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Fiscal Policy and CO₂ Emissions: A Disaggregated Analysis of the Transmission Channels and the Complementarity Between Taxation and Spending Policies

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Abstract

This paper examines the role of fiscal policy in shaping CO₂ emissions for a sample of 23 countries, including the Euro Area, the United States, Canada, and China, over the period 2000–2023. The analysis moves beyond aggregate fiscal measures to identify taxes and expenditure categories contributing most to reduce CO₂ emissions. We investigate the transmission channels through which fiscal policy affects environmental outcomes and address potential non-linear fiscal effects. The study also highlights the critical role of recycling fiscal resources toward environmentally relevant expenditures. The System GMM results suggest that some market-based mechanisms and targeted public expenditure contribute to reducing CO₂ emissions, while other fiscal tools exhibit opposite or context-dependent effects. A non-linear relationship is detected for compliance emissions. Moreover, results reveal that supply-side and demand-side transmission channels generate contrasting effects on emissions. Finally, the effectiveness of environmental fiscal policies is shown to depend critically on the pattern of fiscal revenue recycling. These results provide important insights for the design of effective fiscal strategies aiming to achieve climate objectives.

Keywords: fiscal policy; CO₂ emissions; carbon pricing; environmental taxation; government spending; transmission channels; SGMM



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1. Introduction

Climate change represents one of the major challenges threatening sustainable development, economic stability, and human well-being on a global scale. Rising greenhouse gas (GHG) emissions, particularly carbon dioxide (CO₂), are driving a wide range of environmental disruptions, from ecosystem degradation and extreme weather events to long-term risks to public health and macroeconomic stability. Consequently, the international community has implemented ambitious policy frameworks: the Paris Agreement 2015 committed countries to ambitious decarbonization objectives, while the United Nations 2030 Sustainable Development Goals embedded climate actions across the economic and social dimensions. Similarly, the European Green Deal opted for carbon neutrality within the EU by 2050. Within this global context, governments hold a central position, as they control

the fiscal and regulatory tools necessary to reshape economic behavior and accelerate the decarbonization process.

Fiscal policy, through taxation and government expenditure, represents a major lever for an effective environmental transition. On the revenue side, environmental taxes and compliance-related fiscal instruments are designed to internalize negative externalities by increasing the cost of carbon-intensive activities, thereby promoting cleaner production and consumption behaviors. On the expenditure side, public spending can directly finance environmental protection, pollution abatement, and research and development in low-carbon technologies. Together, these instruments are expected to affect CO₂ emissions through various mechanisms: scale effects (through economic expansion), composition effects (through structural transformation), technological effects (through innovation), and income effects (through higher demand for environmental quality).

Despite the recognized importance of fiscal policy in climate mitigation, empirical evidence remains mixed and often inconclusive. Some studies suggest that environmental taxation and targeted public spending contribute to reduce emissions, while others highlight limited or even counterproductive effects, depending on policy design, economic structure, and institutional context. These contradictory findings reflect three fundamental limitations in the existing literature. First, most studies rely on highly aggregated fiscal indicators, such as total tax revenue or overall public expenditure, thereby neglecting the heterogeneous effects produced by specific fiscal tools. Secondly, taxation and expenditure are rarely analyzed jointly within a unified empirical framework. The complementarities and interactions between the two sides of the fiscal policy remain, therefore, underexplored. In addition, the transmission channels through which fiscal policies are expected to act on the production side and consumption side are often omitted, or, at best, analyzed separately. Finally, most empirical investigations rely on linear frameworks, thereby neglecting the existence of potential thresholds above which fiscal tools may produce the expected environmental outcomes.

This paper seeks to address these gaps by providing a disaggregated analysis of taxation and expenditure tools, investigating the relevant transmission channels, and addressing the non-linearity issue. We move beyond aggregate fiscal indicators predominant in the existing literature by providing a fully disaggregated analysis to capture the specific roles played by different compliance-based instruments, tax components, and expenditure categories, rather than treating fiscal policy as a single undifferentiated block. We also explicitly model two core transmission channels, relative to the production side and the consumption side, through which fiscal policy is expected to shape carbon emissions. Our empirical analysis further extends to the efficiency of fiscal recycling by examining whether environmental revenues are effectively translated into emission-reducing public spending. Previous literature has focused on public spending levels while neglecting the quality of the underlying fiscal recycling mechanism. Moreover, we address the non-linearity issue by investigating the existence of a critical threshold above which the compliance emissions tool contributes significantly to reduce emissions. Finally, our empirical framework includes the major economies of the Euro Area, the United States, Canada, and China, a setting which captures diverse institutional frameworks, energy structures, and climate policy approaches. We also control for the persistence of CO₂ emissions by considering a dynamic panel data setting. We rely on the System GMM estimator [1,2], which addresses the endogeneity of fiscal instruments, the persistence of emissions, and unobserved cross-country heterogeneity, therefore providing robust empirical results.

The remainder of this paper is organized as follows. Section 2 provides a review of the relevant literature and a presentation of the theoretical background. Section 3 develops the conceptual framework and research hypotheses. Section 4 defines the empirical model,

describes the econometric methodology, and provides a preliminary statistical analysis of the data. Section 5 reports and discusses the main empirical results for the compliance revenues, taxes, and transmission channels. Results relative to public expenditure and fiscal recycling are summarized and discussed in Section 6. Finally, Section 7 concludes, provides policy recommendations, and discusses the main limitations of this study.

2. Literature Review

Economic Rationale and Empirical Evidence

Climate change is widely considered as a global negative externality imposing high costs on society. Early contributions in welfare economics established that decentralized market outcomes fail to account for such social costs, generating inefficient levels of pollution and environmental deterioration [3]. Within this framework, Pigouvian taxation provides the theoretical benchmark for a corrective fiscal design: environmental taxes set at a marginal social cost restore allocative efficiency by aligning private incentives with social welfare [4,5]. This approach remains relevant to modern environmental policy, particularly in the design of carbon pricing mechanisms.

More recent contributions reframed climate change, considering that it represents a major macroeconomic and systemic risk with long-run implications for growth, investment, and capital allocation. The Stern Review (2008) [6] characterized climate change as an unprecedented failure of global markets, requiring an immediate and large-scale intervention. In this respect, Acemoglu et al. (2012) [7] demonstrated that directed technical change plays a crucial role in long-run environmental outcomes, suggesting that fiscal policy should not only correct for externalities through pricing, but should also actively redirect technological innovations towards cleaner production systems. This dual mandate (correcting prices and fostering innovation) defines the scope of modern climate-oriented fiscal policy.

A large strand of the literature examined the environmental effectiveness of fiscal policies relying on price-based mechanisms. Building on the Pigouvian framework, environmental taxes including carbon taxes, energy levies, and pollution charges are perceived as corrective tools aiming to re-align private incentives with social welfare by increasing the relative cost of carbon-intensive activities [4,8]. Empirical and theoretical studies have consistently highlighted that such instruments influence both firms and households: on the production side, higher energy and carbon costs foster green-technology adoption and energy efficiency improvements, while on the consumption side, households express a higher demand for less carbon-intensive goods and services.

Recent evidence provides robust support for environmental taxation. Jabeen et al. (2025) [9] demonstrated that environmental tax revenues contribute significantly to reduce CO₂ intensity, while facilitating a structural transition toward sustainable energy systems. Zhang et al. (2025) [10] found that environmental taxes in China reduced carbon emissions by approximately 5.6% through improvements in energy efficiency, increased green R&D investment, and industrial upgrading. Bashir et al. (2023) [11] emphasized that taxation represents a central pillar of ecological sustainability, particularly when implemented with complementary instruments. Consistent with this view, Kaplan Donmez (2026) [12] showed that both carbon taxes and emissions trading systems significantly reduced CO₂ emissions across OECD countries. From a broader cross-country perspective, recent empirical evidence suggests that fiscal instruments, including corporate taxation, environmental taxes, and carbon pricing mechanisms, produce significant long-term effects on CO₂ emission paths. Studies have mainly highlighted the role of fiscal policies in encouraging cleaner production processes, promoting energy efficiency, and supporting the transition toward low-carbon economies [10,13,14].

However, the effectiveness of environmental taxation is not uniform across economic contexts. Its impact depends critically on tax design, stringency, coverage, and institutional integration. In this respect, Goulder (1995, 2013) [15,16] highlighted the existence of a tax-interaction effect and a revenue-recycling effect, according to which the efficiency of environmental taxation depends on how revenues are used within the fiscal system: revenues reallocated to reduce distortionary taxes can generate a 'double dividend', while misallocation of fiscal resources may generate efficiency losses. Moreover, Lilliestam et al. (2025) [17] argued that weak stringent taxes may fail to induce meaningful behavioral changes, particularly in the presence of inelastic energy demand or limited technological substitution. In this vein, Ali and Ali (2026) [18] showed that both environmental tax levels and environmental policy stringency significantly reduced CO₂ emissions in OECD countries, reinforcing the role of regulatory frameworks in determining fiscal policy effectiveness. Such results suggest that the success of environmental taxation is contingent on the structural and institutional characteristics of the economy.

Government expenditure plays a complementary and increasingly central role in climate mitigation through financing green infrastructure, supporting innovation ecosystems, and reducing the costs of the low-carbon transition. Accordingly, Hasan et al. (2026) [19] found that environmentally aligned government expenditure significantly reduces emissions, particularly when associated with renewable energy dynamics. Wang et al. (2024) [20] highlighted that green fiscal policies contribute to reducing carbon emissions mainly by promoting green innovation. Yilmaz (2025) confirmed that environment protection expenditure represents a primary fiscal tool through which governments may operationalize climate commitments [21]. Various studies emphasized that the composition of public spending is a crucial issue. In this respect, Lopez et al. (2011) [22] argued that it is not the level of spending but its allocation to education, R&D, and environmental protection that triggers environmental improvements. Halkos and Paizanos (2013, 2016) [23,24] confirmed that government spending contributes to limiting polluting emissions through direct and indirect channels, with targeted environmental protection expenditure generating the strongest and most consistent effects. On the other hand, Di Bucchianico et al. (2025) [25] highlighted structural changes in the relationship between government spending and CO₂ emissions. While earlier fiscal expansions were associated with increased polluting emissions through the scale effect, this relationship changed significantly due to increased tertiarization and binding environmental regulations.

Empirical studies also emphasized the role of fiscal transparency and institutional quality in shaping environmental expenditure effectiveness. Zhou et al. (2025) [26] showed that fiscal transparency enhances the environmental impact of public spending by improving institutional credibility and facilitating private green investment. These findings support the idea that expenditure effectiveness is conditional on governance effectiveness and the quality of public resources management.

Another stream of the literature emphasized that the effectiveness of environmental fiscal policy cannot be understood by analyzing taxation and expenditure separately. Their interaction, composition, and the channels through which they act jointly determine their final environmental outcomes. In this respect, Goulder (1995) [15] and Bovenberg and Goulder (1996) [27] argued that the optimal carbon tax is endogenous to the structure of the broader fiscal system, including interactions with pre-existing labor and capital taxes. Wu et al. (2026) [28] provided global evidence showing that carbon pricing instruments are significantly shaped by their interaction with complementary policies, including subsidies, regulatory instruments, and public investment, arguing that the coherence of the overall policy mix determines its effectiveness. Such conclusions are corroborated by Fernández-Marín et al. (2026) [29], who found that comprehensive and diversified policy mixes,

combining carbon pricing, taxation, and investment in renewable energy, outperform reliance on single instruments in reducing CO₂ emissions.

The literature identified five main transmission channels through which fiscal policy affects carbon emissions: (i) the production-side channel, where taxation raises the cost of carbon-intensive inputs and promotes technological innovation and industrial restructuring; (ii) the demand-side channel, where fiscal expansion stimulates aggregate demand and income-driven energy use; (iii) the price and incentive channel, according to which carbon pricing modifies relative prices and guides investment toward cleaner alternatives; (iv) the fiscal recycling and compensation channel, through which resources management and redistribution enhance both policy effectiveness and social acceptability; and (v) the institutional and policy interaction channel, which emphasizes the role of governance quality and policy coordination in shaping the transmission of fiscal incentives. Among these channels, the production-side and demand-side channels provide the most robust empirical evidence. In this respect, Wang et al. (2024) [20] and Zhou et al. (2025) [26] confirmed that green innovation, energy efficiency gains, and industrial upgrading are the main mechanisms through which environmental fiscal policies contribute to reduced emissions. On the other hand, Di Bucchianico et al. (2025) [25] and Hasan et al. (2026) [19] showed that the demand-side channel effectiveness depends on the private consumption patterns and structural characteristics of the economy.

Another important issue concerns the role of fiscal revenue allocation in shaping policy effectiveness. The double dividend hypothesis (Goulder, 1995) [15] suggests that environmental taxes can simultaneously improve environmental quality and enhance economic efficiency when revenues are recycled into productive uses. However, empirical evidence reveals the uncertainty of this outcome. Köppl and Schratzenstaller (2023) [30] showed that the probability of achieving a double dividend varies significantly across recycling schemes: reductions in social security contributions generate positive environmental outcomes, while lump-sum transfers are far less effective. Zhoo et al. (2025) [26] confirmed that carbon tax recycling through innovation-oriented investments is essential to achieve successful low-carbon transitions. However, Combet et al. (2025) [31] emphasized that governments face an efficiency–equity trade-off when implementing fiscal recycling policies, while Liljestam et al. (2025) [32] argued that carbon taxes are often set at relatively low levels and may serve fiscal rather than environmental objectives. Public acceptability is another relevant factor. Magnetti et al. (2024) [33] and Maestre-Andrés et al. (2021) [34] found that providing information on revenue use, particularly earmarking for environmental purposes, significantly increases public support for carbon pricing. These findings motivate our explicit analysis of allocation efficiency.

3. Research Hypothesis

Despite the important volume of empirical studies devoted to the environmental outcomes of fiscal policy, the literature review suggests that several important research gaps remain underexplored. In particular, we note a lack of evidence relative to the impact of disaggregated fiscal tools and their transmission channels. Moreover, the literature fails to assess the complementarity between the taxation and expenditure dimensions of fiscal policy. Finally, evidence relating to the recycling efficiency of fiscal revenues remains limited.

This paper tries to address these gaps by conducting a disaggregated analysis of the compliance fiscal tools, environmental tax components, and government expenditure structure within a dynamic panel framework. We also try to highlight the main transmission channels and address the allocation efficiency in order to provide a more comprehensive

and policy-relevant understanding of how fiscal policy may contribute to limiting CO₂ emissions more effectively.

Building on the theoretical framework and empirical review, we develop five hypotheses dealing with distinct analytical dimensions: the aggregate effect of compliance-based instruments, the non-linear effects of emission compliance tools, the transmission channels of fiscal policy, the disaggregated effects of environmental taxes, and the effectiveness and efficiency of government expenditure.

H1. *Market-based compliance instruments contribute to reducing CO₂ intensity.*

Based on the Pigouvian framework, carbon-related fiscal instruments, including compliance revenues and prices, are expected to internalize the social cost of emissions by raising the marginal cost of carbon-intensive activities. They should mainly trigger incentives to adopt cleaner technologies, improve energy efficiency, and reduce fossil fuel dependence [9,35]. Carbon-related fiscal instruments (compliance revenue and compliance price) are, therefore, expected to produce a negative and statistically significant effect on CO₂ emissions, reflecting the emission-reducing role of market-based carbon pricing when properly designed and sufficiently stringent.

H2. *Emission compliances are producing non-linear effects on carbon intensity.*

Emission compliance is expected to reduce CO₂ emissions by constraining polluting activities through regulatory pressure. However, the effectiveness of compliance mechanisms is unlikely to be strictly linear: below a threshold of enforcement intensity or regulatory stringency, compliance requirements may fail to induce meaningful behavioral changes [16,32]. Threshold effects are therefore expected. Emission compliance is expected to negatively affect CO₂ intensity once a minimum level of regulatory enforcement and coverage is reached.

H3. *Production and consumption transmission channels generate opposite effects on CO₂ emissions.*

Compliance-based fiscal instruments are expected to affect CO₂ intensity through two distinct channels, which may potentially produce opposite effects. On the production side, fiscal instruments raise the cost of carbon-intensive inputs, encouraging firms to improve energy efficiency, adopt cleaner technologies, and restructure industrial processes, therefore contributing to reduce emissions per unit of output [20,26]. On the consumption side, compliance revenues and associated income effects may stimulate aggregate demand and energy use, partially offsetting production-side gains, particularly in energy-dependent economies. Accordingly, two sub-hypotheses can be tested:

H3a. *The production-side channel reduces CO₂ intensity through technological innovation, energy efficiency improvements, and industrial restructuring.*

H3b. *The consumption-side channel increases CO₂ intensity through scale effects driven by higher aggregate demand and income-driven energy use.*

H4. *Disaggregated environmental taxes produce heterogeneous effects.*

Different environmental taxes operate through distinct mechanisms and, therefore, generate different environmental impacts [16]. This is consistent with Ugrinov (2025) [36], who found that, among environmental tax components, energy taxes are the most effective in reducing greenhouse gas emissions across EU countries, while pollution and resource

taxes exhibit comparatively weaker effects. Energy taxes, the largest component of environmental taxation, directly target fossil fuel use and are expected to yield the strongest and most consistent emission reductions. Transport taxes depend on vehicle use and ownership decisions, producing an indirect effect on emissions. Pollution and resource taxes, typically set at lower levels and covering narrower tax bases, may exhibit weaker or more context-dependent impacts depending on design and stringency. Accordingly, different environmental taxes are expected to produce heterogeneous effects on CO₂ intensity: energy taxes should lead to the strongest reductions, while pollution and resource taxes should exhibit more limited or context-dependent effects depending on policy design and stringency.

H5. *Government expenditure and fiscal allocation efficiency contribute to reducing CO₂ intensity.*

Higher government spending on environmental protection, pollution abatement, and R&D are expected to reduce CO₂ intensity through complementary mechanisms: direct mitigation of pollution sources, and long-term structural transformation through innovation support [24,37]. However, the efficiency of fiscal recycling, defined as the degree to which compliance revenues are effectively translated into environmental expenditure, is expected to vary substantially across spending categories. Some spending categories may exhibit weaker linkages with fiscal inputs, depending on the effectiveness of the revenue–expenditure transmission mechanisms [29,30,38].

H5a. *Government expenditure on environmental protection, pollution abatement, and energy/environment R&D are expected to reduce CO₂ intensity, reflecting their role in directly mitigating emissions and promoting low-carbon technological innovation [7,8,20,39].*

H5b. *The recycling of compliance revenues into emission-reducing expenditure fosters CO₂ reductions.*

4. Model, Sample, and Methodology

4.1. Model Specification

To assess the impact of fiscal policy on CO₂ emissions, we estimate the empirical model defined by the following equation:

$$CO_2_{i,t} = \alpha CO_2_{i,t-1} + \beta' X_{i,t} + \gamma' Z_{it} + u_i + \varepsilon_{i,t}, \quad (1)$$

where X_{it} and Z_{it} are matrices regrouping control and independent variables, respectively. u_i are country fixed effects, while ε_{it} is the stochastic error term.

The dependent variable is CO₂ emission intensity (CO₂), measured as kilograms of CO₂ equivalent per constant 2021 USD of GDP. This metric captures the carbon intensity of economic activity and reflects how efficiently an economy decouples growth from carbon emissions, making it directly relevant for assessing the environmental effectiveness of fiscal policy.

The independent variables set (Z_{it}) includes compliance variables, disaggregated fiscal taxes, and categories of government expenditure. Three compliance variables capture market-based carbon pricing instruments, encompassing both emissions trading systems (ETs) and carbon taxes:

- Compliance Revenue (ComRev) measures the public revenue generated by carbon pricing mechanisms from carbon tax payments or from auctioning emission allowances under an ETS in millions of USD.

- Compliance Price (ComPrice) captures the cost per ton of CO₂ paid to comply with a carbon pricing policy, either as a fixed carbon tax rate or as the market price of emission allowances (USD/t CO₂).
- Compliance Emissions (ComEm) represents the share of GHG emissions covered by a carbon pricing instrument, reflecting the extent of regulatory coverage.

Four disaggregated environmental taxes, all expressed as a percentage of GDP, are included in the model:

- Energy taxes (EngyTax) are levied on energy products, including fuels used for transport. This is the largest and most directly carbon-related tax component.
- Transport taxes (TranspTax) are imposed on vehicle ownership and use, excluding fuel-related taxes.
- Pollution taxes (PolTax) target pollutant emissions to air, water, or soil.
- Resource taxes (RessTax) are levied on the extraction or use of natural resources.

We also include total environmental taxes (EnvTax) and total tax revenue (Taxrev) as aggregate fiscal policy indicators.

In parallel, we retain five categories of government expenditure:

- Expenditure on environmental protection as a percentage of GDP (ExpEnv) covers public and private spending devoted to preventing, reducing, or eliminating environmental damage.
- Expenditure on pollution abatement as a percentage of GDP (ExpPol) targets controlling or reducing air, water, and soil pollution.
- Expenditure on biodiversity and landscape protection as a percentage of GDP (ExpLB) covers conservation spending.
- Government allocations for R&D in environment (RDEnv) and energy (RDEngy) capture public investment in environmental and energy technologies, respectively.

Five control variables are included to account for structural determinants of CO₂ intensity. GDP per capita (GDPpc) captures economic development and the potential EKC relationship. Governance quality (GovQual) is the average of the six World Bank World-wide Governance Indicators (Voice and Accountability, Political Stability, Government Effectiveness, Regulatory Quality, Rule of Law, and Control of Corruption), ranging from −2.5 to +2.5, and reflecting institutional development. Forest area (ForArea) is a proxy for natural carbon absorption capacity. Total natural resource rents (NatRents) captures structural dependence on resource extraction. Energy intensity (EngyInt) is a measure of the energy efficiency of the economy.

Table 1 summarizes the definitions, units, and sources of the variables.

Table 1. Definitions and sources of the variables.

Variables	Description	Unit	Source
CO ₂	CO ₂ emissions per unit of GDP (dependent)	kg CO ₂ e/2021 USD	World Bank WDI/Climate Watch
ComRev	Carbon pricing compliance revenue	USD millions	World Bank Carbon Pricing Dashboard
ComPrice	Carbon compliance price (ETS or carbon tax)	USD/tCO ₂	World Bank Carbon Pricing Dashboard
ComEm	Share of GHG emissions covered by carbon pricing	Percentage	World Bank Carbon Pricing Dashboard
EnvTax	Total environmental taxes	Percentage of GDP	OECD/IMF
EngyTax	Taxes on energy products (incl. transport fuels)	Percentage of GDP	OECD/IMF

Table 1. *Cont.*

Variables	Description	Unit	Source
TranspTax	Taxes on transport (excl. fuel taxes)	Percentage of GDP	OECD/IMF
PolTax	Taxes on pollution	Percentage of GDP	OECD/IMF
RessTax	Taxes on resource extraction	Percentage of GDP	OECD/IMF
ExpEnv	Expenditure on environmental protection	Percentage of GDP	IMF GFS
ExpPol	Expenditure on pollution abatement	Percentage of GDP	IMF GFS
ExpLB	Expenditure on biodiversity and landscape	Percentage of GDP	IMF GFS
RDEnv	Public R&D for environment	Millions EUR	OECD
RDEngy	Public R&D for energy	Millions EUR	OECD
GDPpc	GDP per capita (constant)	Thousands USD	World Bank WDI
GovQual	Governance quality index	Index [−2.5, +2.5]	World Bank WGI
ForArea	Forest area as share of land	Percentage of land area	AQUASTAT
NatRents	Total natural resource rents	Percentage of GDP	World Bank
EngyInt	Energy supply relative to GDP	MJ/2011 USD PPP	World Bank

Note: Variable definitions and data sources compiled by the authors.

4.2. Sample and Econometric Methodology

The sample includes the 20 Euro Area (ECB) countries (Austria, Belgium, Croatia, Cyprus, Estonia, Finland, France, Germany, Greece, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Portugal, Slovakia, Slovenia, and Spain) alongside the United States, Canada, and China. These countries were selected for three main reasons. First, they represent a mix of advanced and emerging markets with different levels of institutional quality, energy dependence, and environmental regulation intensity. Secondly, some countries are among the largest global GHG emitters and are key contributors to international climate policy design. Finally, they differ substantially in their carbon taxation policies, emissions trading systems (ETSs), environmental levies, and public spending schemes, providing a rich empirical setting to assess fiscal policy effectiveness. The sample period (2000–2023) captures both the gradual evolution of climate policy frameworks and the structural shifts induced by the 2008 financial crisis, post-crisis fiscal consolidation, and the more recent green fiscal stimulus legislation.

Table 2 provides the descriptive statistics for the variables included in the empirical model. The number of observations, ranging from 522 to 552, reflects some data availability constraints across countries and time periods. This variation stems mainly from differences in reporting coverage across the underlying data sources: variables drawn from harmonized international databases, such as GDP per capita and governance quality, are available for the full sample, while some environmental taxes and expenditure categories present minor gaps for a limited number of country-years, reflecting differences in national reporting practices to the OECD, IMF, and World Bank. The System GMM estimator accommodates this unbalanced panel structure.

The dependent variable (CO₂) exhibits substantial variability, with a mean of 207.23 kg CO₂ per USD of GDP and a standard deviation of 122.40, reflecting heterogeneous environmental performance across countries. The important gap between the minimum and maximum values (from 51.13 to 779.42) supports the existence of structural differences in energy systems within the sample countries.

Table 2. Descriptive statistics.

Variable	Obs.	Mean	Std. Dev.	Min.	Max.
CO ₂	552	207.23	122.40	51.13	779.42
GDPpc	552	32.64	21.42	2.19	112.42
GovQual	552	1.04	0.526	−0.62	1.95
ForArea	552	34.23	16.37	1.09	73.74
NatRents	552	0.62	1.097	0.00	9.65
EngyInt	552	4.09	1.753	0.97	10.91
ComRev	552	245.32	1215.14	0.00	11,679.87
ComPrice	552	6.36	15.34	0.00	90.50
ComEm	528	0.009	0.027	0.000	0.094
TranspTax	552	0.542	0.408	0.00	2.19
EnvTax	522	2.442	0.855	0.38	4.64
PolTax	552	0.106	0.140	0.00	2.00
EngyTax	552	1.729	0.702	0.24	3.79
RessTax	552	0.044	0.071	0.00	0.40
ExpEnv	542	0.750	0.366	0.07	1.92
ExpLB	541	0.076	0.066	0.00	0.298
ExpPol	539	0.110	0.152	0.00	1.033
RDEnv	552	249.55	414.85	0.00	2418.80
RDEngy	552	602.53	1360.27	0.00	13,681.96

Note: Descriptive statistics computed by the authors.

Similarly, the descriptive statistics suggest that countries are adopting different carbon pricing policies. The compliance revenue (ComRev) displays an extreme right-skewness (mean of 245 million USD and a maximum of 11,680 million USD), reflecting the dominance of the EU ETS and California cap-and-trade system. Compliance price (ComPrice) exhibits an average of \$6.36 per ton of CO₂ but ranges up to \$90.50, reflecting important disparities in terms of carbon pricing across legislations. Compliance emissions (ComEm) are characterized by a low mean value (0.94%), indicating that a large share of global emissions remains unpriced. Among the environmental tax components, energy taxes represent the dominant instrument (1.73% of GDP), while pollution and resource taxes remain marginal (mean values below 0.11% of GDP), indicating a limited reliance on these instruments. Public expenditure variables display substantial dispersion, particularly R&D spending, pointing to significant cross-country differences in innovation investments.

Table 3 summarizes the pairwise correlations, offering preliminary evidence on the relationships between CO₂ intensity and its main determinants. Energy intensity (0.855) and natural resource rents (0.721) exhibit the strongest positive correlations with CO₂ intensity, confirming that structural factors and resource dependence are major drivers of carbon intensity. Governance quality (−0.502) and GDP per capita (−0.355) display significant negative correlations, reflecting the role of economic development and institutional quality in promoting environmental performance.

Among fiscal variables, environmental taxes (−0.354) and energy taxes (−0.318) show meaningful negative correlations with CO₂ intensity, providing preliminary support for the emission-reducing role of taxation. Similarly, carbon compliance price (−0.222) and compliance revenue (−0.158) show moderate negative associations. However, compliance emissions exhibit a positive correlation (0.429), which suggests an endogeneity pattern: higher-emitting countries are adopting more extensive compliance systems. Pollution taxes (0.070) and resource taxes (0.172) show weak and positive correlations, suggesting limited instrument stringency or narrow coverage. Expenditure variables display generally weak correlations with emissions, consistent with the expectation that their effects are indirect and channel-dependent. The high correlation between energy taxes and environmental taxes (0.855) signals potential multicollinearity, suggesting that these variables should be included alternately in the model. These patterns collectively motivate a dynamic panel approach to properly account for persistence, endogeneity, heterogeneity, and structural differences.

Table 3. Correlation matrix of the variables.

Variable	CO ₂	ComRev	ComPrice	ComEm	EnvTax	EngyTax	TranspTax	PolTax	RessTax	ExpEnv	ExpPol	ExpLB	RDEnv	RDEngy	GDPpc	GovQual	ForArea	NatRents	EngyInt
CO ₂	1.000																		
ComRev	−0.158	1.000																	
ComPrice	−0.220	0.479	1.000																
ComEm	0.423	−0.054	−0.138	1.000															
EnvTax	−0.350	−0.044	0.060	−0.240	1.000														
EngyTax	−0.314	−0.035	0.063	−0.397	0.854	1.000													
TranspTax	−0.159	−0.080	0.004	0.246	0.437	−0.043	1.000												
PolTax	0.071	0.171	0.110	0.031	−0.001	−0.060	−0.146	1.000											
RessTax	0.173	−0.124	−0.096	0.062	0.148	0.069	0.019	0.237	1.000										
ExpEnv	−0.095	−0.022	−0.180	0.251	0.100	−0.018	0.083	0.365	0.289	1.000									
ExpPol	−0.111	−0.027	−0.053	−0.153	0.150	0.196	−0.065	0.009	0.196	0.399	1.000								
ExpLB	−0.137	−0.020	−0.006	0.186	0.233	0.135	0.096	0.220	0.058	0.438	−0.060	1.000							
RDEnv	0.115	0.400	0.069	0.203	−0.402	−0.293	−0.243	0.219	−0.077	0.038	−0.090	−0.150	1.000						
RDEngy	0.541	0.136	−0.011	0.491	−0.585	−0.527	−0.205	0.164	0.065	0.001	−0.160	−0.258	0.671	1.000					
GDPpc	−0.352	0.085	0.199	−0.280	−0.173	−0.143	−0.057	−0.056	−0.183	0.020	0.061	0.022	0.015	−0.081	1.000				
GovQual	−0.501	0.083	0.209	−0.468	0.174	0.048	0.211	0.017	−0.076	−0.036	0.076	0.161	−0.159	−0.465	0.654	1.000			
ForArea	0.048	0.053	0.318	−0.438	0.182	0.414	−0.348	−0.027	−0.085	−0.495	−0.035	−0.176	−0.108	−0.153	−0.098	0.118	1.000		
NatRents	0.719	−0.079	−0.029	0.350	−0.326	−0.285	−0.228	0.045	0.279	−0.122	−0.085	−0.128	0.070	0.469	−0.284	−0.434	0.101	1.000	
EngyInt	0.855	−0.081	−0.057	0.238	−0.344	−0.281	−0.244	0.161	0.202	−0.149	−0.083	−0.241	0.134	0.476	−0.340	−0.340	0.296	0.667	1.000

Note: Pearson correlation coefficients (lower triangular matrix). Source: Elaborated by authors using Stata 17.0 (StataCorp LLC, College Station, TX, USA) software.

To estimate model (1), we rely on the System GMM estimator proposed by Arellano and Bover (1995) [1] and Blundell and Bond (1998) [2] and implemented via `xtabond2` (Roodman, 2009) [40]. This estimator is relevant to our empirical framework for several reasons. First, it allows control for the persistence of CO₂ emissions by including the lagged dependent variable among the independent variables. The lagged dependent variable induces a first order correlation among residuals, which affects the consistency of the standard panel data estimators. Secondly, several fiscal instruments, particularly tax revenues and expenditures, may exhibit reverse causality with CO₂ emissions, leading to an endogeneity problem. The System GMM provides a relevant framework for addressing persistence and endogeneity by using the second and higher lags of the independent variables as instruments. This estimator is also consistent to measurement errors and omitted variable problems which can lead to biased estimates. Moreover, the Difference GMM developed by Arellano and Bond (1991) [41] suffers from weak instrument problems, particularly when the dependent variable is highly persistent. The System GMM estimator addresses this issue by combining the level and first-difference equations, using lagged levels as instruments for the difference equation and lagged differences as instruments for the level equation. Finally, this estimator accounts for country-specific fixed effects which control unobserved heterogeneity across countries.

To avoid the proliferation of instruments, which can lead to an overfit of the endogenous variables, we restrict the instruments' set to a maximum of two lags for each independent variable. We report the two-step estimator with Windmeijer (2005) [42] finite-sample corrected standard errors. The validity of the GMM specification is assessed through standard diagnostic tests: the Arellano–Bond AR(1) and AR(2) tests for first- and second-order autocorrelation of residuals (the validity of the model requires the absence of second order residual correlation), and the Sargan–Hansen overidentification test, which evaluates the joint validity of the instruments. The non-rejection of the null hypothesis (p values associated with the calculated Sargan–Hansen statistic exceeding 0.1) confirms the validity of the instruments' set.

5. The Impact of Compliance-Based Instruments and Taxes on CO₂ Emissions

5.1. Compliance-Based Instruments

We first assess the contribution of compliance-based instruments to limit CO₂ emissions within the sample countries. The empirical model is defined as follows:

$$CO_{2\ i,t} = \alpha CO_{2\ i,t-1} + \beta_1 GDPpc_{i,t} + \beta_2 GovQual_{i,t} + \beta_3 ForArea_{i,t} + \beta_4 NatRents_{i,t} + \beta_5 EngyInt_{i,t} + \gamma Compliance_{i,t} + u_i + \varepsilon_{i,t}, \quad (2)$$

where *Compliance*_{*i,t*} denotes the following compliance fiscal tools introduced alternately into the model: compliance revenues (*Comrev*_{*i,t*}), compliance carbon prices (*Comprice*_{*i,t*}), and compliance emission markets (*Comemm*_{*i,t*}).

Results are summarized in Table 4. The AR(2) test confirms the absence of second-order serial correlation, while the Hansen test attests the validity of the instruments, ensuring the reliability of our estimates. Estimation results reveal the persistence of CO₂ emissions, evidenced by the strong and highly significant coefficient of the lagged dependent variable across all specifications (0.774–0.821).

Among the market-based instruments, both compliance revenue (*ComRev*) and compliance price (*Comprice*) produce negative and statistically significant effects on CO₂ intensity. These findings suggest that carbon-related fiscal mechanisms reduce emissions through two complementary channels. First, a price effect, where higher carbon costs raise the relative cost of pollution-intensive activities, generating incentives to adopt cleaner tech-

nologies and improve energy efficiency. Secondly, an income effect, where fiscal pressure induces behavioral adjustments in production and consumption patterns. These results are consistent with the broader literature on market-based environmental instruments [9,35]. These results provide strong empirical support for hypothesis H1, confirming that market-based compliance instruments significantly contribute to reducing CO₂ intensity, in line with the Pigouvian framework underlying our theoretical expectations.

Table 4. The impact of compliance-based instruments on CO₂ emissions.

Variables	ComRev	ComPrice	ComEm	ComEm ²	ComEm < 0.047
L.CO ₂	0.774 *** (0.0341)	0.821 *** (0.0460)	0.780 *** (0.0373)	0.566 *** (0.0560)	0.633 *** (0.0322)
GDPpc	0.158 ** (0.0741)	0.107 *** (0.0392)	0.152 * (0.0793)	−0.0232 (0.101)	0.240 ** (0.102)
GovQual	−7.940 *** (2.488)	−5.522 * (3.063)	−9.188 *** (3.279)	−2.950 (7.363)	−3.402 (6.332)
ForArea	−0.449 *** (0.113)	−0.270 *** (0.0816)	−0.410 *** (0.0960)	−0.919 *** (0.287)	−0.775 *** (0.128)
NatRents	0.453 (0.540)	1.721 *** (0.516)	0.529 ** (0.222)	−8.619 *** (3.149)	−2.150 (1.489)
EngyInt	17.95 *** (2.749)	13.24 *** (3.491)	17.10 *** (3.000)	33.74 *** (4.643)	30.41 *** (3.009)
ComRev	−0.000706 *** (0.000118)				
ComPrice		−0.147 *** (0.0329)			
ComEm			−39.94 (55.28)	−20,029 *** (5598)	−10,039 *** (3321)
ComEm ²				213,710 *** (59,632)	
Constant	−11.67 *** (3.802)	−9.137 *** (2.348)	−9.935 * (5.605)	11.85 (12.31)	−19.46 *** (6.367)
Nb. Of Obs.	529	529	506	506	460
Nb. of Countries	23	23	22	22	20
AR(1) Prob.	0.097	0.099	0.106	0.107	−0.150
AR(2) Prob.	0.239	0.243	0.246	0.244	0.267
Hansen Prob.	0.197	0.227	0.176	0.287	0.291

Note: Robust standard errors in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. AR(1) Prob and AR(2) Prob correspond to the *p* values of the Arellano and Bond first- and second-order autocorrelation tests. Hansen Prob is the *p* value of the Sargan–Hansen overidentification test. Source: Estimation results obtained by authors using Stata software.

Oppositely, emission compliance (ComEm) does not yield a statistically significant linear effect on CO₂ intensity. While its negative sign aligns with theoretical expectations, the absence of significance for the full sample suggests that compliance-based regulatory mechanisms do not produce a sufficiently uniform and robust influence on company behavior. This finding reflects weak enforcement capacity, limited monitoring, or non-stringent legal penalties.

The estimated control variables exhibit the expected signs and remain largely consistent across all model specifications. Energy intensity emerges as the strongest structural determinant of CO₂ intensity, with a positive and highly significant coefficient ranging from 17.10 to 33.74 (*p* < 0.01), confirming that energy-inefficient production systems substantially hinder decarbonization efforts. Natural resource rents also produce a positive and statistically significant effect, with coefficients varying between 0.529 (*p* < 0.05) and 1.721 (*p* < 0.01), supporting the resource-dependence hypothesis that resource-rich economies tend to generate higher carbon emissions. In contrast, government quality exhibits a consistently negative

and highly significant impact, with coefficients ranging from -3.402 to -9.188 ($p < 0.01$), indicating that developed institutional frameworks enhance environmental governance and lead to significant emission reductions. Similarly, forest area is negatively associated with CO₂ intensity, with coefficients ranging between -0.270 and -0.919 ($p < 0.01$), highlighting the important role of natural carbon sinks in mitigating emissions. Overall, the stability of effects produced by the control variables across the five specifications reinforces the robustness of the estimated relationships reported in Table 4.

These findings provide a clear policy message. Price-based instruments, such as carbon revenues and carbon prices, are effective and robust tools for reducing CO₂ intensity, while regulatory compliance mechanisms remain insufficiently stringent. Strengthening enforcement capacity and implementing compliance schemes that account for non-linear threshold-dependent dynamics are therefore necessary for unlocking the full potential of compliance-based regulation.

The non-significant effect produced by emission compliance tools does not imply policy irrelevance. Rather, it provides motivation for exploring the existence of a threshold effect. To investigate for non-linearity, we estimate Equation (2) while introducing a quadratic term relative to the emission compliance variable (ComEm²):

$$CO_{2\ i,t} = \alpha CO_{2\ i,t-1} + ComEm\ \beta_1 GDPpc_{i,t} + \beta_2 GovQual_{i,t} + \beta_3 ForArea_{i,t} + \beta_4 NatRents_{i,t} + \beta_5 EngyInt_{i,t} + \gamma_1 ComEm_{i,t} + \gamma_2 ComEm^2_{i,t} + u_i + \varepsilon_{i,t}. \quad (3)$$

Results reported in column 4 of Table 4 show that the coefficient associated with ComEm is negative and significant, while its quadratic term is positive and significant, confirming the existence of a non-linear U-shaped relationship. The critical threshold can be estimated from the first-order condition:

$$ComEm^* = 20,029 / (2 \times 213,710) \approx 0.047.$$

This threshold implies that compliance generates meaningful emission reductions only up to a coverage level around 4.7% of regulated emissions. Below this threshold, greater compliance effectively constrains carbon-intensive activities. Above this threshold, legislation becomes too permissive and is not expected to produce any significant effect on emissions. Such results are consistent with Wang et al. (2019) [43] and Al Shammre et al. (2023) [44], who highlight regime-dependent and non-linear fiscal–environment relationships. These findings provide clear empirical support for hypothesis H2, confirming that emission compliance produces a non-linear, threshold-dependent effect on CO₂ intensity, rather than a uniform linear effect.

To confirm the robustness of these results, we estimate model (1) for the subsamples exhibiting compliance levels below and above the critical threshold, respectively. Results in Table 4 (column 5) reveal that the compliance emission variable (ComEm) produces negative and significant effects on CO₂ emissions below the critical threshold, confirming the effectiveness of stringent legal compliance frameworks. However, when the compliance level exceeds the threshold, the number of observations collapses to 46. For such a restricted sample size, the SGMM estimator drops nearly all the regressors, and fails to provide any reliable results. Overall, the empirical evidence suggests that the effectiveness of the compliance mechanisms is non-linear and conditional on regulatory stringency.

Further statistical investigations reveal that the countries exhibiting compliance emission levels exceeding the detected threshold are China and Malta, as shown in Figure 1 and Table 5. To ensure the robustness of our initial findings, we assess the sensitivity of our baseline results (Table 4) to the sample composition by excluding China and Malta from the

sample. The findings reported in Table 6 confirm the stability of the core conclusions. The restricted sample results show that the lagged dependent variable remains highly significant, reaffirming the persistence of CO₂ emissions. Energy intensity continues to produce a strong positive effect, while forest area and governance quality preserve their expected negative associations with emissions. We also notice that the compliance revenue and compliance price continue to produce negative and statistically significant effects, confirming their emission-reducing role when China and Malta do not figure among the sample countries. The coefficient associated with emission compliance (ComEm) remains negative and turns out to be significant, confirming the non-linear effect on carbon emissions. These results confirm that the baseline findings are robust to sample selection bias, and are not driven by the influence of any particular country. This robustness check further reinforces the empirical support for H1 and H2, confirming that these hypotheses hold independently of the influence of China and Malta which are adopting permissive compliance policies compared to other countries.

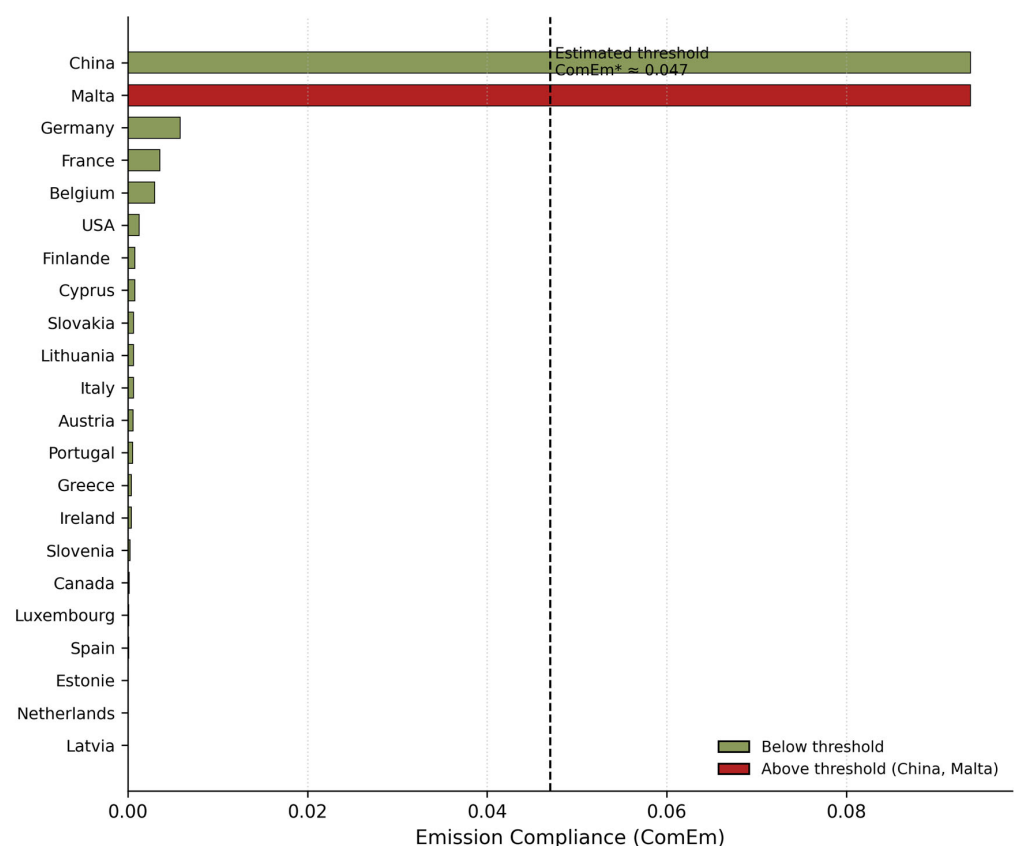


Figure 1. Country-level emission compliance and the estimated threshold. Source: Author's calculations.

Table 5. Emission compliance by country.

Country	ComEm	Position
China	0.0938	Above threshold
Malta	0.0938	Above threshold
Germany	0.0058	Below threshold
France	0.0036	Below threshold
USA	0.0013	Below threshold
Other countries (n = 17)	0.0000–0.0008	Below threshold

Note: Values are computed by authors and correspond to country-level mean values of ComEm.

Table 6. Results for the subsample, excluding China and Malta.

Variables	ComRev	ComPrice	ComEm
L.CO ₂	0.756 *** (0.0185)	0.718 *** (0.0227)	0.555 *** (0.0279)
GDPpc	0.260 *** (0.0738)	0.234 *** (0.0581)	−0.0641 (0.212)
GovQual	−12.79 *** (3.562)	−11.80 ** (5.747)	−0.967 (18.35)
ForArea	−0.398 *** (0.0771)	−0.231 * (0.134)	−0.665 ** (0.319)
NatRents	0.947 (1.527)	2.618 ** (1.052)	−5.475 *** (0.480)
EngyInt	19.37 *** (1.106)	18.88 *** (2.288)	30.42 *** (1.707)
ComRev	−0.000696 *** (0.000137)		
ComPrice		−0.227 *** (0.0569)	
ComEm			−12,710 * (7691)
Constant	−13.47 *** (4.912)	−10.04 ** (5.073)	8.819 (12.48)
Nb. Of Obs.	483	483	460
Nb. of Countries	21	21	20
AR(1) Prob.	0.117	0.097	0.118
AR(2) Prob.	0.223	0.215	0.236
Hansen Prob.	0.461	0.803	0.720

Note: Robust standard errors in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. AR(1) Prob and AR(2) Prob correspond to the *p* values of the Arellano and Bond first- and second-order autocorrelation tests. Hansen Prob is the *p* value of the Sargan–Hansen overidentification test. Source: Estimation results obtained by authors using Stata software.

The second step of our empirical investigation consists of examining the transmission channels through which compliance revenue contributes to shaping CO₂ intensity. To that end, two interaction terms are introduced in the model to account for the supply-side and demand-side channels. The first term, capturing the production channel, is the cross-product of compliance revenue and energy intensity ($EN \times CRev$ = energy intensity $\times$ compliance revenue). As compliance costs rise, firms face stronger incentives to substitute less energy-intensive technologies and cleaner production processes into their actual production process in order to reduce their fiscal exposure. The second term, accounting for the consumption channel, is the product of compliance revenue and GDP per capita ($GDP \times CRev$ = GDP per capita $\times$ compliance revenue). GDP per capita is often used as a proxy for aggregate consumption capacity. Therefore, this interaction term should reflect the extent to which firms pass on carbon-induced costs to consumers through higher prices, thereby reducing demand and indirectly constraining emission-generating consumption. Besides the effectiveness of these two channels, an additional objective assesses whether they operate consistently in reducing CO₂ intensity. Convergent negative effects across both interaction terms would provide robust evidence that carbon pricing produces meaningful emission reductions not only through its direct price effect on supply, but also through complementary demand-side reduction effects, confirming the dual transmission mechanisms of market-based fiscal instruments. The empirical models to assess the effectiveness of these transmission channels are defined as follows:

$$CO_{2\ i,t} = \alpha CO_{2\ i,t-1} + \beta_1 GDPpc_{i,t} + \beta_2 GovQual_{i,t} + \beta_3 ForArea_{i,t} + \beta_4 NatRents_{i,t} + \beta_5 EngyInt_{i,t} + \gamma (En_{i,t} \times CRev_{i,t}) + u_i + \varepsilon_{i,t}, \quad (4)$$

$$CO_{2\ i,t} = \alpha CO_{2\ i,t-1} + \beta_1 GDP_{pc,i,t} + \beta_2 GovQual_{i,t} + \beta_3 ForArea_{i,t} + \beta_4 NatRents_{i,t} + \beta_5 EngyInt_{i,t} + \gamma (GDP_{i,t} \times CRev_{i,t}) + u_i + \varepsilon_{i,t} \quad (5)$$

where “ $En_{i,t} \times CRev_{i,t}$ ” and “ $GDP_{i,t} \times CRev_{i,t}$ ” represent the interaction terms capturing the production and consumption channels, respectively.

The estimations results are reported in Table 7. They confirm that the two transmission channels act in opposite directions. The coefficient associated with $EN \times CREV$ is negative and statistically significant (-0.00199^{***}), confirming that the production channel produces its expected effect: higher compliance costs encourage firms to improve energy efficiency and restructure production toward less carbon-intensive technologies, generating direct emission reductions. This result is reinforced by the strong positive effect of energy intensity on emissions (7.550^{***}), confirming that reduced energy use per unit of output represents a primary driver of the decarbonization process. These results provide strong support for hypothesis H3a, suggesting that the production-side channel reduces CO_2 intensity through technological innovation and efficiency gains. These findings are consistent with Goulder (2013) [15], who emphasized that environmental fiscal instruments reshape production decisions through cost optimization. Similarly, Zhou et al. (2025) [26] showed that efficiency improvement is a key determinant of the environmental impact of fiscal policies.

Table 7. Transmission channels of fiscal policy.

Variables	EN × CREV	GDP × CREV
L.CO ₂	0.926 *** (0.0206)	0.729 *** (0.0251)
GDP _{pc}	0.0901 * (0.0462)	0.329 *** (0.0944)
GovQual	−9.166 ** (4.345)	−19.33 *** (5.503)
ForArea	−0.235 *** (0.0885)	−0.561 *** (0.172)
NatRents	0.347 (1.964)	3.303 (4.652)
EngyInt	7.550 *** (2.205)	24.27 *** (2.851)
ComRev	0.00563 *** (0.00127)	−0.00802 ** (0.00324)
EN × CRev	−0.00199 *** (0.000458)	
GDP × CRev		0.000182 ** (7.63×10^{-5})
Constant	−4.374 (3.541)	−17.68 *** (6.071)
Nb. Of Obs.	483	483
Nb. of Countries	21	21
AR(1) Prob.	0.099	0.118
AR(2) Prob.	0.218	0.228
Hansen Prob.	0.893	0.155

Note: Robust standard errors in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. AR(1) Prob and AR(2) Prob correspond to the p values of the Arellano and Bond first- and second-order autocorrelation tests. Hansen Prob is the p value of the Sargan–Hansen overidentification test. Source: Estimation results obtained by authors using Stata software.

On the other hand, the coefficient associated with $GDP \times CREV$ is positive and statistically significant (0.000182^{**}), suggesting that the consumption channel partially offsets the environmental gains generated by the supply channel. Higher GDP per capita

boosts consumption, generating a scale effect which intensifies CO₂ emissions. These findings confirm hypothesis H3b, according to which the consumption-side channel increases CO₂ intensity through income-driven scale effects. Such conclusions are in line with those of Goulder (2013) [15], which highlighted the income effects of climate policy, and those of Wang et al. (2024) [20], emphasizing the income-contingent dynamics of the fiscal–environment relationship.

In conclusion, the estimation results reveal that carbon pricing operates through dual and asymmetric transmission channels. The supply channel generates environmental improvements through technological adjustment, while the consumption channel introduces an offsetting scale effect driven by income-induced demand expansion. These asymmetric effects lead to an important policy implication: the net environmental effectiveness of compliance revenue depends critically on the relative strength of these two channels, suggesting that demand-side complementary policies, such as consumption taxes, are necessary to limit the extent of negative income-driven effects.

5.2. Disaggregated Analysis of Tax Components

To assess the environmental effectiveness of fiscal policy, we move to a disaggregated analysis of the impact of fiscal revenues on carbon emissions. In particular, we examine the effects produced by energy, pollution, environmental, resources, and transport taxes separately. The objective is to identify which fiscal tools contribute effectively to reducing emissions, and which are detrimental to achieving the targeted environmental objectives.

In line with the Pigouvian framework, a fiscal instrument is considered as environmentally effective if it produces a negative and statistically significant effect on CO₂ intensity, while a positive and significant coefficient suggests that the fiscal tool produces an environmentally counterproductive effect. The magnitude of the associated coefficients is used to rank instruments according to their relative effectiveness. The following empirical specification is estimated to evaluate the individual contribution of each fiscal instrument to CO₂ emission reduction:

$$CO_{2\ i,t} = \alpha CO_{2\ i,t-1} + \beta_1 GDPpc_{i,t} + \beta_2 GovQual_{i,t} + \beta_3 ForArea_{i,t} + \beta_4 NatRents_{i,t} + \beta_5 EngyInt_{i,t} + \gamma Taxes_{i,t} + \varepsilon_{i,t}, \quad (6)$$

where *Taxes*_{*i,t*} stands for one of the following taxes: tax revenues (*Taxrev*_{*i,t*}), transport taxes (*Transptax*_{*i,t*}), environmental taxes (*EnvTax*_{*i,t*}), energy taxes (*Engytax*_{*i,t*}), pollution taxes (*Poltax*_{*i,t*}), and resource taxes (*Resstax*_{*i,t*}).

The estimation results, summarized in Table 8, reveal important heterogeneities in the effects produced by the different taxes on CO₂ emissions, challenging the conventional assumption that environmental taxation automatically generates environmental gains.

First, we note that transport taxes produce a positive and highly significant effect on emissions (13.99 ***), suggesting that in economies characterized by intensive logistics networks and inelastic mobility demand, transport taxation fails to induce any corrective action on carbon emissions. Similar results are detected for aggregate environmental taxes (4.836 ***) and energy taxes (8.811 ***), which are associated with higher CO₂ intensity.

According to these results, these three instruments are classified as environmentally counterproductive, rather than merely “ineffective”, since their coefficients are positive and significant. Our results contrast with previous empirical findings for China [10] and G7 countries [9], showing that environmental and green taxes reduce emissions when embedded within coherent decarbonization strategies and supported by strong institutional frameworks. These divergences suggest that the fiscal policy outcome is highly context-dependent. Effectiveness is mainly conditional on policy stringency, energy system structure, and the degree of integration with broader decarbonization policies. In the

present sample, structural rigidities in energy demand and limited substitution possibilities seem to prevent these fiscal tools from inducing meaningful behavioral changes.

Table 8. Disaggregated effects of taxes on CO₂ emissions.

Variables	Transptax	EnvTax	EngytTax	PolTax	RessTax
L.CO ₂	0.779 *** (0.0337)	0.861 *** (0.0231)	0.849 *** (0.0272)	0.787 *** (0.0357)	0.881 *** (0.0147)
GDPpc	0.185 *** (0.0558)	0.197 *** (0.0400)	0.148 *** (0.0212)	0.146 ** (0.0607)	0.104 *** (0.0348)
GovQual	−11.57 *** (2.364)	−5.334 *** (0.983)	−3.518 *** (1.293)	−6.495 ** (2.661)	−4.357 *** (0.791)
ForArea	−0.250 *** (0.0550)	−0.322 *** (0.0476)	−0.443 *** (0.0910)	−0.423 *** (0.0876)	−0.305 *** (0.0490)
NatRents	0.0167 (0.319)	0.856 *** (0.242)	0.681 ** (0.274)	0.714 (0.536)	0.486 *** (0.184)
EngyInt	16.77 *** (2.706)	11.70 *** (1.545)	12.63 *** (1.940)	16.82 *** (2.870)	9.822 *** (1.038)
TranspTax	13.99 *** (3.368)				
EnvTax		4.836 *** (1.211)			
EngyTax			8.811 *** (1.426)		
PolTax				−16.07 ** (7.986)	
RessTax					−61.72 *** (23.26)
Constant	−19.89 *** (3.592)	−25.98 *** (3.734)	−26.67 *** (4.074)	−10.46 *** (3.964)	−6.230 *** (2.286)
Nb. Of Obs.	529	501	529	529	529
Nb. of Countries	23	23	23	23	23
AR(1) Prob.	0.109	0.107	0.100	0.093	0.098
AR(2) Prob.	0.242	0.233	0.243	0.237	0.233
Hansen Prob.	0.623	0.322	0.393	0.162	0.323

Note: Robust standard errors in parentheses. ** and *** denote significance at the 5% and 1% levels, respectively. AR(1) Prob and AR(2) Prob correspond to the *p* values of the Arellano and Bond first- and second-order autocorrelation tests. Hansen Prob is the *p* value of the Sargan–Hansen overidentification test. Source: Estimation results obtained by authors using Stata software.

Results also reveal that pollution taxes (−16.07 **) and resource taxes (−61.72 ***) produce strong and statistically significant negative effects on CO₂ intensity. Both instruments prove, therefore, to be environmentally effective, with resource taxes standing out as the most effective fiscal tool given the magnitude of its coefficient compared to that of pollution taxes. Such findings provide support to the Pigouvian hypothesis of internalized externalities: by directly targeting emission sources and resource extraction, taxes generate stronger behavioral responses, generating incentives to reduce resource dependency, restructure production, and adopt cleaner technologies. The particularly large magnitude of the resource tax coefficient suggests that taxing natural resource extraction is a structural lever for decarbonization, allowing the reshaping of the production process rather than leading to minor behavioral adjustments. These results offer partial support for hypothesis H4. While the predicted heterogeneous effects across tax instruments are confirmed, the expected ranking is not. H4 expected energy taxes to generate the strongest CO₂ reductions, while the empirical evidence suggests that resource and pollution taxes are the most effective instruments. Energy, transport, and aggregate environmental taxes are found to be counterproductive. H4 is therefore partially validated, and the hierarchy of tax effectiveness should be revised in light of these findings.

The estimated control variables exhibit consistent patterns across all specifications. GDP per capita produces a positive and statistically significant effect, confirming that economic expansion continues to increase CO₂ emissions through the scale effect. Energy intensity remains the most robust structural determinant of emissions, indicating that energy-inefficient production systems represent a major hurdle to decarbonization. Governance quality consistently displays a negative and significant coefficient, highlighting the crucial role of strong institutions in enhancing the environmental effectiveness of fiscal policies. Forest area is also negatively and significantly associated with CO₂ emissions, with coefficients ranging from -0.250 to -0.443 ($p < 0.01$), emphasizing the contribution of natural carbon sinks to climate mitigation. Oppositely, natural resource rents produce a positive effect, with coefficients varying between 0.486 and 0.856 ($p < 0.01$) and significant in three out of the five specifications, providing support to the resource-dependence hypothesis. Overall, the consistency of these control variables across the different models reinforces the robustness of the estimated relationships reported in Table 7.

These findings confirm that fiscal tools cannot be considered as an environmentally homogeneous policy block. Weak targeting tends to generate limited or counterproductive environmental outcomes, while sharp targeting, particularly through pollution and resource taxes, proves to be important for reducing CO₂ intensity. Resource taxes emerge as the strongest lever available to policymakers, followed by pollution taxes, while energy, transport, and aggregate environmental taxes should be carefully restructured given their counterproductive effect on emissions. A central policy implication drawn from these results is that environmental effectiveness of fiscal policy depends on its targeting capacity and structural alignment with the sources of emissions, rather than on its aggregate fiscal pressure.

6. Government Expenditure and Fiscal Recycling

In this section we examine how different categories of public spending impact CO₂ emissions. We also address the allocative efficiency issue by assessing whether revenues generated by environmental policies are effectively recycled into impactful public expenditure. Examining the linkages between spending patterns and compliance levels allows us to highlight effectiveness disparities across expenditure types, and should provide insights into how fiscal resources can be more efficiently aligned with climate objectives.

6.1. Direct Effects of Government Expenditure on CO₂ Emissions

To assess the impact of environmental government expenditure on CO₂ emissions, we consider five different categories of public spending: expenditure on environmental protection (ExpEnv), expenditure on pollution abatement (ExpPol), expenditure on biodiversity and landscape protection (ExpLB), and government allocations for R&D in environment (RDEnv) and energy (RDEnergy). The following empirical specification is estimated to evaluate the contribution of these expenditure components to CO₂ intensity:

$$CO_{2\ i,t} = \alpha CO_{2\ i,t-1} + \beta_1 GDPpc_{i,t} + \beta_2 GovQual_{i,t} + \beta_3 ForArea_{i,t} + \beta_4 NatRents_{i,t} + \beta_5 EngyInt_{i,t} + \gamma Expenditure_{i,t} + \varepsilon_{i,t}, \quad (7)$$

where *Expenditure*_{*i,t*} corresponds to one of the following public spending categories: environmental protection expenditure (*ExpEnv*_{*i,t*}), labor-related expenditure (*ExpLB*_{*i,t*}), pollution-control expenditure (*ExpPol*_{*i,t*}), government budget allocations for environmental research and development (*GBARDEnv*_{*i,t*}), and government budget allocations for energy research and development (*GBARDEngy*_{*i,t*}).

Estimation results, summarized in Table 9, confirm the strong persistence of CO₂ emissions, and show that the control variables produce effects similar to those detected

in the previous regressions. We also note that the validity conditions are satisfied for all the specifications.

Table 9. The effect of government spending on CO₂ emissions.

Variables	ExpEnv	ExpLB	ExpPol	RDEnv	RDEngy
L.CO ₂	0.851 *** (0.0281)	0.815 *** (0.0224)	0.822 *** (0.0261)	0.738 *** (0.0333)	0.664 *** (0.0112)
GDPpc	0.0986 * (0.0532)	0.145 ** (0.0682)	0.130 *** (0.0392)	0.209 *** (0.0517)	0.240 *** (0.0628)
GovQual	−1.521 (2.383)	−7.255 ** (3.183)	−7.529 *** (1.798)	−11.79 *** (2.718)	−12.25 *** (3.571)
ForArea	−0.400 *** (0.113)	−0.350 *** (0.0822)	−0.302 *** (0.0824)	−0.501 *** (0.0987)	−0.511 *** (0.0882)
NatRents	1.072 ** (0.467)	0.125 (0.861)	0.108 (0.428)	−0.828 (1.577)	3.790 *** (0.997)
EngyInt	11.05 *** (1.901)	14.32 *** (1.691)	13.32 *** (1.922)	20.50 *** (2.636)	19.24 *** (0.478)
ComRev	−0.000583 *** (0.000142)	−0.000567 *** (0.000131)	−0.000563 *** (7.10 × 10 ^{−5})	−6.19 × 10 ^{−5} (0.000255)	−0.00113 *** (5.78 × 10 ^{−5})
ExpEnv	−13.99 *** (3.246)				
ExpLB		7.257 (48.21)			
ExpPol			−12.45 ** (6.073)		
RDEnv				−0.00501 *** (0.00153)	
RDEngy					−0.00185 *** (0.000535)
Constant	3.244 (6.628)	−9.206 (7.153)	−6.552 *** (1.833)	−9.059 ** (3.671)	7.938 (4.953)
Nb. Of Obs.	520	520	518	529	529
Nb. of Countries	23	23	23	23	23
AR(1) Prob.	0.097	0.107	0.100	0.106	0.092
AR(2) Prob.	0.237	0.233	0.227	0.250	0.232
Hansen Prob.	0.247	0.155	0.594	0.311	0.961

Note: Robust standard errors in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. AR(1) Prob and AR(2) Prob correspond to the *p* values of the Arellano and Bond first- and second-order autocorrelation tests. Hansen Prob is the *p* value of the Sargan–Hansen overidentification test. Source: Estimation results obtained by authors using Stata software.

For the public expenditure variables, the estimation results reveal that environmental protection expenditure (−13.99 ***) and pollution abatement expenditure (−12.45 **) lead to strong and significant reductions in CO₂ emissions. Such results confirm that spending categories directly targeting pollution are one of the most effective fiscal tools. These findings are consistent with Halkos and Paizanos (2013, 2016) [23,24], who showed that the environmental impact of public spending is driven by targeted rather than aggregate allocation. Similarly, Baştürk (2025) [37] and Katircioglu and Katircioglu (2018) [35] confirmed the emission-reducing effectiveness of well-structured environmental spending. R&D expenditure in both environment (−0.00501 ***) and energy (−0.00185 ***) also contribute negatively and significantly to reducing emissions, reflecting their role as gradual but consistent drivers of long-run decarbonization through technological innovation.

Oppositely, the coefficient associated with biodiversity and landscape expenditure (7.257) is positive and statistically non-significant, suggesting that this spending category does not translate into a measurable short-run reduction in polluting emissions. This result can be explained by long investment horizons, weak linkages with industrial emission processes, or allocative inefficiencies. Compliance revenue (ComRev) remains consistently negative and highly significant across all expenditure categories (−0.000563 to −0.00113),

highlighting its role as a robust complementary policy whose emission-reducing effectiveness persists after controlling for public spending effects. These results provide support for hypothesis H5a, since government expenditure on environmental protection, pollution abatement, and R&D (in both environment and energy) all contribute significantly to reduce CO₂ intensity. Biodiversity and landscape expenditure is the only spending category that produces a non-significant effect on emissions.

Such findings confirm that public spending should be considered as a powerful but differentiated environmental policy tool, whose effectiveness depends critically on its allocation rather than on its aggregate volume. This conclusion relies on the significant emission-reducing effects of ExpEnv (−13.99 ***), ExpPol (−12.45 **), RDEnv (−0.00501 ***), and RDEngy (−0.00185 ***), and the non-significance of the ExpLB variable (Table 9). They also highlight the importance of complementarity between the taxation and spending tools. This conclusion motivates a natural move towards an efficiency-based analysis, which consists of assessing whether compliance revenues collected through taxation are optimally reallocated into emission-reducing spending. The debate therefore shifts from evaluating the government's spending pattern, to assessing how efficiently governments transform environmental revenues into environmentally enhancing spending.

6.2. Fiscal Allocative Efficiency and CO₂ Mitigation

To assess the effectiveness of the fiscal recycling process, we alternately introduce five interaction terms between the compliance revenue on one side and the five categories of spending on the other side. The following model is therefore estimated to examine whether compliance revenues are transformed into effective environmental public expenditure:

$$CO_{2\ i,t} = \alpha CO_{2\ i,t-1} + \beta_1 GDPpc_{i,t} + \beta_2 GovQual_{i,t} + \beta_3 ForArea_{i,t} + \beta_4 NatRents_{i,t} + \beta_5 EngyInt_{i,t} + \gamma AllocEff_{i,t} + \varepsilon_{i,t}, \quad (8)$$

where *AllocEff*_{*i,t*} corresponds to an interaction term assessing the recycling of fiscal revenue towards one of the five expenditure categories: Rev × ExpEnv, Rev × ExpLB, Rev × ExpPol, Rev × RDEnv, and Rev × RDEngy.

Results reported in Table 10 show that environmental protection expenditure produces a strong and significant direct emission-reducing effect (−18.81 ***), while its interaction with compliance revenue (0.000619) is statistically non-significant. This disconnection between fiscal revenue and this spending category suggests that environmental protection expenditure operates effectively as a standalone instrument, but does not benefit from compliance revenue recycling.

Results related to biodiversity and landscape expenditure suggest a finance-dependent pattern. Its direct coefficient is positive and significant (30.92 ***), while its interaction with compliance revenue (−0.0379 ***), is negative and significant. Accordingly, biodiversity spending generates environmental benefits only when properly financed through compliance revenue, suggesting the existence of an allocative effect. This result is consistent with Zhoo et al. (2025) [26] and Lilliestam et al. (2025) [32], who argued that carbon pricing instruments fail to reduce emissions when revenues are not recycled in an optimal way.

Pollution abatement expenditure displays a similar finance-contingent pattern: its direct effect is positive but non-significant, while its interaction with compliance revenue (−0.0132 ***), is negative and significant. Such a result suggests that pollution-related spending becomes environmentally effective only when backed by sufficient compliance revenues.

Expenditure on environmental R&D shows a significant negative direct effect (−0.00849 ***), while its interaction with compliance revenue is statistically non-significant. It seems that innovation-oriented environmental R&D operates through structural and technological channels that are largely independent from revenue-recycling intensity. This

result is consistent with D’Orazio (2025) [45], who argued that long-term climate resilience depends more on innovation capacity than on fiscal reallocation.

Table 10. The recycling effect of compliance revenue on CO₂ emissions.

Variables	Rev × ExpEnv	Rev × ExpLB	Rev × ExpPol	Rev × RDEnv	Rev × RDEngy
L.CO ₂	0.785 *** (0.0154)	0.818 *** (0.0177)	0.814 *** (0.0286)	0.718 *** (0.0382)	0.809 *** (0.0115)
GDPpc	0.133 ** (0.0603)	0.165 *** (0.0499)	0.170 *** (0.0641)	0.191 *** (0.0664)	0.0855 * (0.0492)
GovQual	−8.960 *** (1.906)	−8.450 *** (2.168)	−6.411 *** (2.033)	−12.52 *** (2.488)	−5.661 ** (2.432)
ForArea	−0.457 *** (0.0636)	−0.286 *** (0.0644)	−0.360 *** (0.0958)	−0.532 *** (0.119)	−0.307 *** (0.0583)
NatRents	−1.479 (1.028)	0.329 (0.645)	0.451 (0.749)	−0.567 (0.686)	0.312 (0.357)
EngyInt	13.82 *** (1.458)	14.69 *** (1.353)	14.78 *** (2.295)	21.86 *** (2.903)	14.14 *** (0.247)
ComRev	−0.00152 *** (0.000342)	0.00214 *** (0.000428)	0.000902 * (0.000516)	−0.00100 (0.00145)	0.000807 *** (0.000145)
ExpEnv	−18.81 *** (4.481)				
Rev × ExpEnv	0.000619 (0.000418)				
ExpLB		30.92 *** (9.563)			
Rev × ExpLB		−0.0379 *** (0.00512)			
ExpPol			1.324 (6.237)		
Rev × ExpPol			−0.0132 *** (0.00359)		
RDEnv				−0.00849 *** (0.00277)	
Rev × RDEnv				7.22×10^{-7} (9.69×10^{-7})	
RDEngy					−0.000824 ** (0.000367)
Rev × RDEngy					-5.26×10^{-7} *** (3.78×10^{-8})
Constant	17.94 ** (7.009)	−15.54 *** (2.954)	−12.47 *** (3.505)	−6.228 (4.748)	−8.927 *** (3.188)
Nb. Of Obs.	520	520	518	529	529
Nb. of Countries	23	23	23	23	23
AR(1) Prob.	0.100	0.102	0.106	0.098	0.099
AR(2) Prob.	0.251	0.225	0.230	0.242	0.237
Hansen Prob.	0.843	0.563	0.088	0.225	0.962

Note: Robust standard errors in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. AR(1) Prob and AR(2) Prob correspond to the *p* values of the Arellano and Bond first- and second-order autocorrelation tests. Hansen Prob is the *p* value of the Sargan–Hansen overidentification test. Source: Estimation results obtained by authors using Stata software.

Results relating to R&D expenditure in energy provide the most policy-relevant finding. Both its direct effect (-0.000824^{**}) and its interaction with compliance revenue ($-5.26 \times 10^{-7}^{***}$) produce negative and significant effects, establishing a strong complementarity between energy R&D spending and compliance revenue recycling. When environmental revenues are reinvested into energy innovation, they intensify the CO₂ reduction effect. These results corroborate those of Zhoo et al. (2025) [26] and Combet et al. (2025) [31], who identified innovation-oriented revenue recycling as the most productive pathway for carbon pricing systems.

The overall results reveal that fiscal policy effectiveness is conditional on how environmental taxation revenues are recycled into public spending, confirming that climate outcomes are shaped by a joint revenue–expenditure transmission mechanism rather than by spending levels solely. Moreover, recycling effectiveness is heterogeneous across expenditure categories, exhibiting more supportive effects when revenues are reallocated to expenditure on biodiversity and landscape, pollution abatement, and energy R&D. These findings are consistent with Combet et al. (2025) [31], who demonstrated that no single recycling mechanism is universally optimal, and D’Orazio (2025) [45], who emphasized that fiscal effectiveness depends on institutional capacity to channel revenue into well-targeted expenditure. Our findings align with a fundamental policy principle: carbon pricing systems must be evaluated not only through their revenue-raising capacity but also through the quality of their expenditure allocation pattern. These findings provide strong support for hypothesis H5b, confirming that the efficiency of compliance revenue recycling is heterogeneous across spending categories, ranging from standalone effectiveness (for environmental protection and environmental R&D spending) to finance dependence (for biodiversity and pollution abatement spending) and full complementarity (for energy R&D spending).

7. Conclusions and Policy Recommendations

This paper assesses the effectiveness of fiscal policy in shaping CO₂ intensity through compliance-based instruments, environmental taxes, and government expenditure categories. We also investigate the main transmission channels and the contingency of the environmental outcomes on the fiscal resources recycling scheme. The empirical findings reveal that the considered relationship is neither uniform nor linear, and that fiscal policy effectiveness depends critically on the instrument’s design, targeting accuracy, and allocative efficiency, rather than on the aggregate fiscal effort.

Several key conclusions emerge from the empirical results. Market-based compliance instruments, particularly compliance revenue and compliance price, generate robust and significant emission reductions, confirming the effectiveness of carbon pricing as a corrective fiscal mechanism. Emission compliance, however, exhibits a non-linear effect, producing positive environmental outcomes only beyond a minimum level of regulatory coverage and enforcement intensity.

The transmission channels analysis reveals that compliance revenue generates two opposite effects: the production channel contributes to reducing emissions through energy efficiency improvements and technological restructuring, while the consumption channel produces an offsetting scale effect through income-driven demand expansion. The net environmental outcome depends on the relative strength of these effects, highlighting the need for demand-side complementary policies.

The disaggregated tax analysis reveals important heterogeneity across fiscal tools: pollution and resource taxes produce consistent emission-reducing effects, while energy, transport, and aggregate environmental taxes are associated with higher emissions, reflecting structural rigidities, insufficient stringency, or poor integration within decarbonization

strategies. Government expenditure on environmental protection, pollution abatement, and energy R&D generates significant emission reductions, while biodiversity and pollution spending prove effective only when backed by compliance revenue recycling. Expenditure on energy R&D exhibits the strongest complementarity with compliance revenues, confirming that allocative efficiency, rather than aggregate spending, is a key determinant of fiscal policy effectiveness.

These findings lead to important policy implications. First, policymakers should abandon aggregate fiscal approaches in favor of instrument-specific targeting strategies, as some fiscal tools proved to produce detrimental environmental outcomes. In this respect, pollution and resource taxes seem to be the most relevant fiscal tools. Secondly, governments need to strengthen the enforcement capacity of their compliance mechanisms to account for the existence of threshold effects. Moreover, complementary demand-side policies, such as consumption taxes, are necessary to limit the extent of the negative income-driven effects induced by fiscal policy. Finally, an appropriate recycling strategy of the compliance revenues towards energy innovation and environmental protection are necessary conditions for translating the fiscal effort into sustained emission reductions. Institutional quality emerges throughout as a critical determinant of fiscal effectiveness, reinforcing the idea that an effective institutional framework is a fundamental prerequisite for the success of climate-oriented fiscal policies.

The conclusions drawn from this study should nonetheless be interpreted with caution. The cross-country nature of the panel, while capturing institutional and structural diversity, does not account for firm-level heterogeneity. Firms with different sizes and from different industries should react differently to environmental fiscal policy measures. Similarly, governance quality, assessed at the aggregate level, does not reflect the role of firm-level governance mechanisms in shaping the environmental outcomes of fiscal policies. In addition, the empirical evidence relative to the compliance revenue threshold is based on a relatively small sample. It is important to test the sensitivity of this result to larger samples, mainly those including developing countries. Finally, a major shortcoming of the obtained results is that they do not provide any evidence relative to the difference between the short-run and long-run effects of fiscal policy.

Including developing countries in the sample is an interesting future extension of this work. Country-level analysis should also provide interesting insights into the firm-level behavioral responses to fiscal stimuli. Finally, investigating the fiscal–emissions nexus under different monetary policy regimes is another important avenue for future research. At the empirical level, it would be interesting to rely on econometric methods which would allow us to assess the short-run and long-run effects simultaneously.

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GDP per capita, total natural resource rents, and energy supply relative to GDP were obtained from the World Bank's World Development Indicators (WDI) database. Data on carbon pricing compliance revenues, carbon prices, and the share of greenhouse gas emissions covered by carbon pricing mechanisms were retrieved from the World Bank Carbon Pricing Dashboard. Environmental tax data, including taxes on energy products, transport, pollution, and resource extraction, as well as public expenditure on environmental research and development (R&D) and energy R&D, were obtained from the Organization for Economic Co-operation and Development (OECD) database. Government expenditure on environmental protection, pollution abatement, and biodiversity and landscape conservation were collected from the International Monetary Fund (IMF) Government Finance Statistics (GFS) database and the IMF Climate Change Dashboard. Governance quality indicators were obtained from the Worldwide Governance Indicators (WGI) project of the World Bank. Data on forest area as a share of land area were retrieved from the Food and Agriculture Organization (FAO) AQUASTAT database. The datasets analyzed during the current study are publicly available from the following sources: World Bank World Development Indicators (WDI): <https://data.worldbank.org> (accessed on 25 December 2024); World Bank Carbon Pricing Dashboard: <https://carbonpricingdashboard.worldbank.org> (accessed on 25 December 2024); OECD Statistics Database: <https://stats.oecd.org> (accessed on 10 September 2024); OECD Main Science and Technology Indicators (MSTI): <https://www.oecd.org/sti/msti.htm> (accessed on 10 September 2024); International Monetary Fund Government Finance Statistics (GFS): <https://data.imf.org> (accessed on 15 January 2025); IMF Climate Change Dashboard: <https://climatedata.imf.org> (accessed on 10 September 2024); Worldwide Governance Indicators (WGI): <https://www.worldbank.org/en/publication/worldwide-governance-indicators> (accessed on 25 December 2024); FAO AQUASTAT Database: <https://www.fao.org/aquastat> (accessed on 8 October 2024). No new data were created or generated in this study.

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