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Expanding a Climate Club in Europe: A Network Simulation*

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Coordinating and achieving international climate agreements is a pressing matter to combat climate change. We analyze the expansion of a climate club in Europe from 1996 to 2011. We simulate it as a virus disseminating through a network. For this, one of two alternative thresholds must be surpassed: One in terms of the relative frequency of interactions between countries of the same group or another in terms of the value of trade exchanges. We find that the second threshold fits in a more accurate way the actual sequence of events. Finally, we identify countries that, acting as seeds, accelerate the process of expanding the club throughout the network.

Keywords: Cascades, Climate clubs, Networks, Simulations, Targeting.

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Ⅰ. Introduction

Policies to fight global warming have in recent decades been gathering increasing interest from the economics profession and the wider public. A region of the world that has developed and implemented numerous climate change policies to a certain degree of success is the European Union (EU). The countries that conform it, whether they were original members or joined later, implemented these policies in tandem.

We are interested in studying how a climate club expands as different countries that trade with its members decide to join it. Additionally, we wish to understand if this process can be accelerated by considering the structure of the trade network in which the different trading partners participate. Had the original members of the club been others, which ones would have sped up the expansion of the climate club? This analysis could be useful in the design of incentives for joining a climate club.

Through a network model we simulate how European countries that were and would become members of the EU form and expand a climate club. These countries are connected with each other in the network through their trade flows. In the model, a country chooses whether becoming a member of the club through policy harmonization or not. We depict this as a virus spreading through a network with nodes changing color. To characterize the decision-making process, we rely on two alternative thresholds. The first one evaluates whether the number of neighbors of a target node, who are taking a given action (joining or not the club), is above a predefined value. The second one assesses if trading partners being members of the climate club are more important than those not being part of it, regarding the country's export destination. If the former have a higher weight than the latter, then the exporting country copies behavior and joins the club. In other words: the stronger the ties and volume of trade that a given country has with members of the club, the higher the incentives for it to also "switch" and join. By relying on a network we are able to model the interaction of various players simultaneously while analyzing the expansion of the climate club through various European countries.

We simulate our model by using both data of volumes of international trade and adoptions of climate change policies, for European countries, for the period 1996-2011. The numerical analysis simulates the waves in which countries joined the club. Our results suggest that the second threshold predicts these waves more accurately during the period we analyze. Depending on the parametric values, the threshold's ability to correctly predict each wave can go from 60 to over 70 percent. This is done by comparing the results of the simulations with the real data to see if there are any discrepancies.

Finally, we test which countries would allow for a faster expansion of the club and also determine the minimum number of countries that is sufficient for a cascade effect in our network to occur. We find that the most effective countries for the expansion of the club are Germany, France and Great Britain. Regarding the second goal, we encounter that as few as 1 to 2 countries (depending on the threshold value) are sufficient for the cascade to take place.

The rest of this article is organized as follows. Section 2 discusses the related literature. Section 3 describes the data used. Section 4 outlines the criteria to analyze the expansion of the climate club. Section 5 explains the results of the simulation. Section 6 concludes.[1)]

Ⅱ. Related Literature

Different ways to abate and reduce emissions, such as International Environmental Agreements, have been proposed (Barrett 1994, Barrett 2005). These agreements work as coalitions in which environmental treaties between various trading partners are achieved, establishing conditions for trade and imposing sanctions in case these are not fulfilled. Another method consists of imposing an international harmonized carbon tax (Nordhaus 2006).

A newer approach is that of a "climate club" which works as a combination of the former two methods: A coalition of countries that agree to reduce emissions in a harmonized way. Countries that do not become members of the club or follow its rules once they join are sanctioned by an amount or in a way that offsets the incentives of keeping "business as usual" emissions of Greenhouse gases (GHG).[2] In other words, their access to the markets of those belonging to the climate club or the benefits derived from it are cut or reduced (for example, in 2001 Greece was punished for not complying with EU environmental standards, quickly changing its attitude once it was told it would lose regional aid from the EU). This generates a stable coalition of countries that can, by combining environmental policies and trade sanctions, substantially reduce emissions (Nordhaus 2015). The harmonization works as a mechanism by which countries adopt similar policies (Holzinger and Knill 2005).

In a recent paper, Heal and Kunreuther (2017) explain that it is better to work with a small subset of countries to confront the issue of a global climate regime. If these countries implement certain types of policies to reduce GHG emissions, and if they are sufficiently influential, it can trigger a cascading effect that convinces others to imitate or follow suit.

Efforts by various parties to mitigate GHG emissions have not been efficient due to a lack of enforcement and insufficient participation (Barrett 2008). Furthermore, it is often the case that even if environmental laws are passed, these are not enforced (Cao and Prakash 2010). Due to this, different authors have proposed international trade as a possible way to enforce climate policies (Aldy et al. 2001; De Melo and Mathys 2010; Zhang 2009) having the advantage that it would allow access to others' markets with low trade barriers (Nordhaus 2015).

The relationship between trade and the environment has been extensively studied.[3] Peters and Hertwich (2008) examine the flow of pollution through streams of international trade and determine the CO_2 emissions embodied in international trade for 87 countries. Depending on characteristics such as size and geographic location, a country's embodied emissions will vary. The authors discuss policies such as the formation of a coalition, in which countries commit to binding agreements to diminish the effects that trade may have on global climate policies.

Networks are ubiquitous in economics.[4] Kagawa et al. (2013) make use of networks to identify clusters of CO_2-intensive industries in the automobile supply chains. Vega and Mandel (2018) analyze through a network model the role of wind energy technology transfer in mitigating climate change and ways to speed up this process. Different works have been conducted relying on networks to analyze diffusion processes.[5] Our model is based on Morris (2000), who studies how the behavior from an initial small group can spread to the rest of the population. This is characterized as a local interaction game in which a player's binary choice is a best response to her neighbors' actions from the previous period. Once a critical threshold, the relative frequency of connections between players from a given group compared to nonmembers, is surpassed, this behavior disseminates throughout the network.

Because climate change is a global externality, it requires the collaboration and participation of the whole international community in order to be tackled swiftly and in the least costly way in terms of its impact on the economy, society and the environment (Stern 2008). Taking this into consideration, this paper makes different contributions. First, through the network model we highlight the expansion of the climate club that took place throughout different European countries and the order in which this happened. We consider two different thresholds and compare the predicted outcomes. Notice that without thresholds, the expansion either occurs in one period or it does not occur at all. Furthermore, thresholds play a role in limiting or accelerating the speed at which the club expands, allowing us to model the occurrence of events.

Second, we relate the expansion of the club to the thresholds that determine best response dynamics. This can be interpreted as both obtaining membership in the club and as receiving special benefits from the club members' markets (i.e. mutually advantageous terms of trade). Our model differs from the original model of Morris (2000) in that we work with a finite, directed graph with weighted links, whereas the original one relies on a lattice with unweighted and undirected links. We develop, additionally, an alternative threshold that works well with weighted complete graphs. We then compare the results derived from it to those from the first threshold.

Finally, we show that the expansion of the club can be accelerated by a centralized mechanism wanting to device optimal targeting strategies, by considering the network structure and the number and position of the "seeds" or initial club members. The literature on the role of influential agents in the context of local interactions has been extensively studied in various fields such as physics (Bagnoli et al. 2001), computer science (Kempe et al. 2003; Kempe et al. 2005), marketing (Kirby and Marsden 2006) and economics (Galeotti and Goyal 2009; Tsakas 2017). To the best of our knowledge, this type of analysis hasn't been applied to this problem.

Ⅲ. Data and Methodology

To test our model and its thresholds we use data of bilateral trade, for the EU, from the IMF's direction of trade statistics (DOTS). Specifically, the data are for "Exports, FOB to Partner Countries" in millions of U.S. dollars. These data are publicly available.

We organize the data into adjacency matrices of the network, with a matrix per year under study. From this, we can create the links of the network representing the trade relations between each of the different trading partners. Specifically, the *ij* elements of the adjacency matrix represent the amounts in dollars of export flows between trading partners *i*and *j*. In our model, nodes or countries are "adjacent" if they are connected with each other through trade. In other words, nodes are "neighbors" if they are directly connected with each other regardless of whether they are physically next to each other or not. Thus, the outgoing directed links of the network point to the destination of exports while nodes act as countries.

The dataset for climate change mitigation policies implemented by the European countries comes from the European Environment Agency, and is publicly available. This database has very detailed information regarding the names and types of policies, which countries implemented or adopted them, year this occurred, etc. It also details whether these policies are related to a Union policy or not. We omit Bulgaria, Lithuania and Luxembourg from the list of countries we analyze since their data are not complete for some years. In the next section we explain the criteria used to filter these policies. The simulation routine was programmed for and implemented through R version 3.4.1 (R Core Team 2017), relying on the igraph package (Csardi and Nepusz 2006). The results were then contrasted with the environmental policy data.

Ⅳ. Policies and Club Expansion

European countries have a long tradition in environmental protection policies. By the year 2011, a great amount of policies intended for reducing and abating GHG emissions had been adopted, implemented or planned by different countries. These ranged from waste reduction to alternative ways of efficient land usage. Furthermore, the EU has different climate and energy policy frameworks such as the Effort Sharing Decision (ESD), which covers areas such as transport and industrial processes. These set binding annual emission regulations at the national level and EU countries that do not comply may suffer sanctions. This works as a threat that deters countries from not reducing emissions. As an example, in more recent times both Germany and Ireland faced the prospect of sanctions due to their lack of reductions of emissions, with Ireland having to pay up to ∈600 million in penalties and Germany even higher amounts.

For the purpose of our study, we concentrate in policies that are related to GHG emissions derived from production and exports of goods and services. Due to the large number and ways these policies are categorized, we filter them according to the following criteria that must be simultaneously fulfilled:

1. The measure was either implemented or adopted and did not expire during the period under study.
2. The measure targets an energy supply source, an industrial process, some form of transportation and/or those that cut across different sectors (cross-cutting policies).

The first item's purpose is to keep consistency throughout the simulation, since we wish to unveil how the same set of policies were harmonized across European countries. Policies that expired mid-way through the period under study or that were replaced by others are not considered because the theoretical model assumes that harmonization cannot be reversed.

In the second item, energy supply refers to carbon capture and storage, efficiency improvement in the energy sector, etc. Industrial processes relate to the installation of abatement technologies, the control of fugitive GHG emissions, and so on. Policies associated to transportation include road taxes for high CO_2 emitting vehicles, improvement of the efficiency of vehicles, and the like. Cross-cutting policies associate to issues that cut across numerous environmental laws, regulations and/or programs. (e.g. energy efficiency throughout various sectors in the economy).

From the two criteria, the initial club members that we use to run the simulations are comprised of: Austria, Czech Republic, Denmark, Finland, France, Latvia, Netherlands and Sweden. Table 1 presents the order and year that EU countries began to harmonize policies, according to the criteria we used. All of the eight original club members had one or more environmental policies in place by the year 1996 (the initial period of the simulation).

First period (until 1996):
Austria (1995), Czech Republic (1995), Denmark (1993), Finland (1992), France (1982), Latvia (1993), Netherlands (1992), Sweden (1957).
Second period (until 2004):
Belgium (2004), Estonia (2001), Germany (2000), Greece (1998), Romania (2002), Slovak Republic (1997), Slovenia (2004), Spain (2003), Poland (1997), United Kingdom (2001).
Third period (until 2011):
Croatia (2007), Cyprus (2007), Hungary (2007), Ireland (2005), Italy (2007), Malta (2008), Portugal (2007).

Source: European Environment Agency

Table 1: Harmonization waves

For all countries to harmonize, we need to consider two aspects of the network that will affect the outcome:

1. The adoption threshold.
2. The number of initial seeds or climate club members and their positions.

The threshold establishes a condition or value that must be met so that the "virus" spreads from a node to another (i.e. action 1 is taken by neighboring nodes). As an example, suppose we have a star-shaped network of four players and that we rely on Equation 1 (in the appendix) with a value p of, say, 0.28. This means that a given player needs more than 28% of neighbors belonging to the climate club in order for her to harmonize. An example of said process is shown in Figure 1, in which 1/3 of neighbors (33%) were in the club.

Finally, the initial number of climate club members or seeds also determines the speed at which the club expands. Notice that seeds can be heterogeneous: The higher the eigenvector centrality[6] they have, the higher their influence is.

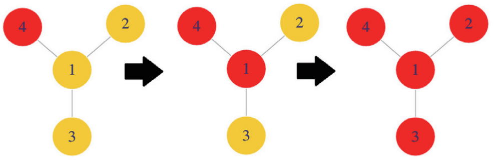

Figure 1: Example of expansion from player 4, the initial seed, with a threshold p=0.28

Ⅴ. Results

We evaluate the two thresholds proposed and see which one does a better job at explaining the spread of the climate club in Europe for the period under study. For the first threshold (which considers the ratio of trading partners in the club to total trading partners), the higher p is, the harder it becomes for the club to expand. We find that for values of p lower than or equal to 0.333, all the countries harmonize inmediately (only one step or wave). This is expected because the network is complete (i.e. each player is neighbors with all other players).

By requesting that more than 33% of neighbors are part of the club, we observe that it takes more steps (waves) for it to expand. Between the threshold values of 0.334 and 0.363 it takes up to two waves. Once we go beyond this last value though, the model does not attain complete harmonization. Instead we reach a scenario of co-existent equilibrium, in which some countries belong to the climate club and others do not and remain in that state (i.e. only the initial seeds remain as members).

We define the hit rate of the thresholds as the percentage at which the model is able to correctly reproduce the real events it is describing. The predictive power of the first threshold is very low, having a hit rate below 50% across different values of *p*. This is presented in Figure 2 along with the distribution of prediction hit rates for *p*. A graphical representation of the club expansion process is depicted in Figure 3. Red nodes represent countries that have harmonized and yellow nodes represent countries that have not.

To compute the hit rate for this threshold, we compare the results obtained from the simulation with the data shown in Table 1. We then proceed to count the number of countries that are correctly predicted through the simulation. Finally, we divide that value by the total number of countries from the first and second wave (i.e. the countries that are not initial seeds).

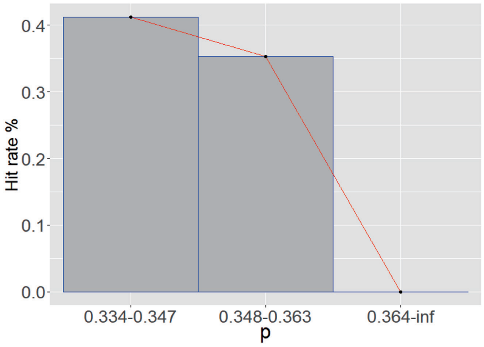

Figure 2: Distribution of hit rates for threshold 1

Since we are dealing with a complete graph, every node has the same degree and thus the degree distribution of the network does not help in understanding the order of the harmonization waves. Threshold 2 then takes into account the weight of links in addition to the number of neighboring nodes. This incorporates the fact that some partners are more influential than

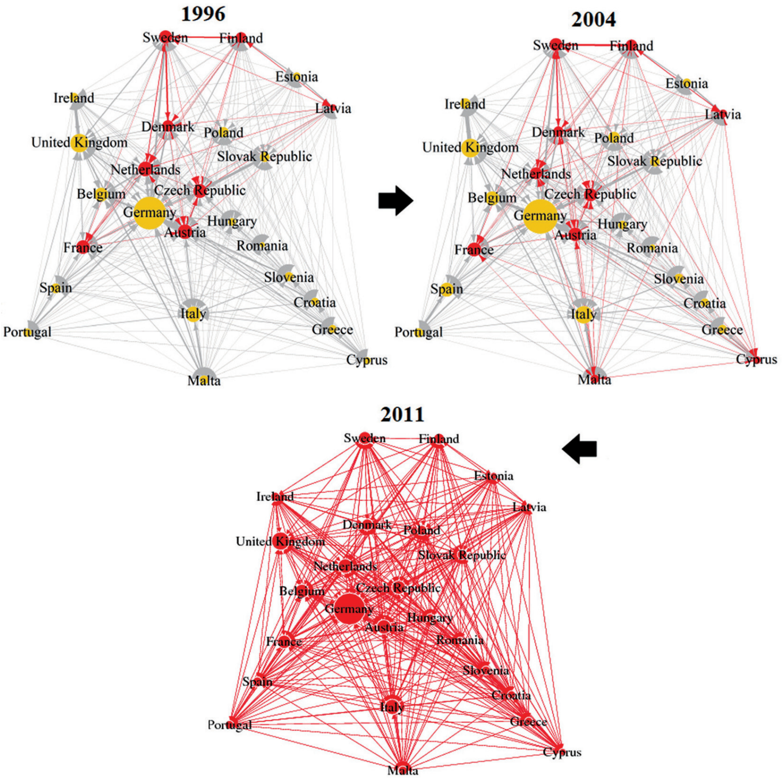

Figure 3: The club's expansion process for threshold 1 with *p* $\in$ [0.334, 0.347]

others, given the volume of their trade exchange. Under this threshold, behavior is also different. The parameter η reflects the importance of exports to countries that belong to the club with respect to those that do not: a higher value of this parameter gives more weight to these markets by the target country, allowing for a greater chance that it decides to harmonize. The importance granted to these countries reflects the added benefits of being a part of the club that are not directly related to the trade flows (e.g. lower or no taxes to capital flows, free movement of people within the club's territory).

For an η of 1.09 or higher, complete harmonization always occurs.[7] When the threshold's parameter

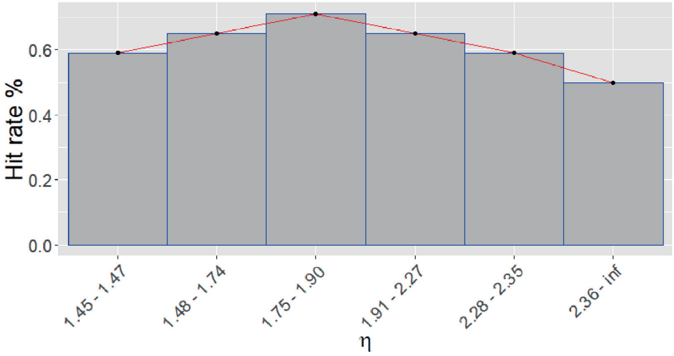

Figure 4: Distribution of hit rates for threshold 2

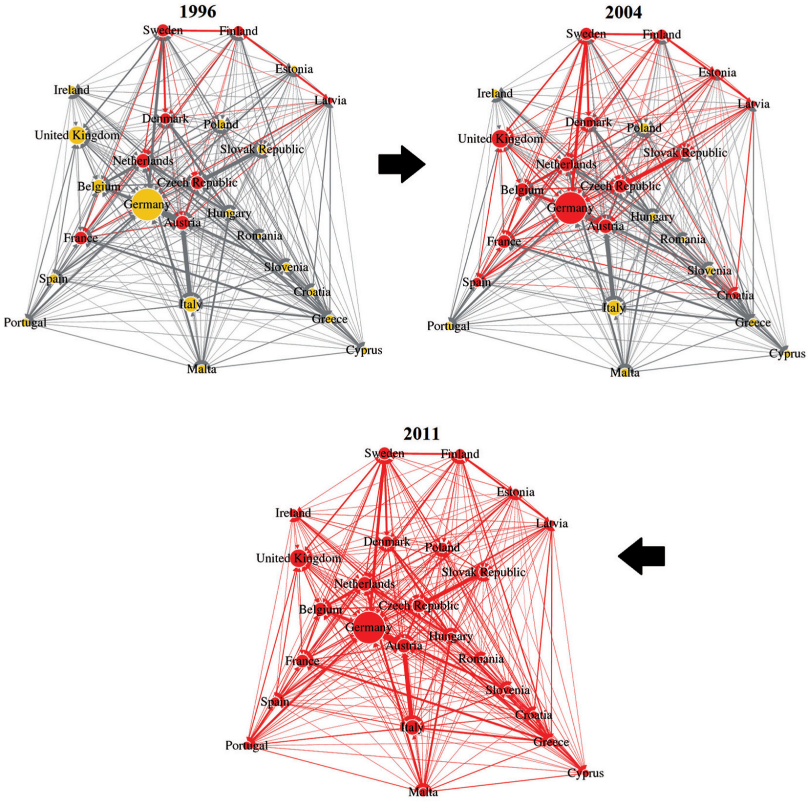

Figure 5: The club's expansion process for threshold 2 with $\eta \in [1.75, 1.90]$

takes a value between 1.48 and 2.27 the model has an average predictive hit rate, with respect to the expansion of the climate club in Europe, above 60%. This is more accurate than in other cases. The distribution of hit rates is depicted in Figure 4. We can observe that the hit rate is highest (71%) for the interval going from 1.75 to 1.90. A graph for this is shown in Figure 5. We calculate the hit rate for this threshold in the same way as in the previous case.

To check the results of this threshold we test the network's robustness by using a null model. We do this for the second network (club expansion up to the year 2004) by shuffling 5 links with their corresponding weights such that the row totals remain unaltered. We then run 1000 simulations to finally contrast the outcomes with those of the original network. Additionally, we assess the statistical significance of the hit rate when $\eta \in [1.75, 1.90]$. By doing this, we see if the network is sensitive to the introduction of a small "perturbation". If the perturbation does not alter the contagion process significantly, then the network is robust. We find that when η takes the above values, the model predicts with a hit rate of 70% in 786 out of the 1000 simulations. In other words, after randomly exchanging links of different nodes, the model is able to predict with a high degree of accuracy the expansion of the climate club. This is shown in Figure 6. Additionally, when we run simulations for the extreme case, (i.e. all nodes with all their links being shuffled), we find that the 70% hit rate of η occurs in less than 15% of the simulations. This confirms that this hit rate is not due to some structural property inherent to the network. The network is then robust.

Now we ask, what would the situation be had the initial seeds been different ones? Given this network, which countries would have the highest influence for the club to expand? The use of simulations allows us to do counterfactual analyses and helps us respond these questions. First we detect the initial injection points (seeds) and then check how fast the expansion process is compared to how it previously was.

To find the best "diffusors of the virus", we search for the most influential countries in the network. For this, we rely on the eigenvector centrality and consider the nodes with the eight highest scores (i.e. the eight countries with the highest rankings in this measure). Germany, France, United Kingdom, Italy, Netherlands, Belgium, Spain and Sweden obtain the highest scores, in that order, and thus are taken as the initial seeds. When we use them and apply the same η values from threshold 2 as before, the climate club's growth process takes a single step instead of two, spreading to the rest of the network in that time. This informs us that, indeed, these countries have a high influence and power in the network, being markets that are very attractive to others.

If we alter the number of best diffusors while maintaining the threshold's value constant, then the number of waves in the club's expansion process also changes. What is the minimum number of countries in the club that is needed for complete club harmonization in this network to happen? From the list of eight best diffusors previously obtained we begin

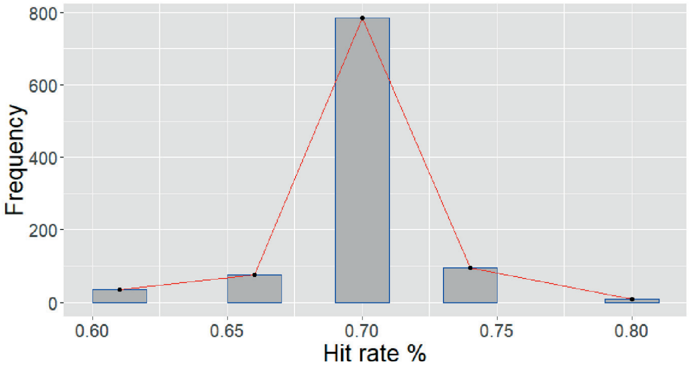

Figure 6: Null model after Shuffling 5 links

omitting countries gradually, from least to most influential, until we reach said minimum number. We find that for an η between 1.75 and 1.90 (for which the prediction hit rate is the highest), only one country, Germany, is sufficient for complete club harmonization to materialize. When we do the same for a threshold value of 1.09 (the minimum value at which complete club harmonization occurs in this network), two countries are necessary: Germany and France.

These results tell us that by understanding and taking into consideration the underlying structure of the network, a centralized mechanism can accelerate the expansion of the climate club. This process can additionally be attained at a wide scale (e.g. regional or world-wide). Since some countries have a higher centrality and weight in the expansion of the climate club, our results show that it matters who the original seeds are and that they can have a definite role: The more central their position in the network is, the higher their influence on others will be. Heal and Kunreuther (2017) also obtain results similar to ours. These authors find that the minimum number of countries necessary in a climate club, for a wide international climate agreement to take place, is two.

The second threshold shows us that under minimum binding sanctions (as in the case of non-tariff trade barriers), the links representing exports are important for European countries concerning the decision of adopting environmental regulations, regardless of whether these countries actually joined the club or not. In other words, once the model takes into account the importance of export markets, it predicts the sequence of policy adoption better.

A climate club should thus be designed with policies that can be implemented with ease and that have a universal appeal (i.e. those that do not depend on or consider only specific characteristics of each country), while being efficient and stable. All this could be achieved through threats from member countries to non-members of imposing either non-tariff trade barriers (an example being imposing additional procedures for importing goods from non-members) or canceling subsidies/international aid to them. Additionally, a club could provide club goods such as mutually advantageous terms of trade and investment, joint R&D programs in renewable energy technology and extension of pipelines or electricity grids to mutually enhance energy security, thus creating incentives for non-members to join it.

Our results imply that, for the case of the EU, Germany and France are essential to achieve this kind of outcomes by acting as initial club members and by threatening to sanction non-members due to their market size and importance.

Owing to large costs associated with developing and deploying green energy technologies, joint research, development and collaboration between different countries can be a way to accelerate its implementation. By being the "pioneers" in the climate club, big-market countries can have a first-mover advantage in the joint development of these technologies, giving them a lead over non-members on these technologies. This could serve as an incentive for countries such as Germany and France to be the "initial diffusors" in our model. Once these countries joined the club, it would become easier for negotiations to tip and more countries would be pressured therefore to become members (accelerating the "contagion process"), while non-members would not be able to free-ride on other countries' effort for global public goods. This type of mechanism could help achieve more satisfying outcomes than voluntary agreements between countries.

Ⅵ. Conclusions

We investigate how the expansion in the harmonization of climate policies across countries can occur and how this is affected by the trade linkages between trading partners. A region such as Europe, with a large pool of climate change policies in effect, serves as a reference point to understand how tightly connected countries can have incentives to join and expand a climate club.

The contribution of the paper is studying this issue through a network approach in which nodes represent European countries taking one of two actions: join a climate club through harmonization or not, based on the trade flows with their trading partners. We use two alternative thresholds that determine best response dynamics. By means of simulations, these thresholds provide an interpretation to the pattern in which different countries in Europe joined the climate club. Through these simulations, we can observe how the expansion of the club occurred and in how many waves this happened.

We find that the second threshold proposed－which considers the importance that exports to countries that belong to the climate club have in comparison with those that are not members of it－does a good job at matching the order in which European countries joined the club, for the period comprising the years 1996-2011. When testing for countries in the network that make the best diffusors, we observe that the minimum number required to trigger a complete club harmonization process is only between 1 and 2. This is in line with previous findings that as few as two countries may foster an international climate agreement by shifting behavior from a given equilibrium to a different one. These results suggest that there may be key or influential players in the network that should be considered in order to accelerate the expansion of the club in a more effective way. When taken at a world-wide scale, these countries can make the difference in tipping negotiations in one direction and obtaining better results in cases in which fast actions are necessary, such as in the case of climate change.

Based on the previous idea, it is possible that these influential countries can actually demand or stipulate that other countries comply with the requirements of harmonizing their environmental policies under the threat of not getting access to the climate club or its benefits.

For future research, we think that the model could be expanded by letting externalities play a role in these relations. By doing so, it would be possible to have a better understanding of the impact that policies have on the emissions generated by various economic activities throughout Europe and other regions of the world. Also, since our model lacks sanctions, explicitly considering them through some kind of variable that captures its effects on player behavior would be an interesting addition to the model, allowing for further insights from the simulations.

Ⅶ. Appendix

The Model

Assume a finite set of players $N = \{1, \ldots, n\}$, with $n \geq 3$. The players in our model represent European countries. We denote a directed network **g** through an adjacency matrix in which each link connecting a node $i \in N$ is given by a (row) vector $\mathbf{g}_i = (g_{i1}, \ldots, g_{ii-1}, g_{ii+1}, \ldots, g_{in})$, where $\mathbf{g}_{ij} \in \{0, 1\}$ for each $j \in N \setminus \{i\}$ and let $g_{ii} = 0$. Let $\mathbf{g}_i \in G_i = \{0, 1\}^{n-1}$. We say player i has a link with player j if $g_{ij} = 1$. The links in the network represent the trade that countries perform with each other.

We define the set of players to which player i has links with as $N_i^{OUT}(\mathbf{g}) = \{j \in N : g_{ij} = 1\}$, while the out-degree of player i is given by $d_i^{OUT}(\mathbf{g}) = |N_i^{OUT}(\mathbf{g})|$. Note that the network of links **g** is a digraph or directed graph. We denote its closure as $\bar{\mathbf{g}} = cl(\mathbf{g})$: an undirected graph for which $\bar{g}_{ij} = max\{g_{ij}, g_{ji}\}$ for each $i, j \in N$. In other words, we substitute each directed link in **g** for an undirected one. Additionally, let $N_i(\bar{\mathbf{g}}) = \{j \in N : \bar{g}_{ij} = 1\}$ be the set of players to which i is connected in the undirected graph $\bar{\mathbf{g}}$. Let $d_i(\bar{\mathbf{g}}) = |N_i(\bar{\mathbf{g}})|$ be i's degree in said graph.

We say that a player has two possible actions she can take, 0 and 1. Denote $u\,(a,\ a')$ for a player's payoff from a specific interaction if she chooses a and her neighbor chooses a'. This payoff function refers to Figure 7 below:

	0	1
0	$q,\ q$	0, 0
1	0, 0	$1-q,\ 1-q$

Figure 7: Payoff matrix

where payoffs are parameterized by $q \in (0, 1)$, so that action 1 is a best response (BR) for a given player if she assigns a value of at least q to the other player also choosing action 1.

At any given period of time, each player i will take an action $a_i \in \{0, 1\}$. Let $R \subset N$ be the set of agents taking the same action, say 1, and $R^C = N \backslash R$. Then, each player in R must have at least a fraction $q \in (0, 1)$ of her neighbors in R, and also each player in R^C must have a fraction of at least $1-q$ of her neighbors in R^C.

Each player maximizes her instantaneous utility. The instantaneous utility considered in this model depends on the trade achieved by each player with her trading partners: The higher the volume, the greater the utility. This interpretation should be understood in a wide sense: It includes economic considerations because, as international trade has similar effects as discovering new technologies, it is total-welfare enhancing; and it also includes political considerations because the probability of being reelected increases as the economy improves.

Following Morris (2000), we define the *configuration* function $s : N \mapsto \{0,1\}$. Given *s,* player *i*'s BR is to select an action such that it maximizes the sum of her payoffs from the interaction with each of her neighbors. Given $\overline{\mathbf{g}}$, we say a is a BR for player i if:

$$\sum_{j\in N_i(\overline{\mathbf{g}})} u(a, s(j)) > \sum_{j\in N_i(\overline{\mathbf{g}})} u(1-a, s(j))$$

Analogously, given $\mathbf{g}$ we say $\tilde{a}$ is a BR for player i if:

$$\sum_{j\in N_i(\mathbf{g})} u(\tilde{a}, s(j)) > \sum_{j\in N_i(\mathbf{g})} u(1-\tilde{a}, s(j))$$

Note that both a and $\tilde{a}$ are binary actions.

It follows that for player i action 1 is a BR if a proportion higher than q of her neighbors choose it as well. In the same way, action 0 will be a BR if a proportion higher than $1-q$ of her neighbors take it. A given configuration s is identified with the subset $R=\{i : s(i)=1\}$; and the subset R is identified with configuration s where

$$s(i)=\begin{cases}1 & \text{if } i\in R\\ 0 & \text{if } i\in R^C\end{cases}$$

The thresholds

In the model, countries join the climate club when a certain threshold is surpassed.[8] Depending on whether this is fulfilled or not, players will respond with action 1 or 0, respectively. We proceed to define two alternative versions of this rule, based on different possibilities:

1. The cohesiveness of *R*. A subset *R* is *p*-cohesive with respect to $\overline{\mathbf{g}}$ if each player in *R* has at least a fraction p of its neighbors in *R*. In other words, a player's BR is given by:

$$a(N_i(\overline{\mathbf{g}}), R, p)=\begin{cases}1 & \text{if } \dfrac{|N_i(\overline{\mathbf{g}})\cap R|}{|N_i(\overline{\mathbf{g}})|} > p,\\ 0 & \text{otherwise}\end{cases} \tag{1}$$

   with $p>0$.

   Equation 1 reflects that countries have a higher incentive to harmonize policies as the number of neighbors harmonizing increases.

2. The relative importance between partners that belong or not to the climate club. Specifically, we consider that a player joins the club if the exports to trade partners belonging to it is greater, by a magnitude η, than those to partners out of it, for a given period *t*:

$$\tilde{a}_t(N_i(\mathbf{g}), R, \eta)=\begin{cases}1 & \text{if } \eta > \dfrac{\sum_{j\in R^C} |N_i^{OUT}(\mathbf{g})\cap R^C| w_{ij}}{\sum_{j\in R} |N_i^{OUT}(\mathbf{g})\cap R| w_{ij}}\\ 0 & \text{otherwise}\end{cases} \tag{2}$$

   $\forall t>0$ and $\eta>0$ and w_{ij} representing the weights of the outgoing links from player i to her neighbors. The t subscript represents the fact that an action a player will take may change from a period compared to the previous one since the network's weights may vary. This is only if a switch in behavior hasn't happened, since there is no reversal from action 1 to 0. Note that for the case of the directed network $\mathbf{g}$, we adapt the concept of cohesiveness to include the specific weights of the links. Equation 2 reflects that not all partners are equally valuable: If the flows (i.e. volumes of trade) are larger with members of the club, the incentives to harmonize increase.

As a note, equation 2 assumes that by becoming club members, countries have implicitly taken into consideration the costs and benefits of joining or remaining out of the climate club. This includes the sanctions for not complying to its rules once they are members.

Losing access to important markets or having higher trading barriers would not have good economic consequences, so they decide to harmonize climate policies with their trading partners in the club.

Steady State

Since we are dealing with a game of strategic complements, we know it is well-behaved. We summarize below the theoretical equilibrium predictions for the first threshold (proposed by Morris 2000). The second threshold, which we propose, is only tested through simulations.[9] We do this in section 4 and compare its results with those from the first one. To the best of our knowledge there are no formal results for this kind of threshold:

Proposition 1 (Jackson and Zenou 2015). *Assume a network* (N, $\overline{\mathbf{g}}$) *and a game as the one previously described. An equilibrium where action 1 is played by* $R \subset N$ *players and action 0 is played by* R^C *players exists if and only if* R *is q-cohesive and* R^C *is* $(1-q)$*-cohesive.*

This proposition tells us that depending on the proportion of players in each set, different combinations of actions will be taken throughout the network. This allows for "co-existent equilibria" in which some players choose action 0 while the remaining players choose action 1.

If there are some players in R who, by acting as the initial seeds, make all players switch from taking action 0 to 1 under a BR, we say that there was a *contagion* from R. To keep consistency with the definitions we use in this work we will refer to this as a complete harmonization by the players in the network. A set R is defined as *uniformly no more than p-cohesive* if R has no nonempty subset that is more than p-cohesive.

Proposition 2 (Jackson and Zenou 2015). *Assume a network* (N, $\overline{\mathbf{g}}$) *and a game as the one previously described. There will be contagion from R if and only if* R^C *is uniformly less than* $(1-q)$*-cohesive.*

Notes

1) The technical model is provided in the appendix for the reader who may be interested to look at it in more detail.
2) For example, EU members pay fines based on their GDP, how many votes they have on the EU council and their solvency (e.g. in 2014 Italy was fined with €40 million for illegal waste dumping.)
3) The connection between welfare effects of trade liberalization in the presence of environmental problems was studied in Baumol (1971) and Copeland (1994), while the effects that trade liberalization has on environmental quality is analyzed in Lopez (1994) and Copeland and Taylor (2013). A great survey on the literature on trade and environment is Copeland and Taylor (2004).
4) The linkage between network economics and the environment is thoroughly described in Currarini et al. (2016). Gallego and Zofio (2018) rely on transport networks to analyze the relationship between trade openness and the spatial location of economic activity.
5) Topics range from the diffusion of strategic behavior (Jackson and Yariv 2007), technology adoption (Bandiera and Rasul 2006) and innovations (Montanari and Saberi 2010) to microfinance (Banerjee et al. 2013). Good surveys on the topic are Jackson and Yariv (2011) and Lamberson (2016).
6) This measure gives a greater score to nodes that have a higher (weighted) degree, are connected to other nodes with a high degree or both.
7) By running simulations with different parameter values, we are able to understand when co-existent equilibria (proposition 1 in the appendix) occurs and when there is complete harmonization (proposition 2 in the appendix). For this threshold, any η value below 1.1 will always be a co-existent equilibrium.
8) Authors such as Granovetter (1978), Morris (2000), Watts (2002) and Jackson and Yariv (2007) deal also with this approach, although in different contexts than ours.
9) Our use of simulations is justified by the necessity pointed out in Lamberson (2016) who argues that to understand how the structure of networks influences diffusion, it is necessary to rely on different methods of analyses.

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