Dirty neighbors

Pollution in an interlinked world[*]

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November 27, 2019

Abstract

We apply a network approach to analyze individual and aggregate consumption that generates predominately local pollution (e.g., noise, water and air quality, waste disposal sites). This allows us to relate the individual pollution levels to network centralities and to determine the effects of transfers among agents on the aggregate contamination. We then apply our theoretical framework to analyze the European data on fossil fuel energy consumption and discuss the impact of EU redistributive transfer policies on the aggregate level of pollution.

Keywords: local pollution, negative externalities, networks
JEL: Q40, Q53, H23, D85

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[*] We are grateful to the participants of the II BiNoMa Workshop on Economics of Networks and to the participants of the Workshop on Network Games at the Queen's University Belfast for their helpful comments. We would also like to thank two anonymous Referees and the Editor in charge, whose detailed comments helped us improve substantially the manuscript. Meléndez-Jiménez acknowledges financial support from Ministerio de Ciencias, Innovación y Universidades through project RTI2018-097620-B-I00 and from Junta de Andalucía-FEDER through project UMA18-FEDERJA-243. The usual disclaimer applies.

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1 Introduction

The unprecedented economic growth experienced around the world over the past decades has been accompanied by an unceasing depletion of natural resources. At the same time, the increasing levels of *global* (e.g., greenhouse gas warming, mercury contamination, stratospheric ozone depletion) and *local* (e.g., water and air quality, noise, waste disposal sites) pollution have significantly endangered the services provided by natural assets. Transboundary air pollution has been a concern since the early twentieth century,[1] and the analysis of the international dimension of greenhouse gas emission control has been an object of research since the seminal paper of Carraro and Siniscalco (1992). However, there have been so far few international attempts to coordinate efforts to reduce *global* emissions of greenhouse gases. For example, the celebrated Kyoto protocol, signed in 1997 by more than 180 countries, was the most prominent international treaty aiming at the abatement of greenhouse gas emissions but it had limited success.[2] A more recent attempt to advance the reduction of emissions is the Paris Agreement, which was signed by nearly 200 countries in December 2015. Motivated by these international concerns, in the recent years scholars have devoted increasing efforts to the study of the abatement of (*global*) emissions, through the analysis of, e.g., the incentives to invest in green technologies and the design of optimal contracts that may facilitate international coordination on environmental issues (e.g., Harstad, 2012, 2016; Batten et al., 2018; and references therein).

Unlike most of the existing literature, this work focuses on *local* pollution. Local pollution affects only neighbors of a polluting site and creates different incentives than global contamination. Moreover, it lends itself to a network approach that helps us understand not only the incentives but also to design appropriate policy measures. This paper aims to be a first step in this direction. Specifically, we propose a model in which different agents (countries, regions,

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[1] See, for instance, Wirth (1996), on the Trail smelter dispute between Candadians and Americans from 1927 to 1941. The Trail settlement is the first international ruling on transboundary air pollution.

[2] As pointed out in Aldy and Stavins (2009, Ch. 1) the main reasons of these insufficient achievements were that some of the world's leading greenhouse gas emitters were not constrained by the Kyoto protocol. This protocol did not take into account that nation-states can hardly be thought of as simple cost-minmizers, and that it may not have provided sufficient incentives for countries to comply.

etc.) decide on the consumption of a clean and a polluting ("dirty") good, where the latter produces negative externalities on the neighboring agents. In this respect, our model is close to Harstad (2012), who studies the case of global contamination, i.e., the situation in which the consumption of the dirty good by each region affects equally all other regions. For this baseline scenario, his focus is on the study of optimal contracts to reduce pollution in a dynamic context. We depart from Harstad (2012) in that we allow the pollution of a region (derived from its consumption of the dirty good) to affect differently distinct regions. This feature is implemented by a (weighted) network that specifies the bilateral exposures to pollution. Given the complexity introduced by the network dimension, in order to keep the model tractable, we focus on a static context.

In this static framework, we first study the incentives to pollute. These incentives depend on the underlying network, consumption preferences and the distribution of wealth (resources) across regions. Then, we study the effects of transfer schemes (potentially implemented by a supranational authority) on aggregate pollution. We find that, in the case of regions that are homogeneous in terms of preferences and endowments, the equilibrium consumption of the dirty good by each region is proportional to its (Bonacich) centrality in the network.[3] Moreover, we observe that, even when regions are heterogeneous in wealth (but still homogeneous in preferences), transfers from regions with high Bonacich centrality to regions with low centrality reduce the aggregate consumption of the polluting good. Similarly, for the case in which countries are heterogeneous in terms of preferences and wealth, we obtain their equilibrium consumption as a function of the network, the distribution of wealth and preference parameters. This analysis allows us to calculate the effects of transfers from/to any country on the (aggregate) consumption levels of the polluting good.

Finally, in an empirical application of our framework, we use a geographic network and data on the GDP and the fossil fuel energy consumption in EU member states to analyze the environmental impact of each member. Then, under the lens of our model, we are able to identify the impact that the redistributive (transfer) policies of the European Union have on the aggregate level

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[3] Bonacich centrality (Bonacich, 1987) is a measure that accounts not only for the connectivity or closeness of a node to other nodes, but also for the "importance" of these nodes (see Section 3 and Jackson, 2008, for details). This measure has been widely employed in theoretical and empirical literature (see, e.g., Ballester et al., 2006).

of pollution. We find, in particular, that these policies entail a negative side effect on the environment.

The remainder of the paper is structured as follows. In Section 2, we review the related literature. In Section 3, we present the model. Section 4 describes our theoretical results. In Section 5, we study the application to the polluting consumption in the European Union. Section 6 concludes.

2 Related literature

Our paper is related to the large literature on environmental economics and to the literature on social and economic networks. An exhaustive review of these two strands is beyond the scope of this work and we focus here on a selection of relevant papers.

Regarding the first strand, a large variety of models dealing with the incentives to abate pollution and to form international environmental agreements has been considered in the literature (see the surveys in Wagner, 2001, and Marrouch and Chaudhuri, 2015). In particular, Buchholz and Konrad (1994) show that countries may strategically adopt costly abatement technologies to credibly commit not to reduce environmentally harmful emission in the future, and free ride on the other countries' reductions instead. Relatedly, several papers focus on negotiations over emission reduction in either one or two periods. For instance, Schmidt and Strausz (2015) study whether cooperation is sustainable without side payments, while Helm and Schmidt (2015) consider coalition formation in the context of climate cooperation with endogenous R&D investments.[4] Other recent papers consider a purely dynamic approach. In particular, Harstad (2012, 2016) and Battaglini and Harstad (2016) study dynamic frameworks in which countries both pollute and invest in substitute technologies over time.[5] They analyze emissions, investments and international environmental agreements, while allowing for renegotiation, short term agreements and endogenous coalition formation. In a complementary approach, Martimort and

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[4] Other related papers are Barret (2001) and Hong and Karp (2012), which study coalition models with binary abatement choices; and Eichner and Pethig (2013) who intergrate international trade in a standard coalition model.

[5] See also Dutta and Radner (2009), which models the global warming process as a dynamic commons game, and Calvo and Rubio (2013) for a survey of applications of dynamic games to international environmental agreements.

Sand-Zantman (2016) use the methodology of mechanism design to investigate how environmental agreements should account for multilateral externalities, incentive compatibility, and participation when information is asymmetric.

On the other hand, one of the main theoretical contributions of this paper is the application of a network approach to the environmental setup. Indeed, the theoretical literature on social and economic networks has produced substantial insights in many areas, once researchers have acknowledged that networks play a prominent role in many aspects of society and economy (see Goyal, 2007; Jackson, 2008; and the recent survey in Jackson et al., 2017). However, applications of this literature to environmental problems are still scarce. A recent paper by Günther and Hellmann (2017) studies the stability of international environmental agreements when pollution has both global and local effects in a context of repeated games. They find that, whereas stable agreements do exist when the underlying network structure is balanced, they may fail to exist under large asymmetries.[6] Additionally, Aller et al. (2015) analyze the impact of the world trade network on the environment, and find that having a higher (betweenness) centrality in the network is beneficial in environmental terms for the developing but detrimental for the developed countries.

Although the network perspective has been barely used to study the local impact of pollution, there have been significant advances in the literature on the provision of public goods in networks (see, for instance, Bramoullé and Kranton, 2007; Allouch, 2015, 2017; Kinateder and Merlino, 2016; and Elliott and Golub, 2019).[7] As contributions to a public good represent a (positive) externality on neighbors, this literature is closely related to our work. In particular, we build on the recent progress made by Allouch (2015), who analyzes the private provision of public goods where consumers interact within a fixed network structure and benefit only from their direct neighbors' provisions. Our model departs from his setup by considering a game where agents may harm their neighbors (by polluting) and by allowing a weighted (rather than binary) network.

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[6] See also Bayer et al. (2019), which studies adaptive learning in the class of weighted network games, with potential applications to the economics of pollution.

[7] Galeotti et al. (2010) apply a network approach to the more general setting of games of strategic subsitutes. Some of the network models have also been tested in the laboratory, finding empirical support for the theoretical results. See, for instance, the experimental papers by Weitzel and Rosenkranz (2012) that considers the model of Bramoulle and Kranton (2007), or Charness et al. (2014), based on the model by Galeotti et al. (2010).

3 The model

We consider the set $N = \{1, ..., n\}$ of agents, which we will usually refer to as countries or regions. Each region $i \in N$ consumes a combination of a "clean" and a "dirty" (polluting) good, maximizing the utility function $u_i(e_i, x_i)$, where $e_i \in [0, \infty)$ and $x_i \in [0, \infty)$ are, respectively, the amounts of the clean and the polluting good consumed by region i. We normalize the price of the clean good to one and denote by $p_i \in (0, \infty)$ the price of the polluting good paid by i. Each region is endowed with a budget $\omega_i \in (0, \infty)$ to spend on consumption. However, the consumption of the polluting good creates (negative) externalities that affect the wealth of the neighboring regions.

The externality that (the consumption of the polluting good by) region k imposes on region i depends on i's exposure to k's emissions. Specifically, we assume that regions are embedded in an exogenous weighted network g, with the associated (weighted) adjacency matrix $G \in R_+^{n \times n}$. This network can represent, for example, geographic distances, where $G_{ik} \geq 0$ measures the exposure of region i to region k. Regarding externalities, we assume that the consumption x_k of the polluting good by country k causes a reduction in the budget of country i that is proportional to G_{ik}. Specifically, the aggregate consumption by i's neighbors of the dirty good, weighted by the respective exposure measures,

$$X_{-i}(g) \equiv \sum_{k \in N} G_{ik} x_k,$$

imposes the cost of $\delta X_{-i}(g)$ on i, which reduces i's budget to $\omega_i - \delta X_{-i}(g)$. The parameter $\delta \in [0, \infty)$ captures the strength of the externalities caused by the relevant pollutant. Alternatively, δ can be interpreted as a normalization factor that adjusts the exposure units implicit in the matrix G.

Note that there are many different forms by which the pollution by a region can affect negatively its neighbors by reducing their budgets to be spent on consumption. The most immediate one is via the health of the inhabitants of the affected regions. It is well documented that pollution has a negative effect on health (see, e.g., Kampa and Castanas, 2008), and that many forms of pollution spread geographically, more intensively to neighboring regions (Liang et al., 2016). Thus, the pollution by a region imposes a cost on other regions in terms of resources lost due to the "imported" contamination.

In this line, some recent studies aim to identify the negative economic impact of pollution. For instance, Romley et al. (2010) measure the impact of air quality on hospital spending, while the OECD (2014) report estimates the health impact of road transport. Even more recently, some studies quantify the negative economic effects of air pollutants (e.g., the fine particulate matter, $\mathrm{PM}_{2.5}$), which informs our assumption on the negative externality derived from the pollution of neighboring regions. Indeed, the OECD (2016) publication on "The Economic Consequences of Outdoor Air Pollution" assesses the effects of air pollution on health by estimating concentration-response functions and linking health impacts to population weighted mean concentrations of air pollutants. This study quantifies also the negative impact of air pollution on agriculture by estimating crop yield changes. In a similar vein, for the case of China, Xie et al. (2019) estimate that in 2030, without control policies, $\mathrm{PM}_{2.5}$ pollution alone could lead to the loss of 2.0% of GDP.

We note that the framework described above defines a simultaneous game $\Gamma = \Gamma(g, \delta, \{u_i, \omega_i\}_{i \in N})$ with continuous strategy spaces $e_i \in [0, \infty)$ and $x_i \in [0, \infty)$ for each player $i \in N$. For any given level $X_{-i}(g)$ of the polluting consumption by i's neighbors in this game, we obtain the reaction function for player i from the solution to the optimization problem,

$$\max_{e_i, x_i} u_i(e_i, x_i), \quad s.t. \quad e_i + p_i \cdot x_i \leq |\omega_i - \delta X_{-i}(g)|_+, \quad x_i, e_i \geq 0, \tag{1}$$

where $|z|_+ \equiv \max\{z, 0\}$. In particular, the utility maximizing consumption of the polluting good obtains, under standard assumptions, from the optimization problem (1) as the demand (Engel) function,

$$x_i \equiv d_i(|\omega_i - \delta X_{-i}(g)|_+). \tag{2}$$

4 Theoretical results

In what follows, we focus on situations where neighborhood externalities - as captured by the parameter δ - are sufficiently small. Specifically, for a given game Γ, we define $\overline{\delta} \equiv \overline{\delta}(\Gamma) \in (0, 1)$ as the maximum value such that, for all $\delta < \overline{\delta}$ an interior Nash equilibrium, i.e., a Nash equilibrium with interior solutions to the optimization problem (1) for all $i \in N$, exists. Such a threshold can be always found when both goods are normal and all players have strictly positive endowments. Moreover, for the sake of empirical applicability, we shall assume Cobb-Douglas utility functions (although part of our results extend to more general settings),

$$u_i(e_i, x_i) = x_i^{\alpha_i} e_i^{1-\alpha_i},$$

with the parameter $\alpha_i \in (0, 1)$, possibly different for each $i \in N$. Under this utility function, the solution to the optimization problem (1) for country i can be interpreted as resulting from the optimization problems solved by the inhabitants of this country, each of them facing the same price p_i and possessing a share of the wealth $|\omega_i - \delta X_{-i}(g)|_+$. The demand function (2) for the polluting good takes then the form,

$$d_i = \frac{\alpha_i}{p_i} |\omega_i - \delta X_{-i}(g)|_+. \tag{3}$$

Hence, α_i/p_i is consumer i's demand of the dirty good per unit of her "net income" $|\omega_i - \delta X_{-i}(g)|_+$. We collect the ratios α_i/p_i in the diagonal matrix A, where $A_{ii} \equiv \alpha_i/p_i$ and $A_{ik} \equiv 0$ for $i \neq k$. It turns out that the square matrix δAG and its eigenvalues $\lambda_1(\delta AG), ..., \lambda_n(\delta AG)$ play a crucial role in our analysis, as spelt out in the following simple but important result.

Proposition 1 *When the spectral radius of the matrix δAG is less than one,*

$$\rho(\delta AG) \equiv \max_i |\lambda_i(\delta AG)| < 1, \tag{4}$$

then the unique interior Nash equilibrium consumption vector exists and is computed as

$$\mathbf{x}^* = (I + \delta AG)^{-1} A\boldsymbol{\omega} = (A^{-1} + \delta G)^{-1}\boldsymbol{\omega}, \tag{5}$$

where I is the identity matrix and $\boldsymbol{\omega} = (\omega_1, ..., \omega_n)$.

Proof. By Eq. (3), the interior Nash equilibrium consumption must verify,

$$\begin{aligned} x_i^* &= \frac{\alpha_i}{p_i}(\omega_i - \delta X_{-i}^*(g)) \Rightarrow x^* = A(\boldsymbol{\omega} - \delta G x^*) \qquad (6) \\ &\Rightarrow (I + \delta AG)x^* = A\boldsymbol{\omega}. \end{aligned}$$

It is well known (see, e.g., Molnár and Szidarovszky, 2002) that the inverse of $I + \delta AG$ exists if and only if the spectral radius of the matrix δAG is less than one. Hence, the claim follows. ■

Clearly, one can always find a sufficiently small value of the parameter δ such that the spectral radius of δAG is less than one. If G is an adjacency matrix, then such a δ may depend on the size of the underlying network. For example, the spectral radius of the adjacency matrix corresponding to the complete network with n nodes is $n-1$. In this case, δ would need to scale with n in order to satisfy the condition in Proposition 1. However, in our empirical application, matrix G is column stochastic independently of the size and topology of the underlying network. This implies that its spectral radius is always one.

In the following corollary of Proposition 1, we relate the Nash equilibrium consumption by players to their Bonacich centralities in the network g in the case of uniform ratios α_i/p_i and budgets ω_i. This centrality measure, due to Bonacich (1987), has been widely employed in the theoretical and empirical literature. Ballester et al. (2006) were first to establish a connection between equilibrium actions and Bonacich centrality in their network game with local complementarities singling it out from the vast catalogue of network centrality measures.

For the binary adjacency matrix G and a constant κ such that the spectral radius of κG is less than one, Bonacich centrality is defined by,

$$\mathbf{b}(G,\kappa) \equiv (I-\kappa G)^{-1}\mathbf{1} = \textstyle\sum_{s=0}^{+\infty} \kappa^s G^s \mathbf{1}, \tag{7}$$

where $\mathbf{1}$ is the all-ones vector. As the ijth entry of the matrix G^s denotes the number of walks of length s emanating from i and terminating at j,[8] it follows that the ith coordinate $b_i(G,\kappa)$ is the sum of all walks in G emanating from i and weighted by $\kappa \in (0,1)$ to the power of their length.

Unlike in Ballester et al. (2006) and related literature, in our setup G is not necessarily a binary matrix (i.e., nodes may be connected by *weighted* links) and the parameter κ is negative (see Corollary 1 and Proposition 2 below). The consequence of the former fact is that weaker connections, i.e., connections via links with smaller weights, have lower impact on Bonacich centrality. The latter fact, on the other hand, implies that direct neighbors of an agent have a negative impact on this agent's centrality, while for neighbors' neighbors this impact is positive.

The next result uses the original definition given in Eq. (7) to characterize the equilibrium outcomes in our game.

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[8] A walk of length s in a graph g emanating from node i and terminating at node j is a succession of s (not necessarily different) edges of the form $k_0k_1, k_1k_2, \ldots, k_{s-1}k_s$, where $k_0 = i$, $k_s = j$ and, for each $l \in \{1, ...s\}$, $k_l \in N$.

Corollary 1 *If* $a \equiv \frac{\alpha_i}{p_i}$ *and* $\omega = \omega_i$ *are constant across agents and Eq. (4) holds, then the interior Nash equilibrium consumption* $\mathbf{x}^*$ *is proportional to the Bonacich centralities* $\mathbf{b}(.)$ *in the graph* g*,*

$$\mathbf{x}^* = a \cdot \omega \cdot \mathbf{b}(G, -\delta a). \tag{8}$$

Proof. By Proposition 1,

$$\begin{aligned}\mathbf{x}^* &= (I+\delta AG)^{-1} A\boldsymbol{\omega} = \textstyle\sum_{s=0}^{+\infty} (-\delta)^s (AG)^s A\boldsymbol{\omega} \\ &= a \cdot \omega \cdot \textstyle\sum_{s=0}^{+\infty} (-\delta a G)^s \mathbf{1} = a \cdot \omega \cdot \mathbf{b}(G, -\delta a),\end{aligned}$$

where $\mathbf{1} = (1, ..., 1)'$. The first equality in the second line follows from our assumptions $A = a \cdot I$ and $\boldsymbol{\omega} = (\omega, ..., \omega)'$. ■

Although Corollary 1 contemplates a particular case of homogeneous wealths and preferences, it neatly illustrates the impact of the exposure structure on equilibrium consumption. It is instructive to combine Eq. (7) and Eq. (8) to obtain an explicit formula for equilibrium consumption of the polluting good,

$$\mathbf{x}^* = a \cdot \omega \cdot b_i(G, -\delta a) = a \cdot \omega \cdot \textstyle\sum_{s=0}^{+\infty} (-\delta a)^s G^s \mathbf{1}.$$

The last formula makes it clear that the direct neighbors ($s = 1$) of a player have a negative impact on the Bonacich centrality and, hence, on the polluting consumption by this player, while for neighbors' neighbors ($s = 2$) this impact is positive. Generally, the neighbors of i in the weighted network G^s decrease (increase) i's consumption of the polluting good for odd (even) s.

When agents have identical preferences but differ in wealth, we can relate Bonacich centralities to the aggregate consumption of the polluting good. Specifically, assume that starting from an endowment vector $\boldsymbol{\omega}$ (not necessarily homogeneous), we add to each ω_i a (possibly negative) transfer t_i (the transfers may or may not sum up to zero). We denote the vector of equilibrium consumptions before and after the transfer as x^* and x^{*t}, respectively. Then, it follows directly from Eq. (5) that,

$$\mathbf{x}^{*t} - \mathbf{x}^* = (I+\delta AG)^{-1} A(\boldsymbol{\omega} + \mathbf{t}) - (I+\delta AG)^{-1} A\boldsymbol{\omega} = (I+\delta AG)^{-1} A\mathbf{t}. \tag{9}$$

For the case of homogenous demands (all players with identical ratios α_i/p_i), we can relate the total pre- and post-transfer consumptions $X^* \equiv \sum_{k=1}^n x_k^*$ and $X^{*t} \equiv \sum_{k=1}^n x_k^{*t}$ to Bonacich centralities.

Proposition 2 *If the ratio* $a \equiv \frac{\alpha_i}{p_i}$ *is constant across agents and Eq. (4) holds, then*

$$X^{*t} - X^{*} = a \sum_{k=1}^{n} t_k \mathbf{b}_k(G, -\delta a).$$

Proof. Let $F \equiv (I + \delta a G)^{-1}$ and $F^i \equiv \sum_{k=1}^{n} F_{ki}$. By Eq. (5), we have that $X^* = a \sum_{k=1}^{n} \omega_k F^k$ and $X^{*t} = a \sum_{k=1}^{n} (\omega_k + t_k) F^k$. Then, $X^{*t} - X^* = a \sum_{k=1}^{n} t_k F^k = a \sum_{k=1}^{n} t_k \mathbf{b}_k(G, -\delta a)$. ■

This result shows that a transfer from a high Bonacich centrality node to a low Bonacich centrality node will always reduce the aggregate consumption of the polluting good, while a transfer between nodes with identical Bonacich centralities has no effect on it. In the next example, we illustrate the effects of a transfer between nodes with different centralities.

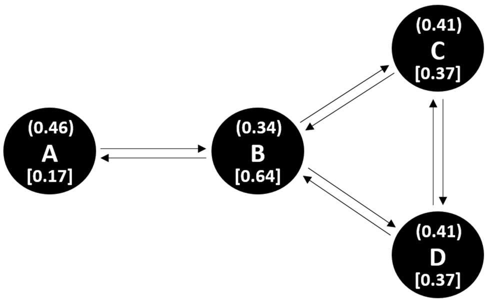

FIGURE 1. An example of equilibrium consumptions of the polluting good before (.) and after [.] a transfer from node A to node B.

Example 1 *Consider the network of four nodes depicted in Figure 1, where* $N = \{A, B, C, D\}$. *For simplicity, assume that the network is binary, i.e., the presence (absence) of an arrow pointing from node* $k \in N$ *to node* $i \in N$ *implies* $G_{ik} = 1$ ($G_{ik} = 0$). *Let* $\delta = \frac{1}{4}$, *and for all* $i \in N$ *assume* $\frac{\alpha_i}{pi} = a = \frac{1}{2}$.

The numbers reported in the upper part of the nodes (within parentheses) correspond to the equilibrium consumptions of the polluting good in the (homogeneous) case in which $\omega_i = 1$ *for all* $i \in N$. *Corollary 1 implies, then, that the Bonacich centrality* $b_i(G, -\delta a)$ *of the node* i *is twice its equilibrium consumption. In Figure 1, we observe then that* $b_A(G, -\delta a) = 0.92$ *for the peripheral node* A *is higher than* $b_B(G, -\delta a) = 0.68$ *for the central node* B. *This is due to the negative sign of the parameter* $(-\delta a)$, *which reverses in this case the expected ordering of centralities.*

The numbers reported in the lower part of the nodes (within square brackets) result after transferring half of the initial endowment of node A to node B (hence corresponding to the equilibrium consumptions of the polluting good in the case with $\omega_A = 0.5$, $\omega_B = 1.5$, *and* $\omega_C = \omega_D = 1$*). Note that the consumption of nodes C and D, which are not involved in the transfer, has also changed. The total consumption of the polluting good is reduced by* 4.3% *by this transfer.*

It is worth noting, however, that our static model does not account for potential long run effects of transfers. Indeed, it is reasonable to consider that, if transfers allow (less developed) countries to progress and invest in green technologies, they could have an additional long term impact on the environment.

Building on the results in this section, we investigate next an application to the fossil fuel energy (FFE) consumption in the European Union. Clearly, the (estimated) ratios α_i/p_i and wealths ω_i will be different across the EU countries. Thus, although it will be impossible to directly relate the polluting consumption of a country to its Bonacich centrality, the characterization of the Nash equilibrium consumption in Proposition 1 will enable us to study the side effects of the redistributive transfer schemes implemented in the EU on the aggregate levels of pollution.

5 Application - Fossil fuel energy consumption in the European Union

In the following empirical exercise, we calibrate the model to EU data. First, we compute the total impacts on the polluting consumption of all EU countries except Malta and Cyprus (EU-26 in what follows) using data from the World Bank on energy consumption, population and GDP for the EU-26 countries reproduced in Table 1.[9],[10]

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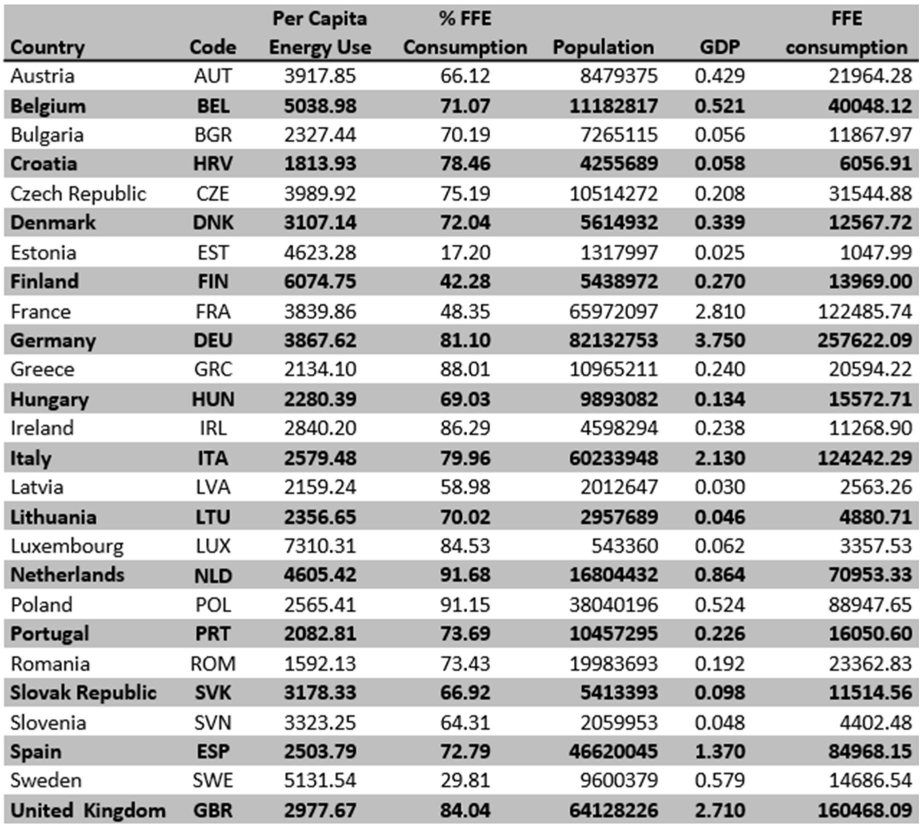
[9] Based on IEA data from the World Energy Balances © OECD/IEA 2016, www.iea.org/statistics. Licence: www.iea.org/t&c; The data for the years 2007-2013 is available at: http://databank.worldbank.org/data/.

[10] We conducted the analysis for the year 2013, the last year for which we had a complete set of data. The results for earlier years are very similar. Malta and Cyprus are excluded from the analysis because they share no (land) borders with any of the other EU countries, which, as explained below, we use to compute the mutual exposures.



Country	Code	Per Capita Energy Use	% FFE Consumption	Population	GDP	FFE consumption
Austria	AUT	3917.85	66.12	8479375	0.429	21964.28
Belgium	BEL	5038.98	71.07	11182817	0.521	40048.12
Bulgaria	BGR	2327.44	70.19	7265115	0.056	11867.97
Croatia	HRV	1813.93	78.46	4255689	0.058	6056.91
Czech Republic	CZE	3989.92	75.19	10514272	0.208	31544.88
Denmark	DNK	3107.14	72.04	5614932	0.339	12567.72
Estonia	EST	4623.28	17.20	1317997	0.025	1047.99
Finland	FIN	6074.75	42.28	5438972	0.270	13969.00
France	FRA	3839.86	48.35	65972097	2.810	122485.74
Germany	DEU	3867.62	81.10	82132753	3.750	257622.09
Greece	GRC	2134.10	88.01	10965211	0.240	20594.22
Hungary	HUN	2280.39	69.03	9893082	0.134	15572.71
Ireland	IRL	2840.20	86.29	4598294	0.238	11268.90
Italy	ITA	2579.48	79.96	60233948	2.130	124242.29
Latvia	LVA	2159.24	58.98	2012647	0.030	2563.26
Lithuania	LTU	2356.65	70.02	2957689	0.046	4880.71
Luxembourg	LUX	7310.31	84.53	543360	0.062	3357.53
Netherlands	NLD	4605.42	91.68	16804432	0.864	70953.33
Poland	POL	2565.41	91.15	38040196	0.524	88947.65
Portugal	PRT	2082.81	73.69	10457295	0.226	16050.60
Romania	ROM	1592.13	73.43	19983693	0.192	23362.83
Slovak Republic	SVK	3178.33	66.92	5413393	0.098	11514.56
Slovenia	SVN	3323.25	64.31	2059953	0.048	4402.48
Spain	ESP	2503.79	72.79	46620045	1.370	84968.15
Sweden	SWE	5131.54	29.81	9600379	0.579	14686.54
United Kingdom	GBR	2977.67	84.04	64128226	2.710	160468.09

Table 1. Energy consumption, population and GDP in the EU-26 in 2013. Columns 1 and 2 contain the names and (ISO 3166-1 alpha-3) codes of the countries, Column 3: per capita energy use (kg of oil equivalent), Column 4: the percentage of energy use that corresponds to FFE consumption. Column 5 and 6: population and the GDP (in billions US$), respectively. Last column: the total FFE consumption (in thousands of tons of oil equivalent).

From the data in Table 1, we compute the total FFE consumption as the product of columns 3, 4 and 5 and report it in the last column of this table (in thousands of tons of oil equivalent). We also observe (in the fourth column of Table 1) that the share of the FFE is considerably above 50% of the total energy consumption in all countries except for Estonia, Sweden, Finland and France, with the Netherlands being the country with the highest percentage of the FFE consumption. In absolute terms, the average FFE consumption in the EU-26 is 45269.56 thousands of tons of oil equivalent, and the countries with the highest (lowest) levels of FFE consumption are Germany, United Kingdom, Italy and France (Estonia, Latvia, Luxembourg and Slovenia).

We create the weighted exposure matrix G from publicly available data on border lengths among countries as provided by the NationMaster database.[11] Clearly, the length of the common border between countries yields a simplistic measure of environmental exposures. Although more sophisticated measures can be constructed,[12] in this methodological paper we focus on easily available data. The border lengths among each pair of countries in the EU-26 are reported in Table A1 in the Appendix. For each $i, k \in N$, $i \neq k$, let $d_{ik} = d_{ki}$ be the length of the common border between countries i and k (in case i and k do not share a border, $d_{ik} = 0$). We set $d_{kk} = \sum_{k \neq i} d_{ik}$, i.e., the total length of country k's borders with other countries in the EU-26. Then, for each $i, k \in N$, we define $G_{ik} = \frac{d_{ik}}{2d_{kk}}$. Implicit in this formulation is the idea that the pollution by country k induces a cost (in terms of resource losses) both for country k and for all its neighbors. The main cost of pollution - one half - is borne by the polluting country (k), being the other half distributed among all neighbors of k according to the (relative) lengths of their common border with country k.[13]

By construction, G is a column stochastic matrix. The corresponding (weighted and directed) network is reproduced in Figure 2, where each node represents a country,[14] and the weight reported on the arrow (directed link) pointing from country k to country i corresponds to the exposure G_{ik} of country i to the pollution by country k.[15]

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[11] See http://www.nationmaster.com/country-info/stats/Geography.

[12] For an estimate of the financial burden imposed on a country by air pollution "imported" from another country see, for instance, Romley et al., 2010.

[13] We also considered alternative specifications of the cost distribution, with the share of the polluting country varying between 0 and 100%. We did not observe qualitative changes to our main results. In particular, Figure A1 in the Appendix reports the total impact of EU transfers on aggregate EU-26 FFE consumption for different values of the externality parameter $\delta \in (0, \widehat{\delta})$ and the share parameter $\gamma \in (0, 1)$ (hence, extending the results reported in Figure 3 below for $\gamma = 0.5$). This impact turns out to be always positive, i.e., EU transfers increase the aggregate FFE consumption for any δ and γ.

[14] We use the country codes reported in Table 1 and three different sizes for nodes, according to the extension of the country: the nodes with the biggest size correspond to countries with more than 350,000 km^2, the medium ones to countries with more than 200,000 km^2 and less than 350,000 km^2, and the smallest ones to countries with less than 200,000 km^2.

[15] Hence, the weights of all links emanating from each country add up to 1.

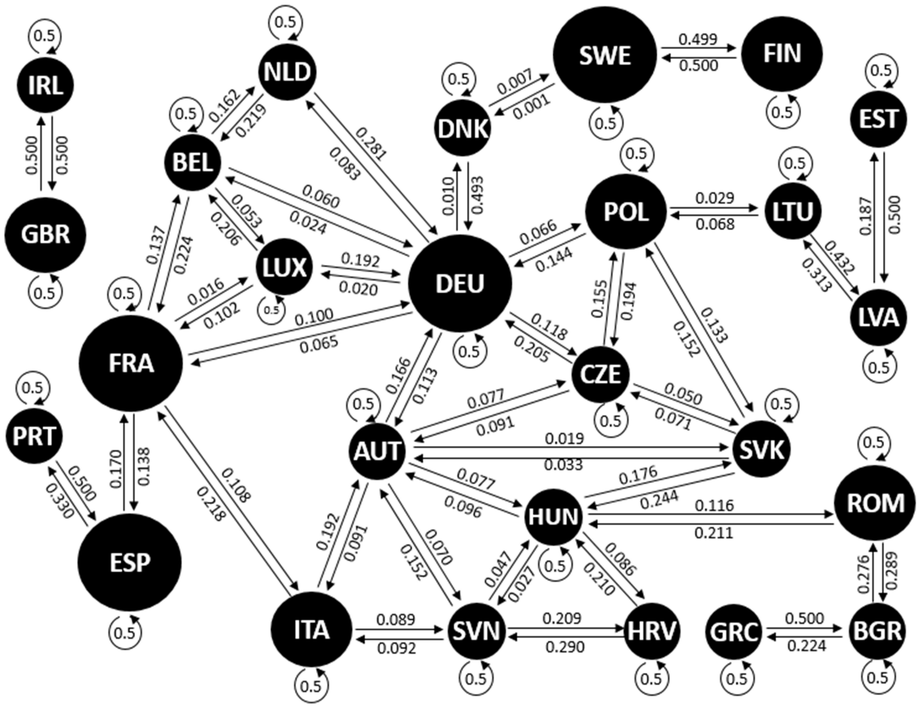

FIGURE 2. Geographic network G of the EU-26. Each node represents an EU-26 country and the weight reported on the arrow (directed link) pointing from country k to country i corresponds to the exposure G_{ik} of country i to the pollution by country k.

Assuming equilibrium consumption x_i^* of the FFE in country i and using the GDP of this country as a proxy of its total consumption spending $\omega_i - \delta X^*_{-i}(g)$, we compute the matrix $A = diag(\frac{\alpha_1}{p_1}, ..., \frac{\alpha_n}{p_n})$ from (6),

$$x_i^* = A_{ii}(\omega_i - \delta X^*_{-i}(g)).$$

Note that we neither observe the initial endowments $\boldsymbol{\omega}$ nor the externalities $\delta G\mathbf{x}^*$ separately. The computed A_{ii} estimates the FFE consumption (in kg of oil equivalent) per \$1 of the GDP in country i and it is a direct indicator of "dirtiness" of this country (see Table A2 in the Appendix, and the first two columns of Table 2 below).

In order to estimate the cross-country impact of the FFE consumption, we use Eq. (5) in Proposition 1,

$$\mathbf{x}^*(\delta) \equiv (I + \delta AG)^{-1}A\boldsymbol{\omega} \equiv \Theta(\delta)\boldsymbol{\omega}. \tag{10}$$

We interpret $\Theta_{ik}(\delta)$ as the marginal increase in FFE consumption x_i^* by country i due to a small increase in wealth ω_k of country k. Importantly, $\Theta(\delta)$ captures the direct and indirect effects of the latter increase on the equilibrium consumption. In particular, when $\delta = 0$ then $\Theta(0) = A$ and the only effect of the unit increase in ω_k is the change in FFE consumption x_i by A_{ik}, where $A_{ik} = 0$ if $i \neq k$ and A_{kk} is the autarkic change in polluting consumption in country k when its GDP increases by \$1.

Although we do not observe δ directly, we can estimate its maximum value $\widehat{\delta}$ (given our proxies for G and A) that is compatible with our model from Eq. (4),

$$\widehat{\delta} : \max_i |\lambda_i(\widehat{\delta} AG)| = 1.$$

For our data, this estimation yields (approximately),

$$\widehat{\delta} = 6.66.$$

In Table 2, we show the total impact $\Theta^k(\delta) \equiv \sum_{i \in N} \Theta_{ik}(\delta)$ of country k on the FFE consumption of the EU-26 countries for $\delta = 0$, $\delta = \widehat{\delta}/2$ and $\delta = \widehat{\delta}$ (the complete matrices $\Theta(0)$, $\Theta(\widehat{\delta}/2)$ and $\Theta(\widehat{\delta})$ are reported in Tables A2-A4 in the Appendix).[16] To illustrate the role of externalities, consider the case of the Netherlands ($k = NLD$). As we observe in Table 2, without externalities ($\delta = 0$) their total impact is $\Theta^k(0) = A_{kk} = 82.12$, i.e., an additional dollar increases the (aggregate) FFE consumption by $82.12g$ of oil equivalent. This impact drops to $65.28g$ when $\delta = \widehat{\delta}/2$ and to $54.02g$ when $\delta = \widehat{\delta}$. This is mostly due to negative externalities of the Dutch FFE consumption on its neighbors. For $\delta = \widehat{\delta}/2$, in particular, the FFE consumption of these neighbors decreases due to the externalities by, e.g., $4.15g$ for Germany and by $3.59g$ for Belgium per \$1 increase in the wealth ω_k (see Table A3 in the Appendix). These reductions in the FFE consumption by neighbors become larger when $\delta = \widehat{\delta}$ (in the mentioned examples, $6.78g$ for Germany and $5.79g$ for Belgium - see Table A4 in the Appendix).

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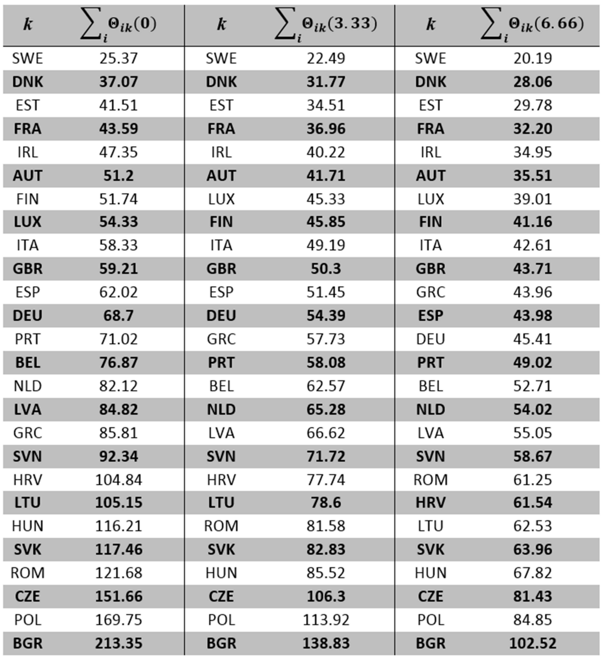
[16] Note that some values $\Theta_{ik}(\delta)$ are positive for $i \neq k$. In these cases, the increase in GDP in country k leads to higher FFE consumption in country i. This is a manifestation of a cumulative effects of indirect impacts (as direct impact is always negative).



k	$\sum_i \Theta_{ik}(0)$	k	$\sum_i \Theta_{ik}(3.33)$	k	$\sum_i \Theta_{ik}(6.66)$
SWE	25.37	SWE	22.49	SWE	20.19
DNK	**37.07**	**DNK**	**31.77**	**DNK**	**28.06**
EST	41.51	EST	34.51	EST	29.78
FRA	**43.59**	**FRA**	**36.96**	**FRA**	**32.20**
IRL	47.35	IRL	40.22	IRL	34.95
AUT	**51.2**	**AUT**	**41.71**	**AUT**	**35.51**
FIN	51.74	LUX	45.33	LUX	39.01
LUX	**54.33**	**FIN**	**45.85**	**FIN**	**41.16**
ITA	58.33	ITA	49.19	ITA	42.61
GBR	**59.21**	**GBR**	**50.3**	**GBR**	**43.71**
ESP	62.02	ESP	51.45	GRC	43.96
DEU	**68.7**	**DEU**	**54.39**	**ESP**	**43.98**
PRT	71.02	GRC	57.73	DEU	45.41
BEL	**76.87**	**PRT**	**58.08**	**PRT**	**49.02**
NLD	82.12	BEL	62.57	BEL	52.71
LVA	**84.82**	**NLD**	**65.28**	**NLD**	**54.02**
GRC	85.81	LVA	66.62	LVA	55.05
SVN	**92.34**	**SVN**	**71.72**	**SVN**	**58.67**
HRV	104.84	HRV	77.74	ROM	61.25
LTU	**105.15**	**LTU**	**78.6**	**HRV**	**61.54**
HUN	116.21	ROM	81.58	LTU	62.53
SVK	**117.46**	**SVK**	**82.83**	**SVK**	**63.96**
ROM	121.68	HUN	85.52	HUN	67.82
CZE	**151.66**	**CZE**	**106.3**	**CZE**	**81.43**
POL	169.75	POL	113.92	POL	84.85
BGR	**213.35**	**BGR**	**138.83**	**BGR**	**102.52**

TABLE 2: Total impact of \$1 increase in the wealth of the EU-26 country k on the aggregate FFE consumption of all EU-26 countries. This impact depends on the value of the externality parameter δ and is reported for $\delta \in \{0, 3.33, 6.66\}$. For each reported δ, countries are sorted from the lowest to the highest total impact.

From the previous section, we know that income redistribution influences the polluting consumption and can lead to the overall decrease in pollution. Below, we modify Eq. (10) by adding taxes (subsidies) $\mathbf{t}$ to the initial wealth vector $\boldsymbol{\omega}$,

$$\mathbf{x}^* = \Theta(\delta)(\boldsymbol{\omega} + \mathbf{t}) = \Theta(\delta)\boldsymbol{\omega} + \Theta(\delta)\mathbf{t}. \tag{11}$$

In light of Eq. (11), redistribution schemes resulting in transfers from country m (l) to country l (m) decrease (increase) the aggregate FFE consumption, where m (l) are the countries with the maximum (minimum) total impact per transferred dollar,

$$m \equiv \arg\max_k \Theta^k(\delta), \quad l \equiv \arg\min_k \Theta^k(\delta).$$

For example, Table 2 shows that, when $\delta = \widehat{\delta}/2 = 3.33$, a transfer of $t = \$1$ from Bulgaria to Sweden would lead to a decrease by

$$\Theta^{BGR}(\widehat{\delta}/2) - \Theta^{SWE}(\widehat{\delta}/2) = 116.34g$$

of oil equivalent in the total FFE consumption by the EU-26 countries.

Given the total impact of each EU-26 country on the aggregate level of pollution, our model can help assess environmental side effects of redistributive policies in the European Union. Table 3 shows the net transfers (expenditures net of contributions) for each member state obtained from the *EU budget 2013 financial report*.[17]

Country	Exp.	Cont.	Net Trans.
AUT	1862	3191.4	-1329.4
BEL	**7209.5**	**5290.8**	**1918.7**
BGR	**1976.9**	**477.6**	**1499.3**
HRV	290	238.2	51.8
CZE	**4893.1**	**1616.6**	**3276.5**
DNK	1434.8	2899.4	-1464.6
EST	973.3	211.9	761.4
FIN	1496.8	2159.1	-662.3
FRA	14239.3	23291.6	-9052.3
DEU	13056.2	29376.2	-16320
GRC	**7214.6**	**1906.4**	**5308.2**
HUN	**5909.8**	**1011.1**	**4898.7**
IRL	1874.3	1731.2	143.1
ITA	12554.3	17167.9	-4613.6
LVA	**1063.2**	**269**	**794.2**
LTU	**1881.2**	**404.8**	**1476.4**
LUX	**1598.2**	**321.8**	**1276.4**
NLD	2264.1	6552.1	-4288
POL	**16179.5**	**4214.4**	**11965.1**
PRT	**6162.8**	**1793**	**4369.8**
ROM	**5560.6**	**1474.3**	**4086.3**
SVK	**2026.1**	**799.3**	**1226.8**
SVN	813.6	425.6	388
ESP	**13752.2**	**11368.7**	**2383.5**
SWE	1661	4211.5	-2550.5
GBR	6308.3	17068.4	-10760.1

TABLE 3. Expenditure and contributions of EU-26 member states in 2013 (million EUR). Column 1 (Country): Country code. Column 2 (Exp.): Total EU expenditure for the country. Column 3 (Cont.): National contribution to the EU budget, including Traditional Own Resources collected on behalf of the EU. Column 4 (Net Trans.): Net transfers = column 2 - column 3.

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[17] The data are publicly available at http://ec.europa.eu/budget/financialreport/2013/lib/financial_report_2013_en.pdf

Note that the net transfers can be positive (for a net recipient) or negative (for a net contributor). In Table 3, the rows corresponding to net recipient countries with net transfers above the median are shaded in grey. From Eq. (9), we can then derive the total impact $\Delta(\delta, \mathbf{t})$ of net transfers $\mathbf{t}$ on the aggregate EU-26 contamination by computing the difference between the post- and the pre-transfer equilibrium consumptions of the polluting good,

$$\mathbf{x}^{*t}(\delta) - \mathbf{x}^{*}(\delta) = (I+\delta AG)^{-1} A\mathbf{t} = \Theta(\delta)\mathbf{t} \Rightarrow$$
$$\Delta(\delta, \mathbf{t}) \equiv \textstyle\sum_{k\in N} x_k^{*t}(\delta) - \sum_{k\in N} x_k^{*}(\delta) = \sum_{k\in N} \Theta^k(\delta) \cdot t_k.$$

When $\Theta^k > 0$, the net recipient k ($t_k > 0$) increases the aggregate FFE consumption by $\Theta^k(\delta) \cdot t_k$, while the net contributor ($t_k < 0$) decreases it by this amount. Clearly, the total impact $\Delta(\delta, \mathbf{t})$ depends on the unobservable "externality parameter" δ. Figure 3 plots $\Delta(\delta, \mathbf{t})$ for the net transfers $\mathbf{t}$, given in the last column in Table 3, and for $\delta \in [0, \widehat{\delta}]$, i.e., for all values of δ that are compatible with our model.

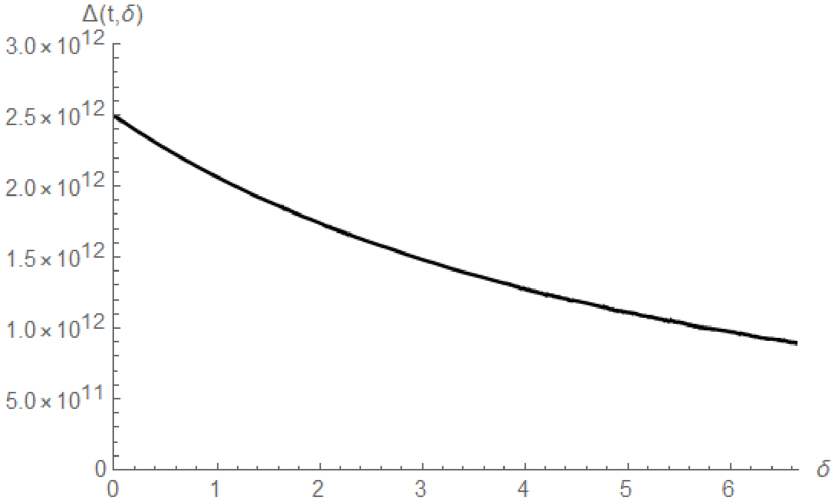

FIGURE 3. Total impact $\Delta(\delta, \mathbf{t})$ as a function of $\delta \in [0, \widehat{\delta}]$ for the net transfers $\mathbf{t}$ given in Table 3.

We observe in Figure 3 that the total impact of transfers is positive, i.e. the aggregate FFE consumption increases for all values $\delta \in [0, \widehat{\delta}]$. Hence, redistributive EU policies in 2013 appear to have had a negative environmental side effect independently of the strength of local environmental externalities. In particular, $\Delta(0, \mathbf{t}) = 2.5 \cdot 10^{12}$ and $\Delta(\widehat{\delta}, \mathbf{t}) = 0.89 \cdot 10^{12}$. Then, according to our model, EU transfers in 2013 increased the aggregate FFE consumption in the range between $8.9 \cdot 10^8$ *kg* and $2.5 \cdot 10^9$ *kg* of oil equivalent. In Figure A1 in the Appendix, we verify the robustness of this finding. This figure reports the total impact $\Delta(\delta, \gamma, \mathbf{t})$ of EU transfers on aggregate EU-26 FFE consumption for different values of the externality parameter δ and the cost sharing parameter $\gamma \in (0, 1)$. The latter parameter captures the share of the pollution cost borne by the polluting country (Figure 3 is a special case of Figure A1 when $\gamma = 1/2$). Figure A1 shows that the total impact $\Delta(\delta, \gamma, \mathbf{t})$ is positive, i.e., EU transfers increase the aggregate FFE consumption, for all values of δ and γ.

Finally, for the sake of illustration, it is instructive to use our analysis in order to identify the sets of countries whose total impacts on the aggregate FFE consumption in the EU are, respectively, the highest and the lowest ones. In Table 2 we already got a first impression on this issue. However, since the externality parameter is unobserved, in order to produce conservative estimates of these sets, we rely on the following procedure: For each $\delta_\tau = \tau \cdot \widehat{\delta}$, where $\tau = 0, \epsilon, 2\epsilon, ..., 1$ for a small ϵ, we construct the vector of total environmental impacts $v(\delta_\tau) = (\Theta^k(\delta_\tau))_{k \in N}$ for all EU-26 countries and compute the median of $v(\delta_\tau)$. Then, we collect the countries corresponding to the elements of $v(\delta_\tau)$ below (above) this median in the set $N^{Below}(\delta_\tau)$ $(N^{Above}(\delta_\tau))$. Finally, we compute the intersections of these sets,

$$N^{Below} = \cap_{\tau=0,\ldots,1} N^{Below}(\delta_\tau), \quad N^{Above} = \cap_{\tau=0,\ldots,1} N^{Above}(\delta_\tau).$$

Thus, the set N^{Below} (N^{Above}) contains countries that generate, through their own consumption and externalities, less (more) pollution per additional dollar than the median country for all $\delta_\tau \in [0, \widehat{\delta}]$. Therefore, according to our model, redistributive policies that consist on transfers to countries in N^{Above} (N^{Below}) from countries in N^{Below} (N^{Above}) would increase (reduce) the total EU-26 FFE consumption, independently of the actual value of δ. In particular, from our data we obtain that the countries in the sets N^{Above} and N^{Below} are those represented, respectively, in the left and right panels of Table 4.

Countries in the set N^{Above}		**Countries in the set N^{Below}**	
Belgium (BEL)	Lithuania (LTU)	Denmark (DNK)	United Kingdom (GBR)
Bulgary (BGR)	Poland (POL)	Spain (ESP)	Ireland (IRL)
Czech Republic (CZE)	Romania (ROM)	Estonia (EST)	Luxembourg (LUX)
Croatia (HRV)	Slovak Republic (SVK)	France (FRA)	Sweden (SWE)
Hungary (HUN)	Slovenia (SVN)		

TABLE 4. Classification of countries as computed from the vectors $v(\delta_\tau)$ of total environmental impacts for $\delta_\tau \in \{0, \epsilon\widehat{\delta}, 2\epsilon\widehat{\delta}, ..., \widehat{\delta}\}$, where $\epsilon = 0.01$ and $\widehat{\delta} = 6.66$.

Note that some countries, like e.g. Portugal and the Netherlands, remain unclassified in Table 4 (i.e., they do not appear either in N^{Above} or in N^{Below}), because their environmental impact is sometimes above and sometimes below the median for different values of δ_τ.[18] Despite this fact, we observe that most of the countries whose net transfers received from the EU are above the median (shaded in grey in Table 3) are indeed contained in the set N^{Above} (left panel of Table 4).[19]

In any case, as pointed out in the previous section, it is important to note that our static model does not capture some long run effects of transfers among countries that might be of importance. For instance, additionally to the spread of pollution, there may be other diffusion processes operating coetaneously through the network. Recent examples, like the increase in the investment of renewable energy by several EU countries (Spain and Portugal, among others), show that the adoption of green technology can also spread to neighboring countries.[20] The development of fully dynamic models that account for these positive externalities would be useful to complement the insights gained in this empirical exercise.

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[18] Note that the inclusion in $N^{Above}(\delta_\tau)$ or $N^{Below}(\delta_\tau)$ may vary with the strength of externalities as parametrized by δ^τ.

[19] Some exceptions are, for example, Spain and Luxembourg, which belong to the set N^{Below}.

[20] For example, Portugal increased the investment in green technology after Spain started adopting it.

6 Conclusion

In this paper, we study the local dimension of pollution, i.e., its direct effect on neighboring agents (regions, countries...) and its (aggregate) impact derived from the exposure network. In particular, we analyze the incentives of agents to pollute as a function of the network, agents' preferences and the distribution of wealth. For the simplest case, in which all agents are homogeneous in terms of preferences and wealth, we observe that their levels of polluting consumption are positively related to their (Bonacich) centralities in the network. For the (more general) case of heterogeneous agents, we characterize the equilibrium pollution profile as a function of the network and the income distribution. We have then applied our results to study the European fossil fuel energy consumption and identify the environmental effects derived from the EU redistributive policies. Our empirical application suggests that the EU transfer policies have a negative (side) effect on the environment independently of the strength of local externalities. Moreover, we identify the sets of countries with highest and lowest total impacts, finding that the first group is mainly composed by the Central and Eastern European countries, whereas the second one is essentially formed by Western European ones.

We believe that this work is just a stepping stone in a much broader agenda that aims at identifying and understanding the role of networks in environmental economics. Most of the extant studies neglect the role of the network structure in which the potential polluters are embedded. Our study shows that local effects of pollution create different incentives than those derived from global contamination. This observation might be of paramount importance for the design of environmental policies. However, there are still many open questions. For instance, our static model does not account for the potential long run effects of transfers. From the Kuznets Curve (EKC), which predicts an inverted U-shaped relationship between environmental pollution and economic development, we should expect that if transfers facilitate the economic development of less developed countries, they would have a positive impact on the environment in the long run (as these economies would reach a certain level of development). We believe that a model that allows countries to invest the transfers in more efficient technologies, hence facilitating sustainable development, would be of great interest. Likewise, it would be instructive to generalize our model to a dynamic context in which regions pollute over time, negatively affecting their neighbors and, at the same time, invest in green technologies spreading them through the network. Another interesting extension would be to consider simultaneously the two levels (global and local) at which pollution operates.

Regarding applications, the results derived from our and similar models could be used to study the environmental effects of the redistributive policies implemented in different regions across the world. Moreover, more sophisticated alternatives to our measure of the exposure to neighbors' pollution could be explored. Finally, we think that our results provide a framework to be tested in the laboratory.[21] In this respect, experimental studies could be fruitfully used to complement the theoretical results and examine the effects of environmental policies.

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[21] See Calzolari et al. (2018) and references therein for laboratory studies of cooperation in a climate change context.

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7 Appendix

TABLE A1. Borders (in km) between EU-26 countries.[22]

	AUT	BEL	BGR	HRV	CZE	DNK	EST	FIN	FRA	DEU	GRC	HUN	IRL	ITA	LVA	LTU	LUX	NLD	POL	PRT	ROM	SVK	SVN	ESP	SWE	GBR
AUT																										
BEL	0																									
BGR	0	0																								
HRV	0	0	0																							
CZE	362	0	0	0																						
DNK	0	0	0	0	0																					
EST	0	0	0	0	0	0																				
FIN	0	0	0	0	0	0	0																			
FRA	0	620	0	0	0	0	0	0																		
DEU	784	167	0	0	815	68	0	0	451																	
GRC	0	0	494	0	0	0	0	0	0	0																
HUN	366	0	0	329	0	0	0	0	0	0	0															
IRL	0	0	0	0	0	0	0	0	0	0	0	0														
ITA	430	0	0	0	0	0	0	0	488	0	0	0	0													
LVA	0	0	0	0	0	0	343	0	0	0	0	0	0	0												
LTU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	576											
LUX	0	148	0	0	0	0	0	0	73	138	0	0	0	0	0	0										
NLD	0	450	0	0	0	0	0	0	0	577	0	0	0	0	0	0	0									
POL	0	0	0	0	615	0	0	0	0	456	0	0	0	0	0	91	0	0								
PRT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0							
ROM	0	0	608	0	0	0	0	0	0	0	0	443	0	0	0	0	0	0	0	0						
SVK	91	0	0	0	197	0	0	0	0	0	0	676	0	0	0	0	0	0	420	0	0					
SVN	330	0	0	455	0	0	0	0	0	0	0	102	0	199	0	0	0	0	0	0	0	0				
ESP	0	0	0	0	0	0	0	0	623	0	0	0	0	0	0	0	0	0	0	1214	0	0	0			
SWE	0	0	0	0	0	1	0	614	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		
GBR	0	0	0	0	0	0	0	0	0	0	0	0	360	0	0	0	0	0	0	0	0	0	0	0	0	

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[22] Given the high proximity of Denmark and Sweden, and the fact that they are connected by the Øresund bridge (operative since 2000), we consider a symbolic frontier (1 km) between these two countries. In this way, they are included in the giant component of the network (see Figure 2).

Table A2. Matrix of impacts $\Theta(0) = A$.

	AUT	**BEL**	BGR	**HRV**	CZE	**DNK**	EST	**FIN**	FRA	**DEU**	GRC	**HUN**	IRL	**ITA**	LVA	**LTU**	LUX	**NLD**	POL	**PRT**	ROM	**SVK**	SVN	**ESP**	SWE	**GBR**
AUT	51.2	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
BEL	0	**76.87**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
BGR	0	**0**	213.35	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
HRV	0	**0**	0	**104.84**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
CZE	0	**0**	0	**0**	151.66	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
DNK	0	**0**	0	**0**	0	**37.07**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
EST	0	**0**	0	**0**	0	**0**	41.51	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
FIN	0	**0**	0	**0**	0	**0**	0	**51.74**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
FRA	0	**0**	0	**0**	0	**0**	0	**0**	43.59	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
DEU	0	**0**	0	**0**	0	**0**	0	**0**	0	**68.7**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
GRC	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	85.81	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
HUN	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**116.21**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
IRL	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	47.35	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
ITA	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**58.33**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
LVA	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	84.82	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
LTU	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**105.15**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**
LUX	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	54.33	**0**	0	**0**	0	**0**	0	**0**	0	**0**
NLD	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**82.12**	0	**0**	0	**0**	0	**0**	0	**0**
POL	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	169.75	**0**	0	**0**	0	**0**	0	**0**
PRT	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**71.02**	0	**0**	0	**0**	0	**0**
ROM	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	121.68	**0**	0	**0**	0	**0**
SVK	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**117.46**	0	**0**	0	**0**
SVN	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	92.34	**0**	0	**0**
ESP	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**62.02**	0	**0**
SWE	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	25.37	**0**
GBR	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**0**	0	**59.21**

Table A3. Matrix $\Theta(\delta)$ of impacts for $\delta = \widehat{\delta}/2 = 3.33$.

	AUT	**BEL**	BGR	**HRV**	CZE	**DNK**	EST	**FIN**	FRA	**DEU**	GRC	**HUN**	IRL	**ITA**	LVA	**LTU**	LUX	**NLD**	POL	**PRT**	ROM	**SVK**	SVN	**ESP**	SWE	**GBR**
AUT	47.29	0.01	-0.02	0.25	-1.65	0.06	0	0	0.04	-1.07	0	-1.44	0	-1.58	0	0	0.03	0.07	0.23	0	0.1	-0.37	-1.87	0	0	0
BEL	0.01	68.37	0	0	0.02	0.01	0	0	-1.27	-0.25	0	0	0	0.05	0	0	-2.31	-3.59	0.01	0	0	0	0	0.04	0	0
BGR	-0.01	0	162.1	-0.04	0	0	0	0	0	0	-20.26	0.6	0	0	0	0	0	0	0	0	-15.84	-0.05	-0.01	0	0	0
HRV	0.08	0	-0.03	89.85	-0.01	0	0	0	0	0	0	-2.48	0	0.08	0	0	0	0	-0.01	0	0.18	0.2	-4.99	0	0	0
CZE	-1.39	0.03	0	-0.02	122.04	0.16	0	0	0.04	-2.79	0	0.18	0	0.05	-0.02	0.21	0.09	0.19	-10.14	0	-0.01	-2.34	0.05	0	0	0
DNK	0	0	0	0	0.01	34.92	0	0	0	-0.07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EST	0	0	0	0	0	0	38.94	0	0	0	0	0	0	0	-1.82	0.23	0	0	0	0	0	0	0	0	0	0
FIN	0	0	0	0	0	0	0	47.79	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1.93	0
FRA	0.04	-2.06	0	0	0.04	0.03	0	0	40.73	-0.54	0	0	0	-1.58	0	0	-0.6	0.14	0.03	0.14	0	0	0.04	-1.3	0	0
DEU	-1.56	-0.63	0	-0.01	-4.85	-3.55	0	0	-0.82	61.95	0	0.03	0	0.08	-0.01	0.07	-1.94	-4.15	-3.54	0	0	0.3	0.06	0.03	0	0
GRC	0	0	-9.08	0	0	0	0	0	0	0	76.22	-0.03	0	0	0	0	0	0	0	0	0.89	0	0	0	0	0
HUN	-1.17	0	1.04	-6.06	0.17	0	0	0	0	0.02	-0.13	98.3	0	0.05	0	-0.01	0	0	0.44	0	-7.08	-7.87	-0.85	0	0	0
IRL	0	0	0	0	0	0	0	0	0	0	0	0	44.18	0	0	0	0	0	0	0	0	0	0	0	0	-3.96
ITA	-0.75	0.04	0	0.11	0.03	0	0	0	-0.78	0.03	0	0.03	0	53.24	0	0	0.01	0	0	0	0	0.01	-1.28	0.02	0	0
LVA	0	0	0	0	-0.01	0	-4.87	0	0	0	0	0	0	0	75.3	-9.69	0	0	0.12	0	0	-0.01	0	0	0	0
LTU	0	0	0	0	0.07	0	0.45	0	0	0.01	0	0	0	0	-7.03	90.41	0	0	-1.16	0	0	0.06	0	0	0	0
LUX	0.01	-0.6	0	0	0.02	0.01	0	0	-0.1	-0.2	0	0	0	0	0	0	49.85	0.05	0.01	0	0	0	0	0	0	0
NLD	0.03	-2.66	0	0	0.1	0.07	0	0	0.07	-1.23	0	0	0	0	0	0	0.13	72.47	0.07	0	0	-0.01	0	0	0	0
POL	0.15	0.02	0	-0.02	-8.07	0.09	-0.01	0	0.02	-1.62	0	0.37	0	-0.01	0.21	-2.74	0.05	0.11	133.55	0	-0.03	-6.47	-0.01	0	0	0
PRT	0	0	0	0	0	0	0	0	0.07	0	0	0	0	0	0	0	0	0	0	63.93	0	0	0	-3.96	0	0
ROM	0.05	0	-15.11	0.24	-0.01	0	0	0	0	0	1.89	-3.88	0	0	0	0	0	0	-0.02	0	102.93	0.31	0.03	0	0	0
SVK	-0.21	0	-0.06	0.35	-1.63	-0.01	0	0	0	0.12	0.01	-5.68	0	0.01	-0.01	0.12	0	-0.01	-5.66	0	0.41	99.02	0.06	0	0	0
SVN	-0.86	0	-0.01	-6.91	0.03	0	0	0	0.02	0.02	0	-0.48	0	-1.24	0	0	0	0	-0.01	0	0.03	0.05	80.49	0	0	0
ESP	0	0.05	0	0	0	0	0	0	-1.06	0.01	0	0	0	0.04	0	0	0.02	0	0	-5.99	0	0	0	56.62	0	0
SWE	0	0	0	0	0	-0.02	0	-1.94	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24.42	0
GBR	0	0	0	0	0	0	0	0	0	0	0	0	-3.96	0	0	0	0	0	0	0	0	0	0	0	0	54.26

TABLE A4. Matrix $\Theta(\delta)$ of impacts for $\delta = \widehat{\delta} = 6.66$.

	AUT	**BEL**	BGR	**HRV**	CZE	**DNK**	EST	**FIN**	FRA	**DEU**	GRC	**HUN**	IRL	**ITA**	LVA	**LTU**	LUX	**NLD**	POL	**PRT**	ROM	**SVK**	SVN	**ESP**	SWE	**GBR**
AUT	44.07	0.02	-0.07	0.71	-2.49	0.19	0	0	0.12	-1.78	0.02	-2.31	0	-2.68	0	-0.02	0.1	0.21	0.58	0	0.29	-0.45	-3.05	-0.01	0	0
BEL	0.01	61.87	0	0	0.04	0.03	0	0	-2.14	-0.3	0	0	0	0.15	0	0	-3.82	-5.79	0.03	-0.02	0	0	-0.01	0.13	0	0
BGR	-0.03	0	135.57	-0.16	0.01	0	0	0	0	0	-30.13	1.5	0	0	0	0	0	0	0.02	0	-22.8	-0.21	-0.02	0	0	0
HRV	0.24	0	-0.11	79.29	-0.03	0	0	0	-0.01	-0.01	0.03	-3.78	0	0.21	0	0	0	0	-0.05	0	0.48	0.52	-7.75	0	0	0
CZE	-2.1	0.05	0.01	-0.07	102.99	0.45	0.01	0	0.1	-4.12	0	0.41	0	0.12	-0.07	0.5	0.24	0.49	-13.76	0	-0.05	-2.97	0.14	-0.01	0	0
DNK	0.01	0	0	0	0.02	33.01	0	0	0	-0.12	0	0	0	0	0	0	0.01	0.01	0.01	0	0	0	0	0	0	0
EST	0	0	0	0	0	0	36.85	0	0	0	0	0	0	0	-3.13	0.7	0	0	-0.01	0	0	0	0	0	0	0
FIN	0	0	0	0	0	0.01	0	44.64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-3.47	0
FRA	0.11	-3.49	0	-0.02	0.11	0.1	0	0	38.37	-0.92	0	-0.01	0	-2.74	0	0	-0.92	0.44	0.08	0.44	0	-0.01	0.11	-2.28	0	0
DEU	-2.6	-0.75	0	-0.03	-7.15	-6.15	0	0	-1.41	56.75	0	0.06	0	0.26	-0.03	0.18	-3.25	-6.78	-4.98	-0.02	-0.01	0.75	0.18	0.08	0	0
GRC	0	0	-13.51	0.02	0	0	0	0	0	0	69.74	-0.15	0	0	0	0	0	0	0	0	2.27	0.02	0	0	0	0
HUN	-1.88	0	2.61	-9.23	0.39	0	0	0	0	0.04	-0.58	86.22	0	0.14	0.01	-0.04	0	0	1.08	0	-10.91	-11.91	-0.87	0	0	0
IRL	0	0	0	0	0	0	0	0	0	0	0	0	41.84	0	0	0	0	0	0	0	0	0	0	0	0	-6.89
ITA	-1.27	0.12	0	0.3	0.07	-0.01	0	0	-1.36	0.08	0	0.08	0	49.08	0	0	0.03	-0.02	-0.02	-0.02	-0.01	0.01	-2.06	0.08	0	0
LVA	0	0	0	0	-0.03	0	-8.37	0	0	-0.01	0	0	0	0	68.96	-15.46	0	0	0.33	0	0	-0.03	0	0	0	0
LTU	-0.01	0	0	0	0.17	0	1.36	0	0	0.04	0	-0.01	0	0	-11.22	80.45	0	0	-1.71	0	0	0.14	0	0	0	0
LUX	0.02	-0.99	0	0	0.04	0.04	0	0	-0.15	-0.34	0	0	0	0.01	0	0	46.1	0.13	0.03	0	0	0	0	0.01	0	0
NLD	0.09	-4.29	0	0	0.25	0.22	0	0	0.2	-2.01	0	0	0	-0.02	0	-0.01	0.38	65.13	0.18	0	0	-0.03	-0.01	-0.01	0	0
POL	0.39	0.03	0.03	-0.09	-10.94	0.25	-0.07	0	0.06	-2.28	-0.01	0.9	0	-0.03	0.57	-4.06	0.13	0.27	111.18	0	-0.11	-9.18	-0.04	0	0	0
PRT	0	-0.02	0	0	0	0	0	0	0.23	-0.01	0	0	0	-0.02	0	0	-0.01	0	0	58.71	0	0	0	-6.66	0	0
ROM	0.13	0	-21.74	0.64	-0.03	0	0	0	0	0	4.83	-5.99	0	-0.01	0	0	0	0	-0.08	0	90.95	0.83	0.06	0	0	0
SVK	-0.26	0	-0.26	0.92	-2.06	-0.03	0	0	-0.01	0.3	0.06	-8.61	0	0.01	-0.04	0.29	-0.02	-0.04	-8.03	0	1.09	86.39	0.12	0	0	0
SVN	-1.4	-0.01	-0.01	-10.74	0.08	-0.01	0	0	0.05	0.06	0	-0.49	0	-2	0	0	0	-0.01	-0.03	0	0.06	0.09	71.88	0	0	0
ESP	-0.01	0.17	0	0	-0.01	0	0	0	-1.85	0.04	0	0	0	0.13	0	0	0.04	-0.02	0	-10.07	0	0	-0.01	52.65	0	0
SWE	0	0	0	0	0	-0.04	0	-3.48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23.66	0
GBR	0	0	0	0	0	0	0	0	0	0	0	0	-6.89	0	0	0	0	0	0	0	0	0	0	0	0	50.6

FIGURE A1. Total impact $\Delta(\delta, \gamma, \mathbf{t})$ as a function of externality parameter $\delta \in [0, \widehat{\delta}]$ and the cost sharing parameter $\gamma \in (0, 1)$ for the net transfers $\mathbf{t}$ given in Table 3. Parameter γ captures the share of the pollution cost borne by the polluting country.