TESTING FOR CAUSALITY BETWEEN CLIMATE POLICIES AND CARBON EMISSIONS REDUCTION

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Testing for Causality between Climate Policies and Carbon Emissions Reduction.[⋆]

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Abstract

In this paper, we evaluate the causal effects of climate policies on carbon emissions reductions. Using Sweden as a case study, we compare the effects of the domestic carbon tax and the Kyoto Protocol over the period 1965–2018. A simulation exercise shows that the test for causality in the frequency domain offers policy-makers a useful tool for evaluating the effect of public policies. The empirical results indicate a significant causal effect of the carbon tax policy on carbon intensity dynamics in the long run.

Keywords: *Granger causality; Spectral analysis; Climate policy; Carbon tax.*

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1. Introduction

In this paper, we evaluate the causal effect of climate policies on carbon emissions reductions. Using Sweden as a case study, we compare the effects of the domestic carbon tax introduced in 1991 and the Kyoto Protocol adopted in 1997. Specifically, Granger causality tests in the time and frequency domains were used to evaluate the impact of these climate policies on the CO2/output ratio over the period 1965–2018. Granger (1969)'s test does not help to distinguish the effects of a policy change, which takes the form of a structural break, whereas Breitung and Candelon (2006)'s test does so. The empirical results indicate a significant causal effect in the long run of the carbon tax policy on carbon intensity dynamics. Finally, this framework offers policy-makers a useful toolbox for evaluating the effect of public policies.

Should the Paris Agreement be replaced with a global carbon tax? This simple question has prompted debate among economists about the effectiveness of climate policies. This debate finds its roots in the unsuccessfulness of the Kyoto Protocol, an international treaty adopted in 1997 that aimed to diminish carbon emissions over the period 2008–2012 and has been widely recognized as a failure. Several arguments have been put forward as to why it has failed. First, the role of the Kyoto Protocol's design has been noted. For instance, Pizer (2006) highlight that the United States and most developing countries have not ratified the treaty. As a result, less than 30% of global carbon emissions were covered by the agreement. Moreover, according to Nordhaus (2006), the failure to initially include the major developing countries has been aggravated by the fact that the design of the agreement did not permit the inclusion of new countries or the extension of the treaty into new periods. Furthermore, Aichele and Felbermayr (2015) provide empirical evidence that emerging countries that were not involved in the Kyoto Protocol have induced carbon leakage via international trade. Other contributions point out that the effectiveness of this treaty has been reduced by the short-termism of its objectives limited to the period 2008-2012 (Olmstead and Stavins, 2006), by the absence of sanctions against nonparticipants (Nordhaus, 2015), and by the fact that targeting a carbon price would have been more efficient than targeting carbon emissions reductions (Weitzman, 2017). Overall, the weaknesses of the Kyoto Protocol are in line with game theory predictions that countries find it optimal to sign weak agreements or to free ride (Battaglini and Harstad, 2020). In contrast, carbon tax policies provide significant results in terms of carbon emissions reductions. Metcalf (2019) report the results of carbon tax policies around the world and highlight Swedish climate policy as a key example. Among the first countries to employ carbon taxes, Sweden has increased this tax level gradually from a rate corresponding to SEK 250 (EUR 25) in 1991 to SEK 1,200 (EUR 118) in 2022. Via a quasi-experimental study, Andersson (2019) found a significant causal effect of carbon taxes on carbon emissions and of value-added tax (VAT) on transport fuels. Specifically, the results indicate that carbon emissions from transport decline more than 10% per year under such schemes. In summary, the results of the carbon tax enacted by Sweden in 1991 are in stark contrast to those of the Kyoto Protocol. More than two decades after the respective launches of the Swedish carbon tax and the Kyoto Protocol, we now have the distance to conduct econometric analyses to evaluate the effectiveness of these public policies (Metcalf and Stock, 2020b). Nordhaus (2019) argues that if the Kyoto Protocol was environmentally effective, then the trend in carbon intensity (i.e., the CO2/output ratio) would have declined sharply after its establishment. Building on this argument, this paper proposes to evaluate the effectiveness of the Kyoto Protocol and the Swedish carbon tax in terms of carbon intensity dynamics. Following White and Pettenuzzo (2014), the analysis is done via the implementation of a causality test à la Granger in the time and frequency domains (Breitung and Candelon, 2006).

The contribution to the literature is twofold. First, in line with Nordhaus (2019), the empirical results indicate that the implementation of a carbon tax in Sweden has been an efficient climate policy, while the Kyoto Protocol has not been effective. Second, it turns out that the Granger causality test in the time domain does not help to distinguish the effects of a policy change, which takes the form of a structural break, whereas the frequency domain causality tests succeed in doing so. This paper therefore concludes that the test for causality in the frequency domain constitutes an adequate tool to evaluate the impacts of policies. The rest of this paper is organized as follows. Section 2 is devoted to the description of the econometric methodology. Section 3 describes the dataset, the simulations, the empirical results and the robustness checks. Finally, Section 4 concludes the paper and highlights some policy implications.

2. Methodology

Following Breitung and Candelon (2006), let us consider $\mathbf{Y}_t = (x_t, y_t)'$ to be a covariance-stationary vector time series that can be represented by a finite-order VAR(p) process,

$$\Theta(L)\mathbf{Y}_t = \varepsilon_t, \tag{1}$$

where $\Theta(L) = \mathbf{I}_2 - \Theta_1 L - \Theta_2 L^2 - \cdots - \Theta_p L^p$ is a 2×2 lag polynomial with the lag operator $L^i\mathbf{Y}_t = \mathbf{Y}_{t-i}, \mathbf{\Theta}_i i = 1, 2, \ldots, p$, is a 2×2 coefficient matrix associated with lag i; and $\varepsilon_t = (\varepsilon_{1t}, \varepsilon_{2t})'$ denotes a vector white-noise process, with $E(\varepsilon_t) = \mathbf{0}$ and positive-definite covariance matrix $\mathbf{\Sigma} = E(\varepsilon_t \varepsilon_t')$. Applying Cholesky factorization, $\mathbf{G}'\mathbf{G} = \Sigma^{-1}$ (where G is a lower-triangular matrix), a moving-average representation of the system in (1) can be written as

$$\begin{aligned} \begin{bmatrix} x_t \\ y_t \end{bmatrix} &= \Phi(L)\varepsilon_t = \begin{bmatrix} \Phi_{11}(L) & \Phi_{12}(L) \\ \Phi_{21}(L) & \Phi_{22}(L) \end{bmatrix} \begin{bmatrix} \varepsilon_{1t} \\ \varepsilon_{2t} \end{bmatrix} \\ &= \mathbf{\Psi}(L)\eta_t = \begin{bmatrix} \Psi_{11}(L) & \Psi_{12}(L) \\ \Psi_{21}(L) & \Psi_{22}(L) \end{bmatrix} \begin{bmatrix} \eta_{1t} \\ \eta_{2t} \end{bmatrix}. \end{aligned}$$

where $\boldsymbol{\eta}_t = \mathbf{G}\varepsilon_t, E(\boldsymbol{\eta}_t\boldsymbol{\eta}_t') = \mathbf{I}, \mathbf{\Phi}(L) = \Theta(L)^{-1}$, and $\Psi(L) = \Phi(L)\mathbf{G}^{-1}$. Using the Fourier transformations of the moving-average polynomial terms, we can write the spectral density of x_t as

$$f_x(\omega) = \frac{1}{2\pi}\left\{\left|\Psi_{11}\left(e^{-i\omega}\right)\right|^2 + \left|\Psi_{12}\left(e^{-i\omega}\right)\right|^2\right\}.$$

Geweke (1982)'s measure of linear feedback from y_t to x_t at frequency ω is defined as

$$M_{y\to x}(\omega) = \log\left\{\frac{2\pi f_x(\omega)}{\left|\Psi_{11}\left(e^{-i\omega}\right)\right|^2}\right\} = \log\left\{1 + \frac{\left|\Psi_{12}\left(e^{-i\omega}\right)\right|^2}{\left|\Psi_{11}\left(e^{-i\omega}\right)\right|^2}\right\}.$$

If $\left|\Psi_{12}\left(e^{-i\omega}\right)\right| = 0$, then $M_{y\to x}(\omega)$ will be 0. This means that y_t does not Granger cause x_t at frequency ω. Breitung and Candelon (2006) show that testing for the noncausality from y to x can be done via $\left|\Psi_{12}\left(e^{-i\omega}\right)\right| = 0$.

It therefore signifies that y_t does not Granger cause x_t at frequency ω if the following condition is satisfied:

$$\left|\Theta_{12}\left(e^{-i\omega}\right)\right| = \left|\sum_{k=1}^{p}\theta_{12,k}\cos(k\omega) - \sum_{k=1}^{p}\theta_{12,k}\sin(k\omega)\mathrm{i}\right| = 0.$$

Here, $\theta_{12,k}$ is the $(1,2)$-element of Θ_k. In this case, necessary and sufficient conditions for $\left|\Theta_{12}\left(e^{-i\omega}\right)\right| = 0$ are

$$\sum_{k=1}^{p}\theta_{12,k}\cos(k\omega) = 0$$
$$\sum_{k=1}^{p}\theta_{12,k}\sin(k\omega) = 0.$$

Breitung and Candelon (2006) reformulated these restrictions by rewriting the equation for x_t in the VAR(p) system,

$$x_t = c_1 + \alpha_1 x_{t-1} + \cdots + \alpha_p x_{t-p} + \beta_1 y_{t-1} + \cdots + \beta_p y_{t-p} + \varepsilon_{1t}, \tag{2}$$

where $\alpha_j = \theta_{11,j}$ and $\beta_j = \theta_{12,j}$. The null hypothesis of $M_{y\to x}(\omega) = 0$ is equivalent to

$$H_0 : \mathbf{R}(\omega)\boldsymbol{\beta} = 0,$$

where $\boldsymbol{\beta} = (\beta_1, \ldots, \beta_p)'$ and $\mathbf{R}(\omega)$ is a $2 \times p$ restriction matrix.

$$\mathbf{R}(\omega) = \begin{bmatrix} \cos(\omega) & \cos(2\omega) & \ldots & \cos(p\omega) \\ \sin(\omega) & \sin(2\omega) & \ldots & \sin(p\omega) \end{bmatrix}.$$

Because these are simple linear restrictions, the usual Wald statistic can be used. Let $\gamma = [c_1, \alpha_1, \ldots, \alpha_p, \beta_1, \ldots, \beta_p]'$ be the $q = (2p+1) \times 1$ vector of parameters, and let $\mathbf{V}$ be a $q \times q$ covariance matrix from the unrestricted regression (2). Then, the Wald statistic is

$$W = (\mathbf{Q}\gamma)' \left(\mathbf{Q}\mathbf{V}\mathbf{Q}'\right)^{-1} (\mathbf{Q}\gamma) \sim \chi^2_2,$$

$\mathbf{Q}$ is the $2 \times q$ restriction matrix such that

$$\mathbf{Q} = \left[\mathbf{0}_{2\times(p+1)} \vdots \mathbf{R}(\omega)\right].$$

This test has paved the way for many studies. Yamada and Yanfeng (2014) have shown its validity at the frequency borders when $\omega = 0$ or π. Farnè and Montanari (2022) propose a bootstrap version to deal with the potential nonnormality properties of the residuals, whereas Breitung and Schreiber (2018) have extended it to test for a frequency range $[\underline{\omega}, \bar{\omega}]$.

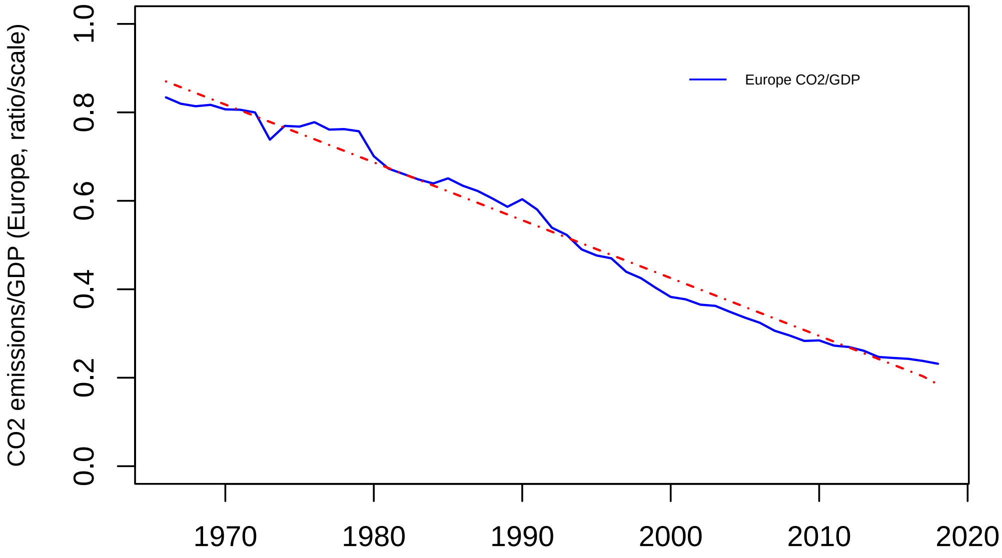
Stoffer (1991) also shows that frequency domain analyses using Fourier transforms can be extended in the case of discrete-valued, categorical-valued time series, as well as of time series that contain sharp discontinuities. It is therefore possible to extend the Breitung and Candelon (2006) approach to test for structural breaks. In such a case, y_t is no longer a continuous variable but a step dummy that takes a 0 before and a 1 after a specific event. In this paper, the different policy actions against climate change are considered.

3. Empirical analysis

3.1. Data

Nordhaus (2019) argues that the CO2/GDP ratio, also called the "carbon intensity" of production, is the best single measure of decarbonization. This indicator measures the trend in the ratio of carbon dioxide emissions to output. Figure 1 replicates for Europe the trend in decarbonization illustrated in Figure 6 (p. 2009) in his paper.

Figure 1: Trend in Global Decarbonization, 1965–2018



Notes: This figure illustrates the European CO2/output ratio from 1965 to 2018 along with a trend curve. The global average intensity declined by 2.3% per year over this period.

Following Nordhaus (2019), our dataset includes 3 variables over the period 1965–2018: (i) the Swedish carbon intensity (first difference), (ii) the Kyoto Protocol dummy (1 from 2008 to 2012, 0 otherwise) and (iii) the Swedish carbon tax dummy (1 from 1991, 0 otherwise) at annual frequency.

Carbon intensity data are published by Global Carbon Budget (v2021) via ICOS' web-

Table 1: Description of the dataset

Variable	Description	Code	Source
Carbon intensity	Annual CO2 emissions per GDP (kg per $PPP)	ICO2	ICOS
Kyoto Protocol	Dummy 2008–2012 budget period	KPRO	
Carbon tax	Dummy 1991–2018 period	CTAX	

Notes: This table provides each variable's name, description, code and source. The panel dataset covers Sweden over the period 1965 to 2018.

site.[1] Table 1 reports the variable names and descriptions and sources.

3.2. Simulation Analysis

Before conducting the empirical analysis, which evaluates the impacts of the different policies on carbon emissions reduction, it is important to determine how the causality tests (in time series and in frequencies) perform to evaluate the effects of policy changes via structural breaks.

To better grasp the properties of the Breitung and Candelon (2006) test for the structural break test, three different data-generating processes (DGPs) were generated to mimic the carbon intensity return. In the first one (DGP_1), carbon emissions follow an i.i.d. normal distribution with an unconditional mean ($\mu = 0$) and standard error ($\sigma = 0.5$), which corresponds to the estimates obtained for the whole sample. A structural break is included in the middle of the sample $t = 27$ of amplitude $\tau = (0, 0.5, 1, 2, 5)$. It is worth noting that when $\tau = 0$ there is no break, and we, therefore, are under the null hypothesis of no causality. In DGP_2, instead of imposing an "abrupt" structural break, carbon emissions exhibit a deterministic trend with a negative constant slope ($\beta = 0.00, -0.05, -0.10, -0.15, -0.20, -0.25, -0.30$). Again, iidness is imposed around the trend. DGP_3 is similar to DGP_1, but instead of imposing iidness, the residuals follow an AR(1) process, where the autoregressive coefficient (ρ)

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[1] ICOS' website: `https://www.icos-cp.eu/science-and-impact/global-carbon-budget/2021`

corresponds to the one estimated on historical data ($\rho = 0.96$). In each case $5,000$ replications were simulated with $T = 53$, corresponding to our empirical size. An initial burn-off of 10 observations is considered to limit the dependence on initial observations. In each case, the time and frequency domain tests were implemented. In Table 2 the rejection frequency of the null hypothesis of noncausality is reported. For the second row (the power experiments), the rejection is calculated using the 95% quantile obtained in the first row simulations (the size experiments). These rejection frequencies, therefore, represent the size-adjusted power.

Table 2: Rejection rates – DGP_1 – $\sigma = 0.5$

	Causality test in the time domain	Causality test in the frequency domain			
		0	$\pi/4$	$\pi/2$	$3\pi/4$
Break size					
$\tau = 0$	5.4	11.7	7.6	5.7	4.3
$\tau = 0.5$	36.0	47.6	4.9	2.9	2.2
$\tau = 1$	78.1	89.7	10.0	4.9	3.0
$\tau = 2$	99.4	99.7	27.9	14.6	8.9
$\tau = 5$	99.8	100.0	64.9	63.2	38.3

Notes: This table provides the rejection frequency of the non-causality test in the frequency domain for different frequencies ω and different break size τ. For τ=0 the asymptotic critical value of the distribution (5.99) is used. The 5% nominal size obtained are used for the other values of τ. The results are computed using a Gretl procedure and Breitung and Schreiber (2018)'s Gretl package *"BreitungCandelonTest"*. The code is available upon request from the authors.

Table 3: Rejection rates – DGP_2 – $\sigma = 0.5$

	Causality test in the time domain	Causality test in the frequency domain			
		0	$\pi/4$	$\pi/2$	$3\pi/4$
Slope size					
$\beta = 0.00$	5.4	11.7	7.6	5.7	4.3
$\beta = 0.05$	12.8	13.0	2.5	1.7	1.5
$\beta = 0.10$	13.7	13.9	0.9	1.9	1.9
$\beta = 0.15$	20.8	27.0	2.3	2.5	2.1
$\beta = 0.20$	33.6	44.2	2.6	1.9	1.7
$\beta = 0.25$	48.5	63.5	2.4	1.6	2.0
$\beta = 0.30$	64.8	81.8	4.8	3.0	2.1

Notes: This table provides the rejection frequency of the non-causality test in the frequency domain for different frequencies ω and different slope of the deterministic trend β. For β=0 the asymptotic critical value of the distribution (5.99) is used. The 5% nominal size obtained are used for the other values of β. The results are computed using a Gretl procedure and Breitung and Schreiber (2018)'s Gretl package *"BreitungCandelonTest"*. The code is available upon request from the authors.

Table 4: Rejection rates – DGP_3– AR 0.96 – $\sigma = 0.5$

	Causality test in the time domain	Causality test in the frequency domain			
		0	$\pi/4$	$\pi/2$	$3\pi/4$
Break size					
$\tau = 0$	5.4	11.7	7.6	5.7	4.3
$\tau = 0.5$	20.9	31.8	0.5	0.6	0.3
$\tau = 1$	61.4	77.5	4.0	1.1	0.7
$\tau = 2$	97.7	98.3	15.9	7.5	2.6
$\tau = 5$	99.8	100.0	43.1	43.9	18.8

Notes: This table provides the rejection frequency of the non-causality test in the frequency domain for different frequencies ω and different break sizes τ. For τ=0 the asymptotic critical value of the distribution (5.99) is used. The 5% nominal size obtained are used for the other values of τ. The results are computed using a Gretl procedure and Breitung and Schreiber (2018)'s Gretl package *"BreitungCandelonTest"*. The code is available upon request from the authors.

Several findings can be drawn from this simulation exercise. First, both causality tests in the time and frequency domains are able to detect the presence of a structural break, confirming the earlier findings in the literature (inter alii Bianchi, 1995). Nevertheless, in such a case, the frequency domain test provides more information, as it unambiguously indicates that causality takes place in the long run, not in the short run. The rejection frequency is therefore the highest at or $\omega = 0$ for abrupt structural breaks (Table 2), smooth breaks (Table 3) and autoregressive processes (Table 4). Second, it is also observable that the rejection frequency under the null is close to the nominal size even if the sample size is relatively small, the rejection frequency is not exactly at 5%. In addition, as in Breitung and Candelon (2006), a small size distortion at frequency $\omega = 0$.[2] Third, the size-adjusted power increases relatively quickly, as it is almost 100% in all cases with τ larger than 2.

3.3. Results

Elaborating on Nordhaus (2019)'s argument, the causality effect of climate policies on domestic carbon emissions reductions was tested in two steps. First, Granger (1969)'s and Breitung and Candelon (2006)'s original tests were used to evaluate the effect of the Swedish

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[2] was observed. As the process is stationary, it is defined at $\omega = 0$, which would not have been the case if it were nonstationary.

carbon tax and the Kyoto Protocol on carbon emissions reductions. Table 5 reports the results.

Table 5: Empirical results – Granger causality test

Policy	Causality test in the time domain		Causality test in the frequency domain			
Variable	Policy $\mapsto$ CO2	CO2 $\mapsto$ Policy	Policy $\mapsto$ CO2		CO2 $\mapsto$ Policy	
			$\omega = 0.25$	$\omega = 2.5$	$\omega = 0.25$	$\omega = 2.5$
Swedish Carbon Tax	0.95	1.57	6.09*	1.56	0.66	2.43
Kyoto Protocol	0.20	0.27	0.07	1.29	0.43	0.31

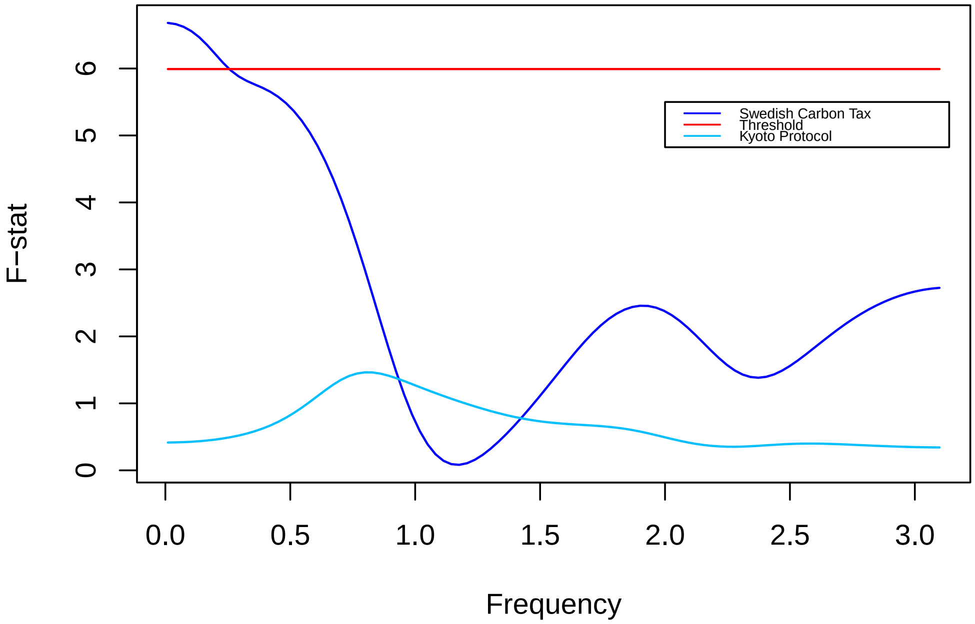
Notes: This table reports causality tests statistics in both the time frequency domains. Test statistics are calculated at a low ($\omega = 0.25$) and a high ($\omega = 2.5$) frequency for permanent and temporary effects, respectively. Results are computed using Breitung and Schreiber (2018)'s Gretl package *"BreitungCandelonTest"*. Labels $***$, $**$ and $*$ indicate significance at 99.5%, 99% and 95% levels, respectively.

These empirical results indicate that the time series form of the Granger causality test is not able to detect the effects of the Kyoto Protocol or the carbon tax in Sweden. In contrast, the frequency domain causality test performs quite well, as it reveals a long-term impact of the carbon tax implementation in Sweden. This difference in results is in line with the outcomes of the simulation exercise and with the empirical results of Metcalf and Stock (2020a). Second, it is worth noting that the empirical exercise assumes a carbon tax, but cannot provide results for a higher or lower tax of carbon emissions. Nevertheless, the simple setup of a carbon tax has a positive impact on carbon emission reductions.

Then, focusing on Breitung and Candelon (2006)'s test results, the main empirical findings are illustrated in Figure 2.

Figure 2 indicates that there exists a significant causality between the Swedish carbon tax and domestic carbon emission reductions only. This causal effect is significant at low frequencies, lower than 0.3, indicating that the effect of the $CO2$ tax on emissions is relatively long term, i.e., longer than 20 years. It is also possible to calculate the Geweke (1982)

Figure 2: Granger causality – Frequency analysis



Notes: This figure illustrates the Granger causality between the CO2/output ratio, the carbon tax reform of 1991 in Sweden (in blue) and the Kyoto Protocol 2008–2012 budget period (in cyan). The results are computed using Breitung and Schreiber (2018)'s Gretl package *"BreitungCandelonTest"*.

intensity measure at this frequency, which lies at 2%.[3] In contrast, the Kyoto Protocol has no significant impact, even in the long run, on carbon emissions in Sweden.

3.4. Robustness checks

Then, for robustness purposes, the empirical analysis was replicated using Farnè and Montanari (2022)'s bootstrapped version of Breitung and Candelon (2006)'s test, which provides more accurate inference in the case of finite samples. The result is illustrated in Figure 3.

Figure 3 confirms that there exists a significant causality between the Swedish carbon tax and the domestic carbon emission reductions in the long run, similar to what has been found

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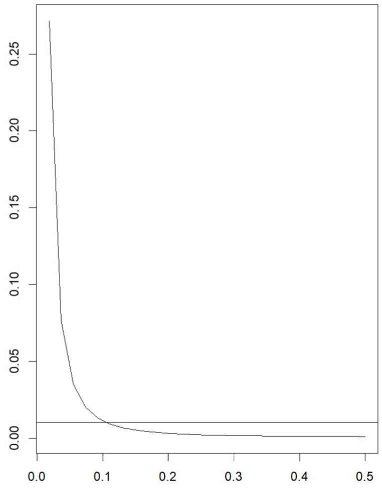
[3] As in Geweke (1982), the intensity is reported here in absolute values, but its signs appear to be negative, indicating that the policies implemented are reducing carbon emissions.

Figure 3: Granger causality - Frequency analysis



Notes: This figure illustrates the Granger causality between the CO2/output ratio and the carbon tax reform of 1991 in Sweden. The results are computed using Farnè and Montanari (2019)'s R package *"grangers"*.

when considering the asymptotic distribution of Breitung and Candelon (2006)'s test.

4. Conclusion and Policy Implications

This paper proposes extending the Breitung and Candelon (2006) causality test to investigate the impact of structural breaks. It appears that the frequency domain version of the test provides satisfactory results contrary to its time series counterpart. This paper therefore shows that the test for causality in the frequency domain constitutes an adequate tool to evaluate the impacts of a policy. The empirical exercise reveals that the Swedish carbon tax has had a significant causal effect on long-run carbon emissions reduction since 1991. The empirical findings confirm that carbon taxes are more efficient than international treaties, such as the Kyoto Protocol (or the Paris Agreement). Climate change remains a challenge for policy-makers who should prioritize climate policies based on carbon tax, while being attentive to various related potential political issues (Battaglini and Harstad, 2020) and popular aversions (Douenne and Fabre, 2022).

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