No Diffusion at All: Trade, Free Riding, and Government Underspending on Environmental Innovation

Muzhou Zhang[1]

Department of Government, University of Essex

muzhou.zhang@essex.ac.uk

November 22, 2021

Abstract

Governments have an irreplaceable role in supporting environmental technologies due to market failure. Nevertheless, I develops a free riding argument that the trade-driven technology transfer incentivizes national governments to strategically underspend on environmental innovation. The data of public research and development (R&D) expenditures and bilateral trade volumes from 32 OECD countries, 1982–2017, is employed to substantiate my argument. Spatial regression finds that government spending on environmental R&D in one country is negatively correlated with such expense from its trading partners in the preceding year. Beyond environmental politics, this article challenges the influential diffusion theory by showing that the strengthening transnational connectivity may actually enable countries to be free riders rather than followers.

Key Words: Environmental innovation, Trade, Free riding, Interdependence

1. I am grateful to Zorzeta Bakaki, Tobias Böhmelt, Martin Elff, Federica Genovese, Howard Liu, and the participants at the Essex PhD IR workshop for valuable comments. All errors are my own.

Introduction

In its ambitious infrastructure proposal, which is named the American Jobs Plan, the Biden-Harris Administration called on Congress to make a 35-billion investment in environmental technologies,[1] the largest ever federal funding increase on R&D outside defense. According to the theories on the international diffusion of norms and policies, it would "rally the rest of the world to meet the threat of climate change,"[2] a key component of the Biden-Harris environmental campaign. Specifically, the socialization theory suggests that the United States' strong demonstration effect and leadership in international organizations would persuade other countries to conform to the norm of generous government funding for environmental R&D (Finnemore and Sikkink 1998). The policy learning theory and the "California effect" indicate that countries with close economic relationships to or share similarities with the United States would follow its massive environmental innovation spending plan (Bennett 1991; Rose 1991; Vogel 1995, 1997).

Nevertheless, this article contends that the public good (though impure) nature of government R&D invalidates the diffusion theories while suggesting free riding instead in the context of state-led environmental innovation. Because international trade catalysts technology transfer (e.g., Keller 2004), trade connections between countries realize the positive externality of government spending on environmental innovation—one country invests, all countries benefit. Thus, national governments tend to strategically underspend on environmental innovation—particularly when their trading partners enlarge such expense—to reduce financial burden and politically awkward innovation failures.

I employ the data on government environmental R&D spending and bilateral trade volumes from 32 OECD countries, 1982–2017, to substantiate my argument. Spatial regression finds that government spending on environmental R&D in one country is negatively correlated with such expense in its trading partners—regardless whether the traded goods are environment-related only or general—in the preceding year. A disaggregated, country-specific analysis further reveals that such worrying free riding exists among all nations, including the leading green innovators such as Japan, Germany, and the United States. The free riding finding still holds when the possible diffusion process is controled for and different estimation

1. The White House, March 31, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/03/31/fact-sheet-the-american-jobs-plan/, accessed May 18, 2021.

2. joebiden.com. https://joebiden.com/climate-plan/, accessed May 18, 2021.

techniques are used.

A wide array of government environmental protection measures, such as institutionalizing environmental agencies, enforcing end-of-pipe regulations, implementing market-pull policies, and mandating information disclosures, are found to become increasingly popular among different countries once they are adopted by first-movers (Holzinger, Knill, and Sommerer 2008; Kern, Jörgens, and Jänicke 2001). But such policy diffusion is absent in a single yet essential case: direct government funding for environmental innovation (Dechezleprêtre, Martin, and Bassi 2019; Grafström et al. 2020; Zachmann, Serwaah-Panin, and Peruzzi 2015). In this article, I provides a strategic explanation to this puzzle by showing that national governments underspend on environmental innovation since they tend to free ride off such spending made by others.

My research contributes to the broader literature in two directions. It sheds new light on when nations free ride. The existing political science literature on this topic primarily focuses on how geographically proximate countries, or those under common international frameworks, free ride off each other by strategically making less contributions to the common good (Bechtel and Sattler 2015; Gaibulloev et al. 2015; Murdoch and Sandler 1984; Passmore, Shannon, and Hart 2018; Plümper and Neumayer 2015). While I advance its research frontier by discovering a form of international interaction in which free riding prevails—international trade. It also adds to our understanding of how nations free ride by revealing that they respond to the varying free riding incentives proportionately rather than uniformly.

This article too shows under which condition the influential diffusion theories in political science do not hold. The strengthening transnational connectivity, such as the growing trade flows and the expanding international organizations, is theorized to push norms and policies to diffuse across different countries because of socialization (Finnemore and Sikkink 1998), learning (Bennett 1991; Rose 1991), and market mechanism (Vogel 1995, 1997). A number of previous studies indeed corroborate the diffusion of environmental norms and policies through trade connections (e.g., Baldwin, Carley, and Nicholson-Crotty 2019; Holzinger, Knill, and Sommerer 2008; Ward and Cao 2012), whereas I find that such diffusion ceases to exist—and even goes to the opposite side—when what one country does has a positive spillover effect on others. This finding echos Franzese and Hays (2008) and Neumayer and Plümper (2016), reminding scholars to take divergence (e.g., free riding) seriously and not to simply considering convergence (e.g., diffusion) as the only possible direction when theorizing and testing the cross-national interdependence of government policies and behaviours.

Theory

The Transnational Interdependence of Environmental Norms and Policies

Government policies and behaviours across different countries are mutually influenced. A prominent example of such interdependence is the transnational diffusion of environmental norms and policies. Beise and Rennings (2005), Huber (2008), Jänicke and Jacob (2004), and Kern, Jörgens, and Jänicke (2001) provide the detailed qualitatively descriptive evidence showing that once new environmental policy instruments are implemented by first-movers, how quickly and widely are they to spread to other countries. Drawing from several case studies, Tews, Busch, and Jörgens (2003) conclude that it is diffusion rather than self-innovation that contributes to the increasing adoption of carbon taxes, environmental disclosure mandates, and centralized sustainable development plans by different governments. Holzinger, Knill, and Sommerer (2008) and Ward and Cao (2012) use quantitative data to corroborate this conclusion and further find that international organizations are influential diffusion drivers.

Beyond international organizations, in which countries can learn from others, international trade is found at least an equally important channel which diffuses environmental norms and policies. In consistency with what the "California effect" suggests, Potoski and Prakash (2005), Prakash and Potoski (2006, 2007), Saikawa (2013), and Zeng and Eastin (2007) all find that a country is likely to voluntarily adopts higher regulatory standards in environmental protection when the country primarily exports to, or receives investments from, greener markets. These findings on the trade-embodied environmental enforcements, to some degree, nullify the prevalent pollution haven hypothesis, which posits that the North-South trade causes environmental degradation in developing countries (Copeland and Taylor 1994). Other than the invisible market mechanism, first-movers in environmental protection sometimes also straightforwardly reveal their environmental preferences and try to translate them to actual actions of their trading partners. In this regard, Bastiaens and Postnikov (2017), Brandi et al. (2020), and Jinnah and Lindsay (2016) show that the environmental provisions in preferential trade agreements improve developing countries' environmental performance on various aspects.

Trade and Free Riding on Government Environmental Innovation Spending

Government investment in environmental innovation faces great technological and market uncertainties. In their investigation into the carbon capture and storage (CCS) investments in the United States, for instance, Abdulla et al. (2020) found more than 80% of them ended up with failure, though they are generously funded by the federal government. Food & Water Watch concludes that the CCS projects oftentimes overrun their budgets and they are not cost-competitive without taxpayer bailouts, meaning that governemnts have to repeatedly make additional investments.[3]

The funding for environmental technologies even brings political troubles for governments sometimes. For example, after the massive Texan power outage in the early 2021, the Republicans heavily criticized the Democratic incumbent's subsidies for renewable energy, attributing the unreliable power supply to them.[4] Among others, the collapse of Solyndra LLC is one of the most high-profile cases illustraing the political cost of funding environmental technologies. The energy start-up company received a 535-million federal grant from the Obama Administration but then soon went into bankruptcy at the end of 2011, just a year ahead of the 2012 presidential election. Seeing Solyndra's failure as an electoral opportunity, Obama's opponents launched an 18-month investigation in Congress[5] and spent six million on advertisements against the president's mishandling of the issue.[6]

The trade-driven technology transfer, however, enables national governments to free ride off the spending on environmental technologies made by their couterparts to reduce their own financial burdens and politically awkward innovation failures. New technologies travel across borders with or without the notice of innovators. Coe and Helpman (1995) and Coe, Helpman, and Hoffmaister (1997), among others, find that a nation's domestic R&D input significantly increases total factor productivity, an often-used indicator for technology-empowered economic output, in other nations. This relationship evidently shows the large-scale and consequential impact that international technology transfer has.

A consensus among scholars, policymakers, and practitioners is that international trade in goods and services is the foremost catalyst for technology transfer, followed by other transna-

3. Food & Water Watch, March, 2020. https://foodandwaterwatch.org/wp-content/uploads/2021/04/ib_2003_carboncapture-web.pdf, accessed September 27, 2021.

4. The Editorial Board, The New York Times, February 19, 2021. https://www.nytimes.com/2021/02/19/opinion/texas-power-energy.html, accessed September 27, 2021.

5. Reuters, August 27, 2012. https://reut.rs/3vvaSJP, accessed May 19, 2021.

6. The Wall Street Journal, January 14, 2012. https://www.wsj.com/articles/BL-WB-33080, accessed May 19, 2021.

tional economic connections, including FDI, licensing, joint venture, and so on (Maskus 2004). Wacziarg (2001) provides strong evidence in support of this view by discovering a positive relationship between trade liberalization and technology transfer across different countries.[7] Through international trade, a country can straightforwardly apply the purchased materials, equipment, and methods to upgrade its existing production processes technologically. It can also access technological information embodied in the directly traded products by imitating or revere-engineering.

From the late 1970s to the early 2000s, the global export rate of green inventions climbed from 10 to 30 percent with an accelerating trend (Dechezleprêtre et al. 2011). Drawing from the case studies on pollution mitigation measures and photovoltaics, Lanjouw and Mody (1996) and De La Tour, Glachant, and Ménière (2011) conclude that it is trading on related products rather than domestic R&D that propels a nation's later environmental technological advancements. Perkins and Neumayer (2009) show that a country's carbon efficiency increases as a result of the deepening trade relationships with the carbon-efficient economies, indicating that trade substantially enables environmental technologies elsewhere to directly empower a country's own environmental protection. Using the gravity model, Garsous and Worack (2021) directly shows that international trade enables countries to acquire advanced renewable technologies that are otherwise impossible for them to access. The massive trade-embodied transfer of environmental technologies means that the government funding for environmental R&D in one country has a public good nature (though impure), or in other words, a positive externality, because all others can benefit from the country's own investment without bearing the financial, technological, and political costs during the innovation process (Gersbach, Oberpriller, and Scheffel 2018; Jaakkola and van der Ploeg 2019).

Despite that the government-funded environmental R&D is not completely non-excludable (so it is an impure public good), the impact of intellectual property rights on environmental technologies and their transfer is very much limited compared to others. As the UN Agenda 21 posits, for example, a large body of environmental technologies is actually in the public domain and off-patented (Less and McMillan 2005), which allows them to travel more easily at no cost. Dechezleprêtre and Sato (2017) find that the spillover rate of low-carbon technologies is indeed greater than that of high-carbon technologies. The trade-driven transfer of environmental technologies is further advocated by international organizations. For instance, the WTO's

7. See Keller (2004) for a review of the economics research on the trade-driven technology transfer.

2001 Doha Declaration explicitly asks countries to reduce and even eliminate any tariff and non-tariff barriers on environmental goods and services.[8] In their evaluations on the impact of the Eco-Patent Commons, a royalty-free patent pool of environmental technologies initiated by a dozen of giant multinationals, Contreras, Hall, and Helmers (2018) and Hall and Helmers (2013) find that the patent waiver does not promote the transfer of environmental technologies, suggesting patent's limited discouraging effect on technology flow.

The positive externality of government spending on environmental innovation and its actualization through international trade incentivizes the cost-minimizing governments to strategically underspend on environmental technologies to free ride. Specifically, nations are expected to reduce their own government environmental R&D spending after seeing the spending increases from their trading partners. When nations free ride, it is impossible for them to know the spending of others simultaneously. Instead, they can only adjust their own expense according to the previous spending records of their counterparts. Thus, a nation's current spending on environmental innovation is influenced by such spending of other countries in the preceding year. Since larger bilateral trade flows bring more intense environmental technology transfers, nations are further expected to be more responsive (i.e., making more funding cuts) to the increasing environmental innovation spending of their larger trading partners while being relatively insensitive to the increasing spending of their smaller trading partners.

Based on my argument showing the internal motive and external incentive that encourage national governments to free ride on environmental R&D expenditures, I make the following testable hypothesis:

> *National governments spend less on environmental R&D as a response to the increasing spending of their trading partners in the preceding year; such responsiveness is proportional to the trade volume between the two countries.*

Data and Variables

Sample and Outcome Variable

My sample is restricted to OECD countries, 1982 to 2017, since only the OECD provides high-quality, sector-specific, and cross-nationally comparable government research funding data

8. WTO, November 20, 2001. https://www.wto.org/english/thewto_e/minist_e/min01_e/mindecl_e.htm, accessed September 27, 2021

with good temporal coverage. Since developed countries are major investors and contributors in environmental innovation worldwide, the limited sample in this research does not undermine the meaningfulness of its finding too much.[9] By focusing on OECD countries, I avoid introducing excessive cross-sectional heterogeneity by pooling categorically different countries together, which may confound my statistical results. I access the data for my outcome variable—government spending on environmental R&D—from the OECD's official statistics.[10] Among 34 high-income OECD members as of 2017,[11] I drop Chile and Switzerland from my sample since their data have excessive missing values for undocumented reasons. After taking missing values in other countries into account (see Appendix Figure A1), my sample size is 939.

Figure 1 displays a considerable spatiotemporal variation of my outcome variable. From the 1980s to 2010s, Germany and the United States always outspent the others in funding environmental R&D, despite their spending patterns were irresolute, while Japan soon joined the leading camp in the 2000s. However, the expenditures made by the Nordic countries, who are generally viewed as green campaigners, actually almost stagnated in the past decades. The Eastern European nations and Benelux also experienced a similar spending stagnation. Although the larger economies expanded their environmental R&D expenditures over time, the trend of their funding expansions is wavering, indicating their spending behaviours are hesitating and strategic. My argument and the descriptive evidence shown in Figure 1 suggest that the countries in my sample would have much larger government spending on environmental R&D if they did not free ride in a counterfactual world. Therefore, I contend that my sample selection does not introduce a ceiling effect into my analysis.

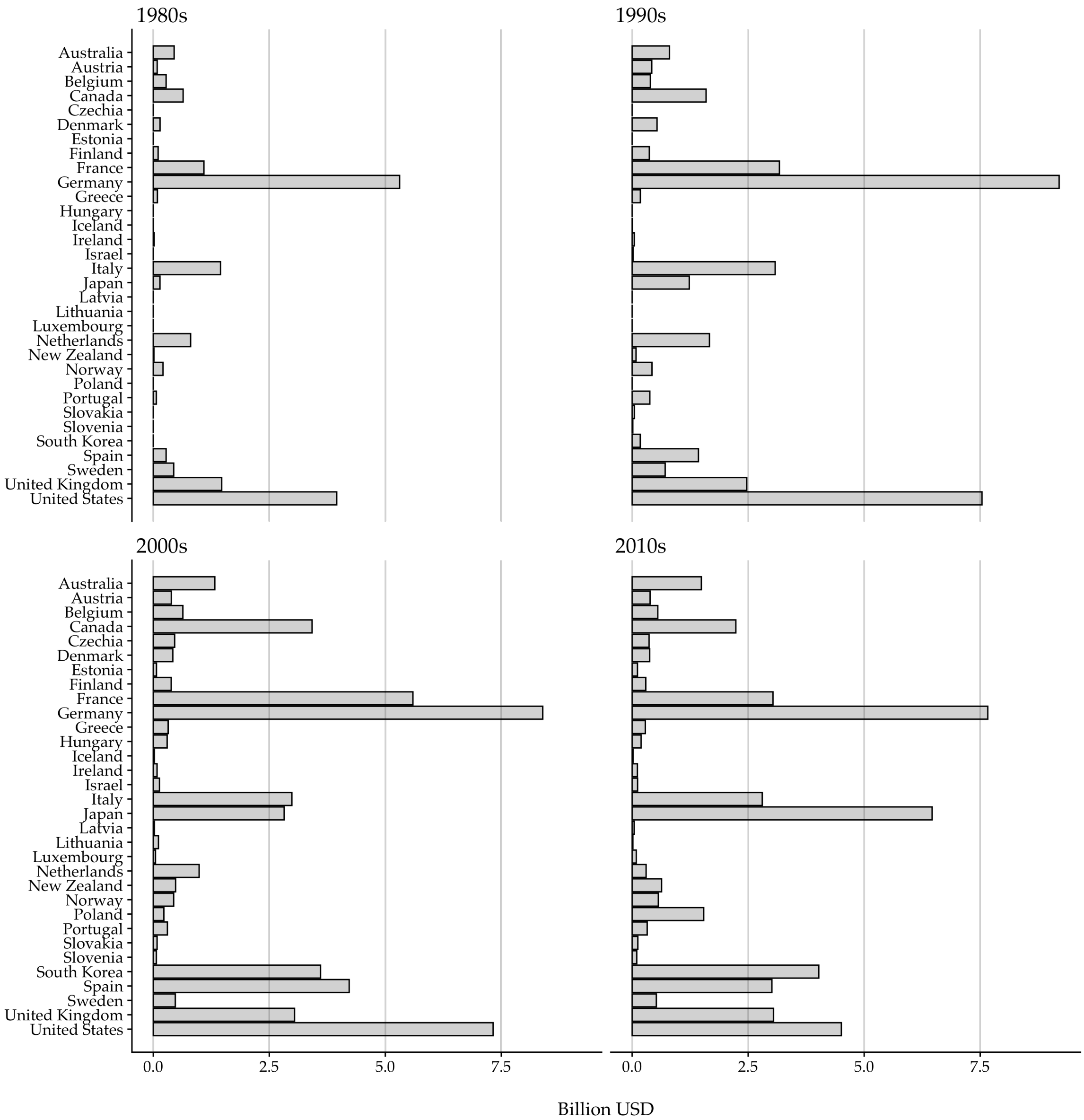
The raw distribution of my outcome variable is right-skewed, which is led by the relatively larger spending of a cluster of leading countries. When free riding, although national governments are more responsive to larger environmental technology investors than to smaller ones, it is hard to argue that this responsiveness discrepancy is strictly proportional to the difference of spending sizes between larger and smaller investors. I thus use natural logarithm

9. Because China's environmental innovation is largely driven by its techno-nationalism and bid for global leadership (Kennedy 2013), the country's government environmental R&D spending is theoretically irrelevant to the free riding argument made in this article. Thus, the exclusion of China from my empirical analysis brings minimal substantive impact.

10. This is done by using the `R` package `OECD: Search and Extract Data from the OECD` (Persson 2019) with the query `GBARD_NABS2007`. But the data can be also viewed and manually downloaded from https://stats.oecd.org/Index.aspx?DataSetCode=GBARD_NABS2007 (accessed October 26, 2021).

11. So that Mexico and Turkey, two non-high-income OECD countries, are excluded.

Figure 1: Government Environmental R&D Expenditures of OECD Countries, 1982–2017



to transform my outcome variable, assuming that the quantitative relationship between a nation's own government environmental R&D spending and that of others is approximately an elasticity. That is to say, nations adjust their own government environmental R&D spending in percentage in response to the percentage change of that spending done by their trading partners.

Explanatory Variable

I use spatial regression to empirically test my hypothesis. This model operationalizes explanatory variable as the weighted outcome variable, which is called spatial lag, to quantify how an observation is influenced by others. Dictated by my argument, I use the bilateral trade volumes on environmental goods,[12], as the spatial weights of interest. (I too use aggregated trade volumes for generalizability in one of my regression models). For such data, I first access the dyadic trade flows at the chapter level, which is classified by the first two digits of the Harmonized Commodity Description and Coding System (HS) code.[13] I then determine what chapters include environmental goods based on the OECD's Combined List of Environmental Goods (see Sauvage 2014). Typical examples of environmental goods in my data include filtering or purifying machinery and apparatus for gases, wind turbines, and photosensitive semiconductor devices. Following my argument that national governments can only respond to others' environmental innovation expenditures in the preceding rather than current year, I temporally lag my explanatory variable *S-Lag by Environmental Trade*.

My explanatory variable has a threefold interpretation.[14] First, for a single nation in each year, this variable measures how the nation is exposed to the previous-year government environmental R&D expenditures of others, which are technically known as spatial stimuli. Second, these stimuli are weighted by the bilateral trade volumes on environmental goods between the nation and its trading partners. This weighting perfectly fits my trade-proportional free riding argument. Third, the weighted stimuli are then added together to quantify the overall free riding incentive that the nation receives from its trading partners. I do not row-standardize the weights, otherwise I would make the homogeneous exposure assumption (Neumayer and

12. Environmental goods are categorized into pollution management, cleaner technologies and products, and resource management (where renewable energy belongs to) according to OECD (1999).

13. These data are originally provided by the United Nations International Trade Statistics Database (UN Comtrade) while I download them through the API wrapper programmed by Vargas (2019). See Appendix Figure A2 for the missing values.

14. I discuss and justify my explanatory variable and spatial model choice in Appendix C.

Plümper 2016), meaning that all of my observations had an identical overall trade volume to all others. This assumption not only discards the contemporaneous variation of total trade flows between different countries but also ignores the fact that all countries trade more over time as globalization deepens.

Control Variables

I include several control variables to alleviate the concern that my statistical results might be produced by the confounding factors that are connected with both my outcome and explanatory variable. How reliant a country is on fossil fuel reveals the degree of carbon lock-in (Aklin and Urpelainen 2013) and the political power that environment-unfriendly industries may have, which are both likely to negatively affect the government's ability and willingness to fund environmental innovation. Conversely, a country's high reliance on fossil fuels may also encourage the environmentally progressive government to expand its financial support for environmental innovation even further. *Fossil Fuel Rents/GDP* in percentage is therefore included in light of these two possibilities. How national governments spend on environmental R&D is naturally affected by their own ideological positions on environmental protection. I thus use the Comparative Manifesto Project data (Volkens et al. 2020) to control how environmentally progressive an incumbent government is. Using the method of Ward and Cao (2012), specifically, I aggregate the seat share-weighted environmental protection progressiveness of each party in an election and use this aggregated value to represent the incumbent's environmental position until the next election.

Compared to other countries, EU members have to meet their supernational, environmentally ambitious targets collectively, so their spending patterns on environmental R&D are likely to be similar. Consequently, I control the binary *EU Membership*, which equals one if a country in a given year is a member state of the EU. I further use the KOF Political Globalization Index (Gygli et al. 2019) as a control variable since it considers three major types of international interactions in which a country is exposed to norms and policy information, namely diplomatic relationships, cross-national operations led by international organizations, and international nongovernmental organizations. The Index ranges from 0 to 100: the larger the value is, the more politically globalized a country is in a given year.

The environmental Kuznets curve reveals an inversely U-shaped relationship between a nation's per capita income and environmental protection level (Grossman and Krueger 1995).

Nevertheless, the countries in my sample are all high-income economies, meaning that they are all beyond the development-environment dilemma's tipping point. That is to say, the relationship between income and environmental protection is expected to be monotonically positive within my sample. I therefore control *GDP per capita* alone without its squared term. I too control *GDP* itself to make my results more comparable among countries with differing economic sizes. Next, I also include *GDP Growth* since governments are found less motivated and capable to address environmental issues during economic downturns (Abou-Chadi and Kayser 2017). I then take *Urban Population* in percentage into account since a country's residential density partly determines the economic efficiency of investing environmental technologies. My final control is *Total Government R&D Spending*, which reflects the overall budget constraint that government environmental R&D spending faces. Further, since environmental R&D cannot be precisely located in all times, including this variable also reduces the measurement error of my outcome variable.[15] In consistency with my explanatory variable, I temporally lag all of these control variables too.

Empirical Analysis

Regression Results

Since governments always adjust their expenditures based on the previous values, I include the temporally lagged dependent variable (TLDV) to take this time dependency into account. I also include twoway fixed effects. The inclusion of country fixed effects absorbs time-invariant or sluggish cross-sectional heterogeneities in terms of the government environmental R&D spending propensities, such as political institutions.[16] The inclusion of year fixed effect takes the common time trend or exogenous shocks, such as energy crises, diffusion, or environmental movements, into account.

Table 1 reports the main regression results. Since my right-hand side variables are measured in rather different scales, the coefficient estimates are standardized in all of my regression tables to facilitate comparisons and improve readability. The standard errors are clustered at the country level to make them robust to intra-country serial correlation and contemporaneous heteroskedasticity. I simply regress my outcome variable to the TLDV and my explanatory

15. This variable is also from the OECD's official statiscs. All other control variables, unless specifically cited, are from the World Development Indicator (World Bank, n.d.). See Appendix Table A1 for summary statistics.

16. Since my sample size is large in terms of its temporal dimension, the Nickell bias is negligible substantively.

variable only to present the baseline results in column (1). The purpose of doing so is to be transparent regarding whether my subsequent results might be simply induced by some control variables (Lenz and Sahn 2020). Column (2) is the complete specification, incorporating the confounders that are likely to affect a nation's trade network and government environmental R&D spending simultaneously.

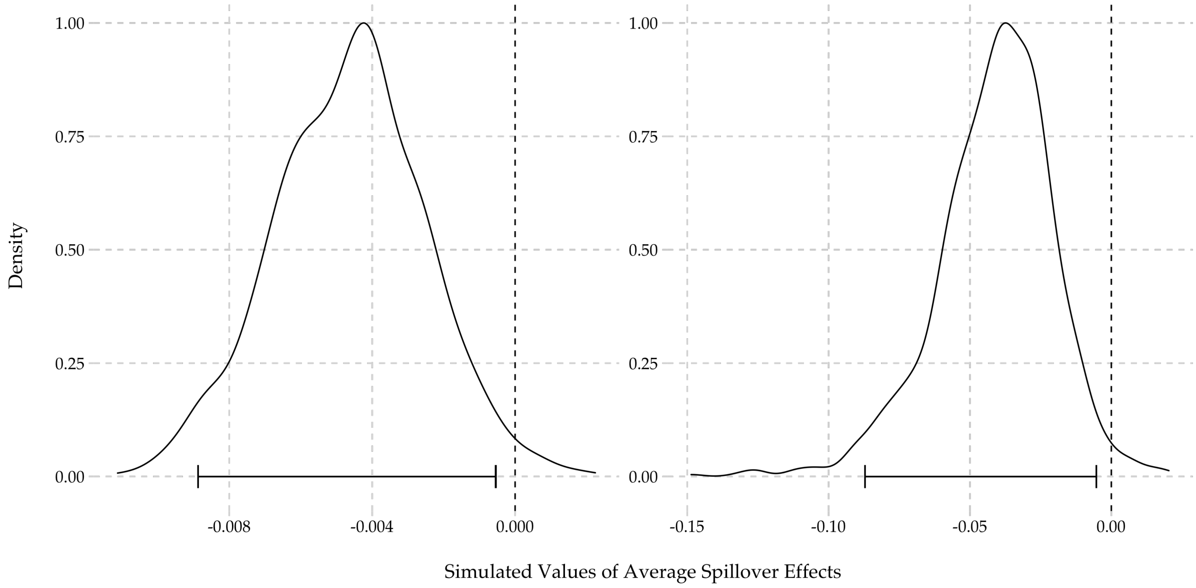
Table 1: Spatial Regression Results on Government Environmental R&D Spending (Environmental Trade as Weights), OECD Countries, 1982–2017, Twoway FEs with Clustered SEs

	(1)	(2)
TLDV	0.705***	0.677***
	(0.046)	(0.045)
S-Lag by Environmental Trade	−0.043**	−0.050*
	(0.000)	(0.000)
Fossil Fuel Rents/GDP (%)		−0.000
		(0.013)
Gov Environmental Position (CMP)		0.015
		(0.038)
EU Membership (Yes = 1)		0.020
		(0.118)
Political Globalization Index (KOF)		0.040†
		(0.003)
GDP per capita (Log)		−0.316†
		(0.625)
GDP (Log)		0.764
		(0.551)
GDP Growth (%)		0.022
		(0.010)
Urban Population (%)		−0.069
		(0.014)
Total Gov R&D Spending		0.083
		(0.007)
Number of Observations	885	885
Number of Countries	32	32
Root-Mean-Square Error	0.383	0.380

Variables are temporally lagged at $t-1$.
Fixed effects are not reported.
Coefficient estimates are standardized.
$^{\dagger}p < 0.100$, $^{*}p < 0.050$, $^{**}p < 0.010$, $^{***}p < 0.001$.

Across the two columns, the coefficient estimates of my explanatory variable—*S-Lag by Environmental Trade*—are all negatively signed and thus corroborate my argument. Their statistical significances are both below the 0.05 threshold, indicating that there is sufficient statistical evidence to reject the null hypothesis that national governments do not free ride on environmental innovation spending. As more control variables enter the estimation, the coef-

Figure 2: Sampling Distributions of Average Spillover Effects with 95% Percentile Intervals



ficient magnitude even enlarges, though its statistical significance slightly decreases without any impact on substantive inference. Specifically, the estimated negative sign means that a nation reduces its own environmental R&D spending after seeing that its trading partners of environmentally related goods, overall, increase such expenditures in the preceding year. This "strategic substitute" spending behavior indicates that national governments indeed free ride when it comes to funding environmental technologies (Franzese and Hays 2008).

Substantive Effects

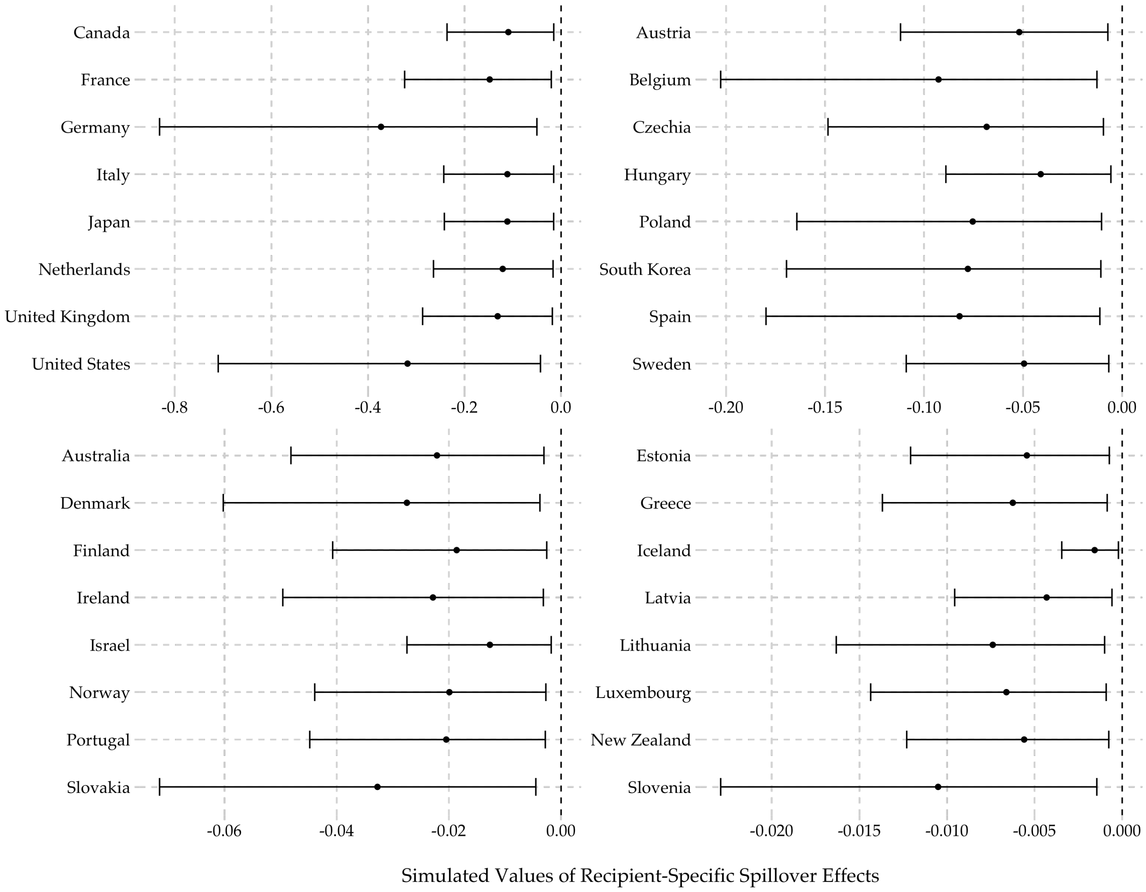
Except for overall direction and statistical significance, estimated coefficients from spatial regression models hardly tell the quantities of interest. In this article's context, such quantities are the spillover effects that countries receive from all of their trading partners on their own government environmental R&D spending. To summarize these effects and then substantively interpret my spatial regression results, I adopt the "general approach" advocated by, among others, Whitten, Williams, and Wimpy (2021). I randomly draw the coefficient of *S-Lag by Environmental Trade* 1,000 times from a multivariate normal distribution using parameters based upon the estimates from column (2), Table 1. I then use these simulated coefficients with the spatial weights of interest (bilateral trade on environmental goods) to calculate the "effect matrices," whose off-diagonal elements quantify the spillover effect a nation receives from a particular trading partner.[17]

Figure 2 visualizes the average off-diagonal row-summations of these "effect matrices," representing the average spillover effects. The 95 percent percentile intervals in the two facets both fall below zero, indicating that the average short-term and long-term quantities of interest are statistically significant. The negative average short-term spillover effect means that nations immediately decrease their own government environmental R&D spending after seeing the increasing expenditures of their trading partners in the previous year. At the same time, the considerably more sizable negative average long-term spillover effect means that trade's discouraging impact on government environmental R&D spending accumulates over time. In other words, once national governments free ride, their environmental R&D expenditures will be perpetually lower than that in a counterfactual world where they did not free ride. This underspending path dependency sharply contradicts the global environmental urgency, which requests countries worldwide to invest in green transition as soon as possible. Since the measurement unit of my environmental trade data is billion USD, the effects presented here are substantively consequential.

I then use the year 2017, the latest time point in my sample, as an example to present the recipient-specific effects that nations receive from their trading partners on their own government environmental R&D spending. This step allows me to better situate my quantitative finding into today's global environmental protection context. The calculation is nearly identical to that used in Figure 2, but I leave each row in the "effect matrices" alone. Figure 3 visualizes these effects through four facets according to their effect sizes. The more a nation trades on environmental goods, the greater extent which the nation free rides off the government environmental R&D expenditures of its trading partners. The top-left facet shows this worrying finding well. It demonstrates that the strategic environmental R&D spending behaviours are mutually influenced across different countries in a symmetric way—not only latecomers but also first-movers themselves free ride. Germany and the United States are the largest free riders on government environmental R&D spending among OECD countries, though they are also the largest investors. These two seemingly contradictory statuses suggest that these two countries would contribute more to the development of environmental technologies if they did not free ride. The free riding degree of Japan, another public environmental R&D leader,

17. Interested readers are referred to panel data spatial econometrics textbooks, such as LeSage and Pace (2009) and Elhorst (2014), for the detailed matrix calculation.

Figure 3: Recipient-Specific Spillover Effects in 2017 with 95% Percentile Intervals



is less than that of Germany and the United States. Nevertheless, the 95 percent percentile interval of the spending-discouraging spillover effect that Japan receives is much narrower, indicating that the stronger statistical evidence is in support of the existence of Japan's environmental R&D free riding. South Korea, whose government environmental R&D spending rocketed since the 2000s, is a relatively relieving case. Because of the country's smaller trading size, South Korea does not free ride as much as other leading environmental technology investors do.

Extensions and Robustness Checks

The cross-national interdependence of government decisions is a theoretically bidirectional process (Neumayer and Plümper 2016). Although I argue that free riding prevails in how national governments decide to spend on environmental R&D in this article, I cannot rule out the possibility that the diffusion may occur simultaneously. Relegating a possible interdependence pattern to regression disturbance would induce the omitted variable bias. So, Hays, Kachi, and Franzese (2010) recommend applied researchers to directly measure the possible confounding interdependence process and include the corresponding variable directly in regression as a covariate. A robust finding in the existing diffusion literature is that nations conform to norms and learn policies from their peers who are similar to themselves (see, for example, Simmons and Elkins 2004). In my case, it means that the government environmental R&D expenditures between similar countries are likely to converge.

To take this similarity-driven diffusion into account, I follow the operationalization of my explanatory variable but use the between-country similarity as the weights to create an additional spatial lag variable. The similarity measure is from Voeten, Strezhnev, and Bailey (2009) and it quantifies the voting record consistency between two countries at the UN General Assembly. It ranges from 0 to 1: larger values are taken when a pair of countries have more identical voting records, and thus, are more similar to each other. Compared to the commonly used sociocultural, ideological, or institutional similarity measures, the voting consistency in intergovernmental organizations better measures how similar are countries in actual and consequential policy issues. So, it better qualifies than other candidates to be a proxy to the latent between-country similarity, which possibly drives the diffusion of government environmental R&D spending in my research context. As Appendix Table B1 shows, the incorporation of this additional spatial lag term does not affect my finding's substantive strength or statistical significance. It means that nations free ride on their trading partners anyway, even though the diffusion of government funding for environmental innovation may simultaneously happen.

It is sometimes hard for trade participants to accurately and exclusively define what goods are environment-related. Also, environmental innovation itself is an interdisciplinary process, which always benefits considerably from other sectors (Nemet 2012). Therefore, the trade on other commodities may also transfer environmental technologies internationally like the environmental trade does and nations probably free ride on not only their trading partners of environment-related goods in particular but also those of general goods. To examine the extent which my free riding finding applies to a general trade context, I replicate Table 1 but use *S-Lag by Aggregated Trade* as the explanatory variable instead (see Appendix Table B2). The regression results show that the coefficient estimates of interest are both negative and statistically significant with even larger magnitude, demonstrating the prevalence of the discovered free riding behaviour in an overall global trade network.

R&D activities are a longtime scientific commitment that cannot be easily paused on short notice. While making a strategic decision regarding their environmental R&D spending, national governments are thus likely to consider such expenditures of others from the distant past. To empirically examine how far do national governments look back when they free ride, I backwards add further temporal lags of *S-Lag by Environmental Trade* in my regression. The linear combination tests regarding the lags reveal that they look back up to two years (see Appendix Table B3). Such a short period is not surprising, though, since the time dependency of R&D spending also means that governments can easily speculate the budgetary trajectory of others without knowing much about the past.

Finally, I demonstrates that my finding is robust to different estimation techniques. In Appendix Table B4, I apply the panel-corrected standard errors (PCSEs, Beck and Katz 1995), which are robust to any unobserved, contemporaneous correlation of government spending on environmental R&D among different countries. In Appendix Table B5, I continue to use the PCSEs but change the way of dealing with my outcome variable's time dependency. Specifically, I drop the TLDV and allow my disturbance to follow an AR(1) process instead. Throughout these two tables, my statistical results remain substantively unchanged.

Concluding Remarks

Innovation is a fundamental yet economically feasible green solution, but its pace considerably lags behind the global environmental urgency. For instance, the renewable share in the world's total primary energy consumption only increased from 6 to 11 percent in the past half-century (BP PLC 2020), whereas the annual carbon dioxide emission rocketed from 11 to 37 billion tonnes during the same period (Our World in Data, n.d.). The International Renewable Energy Agency estimates that until 2050, ensuring a global green transition needs an additional 27-trillion USD investment in low-carbon technologies (IRENA 2018).[18] However, the private sector cannot spontaneously fill the funding gap that environmental innovation faces. Due to such market failure, governments have an irreplaceable role in supporting environmental innovation (Acemoglu et al. 2012; Acemoglu et al. 2016; Fischer, Preonas, and Newell 2017). To meet the Paris Agreement target, the worldwide government research funding for environmental technologies has to grow at least twofold (Dechezleprêtre, Martin, and Bassi 2019).

In this article, nonetheless, I develop the free riding argument that the trade-driven technology transfer incentivizes nations to underspend on environmental innovation as a strategic response to the increasing spending of their trading partners. Using the data on government environmental R&D expenditures and bilateral trade volumes from 32 OECD countries, 1982–2017, spatial regression corroborates my argument, which is in a sharp contrast to environmental innovation's urgent demand for government funding in reality. My finding shows under which condition the diffusion of norms and progressive policies on environmental protection ceases to exist and even goes to the opposite side. It thus challenges the optimistic expectation that environmental pioneers are able to mobilize latecomers to join their progressive campaigns. According to my country-specific analysis, all nations, including those environmental pioneers themselves, have a tendency to free ride on the environmental R&D spending made by their trading partners. An important policy implication is that there should be more international coordination prior to the end-of-pipe regulation and technology deployment stages to address the global environmental crisis before it's too late.

My article broadens the scope of the trade-environment literature. The pollution haven hypothesis is built on the pollution-embodied North-South trade (Copeland and Taylor 1994)

18. See OECD, The World Bank, and UN Environment (2018) for an overview regarding the financing shortage in environmental innovation.

while the race-to-the-bottom theory is established upon the trade competition among the Global South countries (Cary 1974). On the opposite side, the "California effect" is about how developed nations encourage their developing counterparts to voluntarily green themselves (Vogel 1995, 1997). In contrast to them, I present evidence that the trade within the Global North too has a considerable impact on environmental protection. Such impact, importantly, is not confined geographically but global because of the borderless nature of environmental technologies.

This research too sheds light on the interdependence scholarship in general. When it comes to the transnational interdependence of state behaviours and government policies, the previous studies disproportionately focus more on convergence—how closely connected countries become similar to each other—whereas largely neglect the alternative divergence. This scholarly asymmetry is strikingly against the theoretically bidirectional possibility of any interdependence process (Neumayer and Plümper 2016). Although there are a few divergence-focusing exceptions (Aklin 2016; Böhmelt and Freyburg 2015; Franzese and Hays 2006), they only specify cross-national connectivity as geographical contiguity. Thus, our understanding of how political outcomes in different countries are mutually influenced remains incomplete. My article narrows this gap by theorizing and showing that trade connectivity—the foremost politico-economic feature in a globalized era—drives government environmental efforts across different nations to diverge. Future research may consider to further explore under what mechanisms different forms of transnational connectivity may drive political outcomes of interest to become cross-nationally dissimilar.

References

Abdulla, Ahmed, Ryan Hanna, Kristen R Schell, Oytun Babacan, and David G Victor. 2020. "Explaining Successful and Failed Investments in U.S. Carbon Capture and Storage Using Empirical and Expert Assessments." *Environmental Research Letters* 16 (1): 014036.

Abou-Chadi, Tarik, and Mark A Kayser. 2017. "It's Not Easy Being Green: Why Voters Punish Parties for Environmental Policies During Economic Downturns." *Electoral Studies* 45:201–207.

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous. 2012. "The Environment and Directed Technical Change." *American Economic Review* 102 (1): 131–66.

Acemoglu, Daron, Ufuk Akcigit, Douglas Hanley, and William Kerr. 2016. "Transition to Clean Technology." *Journal of Political Economy* 124 (1): 52–104.

Aklin, Michaël. 2016. "Re-Exploring the Trade and Environment Nexus Through the Diffusion of Pollution." *Environmental and Resource Economics* 64 (4): 663–682.

Aklin, Michaël, and Johannes Urpelainen. 2013. "Political Competition, Path Dependence, and the Strategy of Sustainable Energy Transitions." *American Journal of Political Science* 57 (3): 643–658.

Baldwin, Elizabeth, Sanya Carley, and Sean Nicholson-Crotty. 2019. "Why Do Countries Emulate Each Others' Policies? A Global Study of Renewable Energy Policy Diffusion." *World Development* 120:29–45.

Bastiaens, Ida, and Evgeny Postnikov. 2017. "Greening Up: The Effects of Environmental Standards in EU and US Trade Agreements." *Environmental Politics* 26 (5): 847–869.

Bechtel, Michael M, and Thomas Sattler. 2015. "What is Litigation in the World Trade Organization Worth?" *International Organization,* 375–403.

Beck, Nathaniel, and Jonathan N Katz. 1995. "What to Do (and Not to Do) With Time-Series Cross-Section Data." *American Political Science Review,* 634–647.

Beise, Marian, and Klaus Rennings. 2005. "Lead Markets and Regulation: A Framework for Analyzing the International Diffusion of Environmental Innovations." *Ecological Economics* 52 (1): 5–17.

Bennett, Colin J. 1991. "What Is Policy Convergence and What Causes It?" *British Journal of Political Science,* 215–233.

Böhmelt, Tobias, and Tina Freyburg. 2015. "Diffusion of Compliance in the 'Race towards Brussels?' A Spatial Approach to EU Accession Conditionality." *West European Politics* 38 (3): 601–626.

BP PLC. 2020. *Statistical Review of World Energy.* https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/xlsx/energy-economics/statistical-review/bp-stats-review-2020-all-data.xlsx (accessed January 22, 2021).

Brandi, Clara, Jakob Schwab, Axel Berger, and Jean-Frédéric Morin. 2020. "Do Environmental Provisions in Trade Agreements Make Exports From Developing Countries Greener?" *World Development* 129:104899.

Cary, William L. 1974. "Federalism and Corporate Law: Reflections Upon Delaware." *The Yale Law Journal* 83 (4): 663–705.

Coe, David T, and Elhanan Helpman. 1995. "International R&D Spillovers." *European Economic Review* 39 (5): 859–887.

Coe, David T, Elhanan Helpman, and Alexander W Hoffmaister. 1997. "North-South R&D Spillovers." *The Economic Journal* 107 (440): 134–149.

Contreras, Jorge, Bronwyn Hall, and Christian Helmers. 2018. *Green Technology Diffusion: A Post-Mortem Analysis of the Eco-Patent Commons.* National Bureau of Economic Research Working Paper Series 25271, November.

Copeland, Brian R, and M Scott Taylor. 1994. "North-South Trade and the Environment." *The Quarterly Journal of Economics* 109 (3): 755–787.

De La Tour, Arnaud, Matthieu Glachant, and Yann Ménière. 2011. "Innovation and International Technology Transfer: The Case of the Chinese Photovoltaic Industry." *Energy Policy* 39 (2): 761–770.

Dechezleprêtre, Antoine, Matthieu Glachant, Ivan Haščič, Nick Johnstone, and Yann Ménière. 2011. "Invention and Transfer of Climate Change–Mitigation Technologies: A Global Analysis." *Review of Environmental Economics and Policy* 5 (1): 109–130.

Dechezleprêtre, Antoine, Ralf Martin, and Samuela Bassi. 2019. "Climate Change Policy, Innovation and Growth." In *Handbook on Green Growth,* edited by Roger Fouquet, 217–239. Cheltenham, England: Edward Elgar Publishing.

Dechezleprêtre, Antoine, and Misato Sato. 2017. "The Impacts of Environmental Regulations on Competitiveness." *Review of Environmental Economics and Policy* 11 (2): 183–206.

Elhorst, J Paul. 2014. *Spatial Econometrics: From Cross-Sectional Data to Spatial Panels.* Heidelberg, Germany: Springer.

Finnemore, Martha, and Kathryn Sikkink. 1998. "International Norm Dynamics and Political Change." *International Organization,* 887–917.

Fischer, Carolyn, Louis Preonas, and Richard G Newell. 2017. "Environmental and Technology Policy Options in the Electricity Sector: Are We Deploying Too Many?" *Journal of the Association of Environmental and Resource Economists* 4 (4): 959–984.

Franzese, Robert J, and Jude C Hays. 2006. "Strategic Interaction Among EU Governments in Active Labor Market Policy-Making: Subsidiarity and Policy Coordination Under the European Employment Strategy." *European Union Politics* 7 (2): 167–189.

———. 2008. "Interdependence in Comparative Politics: Substance, Theory, Empirics, Substance." *Comparative Political Studies* 41 (4-5): 742–780.

Gaibulloev, Khusrav, Justin George, Todd Sandler, and Hirofumi Shimizu. 2015. "Personnel Contributions to UN and Non-UN Peacekeeping Missions: A Public Goods Approach." *Journal of Peace Research* 52 (6): 727–742.

Garsous, Grégoire, and Stephan Worack. 2021. *Trade as a Channel for Environmental Technologies Diffusion: The Case of the Wind Turbine Manufacturing Industry.* OECD Trade and Environment Working Papers 2021/01.

Gersbach, Hans, Quirin Oberpriller, and Martin Scheffel. 2018. "Double Free-Riding in Innovation and Abatement: A Rules Treaty Solution." *Environmental and Resource Economics* 73 (2): 449–483.

Grafström, Jonas, Patrik Söderholm, Erik Gawel, Paul Lehmann, and Sebastian Strunz. 2020. "Government Support to Renewable Energy R&D: Drivers and Strategic Interactions Among EU Member States." *Economics of Innovation and New Technology,* 1–24.

Grossman, Gene M, and Alan B Krueger. 1995. "Economic Growth and the Environment." *The Quarterly Journal of Economics* 110 (2): 353–377.

Gygli, Savina, Florian Haelg, Niklas Potrafke, and Jan-Egbert Sturm. 2019. "The KOF Globalisation Index – Revisited." *The Review of International Organizations* 14 (3): 543–574.

Hall, Bronwyn H., and Christian Helmers. 2013. "Innovation and Diffusion of Clean/Green Technology: Can Patent Commons help?" *Journal of Environmental Economics and Management* 66 (1): 33–51.

Hays, Jude C, Aya Kachi, and Robert J Franzese. 2010. "A Spatial Model Incorporating Dynamic, Endogenous Network Interdependence: A Political Science Application." *Statistical Methodology* 7 (3): 406–428.

Holzinger, Katharina, Christoph Knill, and Thomas Sommerer. 2008. "Environmental Policy Convergence: The Impact of International Harmonization, Transnational Communication, and Regulatory Competition." *International Organization*, 553–587.

Huber, Joseph. 2008. "Pioneer Countries and the Global Diffusion of Environmental Innovations: Theses From the Viewpoint of Ecological Modernisation Theory." *Global Environmental Change* 18 (3): 360–367.

IRENA. 2018. *Global Energy Transformation: A Roadmap to 2050.* https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_Report_GET_2018.pdf (accessed January 22, 2021).

Jaakkola, Niko, and Frederick van der Ploeg. 2019. "Non-Cooperative and Cooperative Climate Policies with Anticipated Breakthrough Technology." SURED 2016: Dynamic and strategic aspects of environmental economics, *Journal of Environmental Economics and Management* 97:42–66.

Jänicke, Martin, and Klaus Jacob. 2004. "Lead Markets for Environmental Innovations: A New Role for the Nation State." *Global Environmental Politics* 4 (1): 29–46.

Jinnah, Sikina, and Abby Lindsay. 2016. "Diffusion Through Issue Linkage: Environmental Norms in US Trade Agreements." *Global Environmental Politics* 16 (3): 41–61.

Keller, Wolfgang. 2004. "International Technology Diffusion." *Journal of Economic Literature* 42 (3): 752–782.

Kennedy, Andrew B. 2013. "China's Search for Renewable Energy: Pragmatic Techno-Nationalism." *Asian Survey* 53 (5): 909–930.

Kern, Kristine, Helge Jörgens, and Martin Jänicke. 2001. *The Diffusion of Environmental Policy Innovations: A Contribution to the Globalisation of Environmental Policy.* WZB Discussion Paper, No. FS II 01-302, Wissenschaftszentrum Berlin für Sozialforschung (WZB), Berlin.

Lanjouw, Jean Olson, and Ashoka Mody. 1996. "Innovation and the International Diffusion of Environmentally Responsive Technology." *Research Policy* 25 (4): 549–571.

Lenz, Gabriel, and Alexander Sahn. 2020. "Achieving Statistical Significance with Control Variables and without Transparency." *Political Analysis,* 1–14.

LeSage, James, and R. Kelley Pace. 2009. *Introduction to Spatial Econometrics.* Boca Raton, FL: Chapman & Hall/CRC.

Less, Cristina Tébar, and Steven McMillan. 2005. *Achieving the Successful Transfer of Environmentally Sound Technologies: Trade-Related Aspects.* OECD Trade and Environment Working Paper No. 2005-02.

Maskus, Keith Eugene. 2004. *Encouraging International Technology Transfer.* UNCTAD-ICTSD Project on IPRs and Sustainable Development Issue Paper No. 7.

Murdoch, James C, and Todd Sandler. 1984. "Complementarity, Free Riding, and the Military Expenditures of NATO Allies." *Journal of Public Economics* 25 (1-2): 83–101.

Nemet, Gregory F. 2012. "Inter-Technology Knowledge Spillovers for Energy Technologies." *Energy Economics* 34 (5): 1259–1270.

Neumayer, Eric, and Thomas Plümper. 2016. "W." *Political Science Research and Methods* 4 (1): 175–193.

OECD. 1999. *The Environmental Goods & Services Industry: Manual for Data Collection and Analysis.* Paris: OECD Publishing. DOI: 10.1787/9789264173651-en.

OECD, The World Bank, and UN Environment. 2018. *Financing Climate Futures: Rethinking Infrastructure.* Paris: OECD Publishing. DOI: 10.1787/9789264308114-en.

Our World in Data. n.d. *Annual Total CO_2 Emissions, by World Region.* https://ourworldindata.org/grapher/annual-co-emissions-by-region (accessed January 22, 2021).

Passmore, Timothy JA, Megan Shannon, and Andrew F Hart. 2018. "Rallying the Troops: Collective Action and Self-interest in UN Peacekeeping Contributions." *Journal of Peace Research* 55 (3): 366–379.

Perkins, Richard, and Eric Neumayer. 2009. "Transnational Linkages and the Spillover of Environment-Efficiency into Developing Countries." *Global Environmental Change* 19 (3): 375–383.

Persson, Eric. 2019. *OECD: Search and Extract Data from the OECD.* R Package, Version 0.2.4. The Comprehensive R Archive Network (CRAN), https://CRAN.R-project.org/package=OECD.

Plümper, Thomas, and Eric Neumayer. 2015. "Free-riding in Alliances: Testing an Old Theory with a New Method." *Conflict Management and Peace Science* 32 (3): 247–268.

Potoski, Matthew, and Aseem Prakash. 2005. "Green Clubs and Voluntary Governance: ISO 14001 and Firms' Regulatory Compliance." *American Journal of Political Science* 49 (2): 235–248.

Prakash, Aseem, and Matthew Potoski. 2006. "Racing to the Bottom? Trade, Environmental Governance, and ISO 14001." *American Journal of Political Science* 50 (2): 350–364.

———. 2007. "Investing Up: FDI and the Cross-Country Diffusion of ISO 14001 Management Systems." *International Studies Quarterly* 51 (3): 723–744.

Rose, Richard. 1991. "What Is Lesson-Drawing?" *Journal of Public Policy* 11 (1): 3–30.

Saikawa, Eri. 2013. "Policy Diffusion of Emission Standards: Is There a Race to the Top." *World Politics* 65:1.

Sauvage, Jehan. 2014. *The Stringency of Environmental Regulations and Trade in Environmental Goods.* The OECD Trade and Environment Working Paper Series.

Simmons, Beth A, and Zachary Elkins. 2004. "The Globalization of Liberalization: Policy Diffusion in the International Political Economy." *American political science review,* 171–189.

Tews, Kerstin, Per-Olof Busch, and Helge Jörgens. 2003. "The Diffusion of New Environmental Policy Instruments." *European Journal of Political Research* 42 (4): 569–600.

Vargas, Mauricio. 2019. *tradestatistics.* R Package, Version 0.2.5. GitHub, https://github.com/ropensci/tradestatistics.

Voeten, Erik, Anton Strezhnev, and Michael Bailey. 2009. *United Nations General Assembly Voting Data.* Version 27, Harvard Dataverse, DOI: 10.7910/DVN/LEJUQZ.

Vogel, David. 1995. *Trading Up: Consumer and Environmental Regulation in a Global Economy.* Cambridge, MA: Harvard University Press.

———. 1997. "Trading Up and Governing Across: Transnational Governance and Environmental Protection." *Journal of European Public Policy* 4 (4): 556–571.

Volkens, Andrea, Tobias Burst, Werner Krause, Pola Lehmann, Theres MatthieÃŸ, Nicolas Merz, Sven Regel, Bernhard WeÃŸels, and Lisa Zehnter. 2020. *The Manifesto Data Collection. Manifesto Project (MRG/CMP/MARPOR).* Version 2020b, DOI: 10.25522/manifesto.mpds.2020b.

Wacziarg, Romain. 2001. "Measuring the Dynamic Gains from Trade." *The World Bank Economic Review* 15 (3): 393–429.

Ward, Hugh, and Xun Cao. 2012. "Domestic and International Influences on Green Taxation." *Comparative Political Studies* 45 (9): 1075–1103.

Whitten, Guy D, Laron K Williams, and Cameron Wimpy. 2021. "Interpretation: The Final Spatial Frontier." *Political Science Research and Methods* 9 (1): 140–156.

World Bank. n.d. *World Development Indicator.* Dataset, http://databank.worldbank.org/data/download/WDI_csv.zip (accessed April 28, 2021).

Zachmann, Georg, Amma Serwaah-Panin, and Michele Peruzzi. 2015. "When and How to Support Renewables?—Letting the Data Speak." In *Green Energy and Efficiency: An Economic Perspective,* edited by Alberto Ansuategi, Juan Delgado, and Ibon Galarraga, 291–332. Green Energy and Technology. Berlin, Germany: Springer.

Zeng, Ka, and Josh Eastin. 2007. "International Economic Integration and Environmental Protection: The Case of China." *International Studies Quarterly* 51 (4): 971–995.

Appendix (Online Only, Not for Publication)

Overview

- Table A1: Summary Statistics, Monadic Variables
- Table A2: Summary Statistics, Spatial Weights
- Figure A1: Missing Values, Outcome Variable
- Figure A2: Missing Values, Spatial Weights of Interest
- Table B1: Regression with Additional Spatial Lag
- Table B2: Regression with Alternative Explanatory Variable
- Table B3: Regression with (Temporally) Distributed Lags
- Table B4: Regression with PCSEs
- Table B5: Regression with PCSEs and AR(1) Disturbance (TLDV Excluded)
- Appendix C: Spatial Model Discussion

Appendix A: Summary Statistics and Missing Values

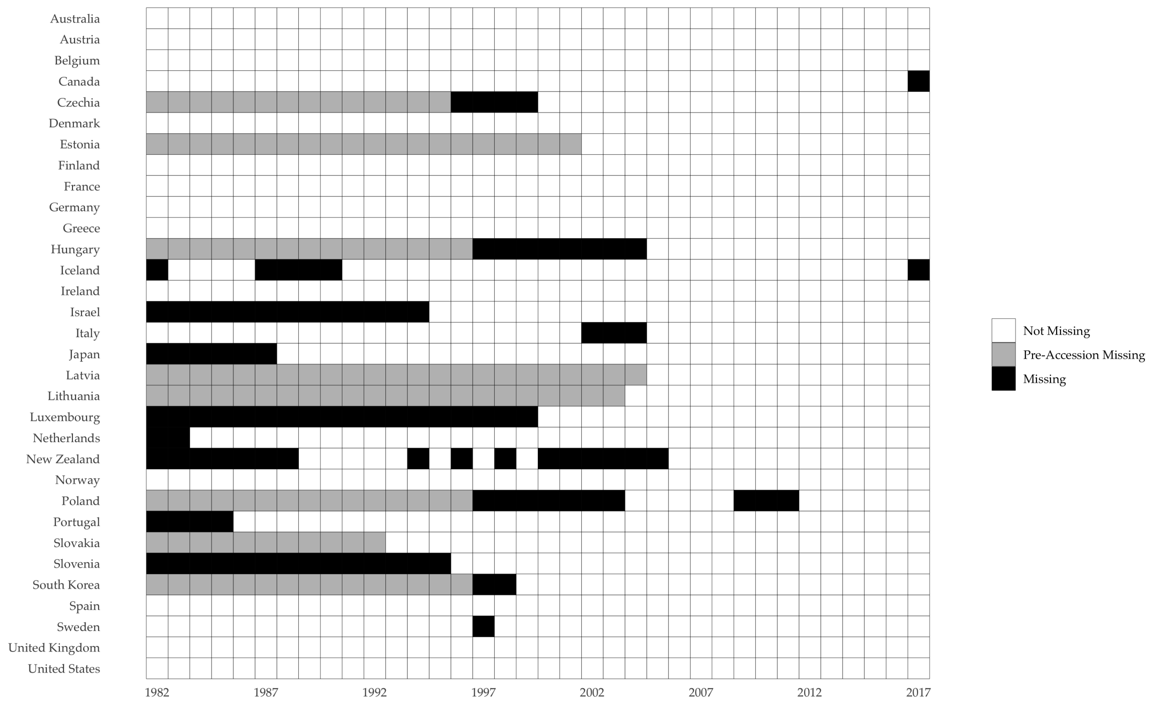
Table A1: Summary Statistics of Outcome and Non-Spatial Control Variables

Variable	Min	Median	Max	Mean	SD	Obs
DV: Gov Env R&D Spending	3.37	10.80	14.17	10.84	1.80	909
Fossil Fuel Rents/GDP (%)	0.00	0.08	12.11	0.60	1.44	1,066
Gov Environmental Position (CMP)	0.00	0.59	3.67	0.78	0.62	1,042
Political Globalization Index (KOF)	0.00	1.00	1.00	0.54	0.50	1,087
EU Membership (Yes = 1)	36.50	87.31	98.85	81.13	15.26	1,090
GDP per capita (Log)	1.36	3.47	4.72	3.36	0.59	1,064
GDP Growth (%)	−14.84	2.75	25.16	2.70	3.15	1,056
Urban Population (%)	43.22	75.65	97.92	74.55	11.59	1,152
GDP (Log)	1.86	5.70	9.74	5.78	1.67	1,064
Total Gov R&D Spending (Billion USD)	0.02	2.27	150.43	9.82	21.82	933
Environmental NGOs	0.00	5.00	82.00	9.44	12.29	778
Environmental Ministry	0.00	1.00	1.00	0.79	0.41	960

Table A2: Summary Statistics of Spatial Weights in Dyadic Format

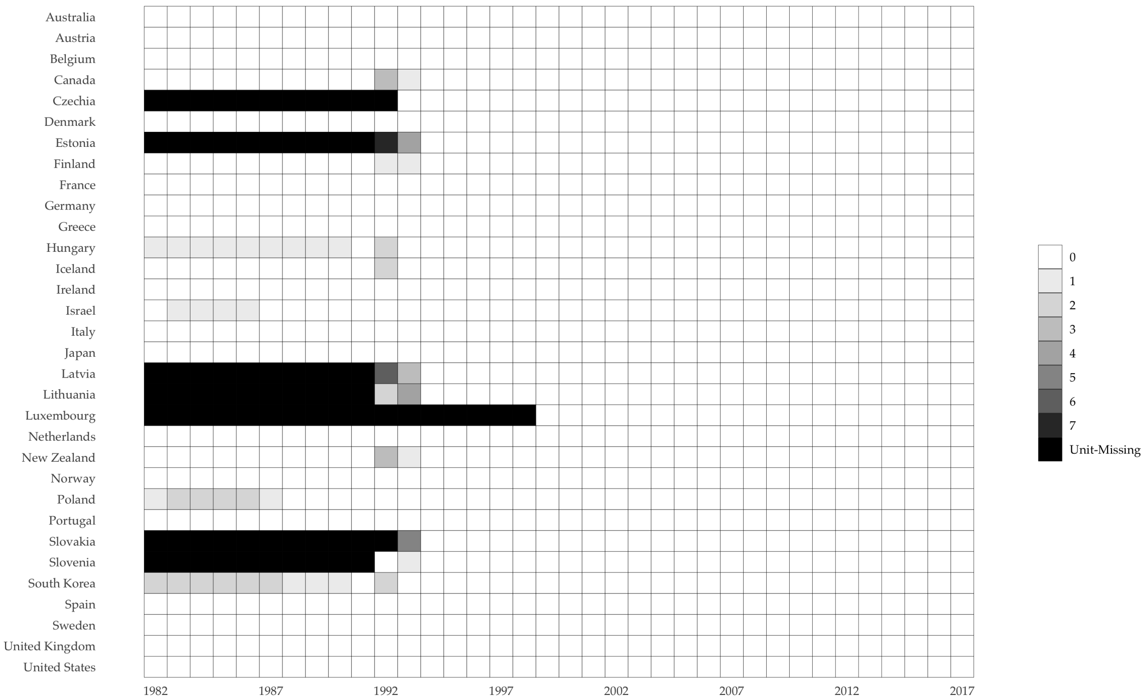
Variable	Min	Median	Max	Mean	SD	Obs
Environmental Trade (Billion USD)	0.00	0.49	333.26	4.78	16.77	33,956
Aggregated Trade (Billion USD)	0.00	1.02	725.32	9.17	32.06	33,412
Similarity	0.00	0.92	1.00	0.85	0.21	34,642

Figure A1: Missing Values in Government Environmental R&D Spending (Outcome Variale)



In the complete data case (i.e., no missing value), my sample size would be $N \times T = 32 \times 36 = 1,152$. The vast majority of missing values in my outcome variable is caused by the later accessions to the OECD of South Korea and the Eastern European nations (labeled as "Pre-Accession Missing"). There is no convincing factor that may endogenize the missing-data process, so I delete the observations with missing values of outcome variable in a listwise way. After doing so, my sample size decreases to 939.

Figure A2: Number of Missing Values in Bilateral Trade Volumes on Environmental Goods (Spatial Weights of Interest) in Each Country-Year (Unit of Analysis)



I omit the sparsely missing values in these data. Since my sample is OECD countries, no unobserved endogenous factor may convincingly govern the missing-data process. In other words, the missing at random (MAR) assumption is very likely to hold. Given that various control variables and spatiotemporal heterogeneities are included in my models, dropping the missing values has no effect on my point estimates and only minimal impact on my estimation efficiency. A missing value is labeled as "Unit-Missing" when the relevant country has no data with all others at all for a given year. Unit-missing values do not count in others' missing values. For example, the bilateral trade data between Australia and all Eastern European countries but Poland are missing for 1981, but Australia still has no missing value for that year.

Appendix B: Extensions and Robustness

Table B1: Spatial Regression Results on Government Environmental R&D Spending (Environmental Trade as Weights), OECD Countries, 1982–2017, Twoway FEs with Clustered SEs and Additional Spatial Lag Variable

	(1)	(2)
TLDV	0.706***	0.687***
	(0.046)	(0.043)
S-Lag by Environmental Trade	−0.043**	−0.060**
	(0.000)	(0.000)
S-Lag by Similarity	0.003	0.064†
	(0.001)	(0.001)
Fossil Fuel Rents/GDP (%)		−0.008
		(0.012)
Gov Environmental Position (CMP)		0.015
		(0.038)
EU Membership (Yes = 1)		0.003
		(0.110)
Political Globalization Index (KOF)		0.028
		(0.003)
GDP per capita (Log)		−0.080
		(0.268)
GDP Growth (%)		0.025
		(0.011)
Urban Population (%)		−0.084
		(0.013)
Total Gov R&D Spending		0.126
		(0.007)
Number of Observations	884	884
Number of Countries	32	32
Root-Mean-Square Error	0.384	0.382

Variables are temporally lagged at $t-1$.

Fixed effects are not reported.

Coefficient estimates are standardized.

$^{\dagger}p < 0.100$, $^{*}p < 0.050$, $^{**}p < 0.010$, $^{***}p < 0.001$.

Table B2: Spatial Regression Results on Government Environmental R&D Spending (Aggregated Trade as Weights), OECD Countries, 1982–2017, Twoway FEs with Clustered SEs

	(1)	(2)
TLDV	0.705***	0.689***
	(0.046)	(0.043)
S-Lag by Aggregated Trade	−0.040**	−0.055**
	(0.000)	(0.000)
Fossil Fuel Rents/GDP (%)		−0.005
		(0.012)
Gov Environmental Position (CMP)		0.013
		(0.036)
EU Membership (Yes = 1)		0.004
		(0.112)
Political Globalization Index (KOF)		0.027
		(0.003)
GDP per capita (Log)		−0.084
		(0.276)
GDP Growth (%)		0.025
		(0.011)
Urban Population (%)		−0.071
		(0.013)
Total Gov R&D Spending		0.096
		(0.006)
Number of Observations	884	884
Number of Countries	32	32
Root-Mean-Square Error	0.383	0.382

Variables are temporally lagged at $t-1$.

Fixed effects are not reported.

Coefficient estimates are standardized.

$^{\dagger}p < 0.100$, $^{*}p < 0.050$, $^{**}p < 0.010$, $^{***}p < 0.001$.

Table B3: Spatial Regression Results on Government Environmental R&D Spending (Environmental Trade as Weights, Distributed Lags), OECD Countries, 1982–2017, Twoway FEs with Clustered SEs

	(1)	(2)	(3)
TLDV	0.671^{***}	0.666^{***}	0.658^{***}
	(0.045)	(0.046)	(0.048)
S-Lag by Environmental Trade	$-0.072^{\dagger}$	-0.065	$-0.090^{\dagger}$
	(0.000)	(0.000)	(0.000)
S-Lag by Environmental Trade, $t-2$	0.019	-0.057	-0.027
	(0.000)	(0.000)	(0.000)
S-Lag by Environmental Trade, $t-3$		0.074	-0.023
		(0.000)	(0.000)
S-Lag by Environmental Trade, $t-4$			$0.094^{\dagger}$
			(0.000)
F (lags = 2)	4.462		
p (lags = 2)	0.043		
F (lags = 3)		3.093	
p (lags = 3)		0.088	
F (lags = 4)			1.793
p (lags = 4)			0.190
Number of Observations	868	850	831
Number of Countries	32	32	32
Root-Mean-Square Error	0.382	0.384	0.386

S-Lag by Environmental Trade is already lagged at $t-1$.

TLDV, control variables, and fixed effects are not reported.

Coefficient estimates are standardized.

$^{\dagger}p < 0.100$, $^{*}p < 0.050$, $^{**}p < 0.010$, $^{***}p < 0.001$.

Table B4: Spatial Regression Results on Government Environmental R&D Spending (Environmental Trade as Weights), OECD Countries, 1982–2017, Twoway FEs with PCSEs

	(1)	(2)
TLDV	0.705^{***}	0.677^{***}
	(0.051)	(0.054)
S-Lag by Environmental Trade	-0.043^{**}	-0.050^{**}
	(0.000)	(0.000)
Fossil Fuel Rents/GDP (%)		-0.000
		(0.011)
Gov Environmental Position (CMP)		0.015
		(0.032)
EU Membership (Yes = 1)		0.020
		(0.092)
Political Globalization Index (KOF)		0.040
		(0.004)
GDP per capita (Log)		$-0.316^{\dagger}$
		(0.699)
GDP (Log)		$0.764^{\dagger}$
		(0.501)
GDP Growth (%)		0.022
		(0.013)
Urban Population (%)		-0.069
		(0.009)
Total Gov R&D Spending		$0.083^{\dagger}$
		(0.004)
Number of Observations	885	885
Number of Countries	32	32
Root-Mean-Square Error	0.390	0.388

Variables are temporally lagged at $t-1$.

Fixed effects are not reported.

Coefficient estimates are standardized.

${}^{\dagger}p < 0.100$, ${}^{*}p < 0.050$, ${}^{**}p < 0.010$, ${}^{***}p < 0.001$.

Table B5: Spatial Regression Results on Government Environmental R&D Spending (Environmental Trade as Weights), OECD Countries, 1982–2017, Twoway FEs with PCSEs and AR(1) Disturbance (TLDV Excluded)

	(1)	(2)
S-Lag by Environmental Trade	-0.144^{***}	-0.120^{***}
	(0.000)	(0.000)
Fossil Fuel Rents/GDP (%)		-0.003
		(0.015)
Gov Environmental Position (CMP)		0.022
		(0.050)
EU Membership (Yes = 1)		0.045
		(0.150)
Political Globalization Index (KOF)		$0.078^{\dagger}$
		(0.006)
GDP per capita (Log)		$-0.727^{\dagger}$
		(1.496)
GDP (Log)		2.373^{*}
		(1.199)
GDP Growth (%)		0.011
		(0.014)
Urban Population (%)		$-0.232^{\dagger}$
		(0.021)
Total Gov R&D Spending		0.087
		(0.006)
Number of Observations	908	891
Number of Countries	32	32
Root-Mean-Square Error	0.427	0.402

Variables are temporally lagged at $t-1$.

Fixed effects are not reported.

Coefficient estimates are standardized.

$^{\dagger}p < 0.100$, $^{*}p < 0.050$, $^{**}p < 0.010$, $^{***}p < 0.001$.

Appendix C: Spatial Model Choice Discussion

In matrix notation, my explanatory variable is generically written as $\mathbf{Wy}$, in which $\mathbf{W}$ is a $NT \times NT$ block diagonal weights matrix and $\mathbf{y}$ is the column vector of the outcome variable at length NT. By temporally lagging it at $t-1$, my regression becomes the temporally lagged spatial lag (TLSL) model (Wimpy, Williams, and Whitten, forthcoming). In scalar notation, each observation in my explanatory variable equals $\sum_{j=1}^{N} trade_{i,j,t-1} \times y_{j,t-1} (i \neq j)$, the year 1981 is t_0.

Some applied researchers use the TLSL model to circumvent the simultaneity bias in the spatial autoregressive (SAR) model. Nevertheless, the decision of temporally lagging my explanatory variable in this research is completely theory-driven, as main text justifies. Actually, Wimpy, Williams, and Whitten (forthcoming) illustrates that the TLSL model shall be better viewed as a variant of the spatial-X (SLX) model rather than a variant of the SAR model. The former one is, in general, more theoretically justifiable and empirically flexible than the latter in political science applications (Drolc, Gandrud, and Williams 2019; Wimpy, Williams, and Whitten, forthcoming). For example, when a contiguity weights matrix is supplied, the SLX model does not automatically assume the existence of global effects, but at the same time, researchers who argue higher order effects exist are also able to incorporate them easily. Rüttenauer (forthcoming) uses Monte Carlo simulations to show that the SLX model outperforms other spatial models in terms the bias of spillover effects. Halleck Vega and Elhorst (2015) provide an interdisciplinary overview on the SLX model. Whitten, Williams, and Wimpy (2021) also discuss it from a political science perspective. It is acknowledged that temporally lagging my explanatory variable makes an assumption about the initial value's stochasticity (Franzese and Hays 2007). Also, a necessary condition for causation when explanatory variable is temporally lagged is that disturbance should not be serially correlated. Thus, I don't mean to make a causal claim by simply taking a temporal lag on my explanatory variable. On this point, see Franzese and Hays (2007) for an illustration for spatial data and Bellemare, Masaki, and Pepinsky (2017) for a more general treatment.

Appendix References

Bellemare, Marc F, Takaaki Masaki, and Thomas B Pepinsky. 2017. "Lagged Explanatory Variables and the Estimation of Causal Effect." *The Journal of Politics* 79 (3): 949–963.

Drolc, Cody A, Christopher Gandrud, and Laron K Williams. 2019. "Taking Time (and Space) Seriously: How Scholars Falsely Infer Policy Diffusion from Model Misspecification." *Policy Studies Journal.*

Franzese, Robert J, and Jude C Hays. 2007. "Spatial Econometric Models of Cross-Sectional Interdependence in Political Science Panel and Time-Series-Cross-Section Data." *Political Analysis,* 140–164.

Halleck Vega, Solmaria, and J Paul Elhorst. 2015. "The SLX Model." *Journal of Regional Science* 55 (3): 339–363.

Rüttenauer, Tobias. Forthcoming. "Spatial Regression Models: A Systematic Comparison of Different Model Specifications Using Monte Carlo Experiments." *Sociological Methods & Research.*

Whitten, Guy D, Laron K Williams, and Cameron Wimpy. 2021. "Interpretation: The Final Spatial Frontier." *Political Science Research and Methods* 9 (1): 140–156.

Wimpy, Cameron, Laron K. Williams, and Guy D. Whitten. Forthcoming. "X Marks the Spot: Unlocking the Treasure of Spatial-X Models." *The Journal of Politics.*