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Dirty neighbors

Pollution in an interlinked world*

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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 design policy measures aimed at reducing the aggregate contamination. We then apply our theoretical framework to analyze the European data on fossil fuel energy consumption and discuss possible transfer schemes that, according to our model, would result in lower aggregate levels of pollution in the EU.

Keywords: local pollution, negative externalities, networks

1 Introduction

The unprecedent 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,

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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. So far, there have been few international attempts to coordinate efforts to reduce *global* pollution. 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.[1] 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, the abatement of (global) pollution has become an important area of research, where scholars analyze, 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; 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, 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.

[1] 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.

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 which transfer schemes (potentially implemented by a supranational authority) may help reduce 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.[2] 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. Furthermore, we illustrate the effects of taxes/subsidies on aggregate levels of pollution. Specifically, we identify two groups of countries such that, according to our model, imposing taxes on countries in the first group and providing (equivalent) subsidies to the countries in the second group would reduce the aggregate polluting consumption in the European Union.

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] 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).

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, 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. Specifically, 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.[3] With regard to the effects of anticipation of negotiations on emissions reduction, Beccherle and Tirole (2011) find adverse consequences of anticipation and, in a broader framework, Açikgöz and Benchekroun (2017) show that the impact on current emissions is ambiguous, and depends on the targeted level of emissions during the phase of cooperation. 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.[4] They analyze emissions, investments and international environmental agreements, while allowing for renegotiation, short term agreements and endogenous coalition formation.[5]

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

[3] See also 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.

[4] See also Dutta and Radner (2009), which models the global warming process as a dynamic commons game, and Mason et al. (2017), which analyzes conditions under which it is possible to achieve efficient mitigation of emissions with a self-enforcing dynamic international agreement.

[5] See Calvo and Rubio (2013) for a survey of applications of dynamic games to international environmental agreements.

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; Elliott and Golub, 2015; and Kinateder and Merlino, 2016).[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.

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

[6] See also Bayer et al. (2017), 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).

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,

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

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 induces a cost on other regions in terms of resources to be spent on cleaning/abating the effects of the "imported" contamination and on addressing the health problems inflicted on the population.[8]

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

[8] Some recent studies aim to identify the economic impact of pollution. See, for instance, Romley et al. (2010), who measure the impact of the quality of air on hospital spending, or the OECD (2014) report on "The Cost of Air Pollution: Health Impacts of Road Transport."

consumption by i's neighbors in this game, we obtain the reaction function for player i from the solution of 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 (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 (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 (3), the interior Nash equilibrium consumption must verify,

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

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. ■

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.[9] 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,[10] it follows that the ith coordinate $b_i(G, \kappa)$ is the sum of all walks in G emanating from i and weighted by κ to the power of their length.

Although G is not necessarily a binary matrix in our framework, we can use the original definition (7) to characterize the equilibrium outcomes in our game.

[9] Ballester et al. (2006) first stablish the connection between equilibrium actions and Bonacich centrality.

[10] 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 (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 (7) and (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 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.

Importantly, Bonacich centralities relate to the aggregate consumption of the polluting good when the demand for the latter (per unit of income as measured by the ratio α_i/p_i) is homogenous across agents. 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 (5) that,

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

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 (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 (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.

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 x_i^*. 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.

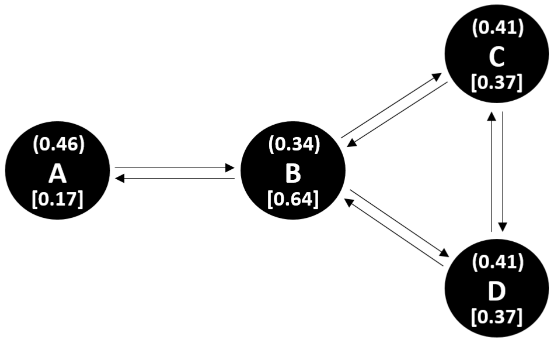

FIGURE 1. An example of equilibrium consumptions of the polluting good before (.) and after [.] a transfer from node A to node B.

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 effects of different transfer schemes on the aggregate levels of pollution in the EU.

5 Application - Fossil fuel energy consumption in the European Union

In the following empirical exercise, we use data from the World Bank on energy consumption, population and GDP for the EU countries except Malta and Cyprus (EU-26 in what follows) reproduced in Table 1.[11,12]

[11] Based on IEA data from the World Energy Balances © OECD/IEA 2016, www.iea.org/statistics. Licence: www.iea.org/t&c; The data are available at: http://databank.worldbank.org/data/.

[12] 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: the population of the country 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 cosumption 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.[13] Clearly, the length of the common border between countries yields a simplistic measure of environmental exposures. Although more sophisticated measures can be constructed,[14] 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.

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,[15] 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.[16]

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

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

[15] 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.

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

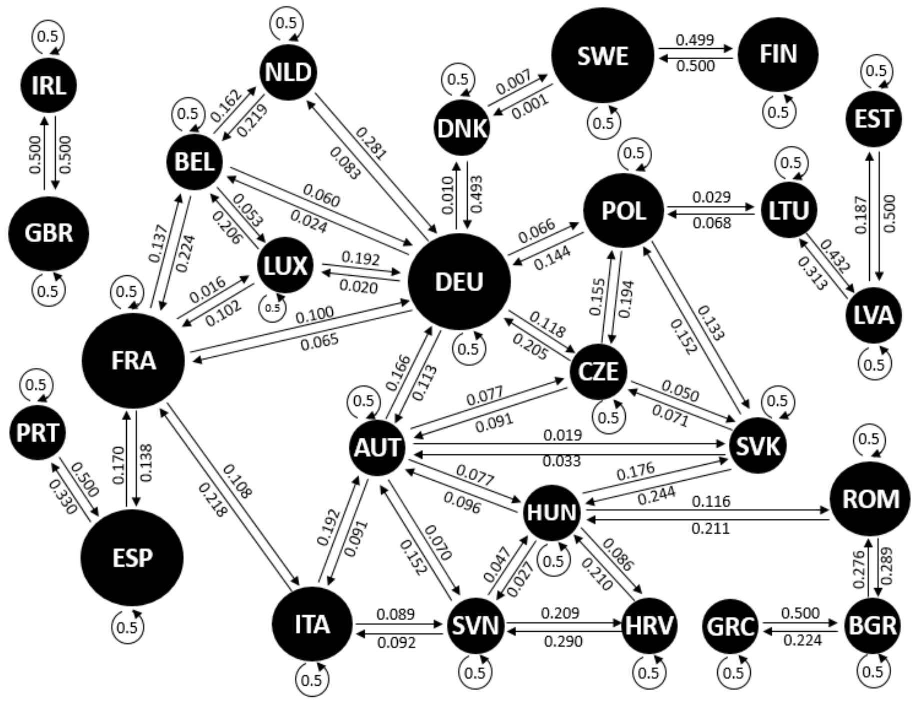

FIGURE 2. Geographic network G of the EU-26. Each node represents an EU-26 country and the weight reported on the arrow (directed link) pointing from country k to country i corresponds to the exposure G_{ik} of country i to the pollution by country k.

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 second column of Table 2 below).

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

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

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 (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 $\sum_{i \in N} \Theta_{ik}(\delta)$ 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).[17] 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 $\sum_{i \in N} \Theta_{ik}(0) = A_{kk} = 82.12$, 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).

[17] 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	$\sum_i \Theta_{ik}(0)$	$\sum_i \Theta_{ik}(3.33)$	$\sum_i \Theta_{ik}(6.66)$
AUT	51.20	41.71	35.51
BEL	**76.87**	**62.57**	**52.71**
BGR	213.35	138.83	102.52
HRV	**104.84**	**77.74**	**61.54**
CZE	151.66	106.30	81.43
DNK	**37.07**	**31.77**	**28.06**
EST	41.51	34.51	29.78
FIN	**51.74**	**45.85**	**41.16**
FRA	43.59	36.96	32.20
DEU	**68.70**	**54.39**	**45.41**
GRC	85.81	57.73	43.96
HUN	**116.21**	**85.52**	**67.82**
IRL	47.35	40.22	34.95
ITA	**58.33**	**49.19**	**42.61**
LVA	84.82	66.62	55.05
LTU	**105.15**	**78.60**	**62.53**
LUX	54.33	45.33	39.01
NLD	**82.12**	**65.28**	**54.02**
POL	169.75	113.92	84.85
PRT	**71.02**	**58.08**	**49.02**
ROM	121.68	81.58	61.25
SVK	**117.46**	**82.83**	**63.96**
SVN	92.34	71.72	58.67
ESP	**62.02**	**51.45**	**43.98**
SWE	25.37	22.49	20.19
GBR	**59.21**	**50.30**	**43.71**

TABLE 2. Total impact of each country for $\delta \in \{0, 3.33, 6.66\}$.

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 (9) by adding taxes (subsidies) $\mathbf{t}$ to the initial wealth vector $\boldsymbol{\omega}$,

$$\mathbf{x}^* = \Theta(\delta)(\boldsymbol{\omega} + \mathbf{t}) = \Theta(\delta)\boldsymbol{\omega} + \Theta(\delta)\mathbf{t}. \tag{10}$$

In light of (10), a simple tax-subsidy scheme that decreases the aggregate FFE consumption would impose a (small) tax t on country m (reducing its wealth to $\omega_m - t$) and transfer this tax as a subsidy to country l (increasing its wealth to $\omega_l + t$), where m (l) are the countries with the maximum (minimum) total impact per transferred dollar,

$$m \equiv \arg\max_k \sum_{i \in N} \Theta_{ik}(\delta), \quad l \equiv \arg\min_k \sum_{i \in N} \Theta_{ik}(\delta).$$

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

$$\sum_{i \in N} \Theta_{i,BGR}(\widehat{\delta}/2) - \sum_{i \in N} \Theta_{i,SWE}(\widehat{\delta}/2) = 116.34g$$

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

However, this scheme depends on a particular value of the unobserved "externality parameter" δ. In the following exercise, we identify the likely contributors and recipients of environmental transfers independently of the values of δ. Specifically, 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 $v(\delta_\tau) = (\sum_{i \in N} \Theta_{ik}(\delta_\tau))_{k \in N}$ 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,

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

The set N^{Below} (N^{Above}) contains countries that generate, through their own consumption and externalities, less (more) pollution per an additional \$1 than the median country for all $\delta_\tau \in [0, \widehat{\delta}]$. Therefore, a transfer scheme that imposes a (small) tax on countries in N^{Above} and transfers the receipts to countries in N^{Below} reduces 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 in Table 3.

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 3. 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 $\epsilon = 0.01$.

The left panel of Table 3 contains the countries whose total impact on the pollution of the EU-26 countries are above the median for all values of δ that are compatible with our assumptions, whereas the right panel contains the countries whose total impact is always below the median. Hence, according to our model, a transfer scheme that imposes small taxes on the first set of countries and provides (equivalent) subsidies to countries in the second set would lead to a reduction in the aggregate level of polluting consumption. Some countries, like e.g. Portugal and the Netherlands, remain unclassified (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] A visual inspection of Table 3 reveals that most of the elements in the set N^{Above} are Central and Eastern European countries, whereas those in N^{Below} are mostly Western European countries, which suggests an environmental underdevelopment of the "New Europe" as compared to the "Old Europe".

We should note, however, that our analysis applies exclusively to the environmental externalities among the EU-26 countries and ignores other considerations such as income inequalities. Indeed, the (weighted) average of the GDP per capita of the countries in N^{Above} is $17,000$ US$, whereas for the countries in N^{Below} it is $41,000$ US$ (the average across all countries in the EU-26 is $35,000$ US$).[19] Hence, although the transfer scheme implied by our model is likely to reduce the aggregate pollution in the EU, it would have also negative side effects in terms of redistribution of wealth from the poorer to the richer members of the Union. We note also that in order to study the impact of the enviromental transfer schemes on the (aggregate) welfare, one would need some estimates of the parameters α_i and of the relevant prices. Their estimation, however, is beyond the scope of this work.

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

[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] We compute the weighted averages of the GDP per capita of the different set of countries from the data reported in Table 1, using as the weight for each country the frequency of its population relative to the total population of the corresponding set of countries.

of wealth. Furthermore, we identify potential transfer schemes that can reduce the aggregate level of pollution. 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 case of European fossil fuel energy consumption and discussed possible tax/subsidies schemes to abate pollution in the EU. Our empirical application suggests that a tax/subsidy scheme that implements transfers from a group composed mainly by the Central and Eastern European countries to a group formed essentially by Western European countries would reduce the aggregate level of polluting consumption in the EU. On the other hand, such a scheme is likely to exacerbate the existing income inequalities across and within member states.

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. Instead, the focus has been typically on global pollution (i.e., on the complete network in our framework). 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. First, on the theory side, it would be instructive to generalize our model to a dynamic context, in which regions pollute (or consume dirty goods) over time, negatively affecting their neighbors and, at the same time, also invest in green technologies. 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 design environmental polices to abate contamination in different regions across the world. Moreover, more sophisticated alternatives to our simplistic measure (the lenght of the common border) of the exposure to neighbours' pollution could be explored. Finally, we think that our results provide a framework to be tested in the laboratory.[20] In this respect, exper-

[20] See Calzolari et al (2016) and references therein for laboratory studies of cooperation in a climate change context.

imental studies could be fruitfully used to complement the theoretical results and validate the potential effects of the different policies.

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7 Appendix

Table A1. Borders (in km) between EU-26 countries.[21]

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

[21] 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**