the *Guidelines for the Classification of Green Insurance (2023 Edition)* issued by the China Insurance Association define green insurance as insurance products that provide risk protection for environmental resource conservation, social governance, green industry operations, and green consumption. The framework identifies ten thematic areas and sixty-nine subtypes, including catastrophe, renewable energy, green building, carbon market, and environmental pollution liability insurance (EPLI). Among these, EPLI remains the core and most representative form of green insurance in China.

*Measurement.* Due to the unavailability of official provincial data on green insurance, we adopt a proxy measure following Zhou et al. (2020). Specifically, we use premium income from agricultural insurance as an indicator of green insurance development.

### Green Bonds

*Definition.* Green bonds are fixed-income securities whose proceeds are used to finance or refinance projects that generate verifiable environmental benefits—such as renewable energy, clean transportation, and pollution control. Their main function is to channel private and public capital toward sustainable development through the bond market.

Internationally, the most widely recognised framework is the *Green Bond Principles (GBP)* developed by the International Capital Market Association (ICMA), which define green bonds as instruments whose proceeds are exclusively applied to projects delivering clear and, where feasible, quantifiable environmental benefits. Eligible project categories typically include renewable energy, energy efficiency, pollution prevention, sustainable water management, clean transportation, and climate adaptation.

In China, green bonds are governed by the *Green Bond Endorsed Project Catalogue*, jointly issued by the People’s Bank of China (PBoC), the National Development and Reform Commission (NDRC), and the China Securities Regulatory Commission (CSRC). Earlier versions included transitional items such as “clean coal utilisation,” but recent harmonisation—most notably through the *Common Ground Taxonomy (CGT)* jointly developed by China and the EU in 2021—has brought Chinese standards much closer to global practice, enhancing the international credibility of China’s green bond market.

*Measurement.* We directly draw on data from the Choice Database, which provides a dedicated classification for “green bonds.” This category aggregates all labelled green bonds issued by Chinese entities. For each province,<sup>5</sup> we measure the size of the green bond market as the total annual issuance amount of new green bonds.<sup>6</sup> It is worth noting that China’s green bond market developed relatively late, with large-scale expansion only after 2016. Although a few provinces issued green bonds before 2015, their issuance volumes were negligible, so they are excluded from the dataset.

### **Public Green Finance**

*Definition.* Public green finance refers to fiscal resources allocated by governments to promote environmental protection, energy efficiency, and low-carbon development. It encompasses green subsidies, tax incentives, direct public investment, and government-backed green funds.

*Measurement.* Governmental green expenditures are used to measure public green finance. Data of green expenditures is derived from the fiscal expenditure on environmental protection projects reported in National Bureau of Statistics. This measurement is based on the consideration that various forms of public green finance—such as tax incentives, direct government investment, and subsidies—ultimately manifest as fiscal transfers, which are reflected in government budget statements under green project categories. Admittedly, this measure may still underestimate the actual scale of public sector green finance, as energy conservation and environmental protection projects do not cover all government spending related to green industries. Other budget categories, such as agriculture, forestry, water conservancy, transportation, and science and technology, may also contain expenditures related to green development.

Table 2.1 summarises the construction of sub-intensity indicators and corresponding data sources for each component of the green finance system.

---

<sup>5</sup>Provincial classification is based on the registered location of the issuing institution.

<sup>6</sup>We do not distinguish between matured and outstanding bonds.

Table 2.1: Specification of Sub-intensity in Each Financial Instrument

Instrument	Sub-Intensity Measurement	Data Source
Green Loan (GL)	$\frac{\text{Borrowing of green-listed companies}}{\text{Borrowing of all listed companies}}$	Eastmoney Choice Financial Dataset
Green Bond (GB)	$\frac{\text{Total amount of green bond issuance}}{\text{Total amount of all bond issuance}}$	Eastmoney Choice Financial Dataset
Green Stock (GS)	$\frac{\text{Market value of green-listed companies}}{\text{Market value of all listed companies}}$	Eastmoney Choice Financial Dataset
Green Insurance (GI)	$\frac{\text{Agricultural insurance premium}}{\text{Total property insurance premium}}$	China Insurance Statistical Yearbook
Green Fiscal Expenditure (GFE)	$\frac{\text{Green fiscal expenditure}}{\text{Total fiscal expenditure}}$	National Bureau of Statistics of China

### 2.4.2 Coverage Analysis

Figure 2.2 shows the national evolution of *Coverage* from 2008 to 2019.<sup>7</sup> *Coverage* rises steadily from 0.54 in 2008 to 0.827 in 2019, with a marked acceleration after 2016. This pattern reflects the progressive adoption of green financial instruments across provinces. The sharp rise after 2016 coincides with the formal establishment of China’s green finance policy framework and the proliferation of local pilot zones, which provided both institutional incentives and regulatory guidance for financial innovation. The continuous upward trajectory suggests that green finance has evolved from a niche policy initiative into a nationally integrated financial subsystem.

Figure 2.3 details the diffusion of each green financial instrument across provinces. Green insurance (proxied by agricultural insurance premiums) and public green finance exhibit full provincial coverage throughout, reflecting the strong presence of fiscal and policy-driven mechanisms. By contrast, tradable instruments show gradual but uneven diffusion. Green loans and green equities expanded from 13 and 8 provinces, respectively, in 2008 to 16 provinces by 2019, indicating a cautious but steady market response. Green bonds, virtually absent before 2015, experienced explosive growth after 2016 and became the main contributor to the post-2016 jump in *Coverage*.

<sup>7</sup>National series are computed as the cross-province mean in each year; the same convention applies to Figures 2.3, 2.4, 2.5, 2.6.

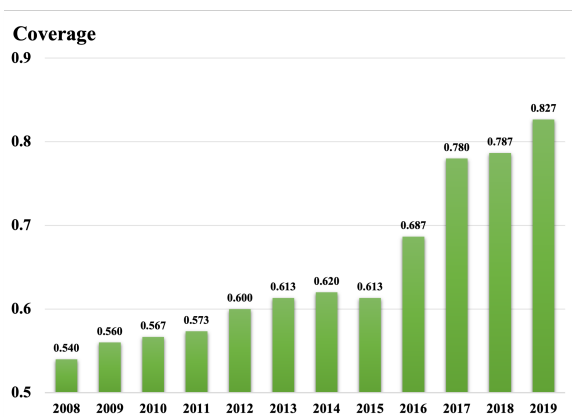


Figure 2.2: Temporal evolution of national Coverage

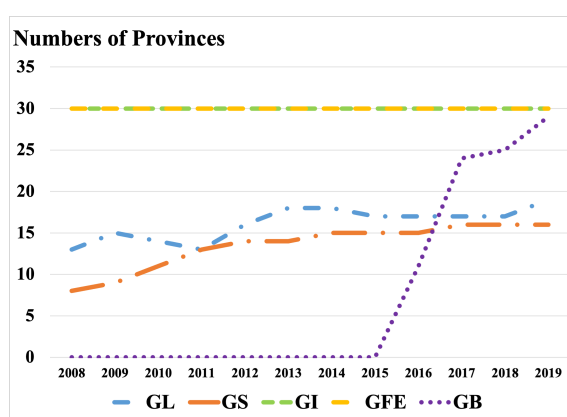


Figure 2.3: Temporal evolution of numbers of provinces adopting each instrument

### 2.4.3 Intensity Analysis

Figure 2.4 traces the national trend of *Intensity* from 2008 to 2019. The index exhibits a modest yet persistent upward trend, rising from 0.021 in 2008 to 0.040 in 2019, punctuated by moderate volatility during 2011–2014 and a pronounced surge after 2016. This evolution indicates that not only have green financial instruments become more geographically widespread (as shown by the increase in *Coverage*), but the degree of financial “greening” within each market has also deepened. The acceleration observed after 2016 coincides with the institutionalisation of the green finance framework through the *Guidelines for Establishing a Green Financial System* and the creation of pilot reform zones, which collectively mobilised both public and private financial actors toward environmental objectives.

Figure 2.5 shows temporal evolution of *sub-intensity* by financial instruments across provinces. Overall, green proportions remain low but show consistent upward movement. Green insurance maintains the highest sub-intensity (around 5–6%). Public green finance retains a relatively stable share of about 3%, implying sustained fiscal engagement in environmental protection. Green loans and green stocks record smaller but rising shares (around 1–2%), indicating a gradual but tangible deepening of green finance within China’s banking and capital markets. Notably, according to data released by the People’s Bank of China, the outstanding balance of green loans reached RMB 10.22 trillion by the end of 2019, accounting for 6.7% of total loans. This comparison suggests that the provincial database constructed in this study likely underestimates the overall scale of green lending in China.

The evolution of green bonds epitomises the transformative role of institutional design in shaping market behaviour. Prior to 2015, green bond issuance was virtually absent due to the lack of definitional clarity and reporting standards. Following the introduction of the Green Bond Endorsed Project Catalogue (PBoC–NDRC–CSRC, 2016) and the Guiding Opinions

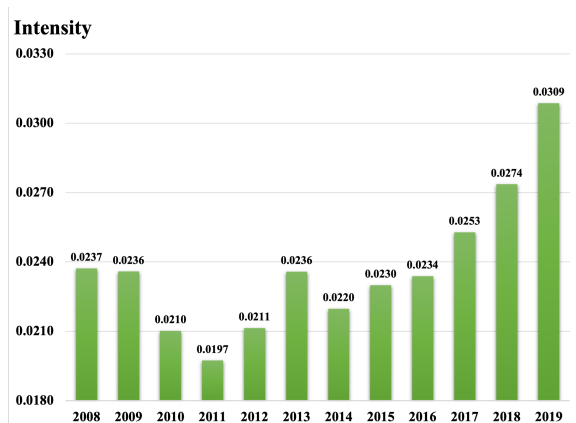


Figure 2.4: Temporal evolution of national *Intensity*

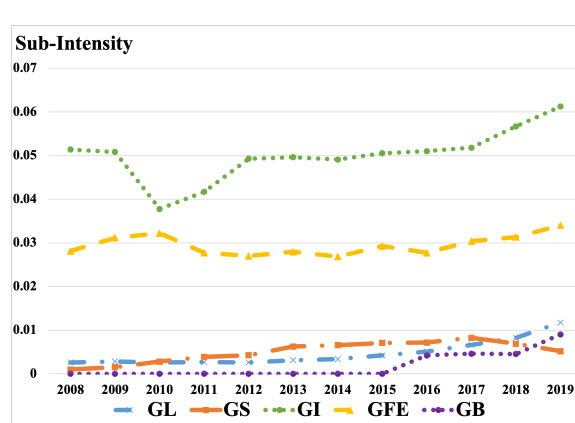


Figure 2.5: Temporal evolution of national *Sub-Intensity* by instruments

on Supporting the Development of Green Bonds (2017), the bond market experienced exponential growth.

Our database also records a sharp rise in the number of green bond issuances, from 87 in 2016 to 586 in 2020, pushing the share of green bonds relative to total bond issuance close to 1% by 2019. According to the China Green Bond Market 2019 Research Report published by the Climate Bonds Initiative (2019), the total issuance of green bonds in China reached RMB 386.2 billion in that year. Combined with the People’s Bank of China’s 2019 statistics reporting total domestic bond issuance of RMB 45.3 trillion, the official estimate of the green bond share was approximately 0.85%, which is closely aligned with the result derived from our database (Climate Bonds Initiative, 2019).

Although China’s issuance was negligible before 2016, within less than a decade after green finance was elevated to a national strategic priority, the country had become one of the world’s largest green bond markets. This rapid rise reveals a defining characteristic of China’s green finance development: it has been guided by government leadership through a “top-down” model, rather than emerging organically from market dynamics as in most Western economies.

In this structure, policy directions originate from the central government and are transmitted through a multilayered administrative and financial hierarchy that includes the central bank, regulatory agencies, provincial governments, and financial institutions. Implementation ultimately reaches market participants such as enterprises and investors. Such coordination demands strong political commitment and institutional capacity.

To ensure policy effectiveness, the central government has incorporated green finance performance targets—such as the expansion of green loans and the issuance of green bonds—into local governments’ annual ecological civilisation assessment. Complementary fiscal incentives,

including preferential lending conditions and dedicated guidance funds, further strengthen this institutional framework. Moreover, the establishment of Green Finance Reform and Innovation Pilot Zones has enabled selected provinces to experiment with new financial products, performance indicators, fiscal subsidies, and risk-compensation mechanisms. The experiences generated from these pilot zones have subsequently been replicated and scaled nationwide. Taken together, these initiatives demonstrate that an active and coordinated “green government” can function both as the initiator and as the enabler of the low-carbon transition.

Over time, however, the dominance of the state has gradually diminished. Government-led coordination in the initial phase established the institutional and market foundations for subsequent expansion, while market forces have increasingly assumed a leading role. Figure 2.6 illustrates this structural shift by comparing the market composition of green finance in 2008 and 2019. In 2008, public green fiscal expenditure accounted for nearly three-quarters of total green capital, reflecting a system that was largely directed by the state. By 2019, its share had fallen below 40%, as market-based instruments, particularly green bonds and loans, expanded rapidly. This compositional change signals a broader transition from a policy-driven initiation phase to a more market-oriented model, where fiscal policy now acts as a catalyst rather than a controller.

This gradual evolution exemplifies a distinctive feature of China’s development model. Strong state coordination in the early stage mobilises market participation, and as institutions mature, the market progressively assumes the dominant role. This sequencing between government leadership and market activation has proven highly effective in sectors that depend on clear macro-policy direction, such as green finance. It also offers valuable insights for other developing economies seeking to establish or strengthen their own green financial systems.

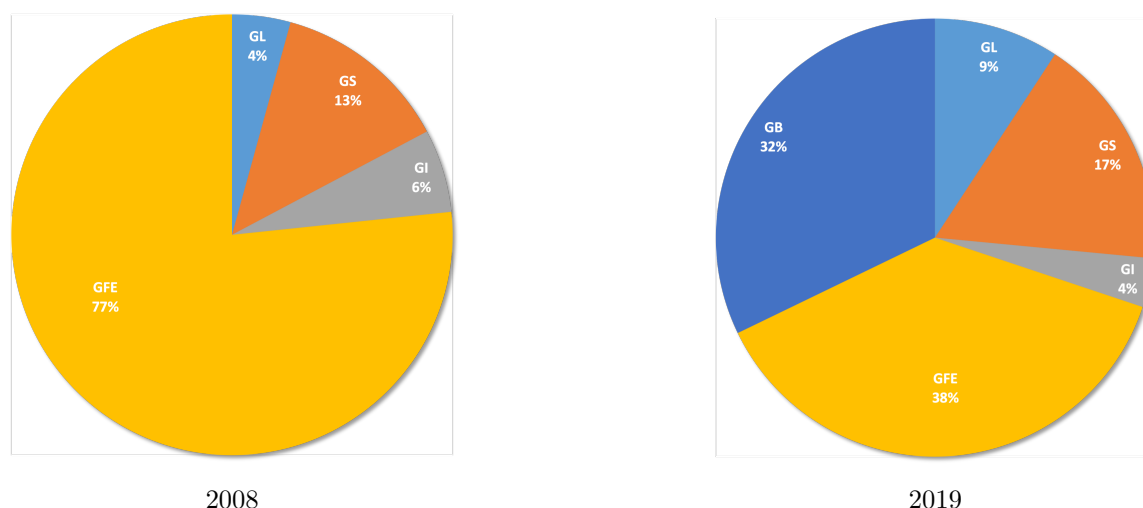


Figure 2.6: Shares of instrument-level green-finance scale: 2008 vs. 2019

### 2.4.4 Green Finance Index (GFI) Analysis

After examining the dynamics of *Coverage* and *Intensity* separately, this section integrates both dimensions to provide an overall assessment of China’s provincial Green Finance Index (GFI).

Figure 2.7 illustrates the national evolution of the Green Finance Index (GFI) from 2008 to 2019. The overall trend exhibits a distinct U-shape: the index declines between 2008 and 2011, stabilises from 2012 to 2014, and rises steadily thereafter. This pattern closely mirrors the earlier dynamics of *Intensity*, with a post-2016 acceleration driven largely by the broader diffusion of green financial instruments, as captured by *Coverage*. Over the twelve-year period, the national GFI rose from 0.0128 in 2008 to 0.0247 in 2019—an increase of 92.3%<sup>8</sup>.

To understand the underlying drivers of the observed upward trend, we decompose the overall increase in the GFI into its *Coverage* and *Intensity* components. The decomposition analysis shows that 61.6% of the cumulative GFI increase stems from higher *Coverage*, whereas 38.4% is attributable to rising *Intensity*. The calculation process is shown in Appendix B.3. This finding suggests that China’s green finance expansion has been driven primarily by introducing and adopting new instruments across regions and markets, rather than by a deepening of green capital within existing financial domains. This pattern is consistent with the early stage of market formation, in which broad participation and institutional diffusion typically precede intensity increasing.

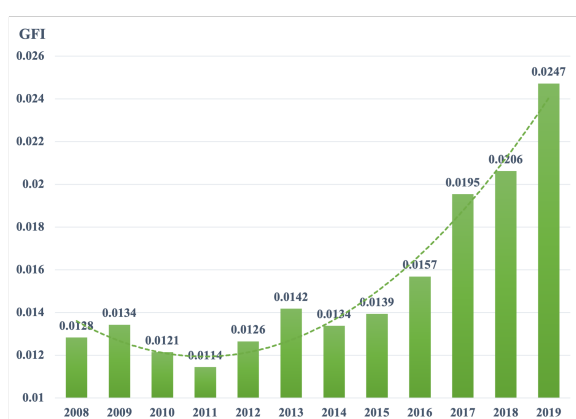


Figure 2.7: Temporal evolution of China’s national *GFI*

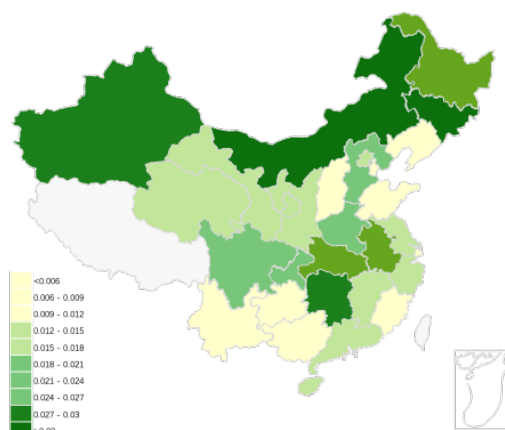


Figure 2.8: Geographic distribution of provincial *GFI*

In addition to its temporal evolution, the spatial heterogeneity of green finance development across Chinese provinces also merits attention. Figure 2.8 presents the spatial distri-

<sup>8</sup>The national series reported here is the cross-province mean; computing the product of national averages yields a nearly identical result, with a mean deviation of only 1%.

bution of the provincial GFI. Regions with higher index values are predominantly located in China's northern border and central inland provinces—such as Inner Mongolia, Xinjiang, Heilongjiang, Hubei, and Sichuan—which are not traditionally regarded as economically or financially advanced regions.

This novel finding diverges from previous reports, e.g. International Finance Forum (IFF) (2024), which generally suggest that regions with higher levels of green finance development are concentrated in China's economically advanced coastal areas. The difference arises from our proportional framework for dataset construction, that is, by expressing both *Coverage* and *Intensity* as shares rather than absolute market size, the GFI captures actual characteristic of regional green financial development.

Then, what explains the observed spatial pattern of green finance across China? Further examination reveals that provinces with stronger green finance performance often possess abundant natural resources that can be transformed into renewable energy outputs.

The northeastern region, for instance, benefits from rich forest reserves and biodiversity, while the northern and northwestern border areas—such as Inner Mongolia and Xinjiang—feature vast wind and solar potential. In central China, high GFI scores are concentrated along the Yangtze River basin, where provinces like Hubei and Sichuan possess significant hydropower capacity, including the Three Gorges Dam, the world's largest hydroelectric project. These spatial patterns highlight that the distribution of green finance is not merely a reflection of financial sophistication, but also of ecological endowment and renewable resource potential.

To confirm these correlations, provinces were classified into three groups according to per-capita GDP, financial development, and natural resource endowments.<sup>9</sup> As shown in Figure 2.9, provinces in the high-income or high-finance groups display no systematic advantage in GFI performance. By contrast, provinces with richer forest and water resources consistently exhibit higher GFIs throughout the sample period. For wind and solar energy, the relationship becomes significant after 2013, coinciding with the nationwide expansion of renewable-energy investment and grid integration. These results collectively indicate that China's green finance development is more closely associated with resource potential and ecological infrastructure than with conventional measures of economic or financial maturity.

---

<sup>9</sup>Grouping is based on the average values of each indicator over 2008–2019, consistent with the temporal span of the GFI. For example, in the case of per-capita GDP, provinces are ranked by their twelve-year average and then divided into three groups of ten each; the annual GFI of each group is calculated as the mean across the ten provinces. Data for GDP, financial development, forest, and water resources are drawn from the National Bureau of Statistics of China. Since no provincial panel data exist for wind and solar resources, rankings for these two indicators are based on total provincial power generation in 2023 (data source: <https://m.bjx.com.cn/mnews/20240119/1357028.shtml>).

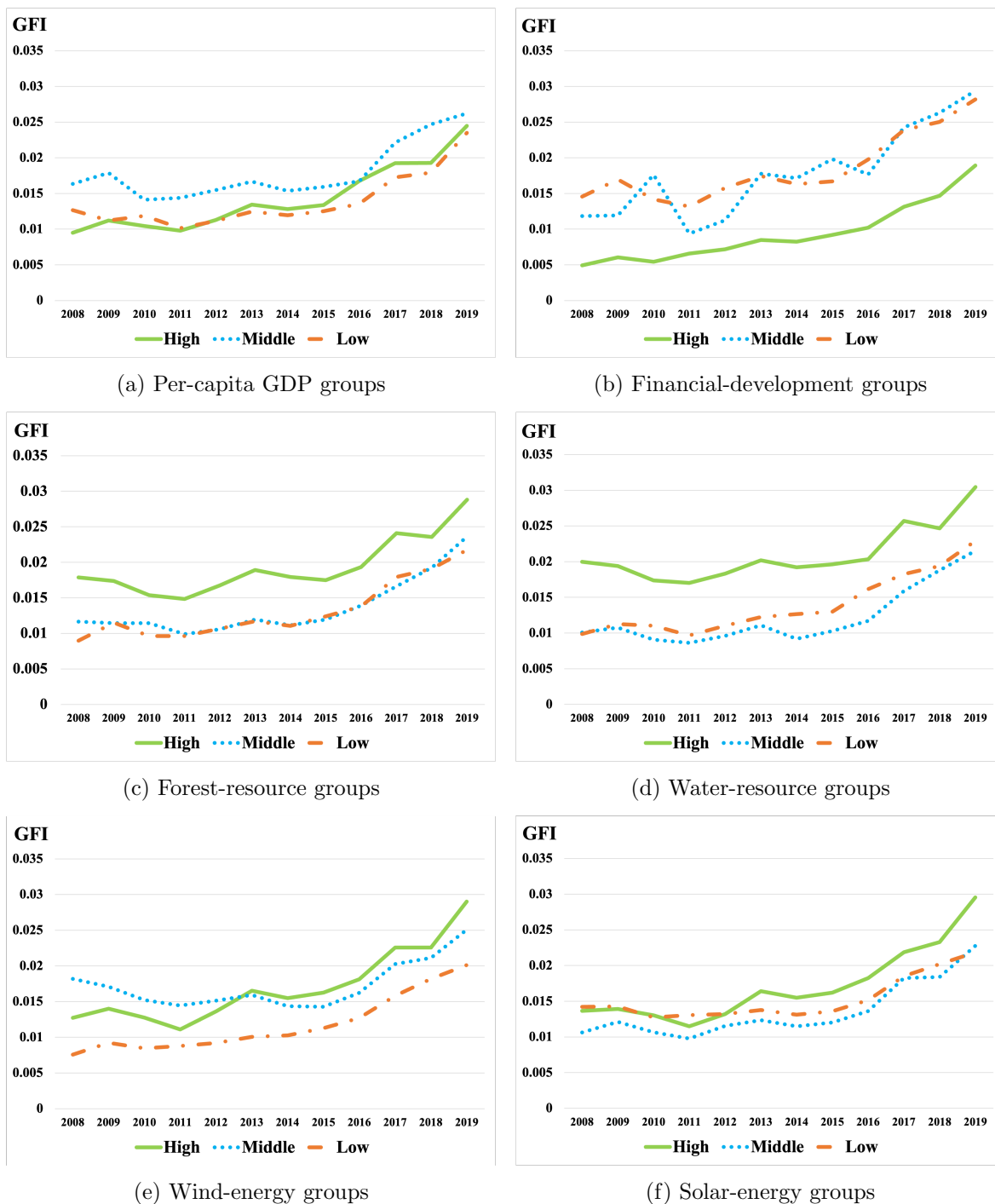


Figure 2.9: Temporal evolution of *GFI* across high, middle, and low groups by regional indicators (GDP per capita, financial development, forest and water resources, wind and solar energy).

### 2.4.5 Policy Implications

Practical experience from China suggests that green capital tends to flow toward regions capable of converting natural endowments into tangible green outputs. Policymakers should therefore encourage less industrialised but resource-rich provinces to leverage their environmental assets as comparative advantages in attracting green investment. Targeted instruments—such as tax incentives, credit guarantees, and dedicated green-finance facilities—can support these provinces in developing renewable-energy industries and ecological infrastructure.

In practice, this strategy has already proven effective. For example, in Xinjiang, enterprises such as Goldwind Science & Technology (002202.SZ / 2208.HK) and Daqo New Energy (688303.SH), operating in wind and photovoltaic sectors, reached a combined market capitalisation of RMB 174.6 billion in 2023, accounting for 22.4% of the total market value of all listed firms in the province. Similar experiences can be found internationally: Wildpoldsried, a municipality in Bavaria, Germany, has generated electricity from wind, solar, and biogas sources exceeding local demand by a factor of seven, producing annual revenues of €6 million in 2016 (about €2,400 per capita). These cases show that renewable energy projects supported by green finance may become potential contributors to regional economic growth. Whether green finance can simultaneously deliver positive outcomes for both the environment and the economy remains an open question that calls for further empirical investigation.

## 2.5 Conclusions

This paper develops a novel measurement framework for the *Green Finance Index* (GFI), which conceptualises green finance along two complementary dimensions: *Coverage* and *Intensity*. *Coverage* captures the extent to which green financial instruments are adopted across different market domains, while *Intensity* measures the degree of greening within each market by assessing the share of green capital in total financial capital. This dual-dimensional design ensures that the GFI reflects both the breadth of market participation and the depth of green integration, while maintaining cross-regional comparability and computational simplicity.

Based on this framework, the study constructs a provincial green finance database for China covering 2008–2019. Several key findings are derived from statistical analysis. First, China’s green finance system reflects its way of economic development, operating under a government-led socialist market economy in which policy coordination and top-down guidance play a pivotal role. Second, green finance has followed a steadily upward path, with a

marked acceleration after 2016, coinciding with the launch of national green finance policies. Third, China remains in the formative stage of green finance development. Growth is primarily driven by the diffusion of new instruments across regions and markets rather than by deepening within existing ones. Finally, pronounced regional disparities persist. Provinces with stronger green finance performance tend to be those endowed with abundant natural resources—such as wind, solar, water, and forest assets—that facilitate the development of renewable energy industries.

As one of the world’s largest and most rapidly expanding green finance markets, China offers valuable insights for other economies. Its experience demonstrates the crucial role of a proactive “green government” in guiding private capital toward sustainable sectors and in establishing the institutional foundations for a low-carbon financial system. It also highlights how regions rich in natural resources can convert ecological endowments into comparative advantages by fostering green industries that reconcile environmental and economic objectives.

Nevertheless, the study has several limitations. The current database does not include emerging instruments such as green funds or carbon allowances due to data unavailability, nor does it yet capture transition finance or the effectiveness of environmental outcomes. Future research could extend the dataset, update the observation period, and empirically test whether green finance—as measured by the GFI—simultaneously promotes economic growth and environmental improvement. Such extensions would further enhance our understanding of how financial systems can support the global transition toward sustainable development.

## Chapter 3

# Can Growth Be Green? Testing the Green Finance Kuznets Curve Hypothesis in China

In recent decades, rapid global economic growth has been accompanied by increasing environmental degradation, resource depletion, and climate-related risks. To reconcile economic expansion with sustainability, green finance (GF) has emerged as a pivotal mechanism that channels capital from high-emission sectors toward clean and low-carbon industries. Nevertheless, its overall effectiveness in fostering sustainable development remains ambiguous. This study investigates the dual impacts of green finance on economic development and environmental degradation using two-way fixed effects models and provincial panel data from China (2008–2019). The empirical results reveal that, at the initial stage of green finance development, structural frictions, investment delays, and information asymmetries constrain its positive influence on both growth and environmental quality. However, once green finance surpasses critical thresholds, it simultaneously promotes economic upgrading and ecological improvement. Building on these findings, the paper proposes the Green Finance Kuznets Curve (GFKC) concept, which characterises the nonlinear relationship between green finance, economic growth, and environmental degradation. The GFKC implies that, in the long run, green finance can foster green growth once the share of green financial capital reaches a sufficiently high level.

**Keywords:** Green Finance, Economic Development, Environmental Degradation, Nonlinear Effects, Green Finance Kuznets Curve.

**JEL:** Q56, Q58, H23, O44, G28.

### 3.1 Introduction

Over the past few decades, the tension between economic growth and environmental degradation has increased significantly due to rapid globalisation and industrialisation. Climate change, resource depletion, and various forms of pollution have emerged as urgent global challenges, transforming sustainable development from a mere policy ideal into a universal consensus. However, implementing this consensus into concrete action faces a key obstacle: financing. According to OECD projections, without significant reforms to the global financial architecture, the annual funding gap to achieve the Sustainable Development Goals (SDGs) could rise to approximately USD 6.4 trillion by 2030 (Organisation for Economic Co-operation and Development, 2025). Therefore, effectively mobilising social and private capital has become a shared challenge across nations.

Green finance has been recognised as a crucial mechanism connecting the financial system with sustainable development objectives. Its core principle is to reshape the allocation of green capital through market-based instruments. It attracts investments away from brown industries and towards green sectors, narrowing the financial gap to achieve sustainability goals.

Although green finance experienced nearly two decades of rapid growth, empirical evidence regarding its effectiveness in delivering its promised sustainability benefits remains mixed. On one hand, green finance can enhance resource allocation efficiency, stimulate technological innovation, and promote industrial upgrading, leading to synergistic benefits for economic growth and environmental protection. On the other hand, during the early stages of transition, structural frictions—such as factor reallocation, investment lags, and institutional immaturity—may impede the adequate flow of financial resources to genuinely green projects. Given green industries' typically capital-intensive and long-gestation nature, short-term economic slowdowns and limited environmental improvements are plausible outcomes. Therefore, the core objective of this study is to empirically examine the effectiveness of green finance in promoting green growth.

China serves as a particularly compelling case study for this purpose. First, China is one of the world's largest green bond issuers, providing practical experience for establishing a green finance system. Moreover, the top-down development approach of green finance in China offers an important reference for examining the role of the green government in supporting the green finance industry.

This study employs balanced panel data from thirty Chinese provinces during 2008–2019 and two-way fixed effects models to examine the dual impact of green finance on economic

development and environmental degradation. The results reveal that, at the early stage of green finance development, the low share of green financial capital weakens its positive effects on growth and environmental quality. However, as green finance keeps growing and passes certain thresholds, it simultaneously promotes economic development and ecological improvement. We conclude this finding and propose the Green Finance Kuznets Curve (GFKC), which depicts a U-shaped relationship between green finance and economic growth and an inverted U-shaped relationship between green finance and environmental degradation. The GFKC highlights green finance's nonlinear effects, underscoring that its long-term contribution to "green growth" depends on the maturity of financial greening.

In addition, we use the U-test (Lind & Mehlum, 2010; Sasabuchi, 1980) to examine the asymmetry of the U-shaped and inverted U-shaped relationships. The results indicate that the slope of green finance concerning economic growth is steeper in the early phase and becomes flatter after the turning point, implying that green finance initially constrains growth but gradually enhances it as the market matures. For environmental degradation, the slope is mild before the turning point. However, it becomes steeper afterwards, suggesting that green finance leads to limited environmental deterioration and later exerts a more substantial pollution-reducing effect.

We further assess China's current green finance development stage by turning points calculated from our regression. The evidence shows that China is still in the early phase of green finance expansion, with most provinces yet to pass the thresholds where positive effects on growth and environmental quality emerge. These nonlinear patterns are consistent with the conclusions of the Extended Green Solow Model<sup>1</sup>, which provides a theoretical foundation for the validity of the proposed GFKC. Moreover, China's experience in building its green financial system offers empirical support for the existence of the GFKC and its dynamic mechanisms.

The main policy implication is that economies seeking to promote green transformation through green finance should recognise the transitional "pain period" during its early stage. Continued financial deepening and institutional improvement are essential for accelerating the transition toward the stage where green finance delivers simultaneous economic growth and environmental sustainability benefits.

The remainder of this paper is structured as follows. Section 2 reviews the relevant literature on the relationships among green finance, economic growth, and environmental quality. Section 3 outlines the model specifications, variables, and data sources. Section 4

---

<sup>1</sup>Refer to *Environmental Policies in a Green Solow Model*, Haomiao Niu, Chapter I in PhD dissertation.

presents the empirical results, nonlinearity analysis, and effect decomposition, followed by a discussion of interprovincial heterogeneity and turning-point analysis. Section 5 concludes with key findings and policy implications.

## 3.2 Literature Review

### 3.2.1 The Effect of Green Finance on Economic Development

Existing research indicates that green finance powers economic development through the chain of capital reallocation, technological progress, and improvements in resource efficiency. From a macro perspective, the Hamiltonian-optimisation model developed by (Ouyang et al., 2023) shows that green financial policies can steer capital toward high-tech industries to form "innovation capital," whose accumulation enhances both the scale and the quality of economic growth. Evidence for Belt and Road economies suggests that public expenditure translates more effectively into green economic growth only when mediated by green finance (Zhang et al., 2021). Evidence from China shows that green finance significantly improves allocative efficiency and promotes green economic growth (Xu & Dong, 2023). Green investment with supportive financial policies on clean energy promotes green transition (Liu et al., 2023). Analysis for Chinese provinces confirms green finance improves economic and environmental performance (Zhou et al., 2020). From the perspective of growth quality, green finance helps reduce environmental pollution and is associated with advances in high-quality economic development (Gao et al., 2023). At the micro level, green-credit policies raise the total factor productivity of affected firms, indicating that green finance enhances output potential through efficiency and innovation channels (Guo & Zhang, 2023). Overall, the evidence from the literature supports the positive effect of green finance on economic development, with its effectiveness contingent on policy design, the intensity of financial support, and coordination with clean energy and green technologies.

Although the green transition enhances allocative efficiency and improves economic growth in the long run, some adverse effects during the transition phase are difficult to avoid. For many developing economies, prevailing development paths remain firmly locked into fossil energy and thus cannot be fully decoupled. When growth models are deeply dependent on traditional energy, pollution-intensive sectors drive economic performance to a large extent. Consequently, advancing the green transition entails factor reallocation and industrial restructuring, with short-term risks of slower growth, such as investment pullbacks and output deceleration. As highlighted by Acemoglu et al. (2012), the shift from "brown"

to "green" technologies requires a reallocation of capital and human resources, leading to short-term frictions but yielding long-term efficiency gains. Similarly, Aghion et al. (2019) emphasise that path dependence and structural inertia in existing industrial systems create temporary output losses and adjustment costs during the low-carbon transition.

Growing evidence points to short-run drag from green finance instruments on economic activity in pollution-intensive sectors. Studies show that the policy reallocated bank credit away from heavy polluters, tightening financing and reducing firm performance (Huang et al., 2023; Yao et al., 2021). At a broader macro angle, provincial evidence suggests green finance may upgrade the scale and quality of output yet lower the near-term growth rate, consistent with adjustment costs during the transition toward cleaner capital and technologies (Ouyang et al., 2023). Complementing this, enterprise studies document a policy trade-off: green credit improves environmental metrics but deteriorates economic performance among heavily polluting firms, highlighting transitional headwinds before productivity payoffs materialise (Peng et al., 2024).

The above research indicates that at low levels of green finance (GF) development, binding financing constraints and adjustment costs render its growth effects insignificant or negative. Over the longer run, however, the effect turns positive through innovation, industrial upgrading, and improvements in total factor productivity. This short-versus long-term inconsistency provides a rationale for a nonlinear perspective on the GF–growth nexus, prompting recent studies to adopt nonlinear models that jointly account for GF’s beneficial and adverse impacts. From a macro perspective, He et al. (2019) investigate the nonlinear relationship between renewable energy investment and green economic development, further corroborating a double-threshold effect of green credit on both renewable energy investment and green economic development. Using a provincial panel within a spatial econometric framework, Gao et al. (2023) conduct threshold tests and show that GF exerts a significant threshold and nonlinear effect on high-quality economic development. Based on the above mechanism analysis and literature review, we propose the following hypothesis, which will be tested empirically.

**Hypothesis 1:** Green finance has a nonlinear effect on economic development.

### 3.2.2 The Effect of Green Finance on Environmental Degradation

In terms of the effect on the environment, some research suggests that green finance contributes to environmental improvement through capital reallocation, technological innovation, and governance enhancement. At the macro level, instruments such as green credit and green

bonds effectively redirect financial resources from high-emission and energy-intensive sectors toward low-carbon and clean energy industries, fostering investment in renewable energy and green infrastructure, and thereby reducing pollutant and carbon emissions (Banga, 2019; Campiglio, 2016; Iqbal et al., 2021). At the micro level, firm-level studies show that the issuance of green bonds and the introduction of stricter disclosure requirements significantly increase firms' environmental investment and performance, while simultaneously lowering financing costs and generating a "greenium" in bond markets (Flammer, 2021; Gianfrate & Peri, 2019). In China, provincial and municipal evidence suggests that green credit and investment policies enhance resource allocation efficiency and total factor productivity, thereby accompanying a pollution reduction (Gao et al., 2023; Hunjra et al., 2023; Zhang et al., 2021). Overall, the reallocation of capital from "brown" to "green" sectors, the diffusion of green technologies, and the improvement of governance mechanisms jointly constitute the main pathways through which green finance improves environmental quality.

However, the environmental effects of green finance are neither linear nor immediate. In the early stages of development, temporary reversals may occur. First, green infrastructure projects typically entail high upfront capital expenditures and long construction periods, meaning their environmental and scale benefits take time to materialise. During the transition phase—when old capacities have not yet been fully phased out and new ones are still under construction—temporary increases in pollution may occur. For example, evidence from China's green finance pilot zones indicates that, in the initial stages, green finance failed to effectively compel heavily polluting enterprises to achieve emission reductions (Cui et al., 2023). Second, when markets anticipate stricter environmental regulation, fossil fuel producers may accelerate extraction and sales in advance, thereby increasing emissions before new policies, the so-called "green paradox" (Sinn, 2008). Such behaviour can temporarily raise emissions during the early stage of the green transition. Third, immature green finance is often characterised by insufficient information disclosure, non-unified certification standards, and inadequate measurement of externalities, which can lead to "light green" projects or greenwashing behaviour (Delmas & Burbano, 2011; Lyon & Montgomery, 2015). This misallocation of capital toward projects with limited mitigation potential weakens the overall environmental performance of green finance. Moreover, Chinese evidence highlights that green finance's environmental and economic effects exhibit significant heterogeneity across ownership structures (e.g., state-owned vs. non-state firms) and regions (Cui et al., 2023; Xu & Dong, 2023; Zhang et al., 2021).

The above literature indicates that the impact of green finance on the environment is

highly dependent on the stage of development and shows considerable heterogeneity. In the early stage, constrained by construction delays, scale effects, market expectations, and information frictions, the environmental benefits of green finance may be weak or even temporarily negative. However, as the scale of green finance expands, technological diffusion accelerates, and institutional quality improves, the effects of emission reduction through capital reallocation and technological progress become increasingly significant, leading to a steady decline in pollution. Accordingly, we propose the following hypothesis to be tested empirically:

**Hypothesis 2:** Green finance has a nonlinear effect on environmental degradation.

In summary, existing studies have reached conflicting conclusions through different mechanistic pathways, providing a rationale for adopting a nonlinear perspective. Similar to the Environmental Kuznets Curve (EKC), the direction of the relationship between economic activity and the environment varies across different stages of development. Moreover, few studies have jointly examined green finance's dual and nonlinear effects on economic and environmental outcomes within a unified analytical framework. To address this gap, this study empirically investigates the dual effects of green finance from a nonlinear perspective.

### 3.3 Modeling Design

#### 3.3.1 Data

Our data is collected in 30 provinces of China<sup>2</sup> from 2008 to 2019, so it is a balanced panel dataset. We select 2008 as the starting point of our dataset for two reasons. First, although China officially established a green financial system only in 2016<sup>3</sup>. Various private and public green investment and financing instruments had already been established well before that date. That year, the Industrial Bank of China became the first Chinese financial institution to adopt the Equator Principles, marking China's initial engagement with an international environmental and social risk management framework. In 2008, the National Environmental Protection Department signed an information-sharing agreement with the banking regulatory authority, thereby institutionalising data exchange between environmental regulators and the financial sector. Together, these developments signify the beginning of Chinese financial institutions' systematic participation in international green finance practices. We take 2019 as the terminal year of our sample period in order to avoid potential distortions arising from the COVID-19 pandemic.

<sup>2</sup>The data of Tibet, Hong Kong, Macao, and Taiwan are not included.

<sup>3</sup>In August 2016, the People's Bank of China, together with six other ministries and commissions, issued the Guidelines for Establishing the Green Financial System, which is widely regarded as marking the starting point of green finance development in China

### 3.3.2 Empirical Model

To test Hypotheses 1 and 2, we incorporate the quadratic term of green finance into the regression models to capture its potential nonlinear effects. In Model 1, *EcoDev* denotes economic development, while in Model 2, *EnvDeg* represents environmental degradation. *GF* refers to the Green Finance Development Index. Further details on variable construction are provided in Section 3.3, Variable Specification.

$$EcoDev_{it} = \alpha_i + \beta_1 GF_{it} + \beta_2 GF_{it}^2 + \mathbf{\Gamma} Controls_{it} + \lambda_t + \varepsilon_{it}. \quad (3.1)$$

$$EnvDeg_{it} = \alpha_i + \beta_1 GF_{it} + \beta_2 GF_{it}^2 + \mathbf{\Gamma} Controls_{it} + \lambda_t + \varepsilon_{it}. \quad (3.2)$$

In both equations,  $i$  denotes the province and  $t$  the year.  $\alpha_i$  captures province-specific fixed effects, while  $\lambda_t$  represents time fixed effects that control for unobserved standard shocks.  $\mathbf{\Gamma}$  is a vector of coefficients associated with the control variables, and  $\varepsilon_{it}$  is the idiosyncratic error term.

### 3.3.3 Variable Specification

For Model (3.1), the dependent variable is economic development, which is measured by the logarithm of per capita real GDP. The procedure for computing real per capita GDP is provided in Appendix C.1. The core explanatory variable, green finance (GF), is derived from the authors' compilation of China's provincial-level Green Finance Database. Regarding the control variables, we select three factors: fixed capital, human capital, and technological progress, standard determinants of economic growth frameworks. Specifically, fixed capital is calculated based on gross fixed capital formation, with the detailed computation method provided in Appendix C.1. Human capital is measured by average years of schooling, while technological progress is proxied by the logarithm of per capita patent grants. All the above data, except for GF, are directly obtained from the National Bureau of Statistics of China. Table 3.1 summarises the variable specifications for Model 1.

Table 3.1: Variables Specifications for Regression Model (3.1)

Variables Category	Name	Abbreviation	Measurement	Unit
Response	Economic Development	<i>EcoDev</i>	Logarithmic Real GDP per capita	CNY
Core Explanatory	Green Finance	<i>GF</i>	Green Finance Index	Index(0-1)
	Green Finance2	<i>GF<sup>2</sup></i>	Quadratic <i>GF</i>	Index(0-1)
Controls	Fixed Capital	<i>FC</i>	Logarithmic Fixed capital stock per capita	Ten thousand CNY
	Human capital	<i>HC</i>	Logarithmic Average years of schooling	Year
	Technological progress	<i>TP</i>	Logarithmic Patents issued per capita	PCs

Data source: GF data come from China's provincial GFI dataset compiled by the author; other data derived from the State Statistics Bureau of China.

For Model (3.2), the dependent variable is environmental degradation, for which we specifically construct a composite index as the measure. Environmental degradation is measured from two dimensions: air quality deterioration, proxied by sulfur dioxide ( $SO_2$ ) emissions, and water pollution, proxied by chemical oxygen demand (COD). Since the two indicators are expressed in different units, we normalise them using the Max–Min method. For a positive indicator  $x_{ij}$  (where larger values indicate greater environmental degradation), the standardised value is defined as:

$$Z_{ij} = \frac{x_{ij} - \min(x_j)}{\max(x_j) - \min(x_j)},$$

where  $i$  indexes province and  $j$  indexes the indicator ( $SO_2$  or COD). The standardised values  $Z_{ij}$  are thus bounded in the  $[0, 1]$  range. Finally, we construct the composite environmental degradation index by assigning equal weights (0.5) to the two dimensions:

$$EnvDeg_i = 0.5 \cdot Z_{i,SO_2} + 0.5 \cdot Z_{i,COD}.$$

Among the control variables, we include the economic indicators, per capita GDP and its squared term, to account for the potential nonlinear relationship between income level and environmental pressure, as suggested by the Environmental Kuznets Curve (Grossman & Krueger, 1995). In addition, population size is controlled to capture scale effects associated

with demographic expansion, while energy consumption reflects the intensity of resource use and its direct link to emissions. Table 3.2 summarises the variable specifications for Model 2.

Table 3.2: Variables Specifications for Regression Model (3.2)

Variables Category	Name	Abbreviation	Measurement	Unit
Response	Economic Degradation	<i>EnvDeg</i>	Pollution Index	Index(0-1)
Core Explanatory	Green Finance	<i>GF</i>	Green Finance Index	Index(0-1)
	Green Finance2	<i>GF<sup>2</sup></i>	Green Finance Index	Index(0-1)
Controls	Economic Development	<i>EcoDev</i>	Logarithmic Real GDP per capita	CNY
Controls	Economic Development2	<i>EcoDev2</i>	Quadratic <i>EcoDev</i>	Million CNY
	Population	<i>PO</i>	Permanent resident	Million
	Energy Consumption	<i>EC</i>	Aggregate Consumption	Billion standard coals

Data source: The author compiles Pollution Index data; other data are derived from the State Statistics Bureau of China.

### 3.3.4 Descriptive Statistics

Table 3.3 reports the descriptive statistics of the main variables. The mean of economic development (*EcoDev*) is 10.194 with a relatively small standard deviation (0.520), suggesting that while some variation exists across provinces, the distribution is concentrated. Environmental degradation (*EnvDeg*) has a mean of 0.387 and a standard deviation of 0.230, ranging from 0.005 to 1.000, indicating substantial heterogeneity in environmental conditions across regions. Green finance (*GF*) exhibits a low overall mean of 0.015, with a maximum of 0.061, implying that although the average level of green finance remains modest, certain provinces have achieved relatively higher values. This uneven distribution provides an essential basis for analysing the effects of green finance at different phases.

Regarding the control variables, fixed capital (*FC*) has a mean of 2.091 with a wide range (0.556 to 3.636). Human capital (*HC*) averages 2.189 with a slight standard deviation (0.103), reflecting a stable distribution across provinces. Technological progress (*TP*) shows

a mean of 1.508 but a minimum of -0.918, suggesting that some provinces or years may experience negative performance in innovation. Population size (PO) exhibits considerable variation, with a mean of 45.435, a standard deviation of 27.819, and a maximum exceeding 120 million. Energy consumption (EC) has a mean of 0.142 and a maximum of 0.414, further highlighting regional disparities. Overall, the descriptive results indicate significant inter-provincial heterogeneity across variables.

Table 3.3: Summary statistics

Variable	N	Mean	SD	Min	Max
EcoDev	360	10.194	0.520	8.812	11.585
EnvDeg	360	0.387	0.230	0.005	1.000
GF	360	0.015	0.011	0.001	0.061
FC	360	2.091	0.591	0.556	3.636
HC	360	2.189	0.103	1.912	2.548
TP	360	1.508	1.161	-0.918	4.097
PO	360	45.435	27.819	5.540	124.890
EC	360	0.142	0.087	0.011	0.414

To examine the distributional properties of the main variables and compare them with the normal distribution, kernel density estimates were plotted. Figure 3.1 approach provides an intuitive assessment of skewness, kurtosis, or potential outliers, thereby guiding variable treatment and model specification in subsequent econometric analysis.

The distribution of green finance (GF) shows a slight right skew, indicating that most provinces have relatively low levels of green finance, with only a few reaching higher values. Nevertheless, the overall shape remains approximately normal. No further preprocessing is applied since GF will later be used to construct indices and decompose marginal effects across quantiles. Economic development (EcoDev) exhibits a near-perfect bell-shaped curve, almost overlapping with the normal distribution, suggesting a stable distribution across provinces and years consistent with the normality assumption. Environmental degradation (EnvDeg) deviates from normality but maintains a roughly symmetric shape without extreme outliers. In sum, the distributional features of these three variables support their application in subsequent panel regressions. While GF shows mild skewness, it remains suitable for empirical

modelling, and the distributions of EcoDev and EnvDeg further reinforce the robustness of the regression estimations.

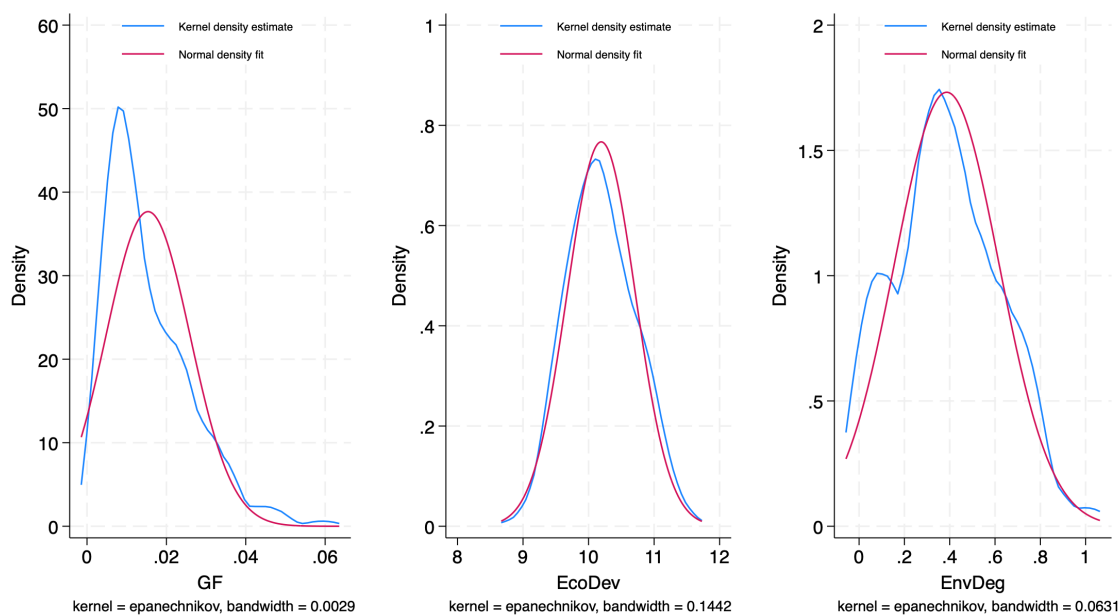


Figure 3.1: Kernel Density Estimate and Normal Fit for GF, EcoDev, and EnvDeg

Figure 3.2 presents the annual trends of economic development (EcoDev), environmental degradation (EnvDeg), and green finance (GF) across Chinese provinces during 2008–2019. All variables have been normalised to the  $[0,1]$  interval using the Max–Min method to ensure comparability of units. The values are computed as the provincial averages for each year, and the curves are drawn based on these annual means. Regarding the detailed trend of EcoDev and EnvDeg in each province, see Appendix C.2.

Figure 3.2 reveals three distinct patterns. EcoDev shows a steady upward trajectory, increasing from about 0.32 in 2008 to approximately 0.63 in 2019, which reflects the continuous improvement of economic performance over the sample period. EnvDeg remains relatively stable within the range of 0.38–0.43, but exhibits a slight decline after 2015, suggesting that pressures of environmental degradation were gradually alleviated, possibly due to the implementation of stricter environmental policies and the progress of green transition. GF starts at a relatively low level (around 0.18–0.20), declines slightly in the early years, but rises markedly after 2015, reaching about 0.38 in 2019. This surge coincides with the institutionalisation of green finance, especially after the issuance of the *Guidelines for Establishing the Green Financial System* in 2016.

Overall, the results suggest that while economic development advanced steadily, environmental degradation did not worsen in parallel but showed signs of improvement in recent

years. This trend coincides with the expansion of green finance, indicating that the latter contributed to balancing growth with environmental protection by helping to decouple economic development from environmental degradation.

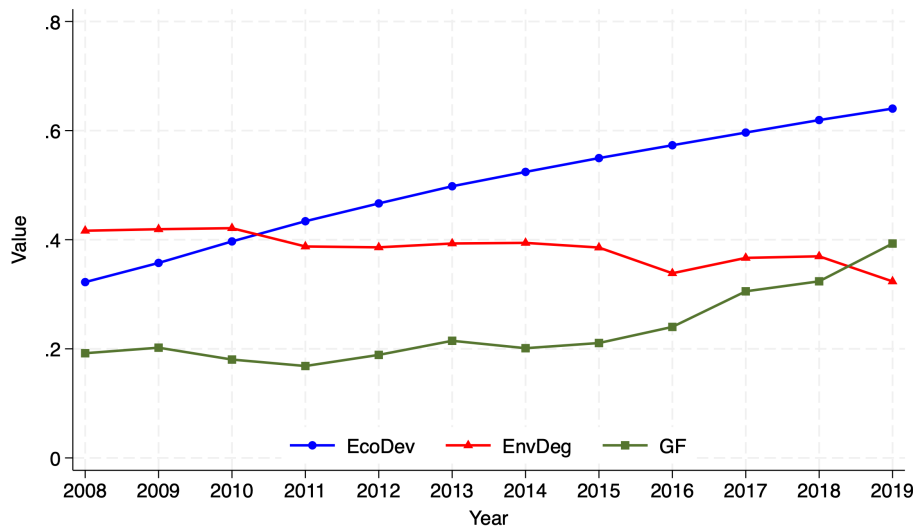


Figure 3.2: Annual Trends of EcoDev, EnvDeg, and GF (Normalised by Max–Min Method).

### 3.3.5 Preliminary Test

For panel data from our 30 provinces over 13 years, we first applied the Levin–Lin–Chu (LLC) test to examine the stationarity of each variable. Table 3.4 indicates that all core explanatory and control variables reject the null hypothesis of a unit root under the trend specification. The adjusted  $t^*$  statistics are significantly negative, confirming that all variables are stationary. This finding implies that spurious regression is not a concern in the subsequent panel regressions, and the original series can be used at different levels.

Table 3.4: LLC panel unit root tests (with trend)

Variables	EcoDev	EnvDeg	GF	FC	HC	TP	PO	EC
Adj. $t^*$	-29.810***	-6.431***	-1.945**	-7.618***	-5.940***	-9.103***	-54.517***	-13.228***

Notes: Levin–Lin–Chu panel unit root tests with deterministic trend. Null hypothesis: unit root (non-stationarity). Significance stars based on  $p$ -values: \* $p < 0.10$ , \*\* $p < 0.05$ , \*\*\* $p < 0.01$ .

In traditional fixed-effects panel regressions, robust or cluster-robust standard errors can correct for heteroskedasticity and within-unit serial correlation, but they still assume independence across cross-sectional units. As a result, they cannot address the issue of cross-sectional dependence, and ignoring this may lead to underestimated standard errors and inflated sta-

tistical significance.

However, provincial panel data analysis observations across regions are often not independent. Nationwide macroeconomic shocks, uniform policy adjustments, fluctuations in energy prices, and spatial spillover effects—such as the diffusion of environmental pollution or the dissemination of technological innovation—may induce correlations among the residuals of different provinces, a phenomenon known as cross-sectional dependence.

We conduct Pesaran’s (2004) cross-sectional dependence (CD) test on our two baseline models to formally test this. The results, reported in Table 5, reject the null hypothesis of cross-sectional independence at the 5% significance level for both models. Specifically, the CD statistics are -2.173 ( $p = 0.0298$ ) for the economic development equation (Model 1) and -2.112 ( $p = 0.0347$ ) for the environmental degradation equation (Model 2). These findings indicate that substantial cross-sectional dependence exists across the 30 provinces, which may stem from nationwide shocks, policy changes, or interregional spillovers.

Table 3.5: Pesaran cross-sectional dependence (CD) tests

Model	CD statistic	$p$ -value	Avg. $ \rho $	$N$ (panels)	$T$ (periods)
Model 1 (EcoDev equation)	-2.173	0.0298	0.582	30	12
Model 2 (EnvDeg equation)	-2.112	0.0347	0.502	30	12

Notes: Pesaran (2004) CD test. Null hypothesis: cross-sectional independence. Both models reject the null at the 5% level, indicating significant cross-sectional dependence.

Given this evidence, it is crucial to adopt estimation methods that account for cross-sectional dependence. Driscoll and Kraay (1998) proposed a nonparametric covariance matrix estimator that yields asymptotically valid standard errors in large- $T$  panels, even in the presence of cross-sectional dependence, serial correlation, and heteroskedasticity. As Hoechle (2007) emphasises, “Driscoll–Kraay standard errors are well calibrated when cross-sectional dependence is present, and ignoring such correlation can severely bias inference.” Therefore, we employ Driscoll–Kraay standard errors in the subsequent analysis to ensure robust statistical results.

## 3.4 Empirical Results

### 3.4.1 Main Regression Results

We estimate two-way fixed effects models with and without control variables, using economic development (Model 1: *EcoDev*) and environmental degradation (Model 2: *EnvDeg*) as the dependent variables, respectively. We employ Driscoll–Kraay standard errors to

ensure valid inference in the presence of cross-sectional dependence, serial correlation, and heteroskedasticity. The sample comprises 30 provinces observed over 12 years, resulting in a total of 360 province-year observations. The regression results are summarised in Table 3.6.

Table 3.6: Regression Results

	Model (1) EcoDev	Model (1) EcoDev	Model (2) EnvDeg	Model (2) EnvDeg
GF	-7.591** (2.710)	-7.065*** (1.849)	3.603* (1.648)	7.766*** (1.695)
GF <sup>2</sup>	101.233** (41.061)	77.378*** (24.393)	-66.924** (23.543)	-144.226*** (20.632)
FC		0.249*** (0.016)		
HC		0.347* (0.171)		
TP		0.059** (0.027)		
EcoDev				0.237 (0.161)
EcoDev <sup>2</sup>				9.167** (4.101)
PO				-0.009*** (0.002)
EC				2.014*** (0.513)
Observations	360	360	360	360
Groups	30	30	30	30
Within R-sq.	0.973	0.986	0.131	0.204
F (joint)	8.412	1770.590	4.063	36.300
Province FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
SE	Driscoll-Kraay	Driscoll-Kraay	Driscoll-Kraay	Driscoll-Kraay

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

The first column of the table reports the regression results of Model 1 without control variables. The coefficient of  $GF$  is negative and statistically significant ( $-7.591^{**}$ ), while that of  $GF^2$  is positive and statistically significant ( $101.233^{**}$ ), indicating a U-shaped marginal effect of green finance on economic development. At the early stage, the expansion of green finance may restrain short-term growth, but once it surpasses a certain threshold, its effect turns positive. The second column shows the results with the inclusion of controls. The results remain robust ( $GF$ :  $-7.065^{***}$ ;  $GF^2$ :  $77.378^{***}$ ).

Among the controls, fixed capital (FC) is positive and statistically significant (0.249\*\*\*), human capital (HC) is positive at the 10% significance level (0.347\*). Technological progress (TP) is positive and significant at the 5% level (0.059\*\*), consistent with the conventional growth theory. The within  $R^2$  increases from 0.973 to 0.986 after adding controls, indicating that they capture more variation across province-years. Overall, the results confirm Hypothesis 1, supporting a "suppression-then-enhancement" pattern: while green finance at low levels may be accompanied by financing constraints, resource misallocation, and transition costs, its positive growth effect emerges and strengthens as the system matures.

The third and fourth columns in Table 3.6 summarise the regression results of Model 2. Without controls, GF is positive and statistically significant (3.603\*), while  $GF^2$  is negative and statistically significant ( $-66.924^{**}$ ), suggesting an inverted U-shaped effect. At lower levels, the expansion of green finance may be associated with rising environmental degradation (e.g., loans flowing to "light green" projects or incomplete retrofits). However, once GF exceeds the turning point, it significantly reduces environmental degradation. After including controls, the directions of GF and  $GF^2$  coefficients are identical, and their significance becomes even stronger (GF: 7.766\*\*\*;  $GF^2$ :  $-144.226^{***}$ ).

The linear economic development term (EcoDev) is insignificant among the controls (0.237), while  $EcoDev^2$  is significantly positive (9.167\*\*), suggesting a deviation from the standard EKC pattern, where environmental degradation tends to increase with income beyond the expected turning point. Energy consumption (EC) is positively associated with degradation (2.014\*\*\*). Population (PO) is negative and statistically significant ( $-0.009^{***}$ ), suggesting that, after controlling for GF and EcoDev, larger populations are linked with reduced environmental degradation. This contradicts the traditional "population-pollution" hypothesis (Dietz & Rosa, 1997) and may reflect faster structural upgrading and stronger environmental governance in densely populated provinces. It may also stem from the choice of indicator: our measure of environmental degradation is based partly on  $SO_2$  emissions rather than  $CO_2$ . As noted by Cole and Neumayer (2004)  $CO_2$  emissions are strongly tied to population-driven economic and consumption activities, whereas  $SO_2$  emissions mainly arise from stable sources such as power generation.

In sum, the results of Model 2 confirm Hypothesis 2, supporting a U-shaped environmental effect. Green finance in its early stages cannot immediately offset the negative environmental externalities of the brown sector. However, once scaled up and past the threshold, it substantially alleviates ecological degradation.

The combined results of both models suggest a consistent conclusion. At low levels, green

finance adversely affects economic growth and environmental quality. Once green finance surpasses its economic and environmental turning points, it contributes positively and simultaneously to growth and ecological improvement, underscoring its dual role as both a growth driver and an environmental mitigation tool.

### 3.4.2 Effect Decomposition of GF on EnvDeg

In model (2), the coefficients of Green Finance ( $GF$ ) and its squared term capture the direct effect of green finance on environmental degradation, that is, whether  $GF$  can directly improve environmental quality after controlling for the level of economic development. Considering the significant impact of  $GF$  on EcoDev in Model (1), EcoDev is treated as a mediating variable through which  $GF$  influences EnvDeg in Model (2). It can be inferred that an additional indirect transmission channel exists, through which  $GF$  influences environmental degradation via economic development, representing a mediating effect. Therefore, the overall effect of green finance on the environment should be understood as the combination of direct and indirect effects. Since the impact of  $GF$  on EcoDev is nonlinear, it is straightforward to show that its impact on EnvDeg is also nonlinear. Appendix C.3 reports the proof.

We next attempt to decompose the direct and indirect effects of  $GF$  on EnvDeg<sup>4</sup>. First, all main variables were standardised ( $z$ -scores) to eliminate measurement scale differences and facilitate the comparability of coefficients. We then calculated the direct effect of green finance on environmental degradation (the marginal impact of  $GF$  holding economic development constant) and the indirect effect (the transmission through economic development). We obtained the total effect as their sum. Finally, based on the sample distribution, we evaluated these effects at different quantiles of  $GF$  (e.g., p10, p30, p50, p70, p90) to uncover how the relationship evolves across various stages of financial development. The computational steps of this decomposition are provided in Appendix C.3.

---

<sup>4</sup>The decomposition is carried out conditional on the set of control variables included in the regressions.

Table 3.7: Marginal effects of Green Finance (standardised) at different quantiles

Quantile	Direct	Indirect	Total
p10	0.2971 (130.2%)	-0.0691 (-30.3%)	0.2280
p30	0.2522 (133.7%)	-0.0635 (-33.7%)	0.1887
p50	0.1955 (140.5%)	-0.0564 (-40.5%)	0.1391
p70	0.0938 (187.2%)	-0.0437 (-87.2%)	0.0501
p90	-0.0527 (67.5%)	-0.0254 (32.5%)	-0.0781

Note: All variables are standardised (z-scores). Reported values are marginal effects of  $GF_z$  on environmental degradation ( $EnvDeg_z$ ) at different quantiles of  $GF_z$ . “Direct” is the effect holding economic development constant, “Indirect” is the effect transmitted via  $EcoDev_z$ , and “Total” is the sum of both. Percentages in parentheses indicate the share of each component (Direct or Indirect) relative to the Total effect at that quantile.

As shown in Table 3.7, the decomposition of marginal effects across different quantiles of  $GF$  reveals a clear nonlinear pattern. The direct impact of green finance on environmental degradation exhibits a turning trajectory: it is positive at lower levels of green finance, but gradually declines and eventually becomes negative at higher levels, suggesting that green finance ultimately contributes to environmental improvement once it reaches a sufficient scale. In contrast, the indirect effect remains consistently negative across all quantiles, reflecting a stable mechanism through which green finance improves environmental quality by fostering economic development and structural upgrading. Examining their relative contributions shows that the share of the direct effect decreases progressively, while the share of the indirect effect increases, implying that the environmental benefits of green finance become increasingly reliant on the indirect channel over time.

The pattern of total effect is mainly similar to the direct impact. At lower quantiles (e.g., p10–p50), the total effect remains positive, meaning that green finance still exacerbates environmental degradation in its early stages. However, once green finance exceeds a certain threshold (around p70–p90), the direct effect turns negative, which drives the total effect into negative territory. This indicates that green finance exerts a net mitigating effect on environmental degradation at higher levels through both direct and indirect channels. Together, these results are consistent with the estimation results of regression Model (2), reinforcing the inverted U-shaped relationship between green finance and environmental degradation.

### 3.4.3 Robustness and asymmetry of nonlinearity

In the above analysis, by incorporating the quadratic term of  $GF$  into the regression model, we demonstrate its nonlinear effects on economic development and the environment.

However, Lind and Mehlum (2010) argue that simply including a quadratic term of the explanatory variable to identify a U-shaped or inverted U-shaped relationship is unreliable. This approach can be misleading because the estimated turning point may fall outside the sample range, and the sign of the quadratic coefficient alone does not ensure that the function changes direction within the observed interval. Moreover, conventional t-tests ignore the joint distribution of the linear and quadratic coefficients and do not verify whether the slope is significantly negative at one end or positive at the other. To address these issues, they adopt the general testing framework of Sasabuchi (1980) and develop the so-called U-test, which jointly evaluates the slope conditions at the lower and upper bounds of the sample to formally test the existence of a U-shaped or inverted U-shaped relationship.

According to the corresponding command in Stata (`utest`), we conducted further tests on the regression model, and the results are reported in Table 3.8.

Table 3.8: U-test results for nonlinearity (Model 1 and Model 2)

	Model (1)	Model (2)
Specification $f(x)$	$x^2$	$x^2$
Alt. hypothesis	U shape	Inverse U shape
Extreme point	0.045654	0.025338
Interval (GF)	[0.001471, 0.060639]	[0.001471, 0.060639]
Lower-bound slope	-6.8375	6.0985
<i>t</i> -value	-3.8362	3.2983
<i>p</i> -value	0.001382***	0.003550**
Upper-bound slope	2.3191	-9.0202
<i>t</i> -value	1.6573	-8.5695
<i>p</i> -value	0.062835*	0.00000169***
Overall <i>t</i> (U/InvU)	1.66	3.30
Overall <i>p</i>	0.0628*	0.00355**

Notes: Model (1): test of U-shape vs. monotone or inverse U-shape. Model (2): test of inverse U-shape vs. monotone or U-shape.

In Model (1), the alternative hypothesis is a U-shaped relationship. The test results show that the lower-bound slope is negative ( $-6.84$ ,  $t = -3.84$ ,  $p = 0.0014$ ), while the upper-bound slope is positive ( $2.32$ ,  $t = 1.66$ ,  $p = 0.0628$ ). The overall U-test statistic is  $t = 1.66$  with a *p*-value of 0.0628, which is significant at the 10%

In model (2), the alternative hypothesis is an inverse U-shape. The results indicate that the lower-bound slope is positive ( $6.10$ ,  $t = 3.30$ ,  $p = 0.0036$ ), while the upper-bound slope is negative ( $-9.02$ ,  $t = -8.57$ ,  $p < 0.001$ ). The overall U-test statistic is  $t = 3.30$  with a *p*-value of 0.0036, which is significant at the 1% level. This provides strong evidence for an inverse

U-shaped relationship between green finance and environmental degradation. While green finance initially exacerbates environmental degradation, once it reaches a sufficient scale, its mitigating effect on the environment becomes dominant.

Regarding the extreme point of Utest, it is at 0.0457 in Model (1), which falls within the sample interval [0.0015, 0.0606]. This indicates that at lower levels of green finance, its expansion tends to hinder economic development, whereas once green finance exceeds approximately 0.046, it begins to foster economic growth. Model (2) 's turning point is 0.0253, within the sample range. This suggests that green finance may exacerbate environmental degradation initially, but once its scale surpasses around 0.027, it gradually contributes to environmental improvement.

Notably, the turning points identified by the U-test are highly consistent with those derived from the panel regression coefficients (about 0.046 for economic development and 0.027 for environmental degradation<sup>5</sup>). This consistency provides robustness for green finance's nonlinear effect on economic development and environmental degradation.

Table 3.8 further indicates that these U-shaped and inverted U-shaped effects are asymmetric, as reflected in the differences in slopes on either side of the turning points. Regarding economic development, the adverse impact of green finance expansion in the early stage is relatively strong, whereas the positive growth effect after the threshold emerges more gradually. Similarly, for environmental degradation, the early expansion of green finance may coincide with the transitional "growing pains" of green transformation, thereby intensifying ecological stress. However, once green finance reaches a sufficient scale, its environmental governance role strengthens rapidly, and its mitigating effect on ecological degradation outweighs the earlier negative impact. This asymmetric feature highlights the distinct mechanisms through which green finance influences economic and environmental outcomes across different stages of development.

#### **3.4.4 Current status analysis for green finance development of Chinese provinces**

We combine the turning points derived from the two regression models with our provincial green finance database to analyse the stage of green finance development across Chinese provinces. To provide a more intuitive view, we plot scatter diagrams for 2008 and 2019 in Figure 3.3. The horizontal axis represents provinces, while the vertical axis shows the Green Finance (GF) index. Horizontal dashed lines indicate the turning points for economic

<sup>5</sup>Calculated by coefficients from Model(1)and (2) with controls in Table 6

development (0.046) and environmental degradation (0.027), allowing us to assess whether and to what extent provinces have surpassed these critical thresholds.

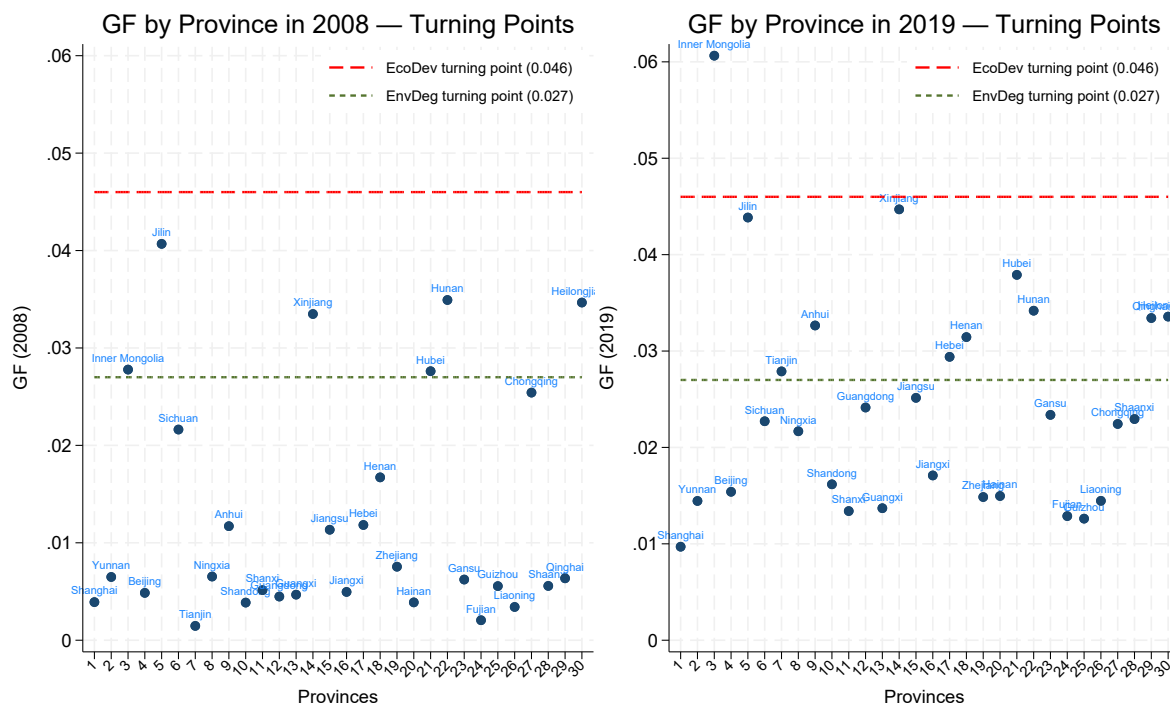


Figure 3.3: GF by Province: 2008 vs 2019 — Turning Points

Most provinces remain at relatively low GF levels, generally far below the turning point for economic development (0.046) and close to or below the turning point for environmental degradation (0.027). This pattern indicates that, at the national scale, green finance is still in its early stage, with insufficient scale to fully unleash its positive effects on economic growth and environmental outcomes.

Regarding the economic development turning point, no province exceeded the threshold of 0.046 in 2008. By 2019, despite the overall increase in GF, only Inner Mongolia had surpassed this level. This finding suggests that for most provinces, the scale of green finance remains too limited to generate sustained positive effects on economic development. Regarding the environmental degradation turning point, only six provinces exceeded the threshold of 0.027 in 2008: Jilin, Heilongjiang, Hunan, Hubei, Inner Mongolia, and Xinjiang. By 2019, this number had risen to 11 provinces: Jilin, Heilongjiang, Hunan, Hubei, Inner Mongolia, Xinjiang, Qinghai, Anhui, Henan, Hebei, and Tianjin. This shift implies that an increasing number of provinces have reached a critical scale of green finance sufficient to exert significant positive effects in mitigating environmental degradation.

In summary, green finance expanded across all provinces from 2008 to 2019. However, over half of China's provinces have not yet reached the critical threshold of green finance development at which its positive effects on economic growth and environmental improvement

become evident. This finding carries important policy implications. For provinces remaining below this turning point, local governments should actively foster the expansion of the green finance sector to accelerate their transition beyond the threshold, thereby enabling green finance to generate simultaneous benefits for economic development and environmental sustainability.

### 3.4.5 Green Finance Kuznets Curve

The above results, including panel regressions, effect decomposition for green finance and U-test, confirm green finance's nonlinear and asymmetrical effects on economic growth and environmental outcomes. Inspired by the classical Kuznets Curve and the Environmental Kuznets Curve, we propose the concept of a Green Finance Kuznets Curve (GFKC), which depicts the impact of green finance on the economy and the environment. Figure 3.4 illustrates it. The GFKC suggests that at the early stage of development, green finance tends to suppress economic growth and exacerbate environmental pressures. However, once its level surpasses the turning point and reaches a more advanced stage, green finance can lead to green growth. Moreover, the nonlinear pattern is asymmetric. Green finance's adverse effect at the early stage is stronger than its positive influence after, while its contribution to environmental improvement rises more quickly once the turning point expands beyond the threshold.

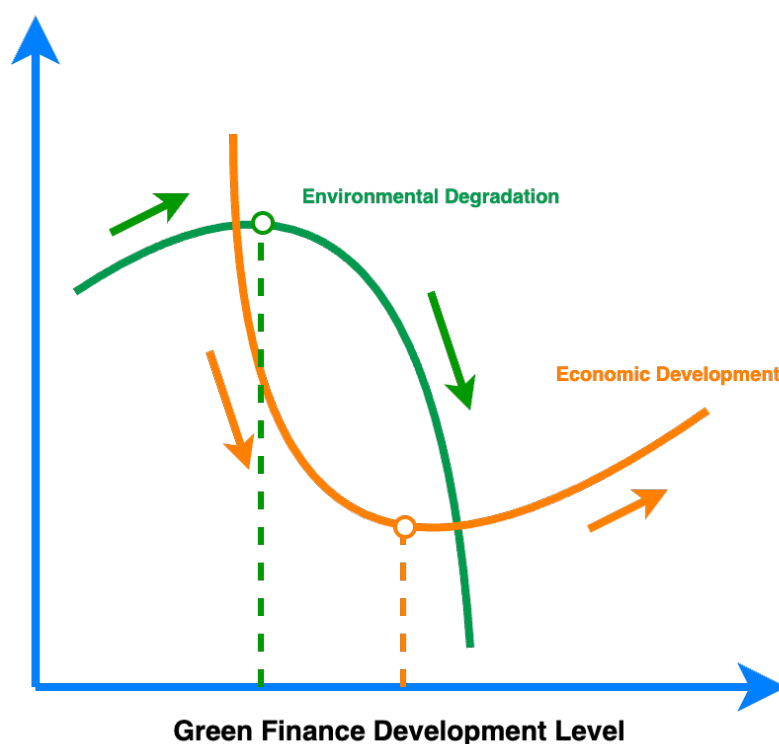


Figure 3.4: Green Finance Kuznets Curve

### 3.4.6 Mechanism Analysis for GFKC

The mechanism analysis for the Green Finance Kuznets Curve (GFKC) is developed from theoretical and practical perspectives.

#### Theoretical Evidence

First, the conclusions of the GFKC are highly consistent with our proposed *Extended Green Solow Model*<sup>6</sup> (see Figure 3.5). The figure's horizontal axis represents the share of green capital in the economy, while  $P$  denotes pollution generated by brown production and  $Y$  denotes total output.<sup>7</sup> The different colored curves illustrate various green-subsidy policy scenarios: the black curve (Naive Tax) corresponds to a pollution tax without green subsidies; the blue curve (Green Finance) represents subsidies directed toward increasing the savings rate of green capital; the red curve (Green Total Factor Productivity) refers to subsidies that enhance technological progress in green production; and the green curve (PAC) represents subsidies allocated to enhance pollution abatement efficiency. Parameter values are calibrated to the Chinese context, and numerical simulations are conducted to explore the dynamic trajectories of economic growth and environmental change under different policy settings.

Although the theoretical model and the empirical analysis differ slightly in variable specification, they convey the exact mechanism. For instance, in Figure 3.4, economic development is measured by per capita GDP, whereas in Figure 3.5, it is represented by total output ( $Y$ ). Similarly, the horizontal axis in Figure 3.5 denotes the overall share of green capital in the economy, while in Figure 3.4, the level of green finance development is measured in terms of its "depth and breadth," where depth refers to the proportion of green financial capital in total financial capital. In short, the theoretical model captures the macro-level relationship between the share of green capital in the economy and its impacts on growth and pollution. In contrast, the empirical model operationalises this mechanism through the share of green finance within the financial system.

We focus on the blue dashed line in Figure 3.5, which represents the policy scenario of green finance (GF). The simulation results indicate that as the share of green capital increases, it exhibits a U-shaped relationship with economic output and an inverted U-shaped relationship with pollution. These theoretical results are highly consistent with the empirical

<sup>6</sup>For a more detailed discussion of this model, see *Essay I: Environmental policies in a green Solow model*, Haomiao Niu

<sup>7</sup>Although labor is excluded from the production function in the theoretical model, the results remain unchanged if all variables are interpreted in per capita terms.

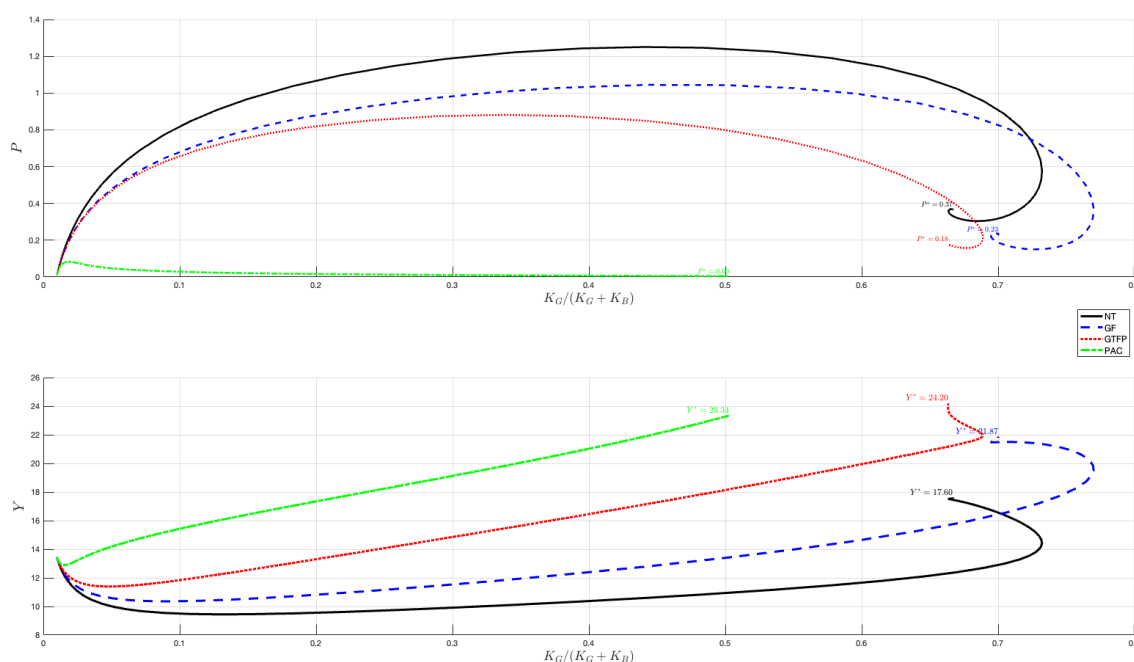


Figure 3.5: Share of Green Capital vs Pollution and Output

findings of a U-shaped effect of green finance on economic development and an inverted U-shaped effect on environmental degradation. Furthermore, both curves display asymmetric patterns: for the environmental curve, the slope before the turning point is flatter than after; for the economic curve, the slope before the turning point is steeper, and the turning point lies roughly within the range of 0–0.1 in green-capital share. These features align well with the asymmetry observed in the empirical results.

The only notable difference between the theoretical simulation and the empirical estimation concerns the turning point of pollution ( $P$ ). In Figure 3.5, the turning point occurs around 0.4–0.5, whereas the empirically estimated value is approximately 0.03. This discrepancy arises primarily from the calibration of initial parameters in the numerical simulation and does not affect the overall consistency of the theoretical and empirical conclusions.

The Extended Green Solow Model provides a solid theoretical foundation for the "Green Finance Kuznets Curve" (GFKC). The mechanism analysis of the model suggests that in the early stage of green transition, the share of green capital ( $K_G$ ) is relatively small<sup>8</sup>. Consequently, green output ( $Y_G$ ) is limited. The economy is dominated by brown production. The environmental mitigation effect generated by green output is insufficient to offset the pollution created by brown output, resulting in an overall increase in total pollution ( $P$ ).

<sup>8</sup>In the model calibration, we assume that at the initial stage of economic development, the ratio of green to brown capital is 1:100.

Since the environmental tax is an increasing function, rising pollution also raises the tax burden, suppressing brown output and reducing total output ( $Y$ ). This mechanism explains the behaviour before the turning point of the GFKC: when the share of green financial capital is low, economic development is constrained while environmental degradation intensifies. The upper graph of Figure 3.6 illustrates this effecting mechanism.

However, as the government implements green finance subsidy policies, the return on green capital increases, which raises the saving rate of green capital and expands its share in the total capital stock. The accumulation of green capital increases green output, whose pollution-abatement effect gradually strengthens and eventually outweighs the pollution generated by brown output. As a result, the overall pollution level declines. This improvement further reduces the environmental tax burden, stimulating a recovery in brown-sector production. The combined expansion of both green and brown outputs contributes to the overall growth of total output. This mechanism is consistent with the pattern after the turning point of the GFKC, indicating that a high level of green finance not only effectively mitigates environmental degradation but also promotes sustained economic growth. The lower graph of Figure 3.6 illustrates this effecting mechanism.

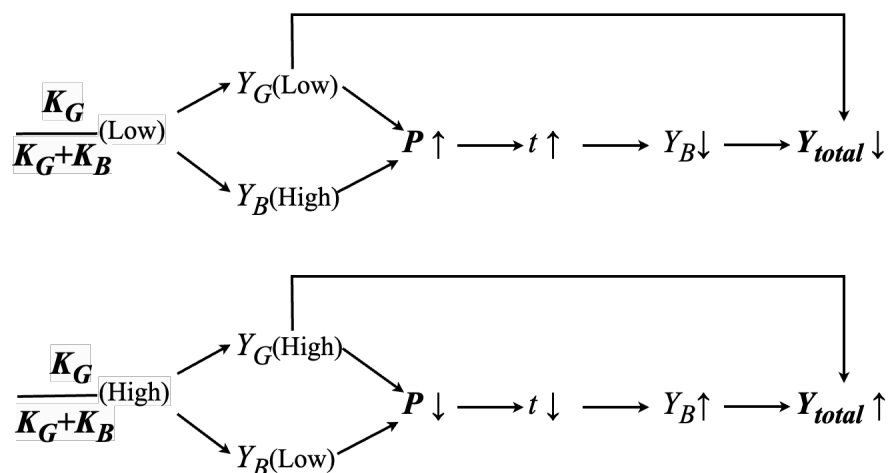


Figure 3.6: Mechanism Analysis from the Extended Green Solow Model

### Practical Evidence

The nonlinear relationship identified by the Green Finance Kuznets Curve (GFKC) can be further explained through several practical mechanisms that characterise the evolution of a green economy. In the early stages of green transition, economic systems experience structural frictions, investment lags, and informational asymmetries that suppress short-term growth and environmental performance. As the scale of green finance expands and institutional quality improves, these constraints gradually diminish, enabling a simultaneous

enhancement of economic output and environmental quality.

**Structural transformation and reallocation costs (“from old to new” pains).** Green transition requires reallocating financial and material resources from high-emission, energy-intensive sectors to emerging green industries. Traditional “brown” sectors possess long-established production chains and mature profit structures, whereas green sectors are often small and nascent. During the transition, capital scrapping, labor retraining, and supply-chain reconfiguration lead to temporary output losses and efficiency declines. Moreover, during the coexistence of “old capacity not yet retired, new capacity not yet established,” economic frictions and emissions may temporarily rise (Acemoglu et al., 2012; Aghion et al., 2019).

**Scale effects, high upfront investment, and delayed payoffs.** Green infrastructure—renewable energy systems, green factory retrofits, and storage or transmission networks—typically requires large initial capital expenditures and long construction periods. During this stage, investments have not yet translated into adequate production capacity, so green sectors’ environmental and economic benefits cannot be fully realised (Campiglio, 2016). As a result, a short-term increase in emissions and delayed economic returns may occur before the long-term benefits emerge.

**The “Green Paradox.”** Suppose market participants expect future environmental regulations to tighten. In that case, fossil-fuel producers may accelerate extraction or sales in the short run, leading to a temporary surge in carbon emissions—an effect known as the “green paradox” (Sinn, 2008). This phenomenon may amplify early-stage environmental deterioration even under expanding green finance.

**Technological diffusion and experience curve effects.** Once green finance reaches a critical scale, technological diffusion and learning-by-doing effects trigger an acceleration phase. With a sufficient project pipeline, economies of scale, and supply-chain coordination, the marginal abatement cost of investment declines sharply while the productivity of green assets rises (Lee & Lee, 2022). Consequently, environmental degradation decreases, and economic returns improve in tandem, reflecting the post-turning-point segment of the GFKC.

**Expectations, information, and institutional quality.** In the early stage, weak information disclosure and immature evaluation standards generate uncertainty and asymmetric information in green finance markets. The prevalence of “light green” projects and “greenwashing” reduces capital allocation efficiency and raises financing costs (Flammer, 2021). As policy frameworks—such as green taxonomies, disclosure systems, performance assessments, and risk-weight regulations—become established, resource allocation improves,

greenwashing space narrows, and long-term investors recognise the stability of green project cash flows. This process lowers risk premia, enhances liquidity, and introduces a "greenium" (pricing premium for green assets), accelerating the transition toward positive economic and environmental returns (Campiglio, 2016).

In summary, these mechanisms jointly explain the empirically observed U-shaped and inverted U-shaped relationships. At low levels of green finance, economies face structural and informational frictions that depress growth and environmental outcomes. As green finance deepens, scale economies, technological learning, and institutional improvements enable an upward shift of both curves, reducing pollution while fostering sustainable economic expansion.

### 3.5 Conclusions

This study employs panel data from 30 Chinese provinces from 2008 to 2019 to systematically examine green finance's impact on economic development and environmental degradation. By introducing a two-way fixed effects model, the paper identifies a significant nonlinear effect of green finance on economic and environmental outcomes. The main findings are summarised below.

First, the impact of green finance on economic development exhibits a clear U-shaped relationship. In the early stages of green finance development, constrained by financing limitations, information asymmetry, and the absence of scale effects, its influence on economic growth is negative. However, once the level of green finance surpasses a critical threshold, it begins to foster economic expansion through innovation and structural upgrading channels.

Second, the impact of green finance on environmental degradation follows a significant inverted U-shaped relationship. At low levels of development, the expansion of green finance may coincide with a temporary increase in emissions—particularly when green technologies are not yet widely adopted. Nevertheless, once the green finance index exceeds its turning point, its positive role in promoting green technology diffusion and industrial upgrading becomes apparent, leading to a substantial decline in pollution. Robustness checks using the U-test confirm the consistency of these nonlinear patterns with the regression results.

Moreover, the decomposition analysis indicates that green finance influences environmental quality primarily through an indirect pathway via economic growth. At lower development levels, the direct effect dominates and may even worsen pollution. At higher levels, the indirect effect, driven by industrial restructuring and technological progress, becomes the leading force for environmental improvement.

Drawing upon China's provincial green finance database, a further heterogeneity analysis reveals that most provinces remain below the identified turning points, suggesting that China's green finance system is still in a formative stage. Only a few provinces have crossed the threshold associated with economic development, while roughly one-third have surpassed the environmental turning point.

Overall, this paper proposes and empirically verifies the existence of the Green Finance Kuznets Curve (GFKC) and demonstrates its strong consistency with both the theoretical predictions of the Extended Green Solow Model and the empirical evidence. The findings imply that green finance may initially entail transitional pains; however, once it reaches sufficient scale, it evolves into a "dual engine" driving economic growth and environmental improvement.

From a policy perspective, these results provide confidence for countries and regions in developing their green finance systems. Although the initial phase of green finance may not yield immediate economic or environmental benefits, continued investment and institutional refinement eventually generate positive returns. Therefore, governments should further strengthen the green finance framework by improving information disclosure and risk-pricing mechanisms, expanding fiscal and financial incentives, and accelerating the development of green capital markets to help regions cross both turning points and advance toward a stage of high-quality, sustainable growth.

# Conclusions

This dissertation develops and validates an analytical framework that links green policy, green finance, economic performance, and environmental quality. The theory clarifies mechanisms and policy comparisons and identifies clear rankings across regimes. The measurement system provides consistent and decomposable indices that separate coverage and intensity. The empirical analysis documents nonlinear and asymmetric effects and advances the Green Finance Kuznets Curve hypothesis. The findings show that a capable green government and a mature green finance market are both necessary for a successful transition. Their complementarity helps close part of the financing gap, shifts the economy toward a cleaner steady state, and does so with more minor output losses during the transition and larger gains in the long run.

The evidence yields five practical policy implications. First, fiscal tools and market development should be aligned with a predictable pollution tax with transparent recycling into green uses so that private incentives match public goals and limit output losses. Second, green finance should be deepened along with coverage and intensity by widening participation across instruments and regions and by raising penetration within each market with consistent verification and disclosure. Third, it recognises transitional costs because turning metric effects imply a phase of weak growth support and modest environmental gains, and it provides points and asymmetric targeted assistance to affected sectors and workers to smooth adjustment. Fourth, select subsidy channels according to objectives, since support for green total factor productivity raises output more while support for abatement lowers pollution, and combine them to reflect local priorities. Fifth, the provincial database should be used to design locally distinct strategies that leverage natural endowments and to monitor progress with transparent measures of coverage and intensity so that policy can adapt in time.

# Appendix A

## A.1 Proof of the existence of Brown-Green equilibrium

First, simplify the first two equations of system 1.18, we get:

$$\begin{cases} K_B = \left( \frac{\delta}{s(1-f(P))A} \right)^{\frac{1}{\alpha-1}} \\ K_G = \left( \frac{\delta}{s(A+\theta_2 f(P))(1+\theta_1 f(P))} \right)^{\frac{1}{\alpha-1}} \end{cases} \quad (\text{A1.1})$$

Then, we rewrite the third equation in 1.18 by substituting  $K_B$  and  $K_G$  from (A1.1), and define the right-hand side as a new function of  $P$ ,  $G(P)$ , we have the following equation:

$$\begin{aligned} G(P) = & \Omega(1-f(P))^{\frac{1}{1-\alpha}} A^{\frac{1}{1-\alpha}} \\ & - (\phi + \theta_3 f(P))(A + \theta_2 f(P))^{\frac{1}{1-\alpha}} (1 + \theta_1 f(P))^{\frac{\alpha}{1-\alpha}} \end{aligned} \quad (\text{A1.2})$$

If we can prove that there exists a unique solution  $P^* > 0$  such that  $G(P^*) = 0$ , then, owing to the monotonicity of  $f(x)$  and system (14), it is equivalent to proving that  $K_B$  and  $K_G$  also have unique solutions. This implies that for system (13), there exists a unique, economically meaningful steady state  $(K_B, K_G, P) > 0$ . Now, we are proving that  $G(P)$  has a unique real root  $P^*$ .

$$\begin{cases} \lim_{P \rightarrow 0^+} G(P) = (\Omega - \phi)A^{\frac{1}{1-\alpha}} \\ \lim_{P \rightarrow \infty} G(P) = -(\phi + \theta_3)(A + \theta_2)^{\frac{1}{1-\alpha}}(1 + \theta_1)^{\frac{\alpha}{1-\alpha}} \\ G'(P) = -f'(P)(T_1(P) + T_2(P) + T_3(P) + T_4(P)) \end{cases} \quad (\text{A1.3})$$

,where

$$\begin{aligned}
 T_1(P) &= \frac{\Omega A^{\frac{1}{1-\alpha}}}{1-\alpha} (1-f(P))^{\frac{\alpha}{1-\alpha}}, \\
 T_2(P) &= \theta_3 (A + \theta_2 f(P))^{\frac{1}{1-\alpha}} (1 + \theta_1 f(P))^{\frac{\alpha}{1-\alpha}}, \\
 T_3(P) &= \frac{\theta_2 (\phi + \theta_3 f(P))}{1-\alpha} (A + \theta_2 f(P))^{\frac{1}{1-\alpha}-1} (1 + \theta_1 f(P))^{\frac{\alpha}{1-\alpha}}, \\
 T_4(P) &= \frac{\alpha \theta_1 (\phi + \theta_3 f(P))}{1-\alpha} (A + \theta_2 f(P))^{\frac{1}{1-\alpha}} (1 + \theta_1 f(P))^{\frac{\alpha}{1-\alpha}-1}.
 \end{aligned}$$

In respect of the first equation in system (A1.3), since  $\Omega > \phi$ , we have  $(\Omega - \phi)A^{\frac{1}{1-\alpha}} > 0$ ; For the second equation, it's intuitive to see all terms in parentheses are positive based on our parameter assumptions so the final sign of the second equation is negative;  $G(P)$  is too long so we write it down separately,  $f'(P)$  is positive, and all the other four terms from  $T_1(P)$  to  $T_4(P)$  are positive because every term in these four equations are positive, so the final sign  $G(P)$  is negative. The summary of the signs of the system (16) is shown below.

$$\left\{ \begin{array}{l} \lim_{P \rightarrow 0^+} G(P) > 0 \\ \lim_{P \rightarrow \infty} G(P) < 0 \\ G'(P) < 0 \end{array} \right. \quad (\text{A1.4})$$

According to intermediate value theorem, only one root  $P^*$  of  $G(P)$  is in the domain of  $P > 0$ . Furthermore, in the system of equation (14), there is a unique corresponding  $K_B^*$  and  $K_G^*$ . Thus, the unique solution of  $(K_B^*, K_G^*, P^*)$  proves the existence of Brown-Green Equilibrium.

## A.2 Proof of stability of equilibrium

Recall that the Jacobian matrix of equation system (1.18) at the equilibrium  $(K_B^*, K_G^*, P^*)$  is given by

$$J^* = \begin{pmatrix} f_{1,K_B} & 0 & f_{1,P} \\ 0 & f_{2,K_G} & f_{2,P} \\ f_{3,K_B} & f_{3,K_G} & f_{3,P} \end{pmatrix},$$

with the corresponding characteristic polynomial

$$\lambda^3 + A\lambda^2 + B\lambda + C = 0.$$

The partial derivatives in our model are:

$$f_{1,K_B} = sA\alpha K_B^{\alpha-1}(1 - f(P)) - \delta,$$

$$f_{1,P} = -sAK_B^\alpha f'(P),$$

$$f_{2,K_G} = s\alpha K_G^{\alpha-1}(1 + \theta_1 f(P))(A + \theta_2 f(P)) - \delta,$$

$$f_{2,P} = sK_G^\alpha f'(P) \left[ \theta_1(A + \theta_2 f(P)) + \theta_2(1 + \theta_1 f(P)) \right],$$

$$f_{3,K_B} = \Omega A \alpha K_B^{\alpha-1}(1 - f(P)),$$

$$f_{3,K_G} = -\alpha (\phi + \theta_3 f(P)) (A + \theta_2 f(P)) K_G^{\alpha-1},$$

$$f_{3,P} = -\Omega A K_B^\alpha f'(P) - K_G^\alpha f'(P) \left[ \theta_3(A + \theta_2 f(P)) + \theta_2(\phi + \theta_3 f(P)) \right].$$

Now, we are investigating the sign of each term. There are some intuitive ones under the assumptions that  $f'(P) > 0$  and all other parameters  $(s, A_B, A_{G0}, \theta_1, \theta_2, \theta_3, \Omega, \delta, \phi)$  are positive. Those are:

$$f_{1,P} < 0; f_{2,P} > 0; f_{3,K_B} > 0; f_{3,K_G} < 0; f_{3,P} < 0.$$

At the equilibrium, the conditions  $\dot{K}_B = 0$  and  $\dot{K}_G = 0$  yield

$$s(1 - f(P)) A_B K_B^{\alpha-1} = \delta \quad \text{and} \quad s(1 + \theta_1 f(P)) (A_{G0} + \theta_2 f(P)) K_G^{\alpha-1} = \delta.$$

Using these, we can rewrite the derivatives  $f_{1,K_B}$  and  $f_{2,K_G}$  as

$$f_{1,K_B} = sA_B \alpha K_B^{\alpha-1} (1 - f(P)) - \delta = \alpha \delta - \delta = (\alpha - 1)\delta,$$

$$f_{2,K_G} = s\alpha K_G^{\alpha-1} (1 + \theta_1 f(P)) (A_{G0} + \theta_2 f(P)) - \delta = \alpha \delta - \delta = (\alpha - 1)\delta.$$

Since  $0 < \alpha < 1$  and  $\delta > 0$ , it follows that

$$f_{1,K_B} < 0 \quad \text{and} \quad f_{2,K_G} < 0.$$

Then, it immediately follows that.

$$A = -\left(f_{1,K_B} + f_{2,K_G} + f_{3,P}\right) > 0.$$

The coefficient  $B$  is given by

$$B = f_{1,K_B} f_{2,K_G} + f_{1,K_B} f_{3,P} + f_{2,K_G} f_{3,P} - f_{1,P} f_{3,K_B} - f_{2,P} f_{3,K_G}.$$

Consider the terms separately:

- Since  $f_{1,K_B} < 0$  and  $f_{2,K_G} < 0$ , the product  $f_{1,K_B} f_{2,K_G}$  is positive.
- $f_{1,K_B} f_{3,P}$  and  $f_{2,K_G} f_{3,P}$  are products of two negative numbers and are thus positive.
- The product  $f_{1,P} f_{3,K_B}$  is negative and the minus sign renders  $-f_{1,P} f_{3,K_B} > 0$ .
- $f_{2,P} f_{3,K_G} < 0$  and again  $-f_{2,P} f_{3,K_G} > 0$ .

Since all five terms are positive, it follows that.

$$B > 0.$$

The coefficient  $C$  is given by

$$C = -\left(f_{1,K_B} f_{2,K_G} f_{3,P} - f_{1,K_B} f_{2,P} f_{3,K_G} - f_{1,P} f_{3,K_B} f_{2,K_G}\right).$$

Examine the three products:

- $f_{1,K_B} f_{2,K_G} f_{3,P}$ : since  $f_{1,K_B} < 0$ ,  $f_{2,K_G} < 0$ , and  $f_{3,P} < 0$ , the product is negative.
- $f_{1,K_B} f_{2,P} f_{3,K_G}$ : here  $f_{1,K_B} < 0$ ,  $f_{2,P} > 0$ , and  $f_{3,K_G} < 0$ ; hence the product is positive.
- $f_{1,P} f_{3,K_B} f_{2,K_G}$ : since  $f_{1,P} < 0$ ,  $f_{3,K_B} > 0$ , and  $f_{2,K_G} < 0$ , this product is also positive.

Thus, the expression inside the parentheses is

$$f_{1,K_B} f_{2,K_G} f_{3,P} - f_{1,K_B} f_{2,P} f_{3,K_G} - f_{1,P} f_{3,K_B} f_{2,K_G} < 0.$$

Taking the negative of a negative number, we conclude that

$$C > 0.$$

Next, we are proving  $AB > C$ . To simplify the algebraic structure and facilitate the comparison between  $AB$  and  $C$ , we introduce the following positive quantities:

$$a \equiv -f_{1,K_B} > 0,$$

$$b \equiv -f_{2,K_G} > 0,$$

$$c \equiv -f_{3,P} > 0,$$

$$p \equiv -f_{1,P} > 0,$$

$$q \equiv f_{2,P} > 0,$$

$$r \equiv f_{3,K_B} > 0,$$

$$s \equiv -f_{3,K_G} > 0.$$

Under these definitions, the coefficients in the characteristic polynomial

$$\lambda^3 + A\lambda^2 + B\lambda + C = 0$$

can be rewritten as

$$A = a + b + c,$$

$$B = ab + ac + bc + pr + qs,$$

$$C = abc + aqs + prb.$$

Our goal is to prove that

$$AB - C > 0.$$

**Step 1. Expand  $AB$ :**

We have

$$AB = (a + b + c)(ab + ac + bc + pr + qs).$$

Split this product into two parts:

$$AB = (a + b + c)(ab + ac + bc) + (a + b + c)(pr + qs).$$

Denote

$$T_1 = (a + b + c)(ab + ac + bc) \quad \text{and} \quad T_2 = (a + b + c)(pr + qs).$$

Expanding  $T_1$  gives

$$\begin{aligned} T_1 &= a(ab + ac + bc) + b(ab + ac + bc) + c(ab + ac + bc) \\ &= a^2b + a^2c + abc + ab^2 + abc + b^2c + abc + ac^2 + bc^2 \\ &= a^2b + a^2c + ab^2 + ac^2 + b^2c + bc^2 + 3abc. \end{aligned}$$

Since  $a$ ,  $b$ , and  $c$  are positive, every term in  $T_1$  is positive. Similarly, for  $T_2$  we have

$$T_2 = a(pr + qs) + b(pr + qs) + c(pr + qs),$$

which is clearly positive. Thus,

$$AB = T_1 + T_2 = a^2b + a^2c + ab^2 + ac^2 + b^2c + bc^2 + 3abc + a(pr + qs) + b(pr + qs) + c(pr + qs).$$

## Step 2. Compare $AB$ with $C$ :

Recall that

$$C = abc + aqs + prb.$$

Subtracting  $C$  from  $AB$  gives

$$\begin{aligned} AB - C &= \left[ a^2b + a^2c + ab^2 + ac^2 + b^2c + bc^2 + 3abc + a(pr + qs) + b(pr + qs) + c(pr + qs) \right] \\ &\quad - \left[ abc + aqs + prb \right] \\ &= a^2b + a^2c + ab^2 + ac^2 + b^2c + bc^2 + 2abc \\ &\quad + \left[ a(pr + qs) + b(pr + qs) + c(pr + qs) - (aqs + prb) \right]. \end{aligned}$$

Then, simplify the bracketed term:

$$\begin{aligned} a(pr + qs) + b(pr + qs) + c(pr + qs) - (aqs + prb) &= apr + aqs + bpr + bqs + cpr + cqs - aqs - bpr \\ &= apr + bqs + c(pr + qs). \end{aligned}$$

Since  $a, b, c, p, q, r,$  and  $s$  are all positive, it follows that

$$apr + bqs + c(pr + qs) > 0.$$

Therefore,

$$AB - C > 0.$$

which completes the proof.

### A.3 Proof of pollution dominance of environmental policies

*Step 1 (No tax).* When  $f \equiv 0$  and  $\boldsymbol{\theta} = \mathbf{0}$ , The capital dynamics reduce to

$$\dot{K}_i = sAK_i^\alpha - \delta K_i, \quad i \in \{B, G\},$$

with steady-state capital stocks  $K_B^* = K_G^* = (sA/\delta)^{1/(1-\alpha)}$ . Pollution evolves as

$$\dot{P} = \Omega AK_B^\alpha - \phi AK_G^\alpha = A(\Omega - \phi) \left( \frac{sA}{\delta} \right)^{\frac{\alpha}{1-\alpha}} > 0,$$

so  $P(t) \rightarrow +\infty$  and no finite steady-state pollution exists. For ranking purposes we set  $P_{0,0}^* = +\infty$ .

*Step 2 (Tax only).* With  $f \in \mathcal{F}$  and  $\boldsymbol{\theta} = \mathbf{0}$ ,

$$K_B^* = \left( \frac{s(1-\tau)A}{\delta} \right)^{\frac{1}{1-\alpha}}, \quad K_G^* = \left( \frac{sA}{\delta} \right)^{\frac{1}{1-\alpha}},$$

and the pollution steady-state condition  $\Omega A(1-\tau)(K_B^*)^\alpha = \phi A(K_G^*)^\alpha$  yields  $1-\tau^0 = (\phi/\Omega)^{1-\alpha} \in (0, 1)$ , hence  $P_{f,0}^* = f^{-1}(\tau^0) < +\infty$ .

*Step 3 (Tax plus subsidies).* With  $f \in \mathcal{F}$  and  $\boldsymbol{\theta} \in \Theta \setminus \{\mathbf{0}\}$ , the steady-state condition can be written as

$$L(\tau) = R(\tau, \boldsymbol{\theta}), \quad L(\tau) = \Omega A(1-\tau)[K_B^*(\tau)]^\alpha, \quad R(\tau, \boldsymbol{\theta}) = (\phi + \theta_3\tau)(A + \theta_2\tau)[K_G^*(\tau, \boldsymbol{\theta})]^\alpha.$$

Since  $L'(\tau) < 0$  and  $R_\tau(\tau, \boldsymbol{\theta}) > 0$ , the implicit-function theorem gives

$$\frac{\partial \tau^*}{\partial \theta_i} = -\frac{R_{\theta_i}(\tau^*, \boldsymbol{\theta})}{L'(\tau^*) - R_\tau(\tau^*, \boldsymbol{\theta})} < 0,$$

so  $\tau^*(\boldsymbol{\theta}) < \tau^0$ . Because  $f'(P) > 0$ , we obtain

$$P_{f,1}^* = f^{-1}(\tau^*(\boldsymbol{\theta})) < f^{-1}(\tau^0) = P_{f,0}^*.$$

*Step 4 (Conclusion).* Combining the three cases yields

$$P_{0,0}^*(= +\infty) > P_{f,0}^* > P_{f,1}^*,$$

which establishes the claimed ordering.

## A.4 Proof of output dominance of environmental policies

*Step 1 (No tax vs. tax only):*  $Y_{0,0}^* > Y_{f,0}^*$ . With  $f \equiv 0$  and  $\boldsymbol{\theta} = \mathbf{0}$ , the capital steady states are  $K_B^0 = K_G^0 = (sA/\delta)^{1/(1-\alpha)}$ . Hence

$$Y_{0,0}^* = A(K_B^0)^\alpha + A(K_G^0)^\alpha = 2A\left(\frac{sA}{\delta}\right)^{\frac{\alpha}{1-\alpha}}.$$

With  $f \in \mathcal{F}$  and  $\boldsymbol{\theta} = \mathbf{0}$  (tax only),

$$K_B^0(\tau) = \left(\frac{s(1-\tau)A}{\delta}\right)^{\frac{1}{1-\alpha}}, \quad K_G^0 = (sA/\delta)^{1/(1-\alpha)},$$

and the tax-only steady-state satisfies  $1 - \tau^0 = (\phi/\Omega)^{1-\alpha} \in (0, 1)$ . Therefore

$$Y_{f,0}^* = A(1 - \tau^0)[K_B^0(\tau^0)]^\alpha + A[K_G^0]^\alpha = A\left(\frac{sA}{\delta}\right)^{\frac{\alpha}{1-\alpha}} \left\{ (1 - \tau^0)^{\frac{1}{1-\alpha}} + 1 \right\}.$$

Since  $(1 - \tau^0)^{\frac{1}{1-\alpha}} < 1$  for any  $\tau^0 \in (0, 1)$ , we obtain  $Y_{f,0}^* < 2A\left(\frac{sA}{\delta}\right)^{\frac{\alpha}{1-\alpha}} = Y_{0,0}^*$ .

*Step 2 (Tax plus subsidies vs. tax only):*  $Y_{f,1}^* > Y_{f,0}^*$ . For  $f \in \mathcal{F}$  and  $\boldsymbol{\theta} \in \Theta \setminus \{\mathbf{0}\}$ , the steady-state pollution condition can be written as  $L(\tau) = R(\tau, \boldsymbol{\theta})$ , where

$$L(\tau) = \Omega A(1 - \tau)[K_B^*(\tau)]^\alpha, \quad R(\tau, \boldsymbol{\theta}) = (\phi + \theta_3\tau)(A + \theta_2\tau)[K_G^*(\tau, \boldsymbol{\theta})]^\alpha.$$

As  $L'(\tau) < 0$  and  $R_\tau(\tau, \boldsymbol{\theta}) > 0$ , the implicit-function theorem yields

$$\frac{\partial \tau^*}{\partial \theta_i} = -\frac{R_{\theta_i}(\tau^*, \boldsymbol{\theta})}{L'(\tau^*) - R_\tau(\tau^*, \boldsymbol{\theta})} < 0,$$

so the steady-state tax under subsidies is strictly lower:  $\tau^*(\boldsymbol{\theta}) < \tau^0$ . Brown-sector steady-

state output is

$$Y_B^*(\tau) = (1 - \tau)A[K_B^*(\tau)]^\alpha = A\left(\frac{sA}{\delta}\right)^{\frac{\alpha}{1-\alpha}}(1 - \tau)^{\frac{1}{1-\alpha}},$$

which is strictly decreasing in  $\tau$ . Therefore, lowering  $\tau$  from  $\tau^0$  to  $\tau^*(\theta)$  strictly raises  $Y_B^*$ .

For the green sector,

$$Y_G^*(\theta) = (A + \theta_2\tau^*) [K_G^*(\tau^*, \theta)]^\alpha = (A + \theta_2\tau^*) \left( \frac{s(1+\theta_1\tau^*)(A+\theta_2\tau^*)}{\delta} \right)^{\frac{\alpha}{1-\alpha}},$$

which (weakly) increases whenever  $\theta_1 > 0$  and/or  $\theta_2 > 0$ ; if  $\theta_1 = \theta_2 = 0$  (pure abatement subsidies), then  $Y_G^*$  coincides with the tax-only green output, while the strict fall in  $\tau$  still raises  $Y_B^*$  as shown above. Hence in all cases  $Y_{f,1}^* > Y_{f,0}^*$ .

*Step 3 (Conclusion).* Combining Steps 1 and 2 proves

$$Y_{0,0}^* > Y_{f,0}^* \quad \text{and} \quad Y_{f,1}^* > Y_{f,0}^*,$$

## A.5 Parameter Specification

### Saving rate

The government is assumed not to impose any pollution tax on brown output in the benchmark setting. According to global statistics, China's gross saving rate has remained around 45% in recent years (CEIC Data, 2023). This value is therefore adopted as the baseline saving rate in the numerical simulations.

### Total Factor Productivity

At present, there is no precise statistical measure of total factor productivity (TFP) in China, as official data usually report only its growth rate or contribution to GDP growth. While recognizing that TFP is not constant in reality, we set  $A = 1$  for calibration purposes, since productivity dynamics are not the focus of this study. This simplification allows the numerical analysis to concentrate on policy-induced effects rather than exogenous technological shocks.

### Output elasticity of capital

Empirical studies estimate that China's output elasticity of capital ranges between 0.5 and 0.6 (Lin & Liu, 2017). We take the midpoint of this interval,  $\alpha = 0.55$ , as a representative value consistent with the production structure of the Chinese economy.

### Depreciation rate

According to Holz (2006), the average capital depreciation rate of Chinese state-owned enterprises was approximately 6% in the early 21st century. This estimate remains widely

used in macroeconomic calibrations and is therefore applied here.

### **Pollution generating coefficient of brown production**

Estimating  $\Omega$  is challenging because pollutants are heterogeneous across types (air, water, and solid waste) and units of measurement are not easily comparable. To obtain an approximate value, we employ an “economic loss” approach that evaluates pollution intensity through its economic cost. We first use carbon emissions as a representative pollutant, with carbon emission intensity (emissions per unit of GDP) serving as the proxy for pollution intensity. Multiplying this intensity by the carbon price yields the pollution cost per unit of output:

$$\Omega = \text{Carbon Intensity (per unit GDP)} \times \text{Carbon Emission Price.}$$

According to Fan et al. (2007), carbon intensity in China’s material production sector declined from about 340 tons per million CNY in 1980 to around 150 tons in 2002. Considering the continuous improvement in energy efficiency, we adopt a further reduced value of 100 tons per million CNY (i.e., 0.1 kg/CNY) for the current stage. The average price of carbon emission allowances (CEA) in China’s carbon market was approximately 100 CNY per ton at the end of 2024, equivalent to 0.1 CNY/kg. Combining these values gives:

$$\Omega = 0.1 \text{ kg/CNY} \times 0.1 \text{ CNY/kg} = 0.01.$$

### **Pollution abatement coefficient of green production**

As indicated by condition (1.14), the pollution-abatement efficiency is assumed to be lower than the pollution-generation coefficient ( $\phi < \Omega$ ). Because  $\phi$  is even more difficult to measure empirically, it is approximated at half of  $\Omega$ , implying that the pollution-mitigation capacity of green production is about 50% of the pollution generated by brown production. Hence,  $\phi = 0.005$  is adopted as a reasonable benchmark.

### **Initial points setting**

We initialize the model with the following starting values for the three endogenous variables. First, brown capital is taken as the benchmark and set to  $K_{B0} = 100$ . Second, we set  $K_{G0} = 1$ , implying that the share of green capital is relatively small in the early stages of economic development. Although the precise proportion of green capital is difficult to measure, this assumption is grounded in empirical evidence.

According to TheCityUK (2022), global green finance represented only about 1.7% of total finance between 2012 and 2021. Based on our provincial-level dataset for China, the

corresponding share of green financial capital is approximately 1.9%. In countries where green finance systems remain less developed, this ratio would likely be even lower. Hence, we assume the initial share of green capital to be 0.01.

Regarding the initial pollution level, given the baseline setting of  $K_{B0}$ , the initial brown output can be computed as  $Y_{B0} = AK_{B0}^\alpha$  (without taxation at  $t = 0$ ). Using the estimated pollution coefficient for brown production  $\Omega = 0.01$ , the initial pollution stock is given by

$$P_0 = Y_{B0} \times \Omega = 0.126,$$

which we approximate as  $P_0 = 0.1$ .

Preliminary tests indicate that these initial values allow the model to produce a smooth and realistic trajectory of economic and environmental dynamics. Therefore, the initial state of the system is summarized as:

$$(K_{B0}, K_{G0}, P_0) = (100, 1, 0.1).$$

## A.6 Robustness check

Taking Figure 1.6 in the main text as an example, we modify the pollution-tax function to compare how alternative specifications affect the steady state. Specifically, we consider three functional forms that satisfy the assumptions of  $f(P)$ :

$$f_1(P) = \frac{e^P - 1}{e^P}, \quad f_2(P) = \frac{\ln(1 + P)}{\ln(1 + P) + 1}, \quad f_3(P) = \frac{P}{\sqrt{1 + P^2}}.$$

The following figures show that altering the functional form of the pollution tax leaves the steady-state values of  $K_B$  and  $K_G$  unchanged, while causing only a marginal shift in the steady-state pollution stock  $P$ . Nonetheless, all qualitative results remain identical: the GF policy leads to the highest green capital, the PAC policy delivers the lowest equilibrium pollution, whereas the GTFP policy yields the highest output.

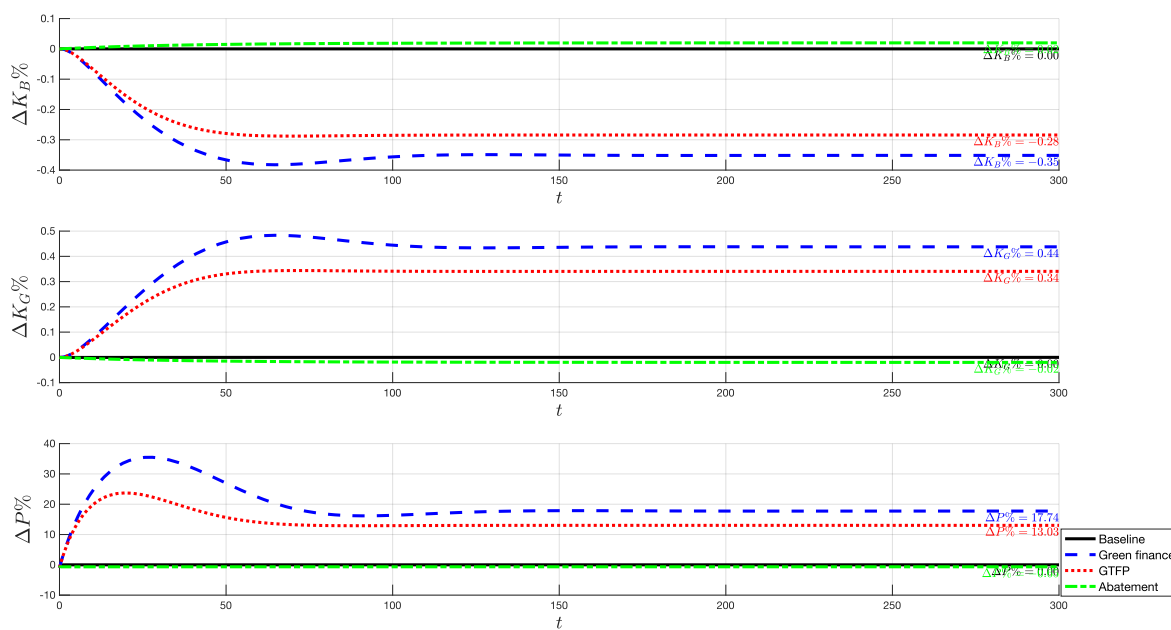


Figure A6.2: Evolution of  $K_B$ ,  $K_G$  and  $P$ : Alternative policies VS Baseline with pollution function:  
 $f(P) = \frac{\ln(1+P)}{\ln(1+P)+1}$ ;

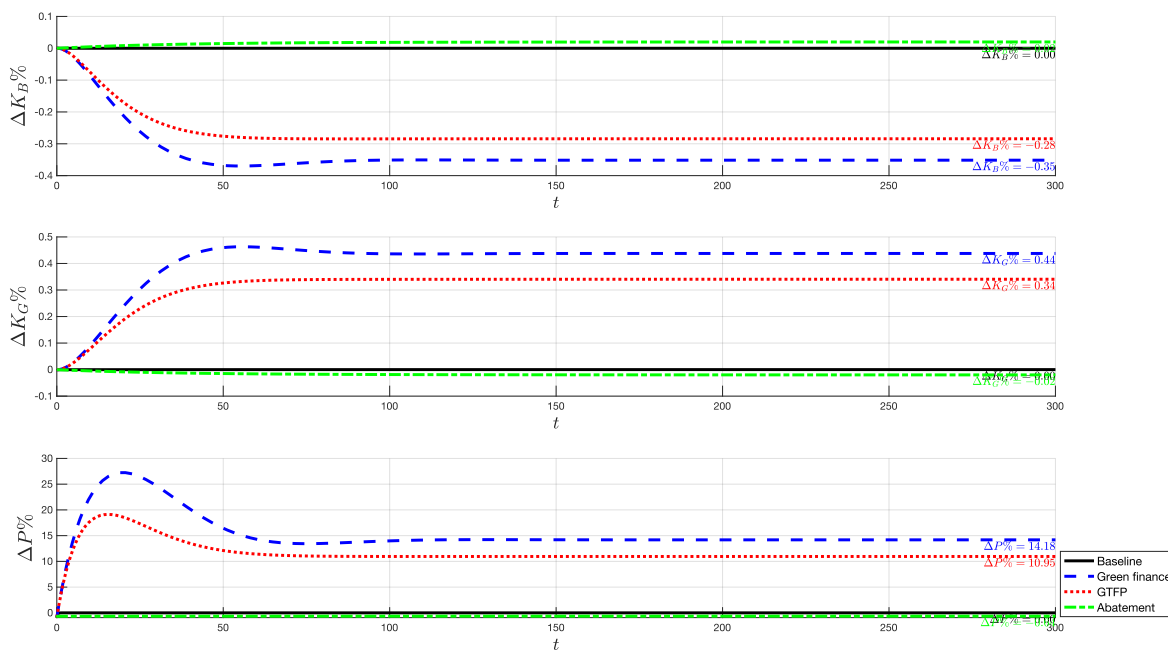


Figure A6.1: Evolution of  $K_B$ ,  $K_G$  and  $P$ : Alternative policies VS Baseline with pollution function:  
 $f(P) = \frac{e^P}{e^P - 1}$ ;

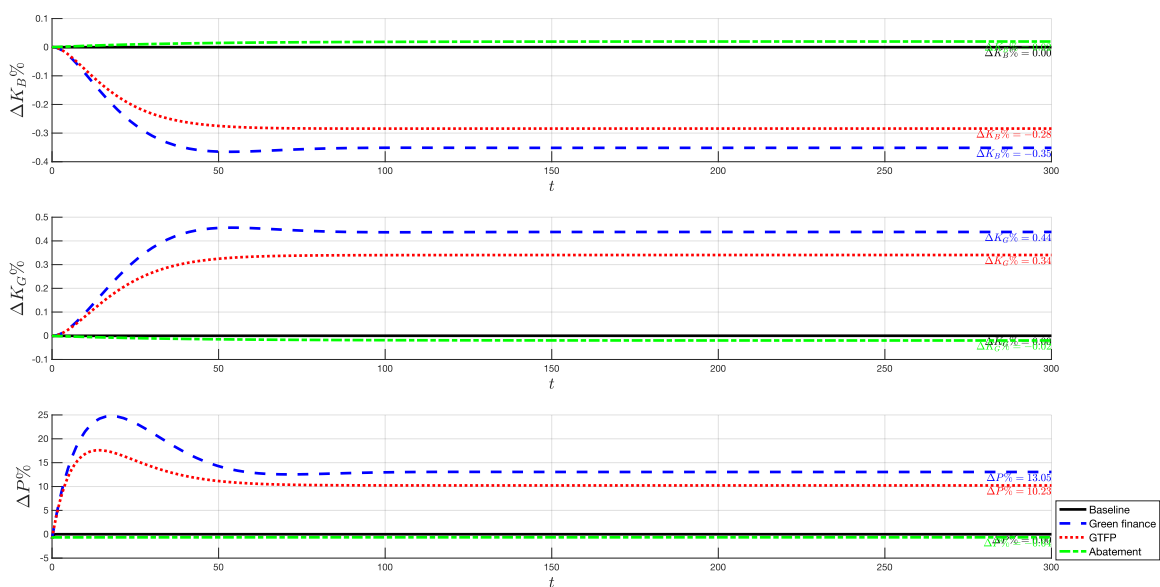


Figure A6.3: Evolution of  $K_B$ ,  $K_G$  and  $P$ : Alternative policies VS Baseline with pollution function:  

$$f(P) = \frac{P}{\sqrt{1+P^2}};$$

# Appendix B

## B.1 Various Definitions of Green Finance

---

Proposers	Definition
Asian Development Bank (ADB)	Green Finance comprise all forms of investment or lending that consider environmental effects and enhance environmental sustainability.
Bangladesh Bank	Green Finance, as part of green banking, contributes to the transition to resource-efficient and low-carbon industries and a green economy in general.
G20 Green Finance Study Group	Green finance is the financing of investments that provide environmental benefits in the broader context of environmentally sustainable development.
Government of Germany	Green Finance is a strategic approach to involve the financial sector in the transformation toward low-carbon, resource-efficient economies and adaptation to climate change.
Höhne et al. (2012)	Green finance is a broad term referring to financial investments in sustainable development projects and initiatives, environmental products, and policies fostering a more sustainable economy.
International Development Finance Club (IDFC)	Green Finance denotes financial investments flowing into sustainable development projects and initiatives, environmental products, and policies that encourage a more sustainable economy (including but not limited to climate finance).

---

Proposers	Definition
OECD	Green Finance supports economic growth while reducing pollution and greenhouse gas emissions, minimising waste and improving resource-use efficiency.
People's Bank of China	Green finance policy comprises institutional arrangements that attract private capital into green industries (environmental protection, energy conservation, clean energy) via loans, private equity funds, bonds, equities and insurance.
United Nations Environment Programme (UNEP)	Green financing seeks to increase financial flows (banking, micro-credit, insurance, investment) from public, private and non-profit sectors to sustainable development priorities, managing environmental and social risks and delivering returns with environmental benefits.
Volz (2018)	Green finance includes all forms of investment or lending that consider environmental effects and enhance environmental sustainability.
World Bank	Green finance is the financing of investments that provide environmental benefits within the wider context of environmentally sustainable development, such as pollution reduction, greenhouse gas mitigation and energy-efficiency improvements.

---

Sources: ADB; Bangladesh Bank (BRPD Circular No.02/2011); G20 Green Finance Study Group Report (2016); German GIZ Green Finance paper (2011); Höhne et al. (2012); IDFC Green Finance Mapping Report (2012); OECD Green Finance and Investment series; PBoC Guidelines for Establishing the Green Financial System (2016); UNEP Green Finance resources; World Bank Green Finance background note.

## B.2 Crucial policies and events in the Development of Green Finance in China

Policy or Event	Date	Main Content
<i>Guiding Opinions on Energy Conservation and Emission Reduction Credit</i>	Dec. 2007	First time the CBRC required banks to integrate energy conservation and emission reduction goals into credit management, marking the emergence of "green credit" in China.
<i>Green Credit Guidelines (CBRC [2012] No. 4)</i>	Feb. 2012	Set systematic requirements for environmental and social risk management, information disclosure, and regulatory assessment, elevating green credit to a mandatory industry norm.
<i>Guidelines for the Issuance of Green Bonds (NDRC [2015] No. 3504)</i>	Dec. 2015	The NDRC defined green bonds for the first time, setting rules on fund use and information disclosure, laying the institutional foundation for the green bond market.
<i>Establishing China's Green Financial System</i>	Apr. 2015	A joint report by PBoC and UNEP proposing 14 policy recommendations, sparking subsequent top-level green finance design.
<i>Guiding Opinions on Building a Green Financial System</i>	Aug. 2016	China's first national-level green finance framework, proposing policies across seven areas including credit, bonds, insurance, funds, and carbon markets.
G20 Leaders' Communiqué – Hangzhou Summit	Sep. 2016	For the first time, G20 recognised green finance under China's presidency and endorsed the "G20 Green Finance Synthesis Report," positioning China as a global advocate.

Policy or Event	Date	Main Content
<i>Catalogue of Green Bond Endorsed Projects (2021 Edition)</i>	Apr. 2021	Jointly issued by PBoC, NDRC, and CSRC; removed high-carbon items like "clean coal," unified domestic standards, and aligned with international practices.
Launch of the National Carbon Emissions Trading Market	Jul. 2021	Opened by the Shanghai Environment and Energy Exchange, covering 5 Gt CO <sub>2</sub> in the power sector, making it the world's largest carbon market and a pricing benchmark for green finance.
The policy of Carbon Reduction Supporting Tools (CRST)	Nov. 2021	PBoC introduced a facility with a 1.75% re-lending rate covering 60% of loan principal to incentivise banks' green lending—combining monetary and green policy tools.
<i>China-EU Common Ground Taxonomy (CGT) – First Edition</i>	Nov. 2021	Compared EU and China green standards, identified 72 common climate mitigation activities, reducing costs of cross-border green capital flows and laying the groundwork for global taxonomy convergence.
<i>Catalogue for Green and Low-Carbon Transition Industries (2024 Edition)</i>	Feb. 2024	Revised by NDRC and 10 ministries; upgraded to a "dual-carbon" policy tool; detailed seven categories and 246 industries, providing labelling basis for green and transition finance.
<i>China-EU-Singapore Joint CGT 2024 &amp; Multi-jurisdiction Common Ground Taxonomy (M-CGT)</i>	Nov. 2024	Expanded CGT to 110 activities and launched multilateral version, promoting wider international adoption of a unified green classification.

### B.3 Log-decomposition of GFI growth (2008–2019)

Let

$$G_t = D_t \times B_t,$$

where  $D_t$  is *Depth*,  $B_t$  is *Breadth*, and  $G_t$  is the resulting *GFI*. Taking natural logarithms and differencing between a baseline year  $t_0$  and an end year  $t_1$  gives

$$\Delta \ln G = \Delta \ln D + \Delta \ln B, \quad (\text{B3.1})$$

$$\text{Share}_{D \rightarrow G} = \frac{\Delta \ln D}{\Delta \ln G}, \quad \text{Share}_{B \rightarrow G} = \frac{\Delta \ln B}{\Delta \ln G}, \quad (\text{B3.2})$$

with  $\text{Share}_{D \rightarrow G} + \text{Share}_{B \rightarrow G} = 1$  (up to rounding).

#### Data and computation (2008–2019).

	2008	2019
Depth ( $D$ )	0.0237	0.0309
Breadth ( $B$ )	0.54	0.827
GFI ( $G = D \times B$ )	0.012798	0.025554

$$\Delta \ln D = \ln(0.0309) - \ln(0.0237) = 0.2653,$$

$$\Delta \ln B = \ln(0.827) - \ln(0.54) = 0.4263,$$

$$\Delta \ln G = \ln(0.025554) - \ln(0.012798) = 0.6916.$$

$$\text{Share}_{D \rightarrow G} = \frac{0.2653}{0.6916} = 0.3835 \approx 38.4\%,$$

$$\text{Share}_{B \rightarrow G} = \frac{0.4263}{0.6916} = 0.6165 \approx 61.6\%.$$

Between 2008 and 2019, the GFI roughly doubled ( $e^{0.6916} - 1 \approx 100\%$ ); about 38.4% of this growth is attributable to Depth, while the remaining 61.6% is explained by Breadth.

# Appendix C

## C.1 Variable Specification

**Calculation for Real GDP per capita:** To construct the measure of real GDP per capita, we first collected annual data on nominal GDP ( $\text{NGDP}_{i,t}$ ), real GDP growth rates ( $g_{i,t}^{\text{real}}$ ), and provincial population sizes ( $\text{POP}_{i,t}$ ) from the official website of the National Bureau of Statistics of China. Second, we set the year 2000 as the base year and used its nominal GDP ( $\text{NGDP}_{i,2000}$ ) as the benchmark. Real GDP for subsequent years ( $\text{RGDP}_{i,t}$ ) was then computed recursively by applying the officially reported real GDP growth rates ( $g_{i,t}^{\text{real}}$ ) to the base-year value. Finally, provincial real GDP per capita ( $\text{RGDPpc}_{i,t}$ ) was obtained by dividing the estimated real GDP ( $\text{RGDP}_{i,t}$ ) by the corresponding provincial population figures ( $\text{POP}_{i,t}$ ). This procedure is equivalent in spirit to the standard deflation method, but it relies on officially published real GDP growth rates rather than constructing an independent deflator. The calculation process is shown below:

$$\begin{aligned}\text{RGDP}_{i,2000} &= \text{NGDP}_{i,2000}, \\ \text{RGDP}_{i,t} &= \text{RGDP}_{i,t-1} \times (1 + g_{i,t}^{\text{real}}), \quad t = 2001, \dots, T, \\ \text{RGDPpc}_{i,t} &= \frac{\text{RGDP}_{i,t}}{\text{POP}_{i,t}}.\end{aligned}$$

**Calculation for Real Fixed Capital Stock per capita:** A key challenge is that China's National Bureau of Statistics (NBS) only reports annual fixed capital formation, a flow variable. In contrast, capital stock is a stock variable. Following the method proposed by (Shan, 2008), we construct provincial real fixed capital stock using the perpetual inventory method (PIM), which accounts for both investment growth and depreciation. The procedure consists of three steps.

Step 1. Construct real fixed capital formation. We first download nominal fixed capital

formation ( $I_{i,t}^{\text{nom}}$ ) from the NBS. The growth rate of nominal investment approximates the investment price index:

$$g_{i,t}^I = \frac{I_{i,t}^{\text{nom}}}{I_{i,t-1}^{\text{nom}}} - 1.$$

Using this, real fixed capital formation is obtained as

$$I_{i,t}^{\text{real}} = \frac{I_{i,t}^{\text{nom}}}{1 + g_{i,t}^I}.$$

Step 2. Compute the initial capital stock (base year 2000). The initial stock is determined using the average investment growth rate during 2001–2005, denoted  $\bar{g}_i^I$ . Then, we compute

$$K_{i,2000} = \frac{I_{i,2001}^{\text{nom}}}{\delta + \bar{g}_i^I},$$

where  $\delta = 10.96\%$  is the depreciation rate.<sup>9</sup>

Step 3. Apply the perpetual inventory method (PIM). Starting from the base year, capital stock is recursively updated as

$$K_{i,t} = (1 - \delta) K_{i,t-1} + I_{i,t}^{\text{real}}, \quad t = 2001, \dots, T.$$

Finally, the real fixed capital stock per capita is obtained as

$$k_{i,t} = \frac{K_{i,t}}{POP_{i,t}},$$

where  $POP_{i,t}$  is the provincial population.

## C.2 Trend of Economic Development and Environmental Degradation by Province

---

<sup>9</sup>This depreciation rate is also adopted from (Shan, 2008)

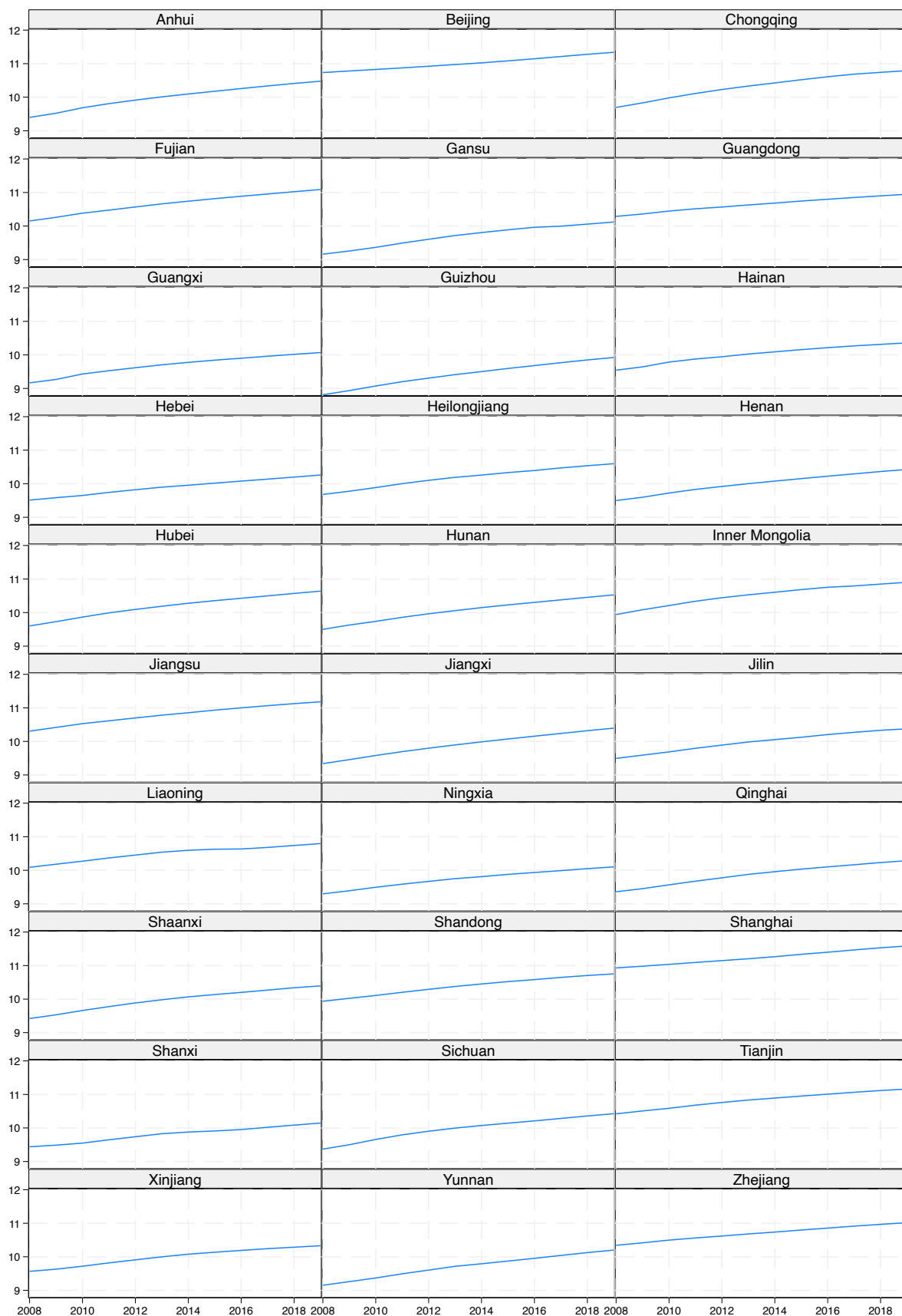


Figure C2.1: Trends of EcoDev by Province (2008–2019).

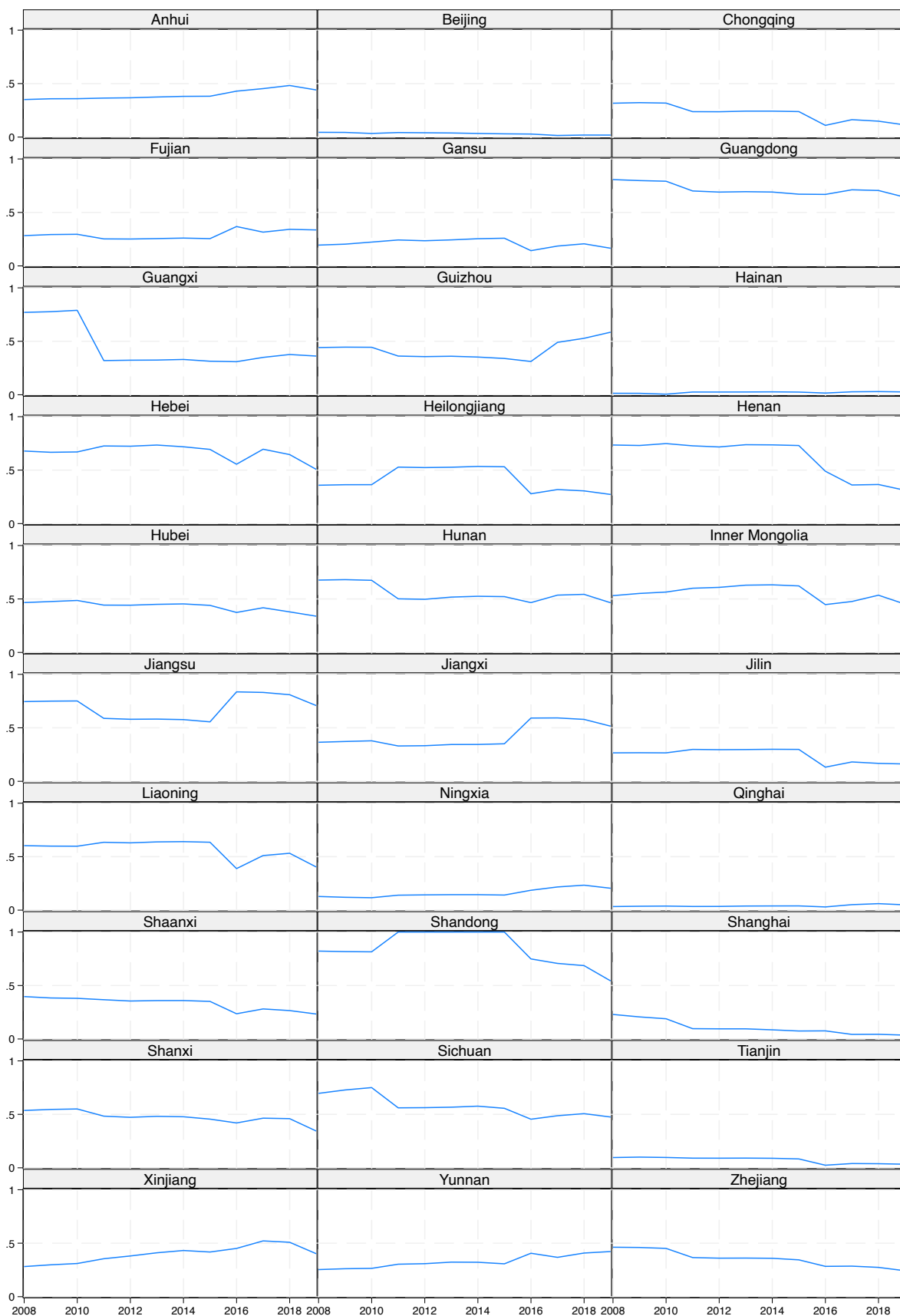


Figure C2.2: Trends of EnvDeg by Province (2008–2019).

### C.3 Decomposition of the Total Effect of Green Finance on Environmental Degradation

This subsection first demonstrates the nonlinear nature of the indirect effect, and then explains how we compute the direct, indirect, and total effects at different quantiles of  $GF$  for empirical implementation.

**Demonstration of the nonlinear indirect effect.** We consider the following two equations:

$$(1) \quad \text{EcoDev} = \alpha_0 + \alpha_1 GF + \alpha_2 GF^2,$$

$$(2) \quad \text{EnvDeg} = \beta_0 + \beta_1 GF + \beta_2 GF^2 + \gamma_1 \text{EcoDev} + \gamma_2 \text{EcoDev}^2.$$

The direct effect of  $GF$  on  $\text{EnvDeg}$ , holding  $\text{EcoDev}$  constant, is given by the partial derivative:

$$\text{Direct}(g) = \left. \frac{\partial \text{EnvDeg}}{\partial GF} \right|_{\text{EcoDev}} = \beta_1 + 2\beta_2 g,$$

where  $g$  denotes the value of  $GF$ .

The indirect effect of  $GF$  on  $\text{EnvDeg}$  through  $\text{EcoDev}$  follows from the chain rule:

$$\text{Indirect}(g, e) = \frac{\partial \text{EnvDeg}}{\partial \text{EcoDev}} \cdot \frac{\partial \text{EcoDev}}{\partial GF} = (\gamma_1 + 2\gamma_2 e) (\alpha_1 + 2\alpha_2 g),$$

where  $e = \text{EcoDev}$ .

Since  $\text{EcoDev}$  itself depends on  $GF$  through equation (1), i.e.

$$e(g) = \alpha_0 + \alpha_1 g + \alpha_2 g^2,$$

The indirect effect expressed solely in terms of  $g$  is

$$\text{Indirect}(g) = \left[ \gamma_1 + 2\gamma_2(\alpha_0 + \alpha_1 g + \alpha_2 g^2) \right] (\alpha_1 + 2\alpha_2 g).$$

Defining constants  $C_0 = \gamma_1 + 2\gamma_2\alpha_0$ ,  $C_1 = 2\gamma_2\alpha_1$ , and  $C_2 = 2\gamma_2\alpha_2$ , we obtain

$$\begin{aligned} \text{Indirect}(g) &= (C_0 + C_1 g + C_2 g^2)(\alpha_1 + 2\alpha_2 g) \\ &= A_0 + A_1 g + A_2 g^2 + A_3 g^3, \end{aligned}$$

with coefficients

$$\begin{aligned} A_0 &= C_0\alpha_1, \\ A_1 &= 2C_0\alpha_2 + C_1\alpha_1, \\ A_2 &= 2C_1\alpha_2 + C_2\alpha_1, \\ A_3 &= 2C_2\alpha_2 = 4\gamma_2\alpha_2^2. \end{aligned}$$

As long as  $\gamma_2 \neq 0$  and  $\alpha_2 \neq 0$ , we have  $A_3 \neq 0$ , which implies that the indirect effect is a cubic (third-order polynomial) function of  $GF$ . Therefore, the indirect effect is *inherently nonlinear* by construction only when either  $\gamma_2 = 0$  (linear effect of EcoDev on EnvDeg) or  $\alpha_2 = 0$  (linear effect of  $GF$  on EcoDev) does the indirect effect reduce to a linear form.

**Evaluation at distributional quantiles.** Let  $g_q$  denote the  $q$ -th quantile of  $GF$  (e.g.,  $q \in \{0.10, 0.30, 0.50, 0.70, 0.90\}$  in our tables), and let  $\bar{e} = \mathbb{E}[\text{EcoDev}]$  be the sample mean of EcoDev. Then the direct, indirect, and total effects evaluated at  $g_q$  (holding EcoDev fixed at its mean) are:

$$\begin{aligned} \text{Direct}(g_q) &= \beta_1 + 2\beta_2 g_q, \\ \text{Indirect}(g_q, \bar{e}) &= (\gamma_1 + 2\gamma_2 \bar{e})(\alpha_1 + 2\alpha_2 g_q), \\ \text{Total}(g_q, \bar{e}) &= \text{Direct}(g_q) + \text{Indirect}(g_q, \bar{e}). \end{aligned}$$

In practice, we evaluate the indirect effect at the sample mean  $\bar{e}$  rather than at  $e(g_q)$ , which facilitates comparison across quantiles of  $GF$  and avoids confounding nonlinearities in both arguments simultaneously.

**Remark.** In the empirical regressions, additional controls  $Z$  (e.g.  $FC, HC, TP, PO, EC$ , and year dummies) enter linearly. When computing the marginal effects of  $GF$ , these covariates are conditioned on and hence do not appear explicitly in the derivative formulas. The reported direct and indirect effects should therefore be interpreted as conditional effects.

# References

- Acemoglu, D., Aghion, P., Bursztyn, L., & Hémous, D. (2012). The environment and directed technical change. *American Economic Review*, *102*(1), 131–166.
- Aghion, P., Hepburn, C., Teytelboym, A., & Zenghelis, D. (2019). Path dependence, innovation and the economics of climate change. *Environmental and Resource Economics*, *72*(2), 393–411.
- Baines, T., Brown, S., Benedettini, O., & Ball, P. D. (2012). Examining green production and its role within the competitive strategy of manufacturers. *Journal of Industrial Engineering and Management*, 53–87.
- Banga, J. (2019). The green bond market: A potential source of climate finance for developing countries. *Journal of Sustainable Finance & Investment*, *9*(1), 17–32.
- Baumol, W. J., & Oates, W. E. (1988). *The theory of environmental policy*. Cambridge University Press.
- Bloomberg Index Services Limited. (2022, October). Bloomberg global aggregate green social sustainability bond index methodology. <https://assets.bbhub.io/professional/sites/10/Bloomberg-Global-Agg-GSS-Methodology.pdf>
- Bovenberg, A. L., & De Mooij, R. A. (1997). Environmental tax reform and endogenous growth. *Journal of Public Economics*, *63*(2), 207–237.
- Brock, W. A., & Taylor, M. S. (2010). The green solow model. *Journal of Economic Growth*, *15*, 127–153.
- Campiglio, E. (2016). Beyond carbon pricing: The role of banking and monetary policy in financing the transition to a low-carbon economy. *Ecological Economics*, *121*, 220–230.
- CEIC Data. (2023). China: Gross savings rate [Retrieved from <https://www.ceicdata.com/en/indicator/china/gross-savings-rate>].
- Choudhury, T., Kayani, U. N., Gul, A., Haider, S. A., & Ahmad, S. (2023). Carbon emissions, environmental distortions, and impact on growth. *Energy Economics*, *126*, 107040.
- Climate Bonds Initiative. (2019). *China green bond market 2019 research report* (tech. rep.) (Accessed: October 2025). Climate Bonds Initiative. <https://www.climatebonds.net/data-insights/publications/china-green-bond-market-2019-research-report>
- Climate Bonds Initiative. (2024). *China sustainable debt market 2023: State of the market* (Retrieved from [https://www.climatebonds.net/files/releases/chinasotm\\_mediarelease\\_16052024\\_0.pdf](https://www.climatebonds.net/files/releases/chinasotm_mediarelease_16052024_0.pdf)). Climate Bonds Initiative.

- Climate Policy Initiative. (2023). Global landscape of climate finance 2023. <https://www.climatepolicyinitiative.org/publication/global-landscape-of-climate-finance-2023/>
- Cole, M. A., & Neumayer, E. (2004). Examining the impact of demographic factors on air pollution. *Population and Environment*, 26(1), 5–21.
- Cui, H., Wang, B., & Xu, Y. (2023). Green finance innovation, financial resource allocation, and enterprise pollution reduction [in Chinese]. *China Industrial Economics*, 10(2), 42–59.
- Delmas, M. A., & Burbano, V. C. (2011). The drivers of greenwashing. *California Management Review*, 54(1), 64–87.
- Dietz, T., & Rosa, E. A. (1997). Effects of population and affluence on CO<sub>2</sub> emissions. *Proceedings of the National Academy of Sciences of the United States of America*, 94(1), 175–179. <https://doi.org/10.1073/pnas.94.1.175>
- Driscoll, J. C., & Kraay, A. C. (1998). Consistent covariance matrix estimation with spatially dependent panel data. *Review of Economics and Statistics*, 80(4), 549–560.
- Fan, Y., Liu, L. C., Wu, G., Tsai, H. T., & Wei, Y. M. (2007). Changes in carbon intensity in china: Empirical findings from 1980–2003. *Ecological Economics*, 62(3-4), 683–691.
- Fischer, C., & Newell, R. G. (2008). Environmental and technology policies for climate mitigation. *Journal of Environmental Economics and Management*, 55(2), 142–162.
- Flammer, C. (2021). Corporate green bonds. *Journal of Financial Economics*, 142(2), 499–516.
- Friedlingstein, P., Jones, M. W., O’Sullivan, M., et al. (2022). Global carbon budget 2022. *Earth System Science Data*, 14, 4811–4900.
- Gao, J., Wu, D., Xiao, Q., Randhawa, A., Liu, Q., & Zhang, T. (2023). Green finance, environmental pollution and high-quality economic development: A study based on china’s provincial panel data. *Environmental Science and Pollution Research*, 30(11), 31954–31976.
- Gianfrate, G., & Peri, M. (2019). The green advantage: Exploring the convenience of issuing green bonds. *Journal of Cleaner Production*, 219, 127–135.
- Grossman, G. M., & Krueger, A. B. (1995). Economic growth and the environment. *The Quarterly Journal of Economics*, 110(2), 353–377. <https://doi.org/10.2307/2118443>
- Guo, S., & Zhang, Z. (2023). Green credit policy and total factor productivity: Evidence from chinese listed companies. *Energy Economics*, 128, 107115.
- Hallegatte, S., Heal, G., Fay, M., & Treguer, D. (2012). *From growth to green growth: A framework* (tech. rep. No. w17841). National Bureau of Economic Research.
- He, L., Zhang, L., Zhong, Z., Wang, D., & Wang, F. (2019). Green credit, renewable energy investment and green economy development: Empirical analysis based on 150 listed companies of china. *Journal of Cleaner Production*, 208, 363–372.
- Hoehle, D. (2007). Robust standard errors for panel regressions with cross-sectional dependence. *The Stata Journal*, 7(3), 281–312.
- Höhne, N., Khosla, S., Fekete, H., & Gilbert, A. (2012). Mapping of green finance delivered by idfc members in 2011.
- Holz, C. A. (2006). New capital estimates for china. *China Economic Review*, 17(2), 142–185.

- Huang, Z., Gao, N., & Jia, M. (2023). Green credit and its obstacles: Evidence from china's green credit guidelines. *Journal of Corporate Finance*, *82*, 102441.
- Hunjra, A. I., Hassan, M. K., Zaied, Y. B., & Managi, S. (2023). Nexus between green finance, environmental degradation, and sustainable development: Evidence from developing countries. *Resources Policy*, *81*, 103371.
- International Energy Agency. (2023). Green transformation (gx) policy [Retrieved from <https://www.iea.org/policies/17443-green-transformation-gx-policy>].
- International Finance Forum (IFF). (2024). Global green finance development index & country rankings. <https://iifg-china.com/global-green-finance-development-index-ggfdi-and-country-rankings-green-finance-progress-in-worlds-55-largest-economies>
- Iqbal, S., Taghizadeh-Hesary, F., Mohsin, M., & Iqbal, W. (2021). Assessing the role of the green finance index in environmental pollution reduction. *Studies of Applied Economics*, *39*(3), 1–13.
- Kartal, M. T., Pata, U. K., & Alola, A. A. (2025). Impact of green bonds on co2 emissions and disaggregated level renewable electricity in china and the united states of america. *Humanities and Social Sciences Communications*, *12*(1), 1–17.
- Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, *127*, 221–232.
- Krausmann, F., Gingrich, S., Eisenmenger, N., Erb, K. H., Haberl, H., & Fischer-Kowalski, M. (2009). Growth in global materials use, gdp and population during the 20th century. *Ecological Economics*, *68*(10), 2696–2705.
- Lee, C.-C., & Lee, C.-P. (2022). How does green finance affect green total factor productivity? evidence from china. *Energy Economics*, *107*, 105863.
- Lim, J. S., & Kim, Y. G. (2012). Combining carbon tax and r&d subsidy for climate change mitigation. *Energy Economics*, *34*, S496–S502.
- Lin, B., & Liu, K. (2017). Energy substitution effect on china's heavy industry: Perspectives of a translog production function and ridge regression. *Sustainability*, *9*(11), 1892.
- Lind, J. T., & Mehlum, H. (2010). With or without u? the appropriate test for a u-shaped relationship. *Oxford Bulletin of Economics and Statistics*, *72*(1), 109–118.
- Lindenberg, N. (2014). Definition of green finance. <https://www.cbd.int/financial/gcf/definition-greenfinance.pdf>
- Liu, X., Zhao, T., & Li, R. (2023). Studying the green economic growth with clean energy and green finance: The role of financial policy. *Renewable Energy*, *215*, 118971.
- Lv, C., Bian, B., Lee, C.-C., & He, Z. (2021). Regional gap and the trend of green finance development in china. *Energy Economics*, *102*, 105476.
- Lyon, T. P., & Montgomery, A. W. (2015). The means and end of greenwash. *Organization & Environment*, *28*(2), 223–249.
- National Climate Initiative. (2021). *Funding programmes and activities under germany's national climate initiative* (Retrieved from [https://www.klimaschutz.de/sites/default/files/NKI\\_](https://www.klimaschutz.de/sites/default/files/NKI_)

- [Praesentation\\_Feb\\_2021\\_EN.pdf](#)). German Federal Ministry for Economic Affairs and Climate Action.
- Nordhaus, W. D. (1993). Optimal greenhouse-gas reductions and tax policy in the “dice” model. *American Economic Review*, *83*(2), 313–317.
- Organisation for Economic Co-operation and Development. (2025). Global outlook on financing for sustainable development 2025: Towards a more resilient and inclusive architecture. [https://www.oecd.org/en/publications/global-outlook-on-financing-for-sustainable-development-2025\\_753d5368-en.html](https://www.oecd.org/en/publications/global-outlook-on-financing-for-sustainable-development-2025_753d5368-en.html)
- Ouyang, H., Guan, C., & Yu, B. (2023). Green finance, natural resources, and economic growth: Theory analysis and empirical research. *Resources Policy*, *83*, 103604.
- Peng, C., Zhang, S., Rong, X., & Chen, D. (2024). Is china’s green credit policy effective?-based on the perspective of enterprise environmental performance and economic performance. *International Review of Economics & Finance*, *94*, 103410.
- Sachs, J. D., Woo, W. T., Yoshino, N., & Taghizadeh-Hesary, F. (2019). Importance of green finance for achieving sustainable development goals and energy security. In *Handbook of green finance: Energy security and sustainable development* (pp. 1–10).
- Sasabuchi, S. (1980). A test of a multivariate normal mean with composite hypotheses determined by linear inequalities. *Biometrika*, *67*, 429–439.
- Shan, H. (2008). Reestimating the capital stock of china: 1952–2006 [in Chinese]. *Journal of Quantitative and Technical Economics*, *25*(10), 17–31.
- Siderius, T., & Zink, T. (2023). Markets and the future of the circular economy. *Circular Economy and Sustainability*, *3*(3), 1569–1595.
- Sinn, H.-W. (2008). Public policies against global warming: A supply side approach. *International Tax and Public Finance*, *15*(4), 360–394.
- Solow, R. M. (1956). A contribution to the theory of economic growth. *The Quarterly Journal of Economics*, *70*(1), 65–94. <https://doi.org/10.2307/1884513>
- Taghizadeh-Hesary, F., & Yoshino, N. (2019). The way to induce private participation in green finance and investment. *Finance Research Letters*, *31*, 98–103.
- TheCityUK. (2022). Green finance: A quantitative assessment of market trends. <https://www.thecityuk.com/our-work/green-finance-a-quantitative-assessment-of-market-trends/>
- Tzeng, G.-H., & Huang, J.-J. (2011). *Multiple attribute decision making: Methods and applications*. CRC press.
- Uhrenholt, J. N., Kristensen, J. H., Rincón, M. C., Jensen, S. F., & Waehrens, B. V. (2022). Circular economy: Factors affecting the financial performance of product take-back systems. *Journal of Cleaner Production*, *335*, 130319.
- United Nations Environment Programme Finance Initiative. (2020). *Financing circularity: Demystifying finance for the circular economy* (Retrieved from <https://www.unepfi.org/publications/financing-circularity>). UNEP FI.

- Volz, U. (2018). Fostering green finance for sustainable development in asia. In *Routledge handbook of banking and finance in asia* (pp. 488–504). Routledge.
- Wang, K.-H., Zhao, Y.-X., Jiang, C.-F., & Li, Z.-Z. (2022). Does green finance inspire sustainable development? evidence from a global perspective. *Economic Analysis and Policy*, *75*, 412–426.
- Wang, Z., & Wang, X. (2022). Research on the impact of green finance on energy efficiency in different regions of china based on the dea-tobit model. *Resources Policy*, *77*, 102695.
- Xu, S., & Dong, H. (2023). Green finance, industrial structure upgrading, and high-quality economic development: An intermediation model based on the regulatory role of environmental regulation. *International Journal of Environmental Research and Public Health*, *20*(2), 1420.
- Yao, S., Pan, Y., Sensoy, A., Uddin, G. S., & Cheng, F. (2021). Green credit policy and firm performance: What we learn from china. *Energy Economics*, *101*, 105415. <https://doi.org/10.1016/j.eneco.2021.105415>
- Yue, M., & Nedopil, C. (2025). China green finance: Status and trends 2024–2025. [https://greenfdc.org/wp-content/uploads/2025/03/Yue-and-Nedopil-2025\\_China-green-finance-status-and-trends-2024-2025-final.pdf](https://greenfdc.org/wp-content/uploads/2025/03/Yue-and-Nedopil-2025_China-green-finance-status-and-trends-2024-2025-final.pdf)
- Zhang, S., Wu, Z., Wang, Y., & Hao, Y. (2021). Fostering green development with green finance: An empirical study on the environmental effect of green credit policy in china. *Journal of Environmental Management*, *296*, 113159.
- Zhou, X., Tang, X., & Zhang, R. (2020). Impact of green finance on economic development and environmental quality: A study based on provincial panel data from china. *Environmental Science and Pollution Research*, *27*(16), 19915–19932.
- Zhu, F., Liu, Z., & Kong, X. (2024). The effect of green credit policy on carbon emissions. *Scientific Reports*, *14*, 1234.
- Z/Yen Group & Finance Watch. (2025). Global green finance index 15. <https://www.longfinance.net/programmes/financial-centre-futures/global-green-finance-index/>