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Network-Based Analysis of EU Emissions Trading Scheme

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Abstract

The European Union Emissions Trading Scheme (EU ETS) has been instrumental in mitigating carbon dioxide (CO2) emissions across Europe since its initiation on January 1, 2005. CO2 has emerged as a traded commodity in the EU ETS, governed by market fundamentals similar to those in other global commodity markets. The interplay of supply and demand, driven by the allocation of allowances, plays thus a crucial role. Here, using real data, we developed networks of EU ETS to model exchanges of allowances between EU countries. Our results provide new insights into the topological structure of trading from 2005-2020. Combining the results from centrality measures, clustering and modularity, the EU ETS networks can be seen in the transition from a structure with few clusters to a structure characterized by numerous clusters organized around new nodes with acquired centrality.

keywords: Emissions Trading Scheme, Network Analysis, CO2 Trading, Allocation of Allowences

1 Introduction

The European Union Emissions Trading Scheme (EU ETS) has been instrumental in mitigating carbon dioxide (CO2) emissions across Europe since its initiation on January 1, 2005. At its launch, the region accounted for approximately 17% of global energy-related CO2 emissions, prompting the implementation of a quantitative emissions cap and the creation of a market-driven price for CO2 allowances among virtually all EU stationery, industrial and electricity-generating installations. Although the EU ETS operates independently, its primary aim is to ensure compliance with Kyoto Protocol's emissions targets.

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1.1 EU ETS political and institutional background

Within the EU ETS framework, CO_2 units traded by energy-intensive plants are known as European Union Allowances (EUAs). This trading scheme has succeeded in generating a price signal via the trading price for EUAs that reflects the limited capacity of the atmosphere to absorb greenhouse gas emissions. After entering the EU ETS, each member state is required to develop a National Allocation Plan (NAP) to determine the total EUAs and their distribution, which forms the foundation for market supply and demand dynamics. Approval of the NAP by the European Commission and the establishment of electronic registries are essential for installations to receive allowances and participate in the market. The EU ETS is a "bottom-up" scheme, with each member state making the allocations, establishing and operating the registry, and enforcing compliance. As member states attempt to meet their own self-interest, they influence price by shaping the quantity and timing of allowances coming to market (1).

Overallocation, supply and demand in the EUAs market

The effectiveness of the EU ETS may be compromised when too many allowances are distributed, rendering the emissions cap non-binding and failing to reduce CO_2 emissions. This overallocation results in "long" and "short" positions, where long positions indicate a surplus of allowances relative to emissions, and short positions indicate a deficit. As a consequence, the supply and demand dynamics in the EUA market are influenced by these positions: long-position installations become potential sellers, while short-position installations become potential buyers. CO_2 has emerged as a traded commodity in the EU ETS, governed by market fundamentals similar to those in other global commodity markets. The interplay of supply and demand, driven by the allocation of allowances, plays thus a crucial role in determining the flow of EUAs.

Third parties and EU ETS out-border expansion

Installations, i.e. regular allowance holders of the EU ETS market, need to buy or sell allowances based on their allocation, emissions, and abatement options. While emission installations are primary market participants, third-party non-regulated entities can also trade without restrictions. Since 2005, the EUA market has evolved with intermediaries like brokers and exchanges facilitating bilateral trades and futures trading gaining momentum. This has led to increased market participation for both compliance-driven and speculative purposes. In addition, from 2008, the EU ETS expanded beyond EU borders, with installations competing for Kyoto Protocol's CDM and JI credits[1] with global governments and private companies. This out-border expansion has extended the ETS market to include non-EU governments and entities, broadening its scope and impact (1).

EU ETS CO2 abatement potential

[1] Known also as Certified Emission Reductions (CERs) and Emission Reduction Units (ERUs), respectively.

Persistently high prices for EUAs, in a market with ample liquidity, suggest a strong potential for CO2 abatement. Power companies are likely to incorporate EUA prices into their dispatch decisions, shifting generation to plants with lower emissions. This trend has been evident among most installations participating in the EU ETS since its pilot phase.

The EU ETS has thus successfully imposed a price on CO2 emissions, achieving significant reductions in emissions, establishing a multilateral trading system among nations, and influencing global climate policy. While similar to other cap-and-trade systems, the EU ETS uniquely addresses CO2 abatement, a challenge distinct from conventional pollutants; in this respect, the prevailing view in the literature is that CO2 abatement, aside from switching from coal to natural gas in power generation, is limited to reducing overall output (2).

Outlook beyond Phase III and IV

Emissions trading has continued beyond the Kyoto Protocol, continuing through Phase III (2015-2020). It is to be expected that EU emission trading scheme will continue in Phase IV and more due to several factors: *i)* strong political commitment within the EU; *ii)* established administrative bureaucracies in each member state, fostering an interest in maintaining the system; *iii)* financial intermediaries profiting from the EU ETS; iv) considerable support from industry; v) strategic necessity due to the EU's vulnerability to energy supply interruptions from the Middle East (oil) and Russia (gas), underscoring the need to reduce dependence on imported fossil fuels. The CO2 emissions trading system has required power generation companies to internalize their emissions costs, making heavy polluters more expensive than their lighter counterparts. Despite the initial shocks to the power industry and increased costs for generation companies, many generators have seen profit increases mainly because lower emissions have enhanced benefits in the face of rising power prices. Moreover, literature suggests that the EU ETS impacts the valuation of power generation firms, as carbon emission allowances are viewed as a benchmark for investors (3).

1.2 Motivations behind the use of Network Theory

Network analysis is crucial for examining complex systems, which consist of elementary units (nodes) with interdependencies (links) that naturally suggest a network representation. Our EU ETS reference network involves tangible exchanges of allowance units between EU countries, regulated and occurring daily. This system's historical data allows for an extended temporal study, facilitating observations of exchange evolution over time (references (4) and (5)).

In this context, national registries (i.e., countries) can be topologically represented as nodes. Similarly, a different network can be defined where nodes correspond to accounts. In each case, either countries or accounts exchange allowances. Therefore, the transactions between these entities (countries or accounts) define the links within each of these networks. In both networks, edge weights represent the number of allowances being exchanged. By applying statistical tools from Network Theory, networks of ETS subjects (national registries and accounts) have been induced and the computation and interpretation of relevant statistical indicators used in Network Theory will be discussed.

1.3 Objectives and research questions

Despite the expanding body of literature on this system, analyses of transactions and market structure within the EU ETS remain limited. Flori and Borghesi's (6) work addresses this lacuna by extending temporal analysis to encompass Phases I and II, incorporating additional account types, and aggregating data at the national registry level to analyse the role of single Member States. Utilizing Network Theory tools, they provide a novel perspective on the EU ETS. Their analysis highlights the centrality of specific nodes (France, Germany, Great Britain, Denmark, and Netherlands) and the migration patterns of accounts towards these nodes, also observing increased homogeneity and diversification of trading partners as the EU ETS evolves from Phase I to Phase II.

Building upon Flori and Borghesi's recommendations, the present study aims to incorporate their findings from Phases I and II with more recent data from Phase III (2012-2020), addressing three main research questions:

1. How can Network Theory be applied to study the network of national registries at the installation level, providing new insights into the structure of permit trading from 2005-2020?
2. How can Network Theory tools be used to analyse the distributions of accounts in time and space (regions)?
3. What systematic information can be obtained by identifying clusters of similar partners within these networks from 2005-2020?

Due to data scarcity from active installations and institutions in the EU ETS, no analyses for Phase IV (2020-2030) is proposed.

2 Data Description

2.1 Sources and overview of the database

The European Union Transaction Log (EUTL) functions as the principal reporting instrument within the framework of the European Emissions Trading System, since it provides comprehensive insights into the compliance status of each installation encompassed by the system.

In May 2023, Jan Abrell (7) undertook the construction of a database aimed at reconstructing the EUTL[2]. The primary objective of Abrell's project is to offer a structured framework for assessing EUTL information and at this scope he interlinked various pieces of information from the EUTL organizing the data within a relational database model. For

[2]https://www.euets.info./

a more detailed, comprehensive and clear analysis, Abrell dataset has been downloaded and utilized directly from the source data files, instead on working with the original EUTL database.

The European Union Transaction Log (EUTL)

Annually, each installation is mandated to surrender allowances equivalent to, at a minimum, its verified emissions from the preceding year to the regulatory authority. These allowances are acquired either through a process of free allocation or by purchasing them on the allowances market.

To make the trading of allowances possible, a system to account and transfer allowances between different actors is necessary, and in the case of the EU ETS, this role is fulfilled by the EUTL. The EU ETS introduces several key "building blocks" (7) in conjunction with the EUTL: *(i)* **Installations**, regarded as regulated entities, bear the obligation to surrender allowances for verified emissions and engage in emission accounting; *(ii)* **Transactions** involve the transfer of allowances among actors within the EU ETS and are conducted at the level of *(iii)* **Accounts**. Following, some information pertaining to each constituent of the European Union Transaction Log (EUTL) that is of interest for the scope of the present research:

1. **Installations**: each installation is uniquely identifiable by a specific "id", and additional details comprise the registry in which the installation is registered. It is noteworthy that, for stationary installations, the national registry aligns with the country of location; in other words, an installation's registry coincides with the country of origin of the specific installation.
2. **Transactions**: they occur between two accounts. In addition to details about the involved accounts and unit types, the dataset includes the transaction date and the volume of allowances transferred.
3. **Accounts**: every participant in the European Union Emissions Trading System is represented by an account. Similar to installations, each account is identifiable by a unique account "id" and the account dataset further reveals information such as opening/closing dates.

The EUTL furnishes an extensive array of information pertaining to the European Union Emissions Trading System, the world's largest carbon market. This encompasses data on compliance behaviour, details on surrendered units and the transfer of allowances among participants.

2.2 Raw data organization: a registry-based approach

The following variables were extracted from the EU ETS database for constructing the registry-level network: *accounts_id*, *registry_id*, *date*, *sourceid*, *destid*, *amount*, and *installation_id*.

From the data we induced: *1)* a primary network wherein nodes correspond to national registries, links represent transactions occurring between two **accounts belonging to**

any entity (installations and non-regulated entities), and the weight of each link corresponds to the number of allowances transferred; *2)* a secondary network wherein nodes correspond to national registries, links represent transactions occurring between two **accounts belonging exclusively to installation entities**, and the weight of each link corresponds to the number of allowances transferred. Since the two induced networks have national registries as nodes rather than accounts, it is necessary to aggregate the data at the registry level.

3 Methodology

In recent years, methodologies related to the study of complex systems have been applied across various domains for the analysis of a system. The fundamental approach in these studies involves representing a system as a graph or network, denoted as $G=(V,E)$, where V is the set of nodes representing agents and E is the set of edges standing for the links (e.g., economic or physical, directed or undirected) between pairs of nodes. Specifically, in a directed network, if i and j are nodes, and there is an edge from i (source) to j (target), this is represented as the pair $(i, j) \in E$, and i is considered a neighbour of j. Consequently, the network is characterized by an adjacency matrix A, where $Aij=0$ if there is no edge from i to j, and $Aij=1$ if such an edge exists. Moreover, a weighted version (w) of the adjacency matrix assigns a weight to each edge ($Aij=w$). Alternatively, in an undirected network, if i and j are nodes connected by an edge, this is still represented as the pair $(i, j) \in E$, and i and j are considered adjacent. In this second case, the adjacency matrix A has $Aij=1$ if there is an edge between nodes i and j, and $Aij=0$ if no such edge exists; the adjacency matrix is thus symmetric, i.e., $Aij=Aji$, indicating that the order of nodes in the pair does not affect the edge's existence.

Formally, within the context of the first research question, each node i corresponds to a registry. The considered registries exclusively pertain to regulated installations, excluding those registries where non-regulated entities (i.e., non-regulated companies, individuals, financial institutions and administrative regulatory authorities) have been registered throughout 2005-2020. To gain deeper topological insights into the structure of the EU ETS network and identify potential differences between the two versions, a parallel approach is adopted, involving both a directed and undirected representation of the network. In both network representations, an edge (i,j) is weighted based on the amount of transferred allowances from the transferring registry i to the acquiring registry j.

Network Centrality Metrics to answer the first research question

To examine how the overall network structure has evolved over the three Phases, a sequence of networks is constructed, one for each year from 2005 to 2020, aggregating transactions on a yearly basis. Finally, the decision to utilize a registry-level representation aligns with the original structure of the EU ETS established from national registries.

Network measures for the Weighted Directed Graph

Given a certain network, one may want to disentangle the importance of the nodes by providing a ranking according to measures of centrality (6). In our context, more centrally positioned nodes represent national registries that play a more active role in the EU ETS; in this respect, it can be relevant to distinguish between a network where connections are evenly distributed among pairs of nodes and the emergence of a polarized network characterized by a core of well-connected nodes surrounded by a cloud of peripheral nodes.

Within the framework of a directed graph, it has been chosen to focus on the following network measures: In-Out Degree, In-Out Strength, PageRank, Betweenness, In-Out Closeness, Hubs Centrality. In-Degree quantifies the number of incoming transactions for a registry (node), indicating the extent to which other nodes direct allowances toward it. Out-Degree measures the sum of outgoing transactions from a registry, highlighting its role in distributing weighted information (allowances) to other nodes. The In- or Out-Strength of a node quantifies the volume of In- or Out-flows directed towards or emanating from that particular node; this information proves valuable in delineating the level of activity of registries in the market, spotlighting those nodes that are more actively engaged in either acquiring or transferring setups. Eigenvector centrality measures rank registries by considering not only their incoming links but also the sources of these flows, thereby incorporating the system's structure into the measurement of centrality scores; in this context, PageRank has been leveraged to assess which nodes have exhibited greater centrality. Betweenness quantifies the node's importance in facilitating the flow of information between other nodes, considering both shortest and, as in our study, longest paths. In-Closeness based again on longest paths measures how quickly a node can receive information from other nodes, being useful for us for identifying registries that are central to allowances reception. On the other hand, Out-Closeness measures how quickly a node can reach other nodes, considering longest paths. Finally, Hubs Centrality emphasizes nodes with high in-degree and out-degree combined, highlighting then their pivotal role in attracting or distributing significant connections.

Network measures for the Weighted Undirected Graph

Directed and undirected graphs' distinction represents a fundamental dichotomy with significant implications for modelling and understanding complex systems. The current study, aspiring to offer insights into community dynamics, dependency relationships, directionality of allowances transfers and hierarchical structure among EU States within the ETS context, has opted to conduct a dual analysis of the network conceived both as directed and undirected graph.

Here listed, the typical centrality measures calculated for the network conceived as an undirected graph: Degree, PageRank, Eigenvector, Betweenness and Closeness. Not much different from PageRank, with the only exception that this metric is not employable with digraphs (i.e., directed), Eigenvector Centrality is a measure of node importance that takes into account both the quantity and quality of connections by considering the centrality of neighbouring nodes.

Size, Average Total Flow and Diameter for the Weighted Undirected Graph

In the framework of an undirected graph, some statistics have been computed in order to provide additional insights into the characteristics of the EU ETS network and its evolution in terms of size and degree of concentration in allowances exchanges over time. The network topology is still conceptualized with registries as nodes, where the registration exclusively refers to accounts opened by the installation agents' subset. Here the three metrics calculated: Size, Average Total Flow and Diameter. The Size, i.e. the total number of nodes in a certain point in time, is a basic metric that provides insight into the scale and complexity of a network. The Average Total Flow can also serve as a valuable centrality measure, since it goes beyond basic connectivity and provides information about the average strength of interactions across all registries. Thirdly, the Diameter can be a good indicator of the network overall efficiency and connectivity: by revealing the longest shortest path between any pair of registries, it offers insights into the network's accessibility and potential bottlenecks.

For the sake of simplicity, values for these statistics have been computed for three reference years: 2007, 2012, and 2020, corresponding, respectively, to the concluding years of each EU ETS Phase. In this way, by selecting these three years as a sample, a precise numerical snapshot of the network's status at the conclusion of each phase is obtained.

Account-level Distributions to answer the second research question

The approach used in this second stage of the research has been to consider all accounts registered in national registries by any type of agent, both installations and any other unregulated one. This more general perspective allowed to detect the role and calibre of national registries in the network accounting also for their participation in the flow of permits between different types of agents.

Also in this case, a parallel analysis has been undertaken for both a directed and undirected graph. National registries are considered here aggregated in their roles as Acquiring and/or Transferring Registries, a methodological choice made for both simplicity of calculation in order to solely understand the general "activity" level of individual nodes/registries within the network. This way, it is possible to discern which registries have been more or less active during the first three Phases as a source and destination country for permits when any type of agent is involved.

Size and Average Total Flow at account-level in the Undirected Network

Remaining within the framework of the network conceived as an undirected graph, the Size and Average Total Flow of the network have been calculated in a topology such that nodes correspond to accounts rather than national registries, and links correspond to transactions between pairs of accounts.
Differently from the study on the directed graph, here a parallel analysis is conducted, by generating firstly calculations for accounts owned exclusively by installations and secondly for accounts owned by any type of agent, whether regulated or not. This comparison can

be useful for understanding the calibre of the network when all its agents are taken into account, and in parallel, investigating the relative weight played by installations compared to all subjects active in the system. This last aspect may help deduce the extent to which the EU ETS system is effectively regulated, involving thus entities that emit and exchange permits for compliance purposes, and conversely how much it is dominated by non-regulated parties with intentions other than compliance (primarily monetary gain).

Community Detection on Minimum Spanning Trees to answer the third research question

To answer this third question, the topological framework remains the one of the network conceived as an undirected graph. For the scope of this step of the research, nodes have been referred to national registries at the only installation level, thus considering exclusively the subset of permits owned by and exchanged between regulated entities. Annual graphs from 2005 to 2020 have been generated to detect states of the network of particular interest for certain years (or Phases) in comparison to others.

Initially, the Prim's algorithm has been applied to visualize the network structure through the Minimum Spanning Tree (MST). MST serves various purposes in Network Theory, including cluster analysis to identify groups of closely related nodes, aiding in the identification of cohesive substructures. Consequently, to extract national registry communities from each year (throughout 2005 and 2020) and visualize them easily on the tree structure obtained through the aforementioned algorithm, a second community detection algorithm has been employed, i.e., the Louvain algorithm.

Among community detection objectives, the first and most important one is identifying communities that maximize modularity, a metric that quantifies the strength of the community structure within a graph, revealing subgroups of nodes with dense internal connections and sparser connections between groups. This method thus helped extracting cohesive clusters of registries that exhibit strong internal connectivity and which foster more efficient permits trade within the EU ETS community, with consequent insights into the structural organization of the network and patterns of relationships with functional or thematic significance.

The Louvain algorithm (8) is utilized for its simplicity in visualizing the network structure. Based on the principle of modularity maximization, the algorithm states that two nodes belong to the same community if the link between them is stronger than would be expected in the case of a random network. Thus, two nodes belonging to the same community are supposed to engage in transactions with substantial weight.

Three descriptive statistics able to provide an intuitive idea of how the communities have evolved over time have been calculated: *i)* the number of clusters at each year; *ii)* the size of the largest cluster at each year; *iii)* the modularity value at each year, denoted as Q, which provides information about the quality of the network's divisibility into clusters. A network with high modularity will thus indicate that the division into clusters is significant, and nodes within the clusters are strongly interconnected, while connections between clusters are relatively less frequent. From a practical standpoint and in the specific context of our EU ETS network, high modularity could indicate the presence of functionally distinct registry communities or groups of registries with very similar characteristics; by contrast, low modularity might suggest that the EU ETS network is more homogeneous or less prone to a clear subdivision into groups of national registries.

For the sake of analytical simplicity, the values of the three statistics at each year (from 2005 to 2020) have been grouped into a single table, which facilitates a straightforward numerical overview of the clustered network's evolution over time. Additionally, three graphs have been created to illustrate the same trends through three distinct curves, one for each descriptive statistic. (Paolella, 2024).

4 Results and Discussion

Hubs and marginal nodes: the role of trading platforms and financial markets

The PageRank descriptive statistics suggested them that numerous registries have played only a marginal role over time, with especially Denmark (DK), France (FR), Germany (DE), Great Britain (GB) and the Netherlands (NL) being more active during the sample period. Notably, DE and GB exhibit distinctive patterns among them all and appear to lack direct peers in terms of PageRank centrality scores. These two countries host indeed key trading platforms, namely the European Energy Exchange (EEX) in Leipzig and the Intercontinental Exchange (ICE) in London, which definitely contribute to their role as outliers. This implies that the trade of allowances may be influenced by factors beyond simple compliance purposes, and the presence of trading platforms is instrumental in helping these registries to offer more favourable conditions for trading allowances and, consequently, for locating accounts. This initial observation aligns with the results obtained in the present research. With a network conceptualized as directed and weighted, and focused solely on installations, various centrality measures, including PageRank, Betweenness and Hubs among others, were computed. From the distribution of PageRank centrality, it was observed that in the early stages of the EU ETS program, countries such as AT, BE, DE, ES, FR, GB, PT and SE constituted a fundamental and connected core, acting as crucial nodes and mutually reinforcing their centrality in the network (Figure 1). Similarly, by computing Betweenness centrality in its longest-path version, it was again observed that a higher degree of importance was associated with a few countries compared to all others, specifically DE, EE, GB, IT and NL, with GB and DE consistently present throughout the 2005-2012 time-frame; IT also appeared as a crucial intermediary in specific years, especially in 2012 and 2017. A few key nodes, primarily DE and GB, played thus a vital role in connecting the entire network during Phases I and II, but also during the subsequent third Phase (Figure 2).

Finally, by observing the outcomes of the Hubs function, it was still evident the predominant role played in specific years by DE, especially towards the end of the first phase and the beginning of the second, with a peak in 2016; ES at the beginning of the program with two significant peaks in 2012 and 2018; and finally, IT towards the end of the second phase and the beginning of the third (Figure 3).

The results obtained by Flori and Borghesi are confirmed in our analysis even when considering the network in its weighted but undirected version.
Having induced a **directed** and **weighted** network of countries, focused solely on installations, various centrality measures, including PageRank, Betweenness and Hubs among others, were computed. The distribution of PageRank centrality (Figure 1) shows that in the early stages of the EU ETS program, countries such as AT, BE, DE, ES, FR, GB, PT and SE constituted a fundamental and connected core, acting as crucial nodes and mutually reinforcing their centrality in the network.

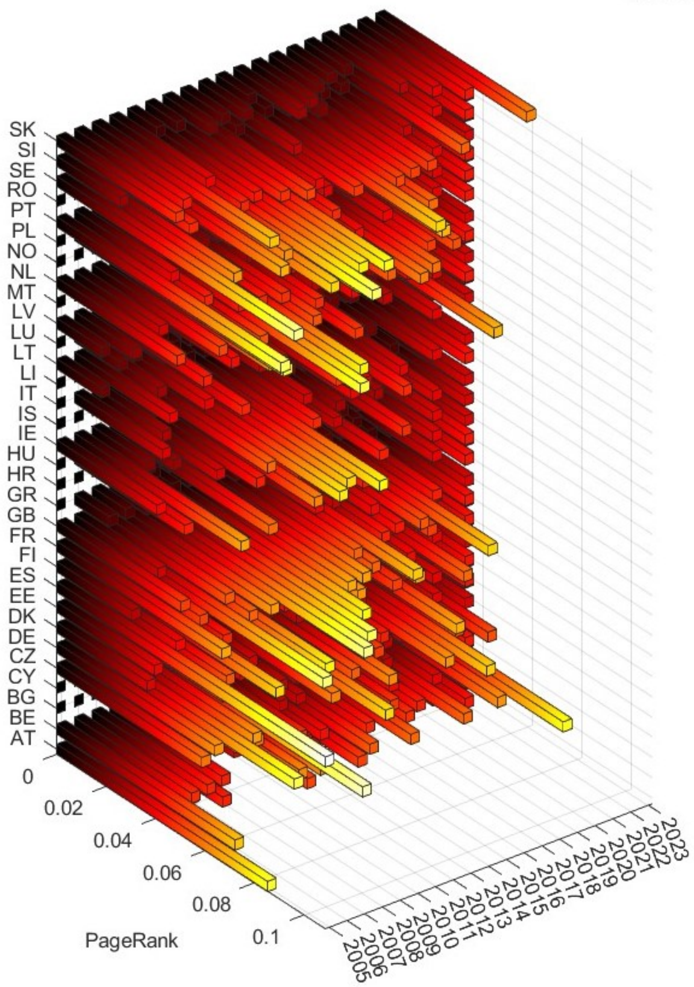

Figure 1: Distribution of PageRank values

Similarly, by computing Betweenness centrality in its longest-path version, Figure 2) shows that a higher degree of importance is associated with a few countries compared to all others, specifically DE, EE, GB, IT and NL, with GB and DE consistently present throughout the 2005-2012 time-frame; IT also appeared as a crucial intermediary in specific years, especially in 2012 and 2017. A few key nodes, primarily DE and GB, played thus a vital role in connecting the entire network during Phases I and II, but also during the subsequent third Phase.
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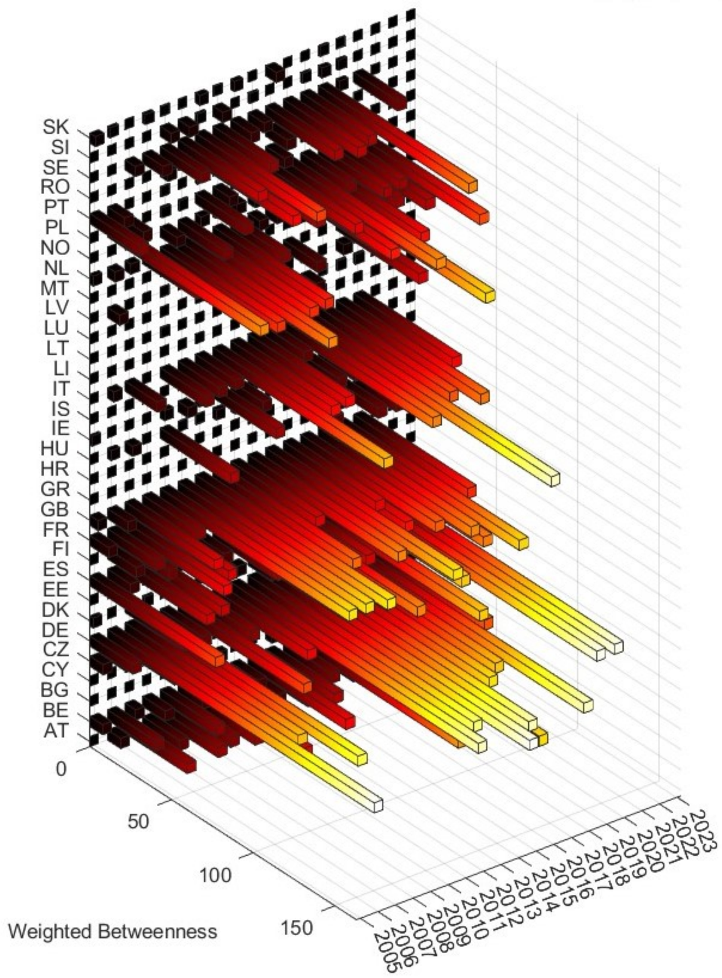

Figure 2: Distribution of Betweenness centrality

Overtime network depolarization: risk diversification and increased membership

If we now turn our attention to the Assortativity coefficient and its evolution over time, a clear decreasing trend is evident. Interestingly, following the collapse of the capital markets (2007-2008), the network exhibited a slightly disassortative pattern, indicating that nodes tended to connect (i.e., exchange allowances) with more dissimilar counterparts. Possible explanations for this trend may involve, on one hand, risk diversification and, on the other hand, the expansion of the EU ETS network, which could have facilitated the exploration of new markets and increased exchanges across a broader array of counterparts.

As for the distribution of PageRank in the network in its undirected version, we observed that from 2005 to 2012, centrality was distributed among few highly central hubs and many peripheral nodes of low importance; then, the network became drastically more connected and denser during the transition from 2008 to 2009 (between Phase I and II), remaining so until 2013. From that year onwards the distribution of node centrality became more homogeneous, a scenario even more pronounced until the end of Phase III. In general, a progressive network centrality homogenization, staying for new nodes that

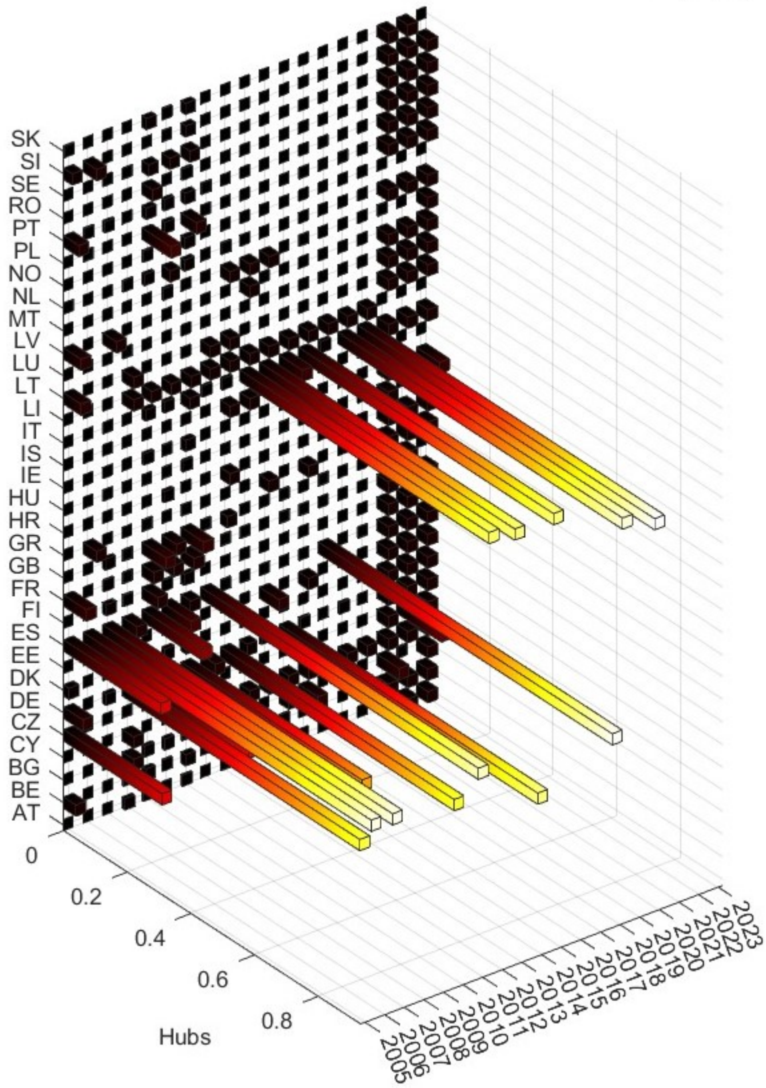

Figure 3: Distribution of Hubs

increase in size and gain centrality over time, indicates that the allowance exchanges cease to be dominated by a few core registries and more countries become active players in EU ETS trade throughout years.

Also for this second finding, our results mirror those obtained by Flori and Borghesi: the distribution of In-Closeness centrality confirmed this centrality "dispersion" overtime as presented in Figure 4: countries become, on average, less quickly accessible in terms of incoming connections from all other nodes over the years, with a more evenly distributed level of centrality among them all. In the years between 2009 and 2012, some countries, especially SE, NL and GB, show high values of In-Closeness centrality, ending up from 2013 onwards in a situation where no receiving registry is particularly more central than others.

Size and Diameter as a way to explain disassortativity

Even from Size and Diameter metrics it is possible to infer that: the Size curve showed

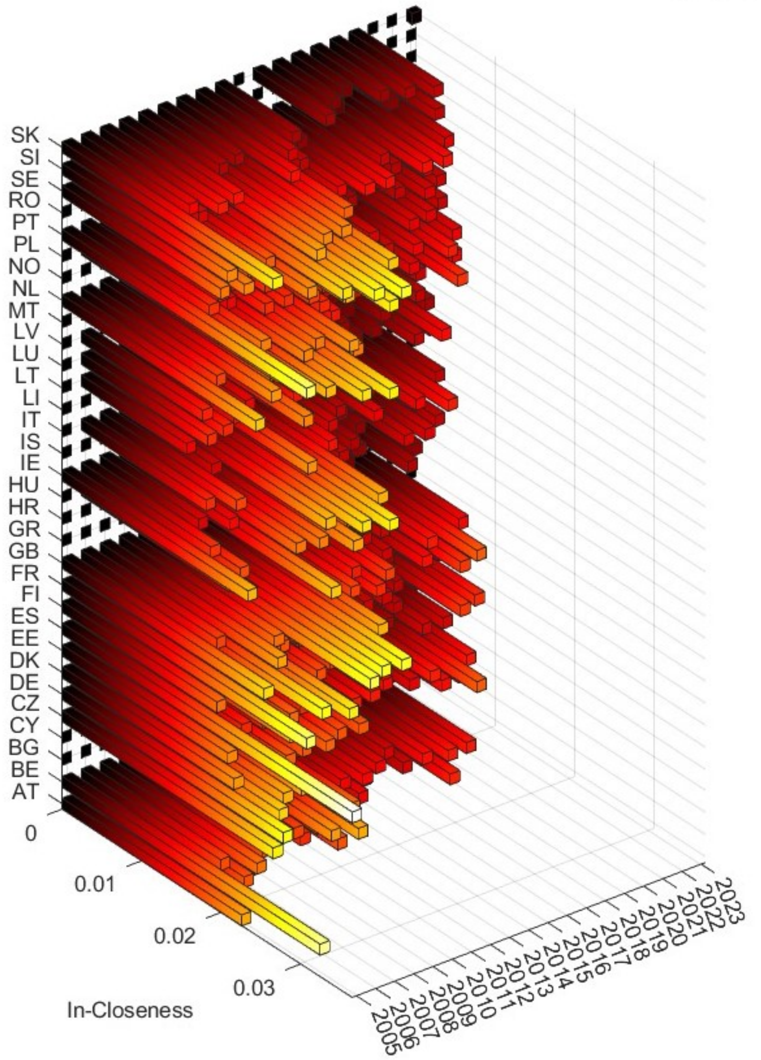

Figure 4: Distribution of In-Closeness centrality

an overall increase since the program's first Phase, experiencing a rapid surge at the onset of Phase II, with the trend remaining relatively stable between 2009 and 2020, except for a small dip between 2012 and 2013 (Figure 5). The system expansion can be attributed to the success of the EU ETS program itself since its first pilot phase: the absence of significant declines, even during Phase III, suggests the program's effectiveness, with national registries actively participating and installations consistently registering throughout all years.

As for the Diameter, networks with smaller diameters are generally more efficient, interconnected and less dispersed. In our case, it has generally increased over time, remaining at very low levels during the first two Phases of the program and starting to grow slightly during the third Phase, signifying thus a network's dispersion over time (Figure 6). Secondly, a larger diameter may indicate greater variety of paths between nodes, contributing to the diversity of relationships; then, the increasing curve confirms that registries have gradually started to engage in permit exchanges with nodes characterized by different levels of centrality. Similarly, the up-warding curve confirms the increased network size

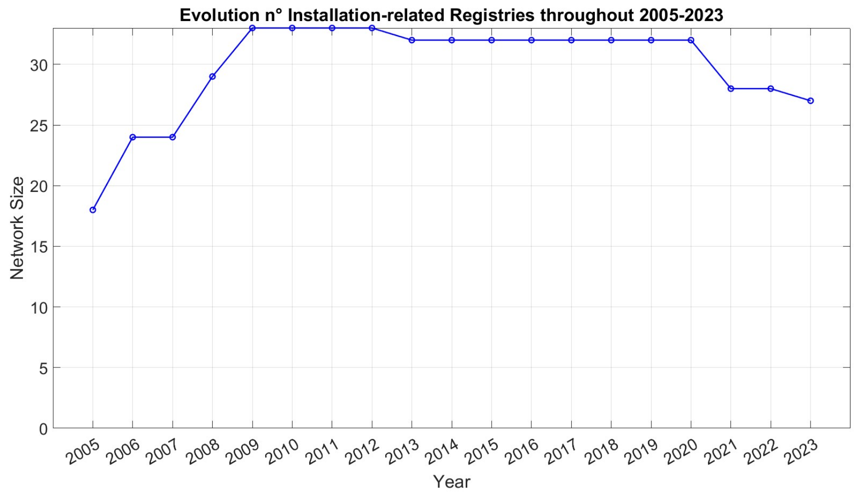

Figure 5: Evolution of the size of networks

resulting from the entry of new Member Countries into the Union, and contextually, of new national registries into the EU ETS system.

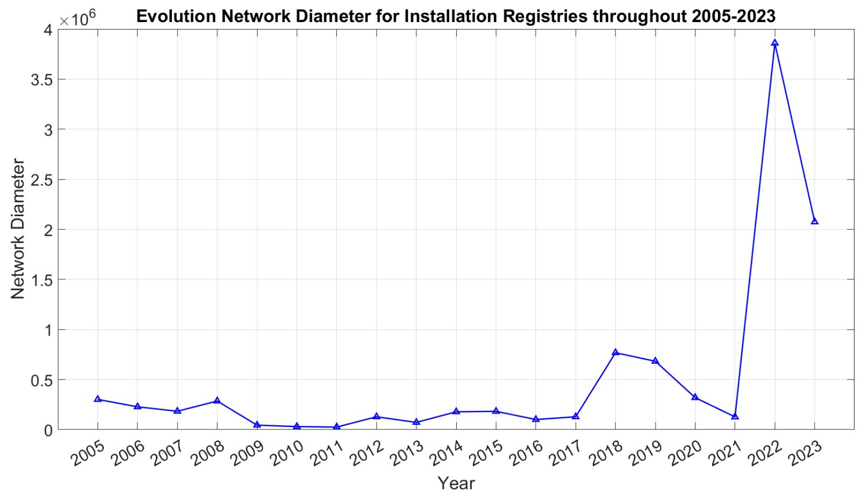

Figure 6: Evolution of the Diameters

5 Concluding remarks

The reliability of our results been then confirmed through comparison with those by Flori and Borghesi, the objective of the incoming paragraph is to advance new hypotheses and interpretations concerning our three specific research questions. From certain perspectives, some of them will reiterate, those already advanced by the two authors, while others will be new, aiming at representing additional points of reflection in the EU ETS literature.

Final considerations on research question 1: Is the EU ETS a successful project?

From the study of the centrality measures, it emerged that in Phase I but even more so in Phase II there is an increase in the overall activity level within the network, i.e., in the amount of allowances' transactions between countries both inbound and outbound, from Acquiring and Transferring countries respectively. It could be presumed that **higher activity levels are linked to higher emission levels**. Hence, between 2005 and 2012, but especially between 2009 and 2012, installations registered in European national registries may have recorded more accounts through which exchanging permits in response to higher CO2 emissions.

A higher level of exchanges during Phase II presumes however that, along this time frame, there has been greater disparity between registries with a surplus and registries with a deficit of allowances, compared to other years.

While it is not possible for us to put forth any hypotheses regarding the compliance of agents in the EU ETS system, as compliance data are not subject of this study, we can presume that, as Phase III progressed, installations (and therefore the countries where they are registered) have become progressively more "self-sufficient" and have increasingly relied on their national allowance portfolios for being compliant, without doing so on prior permit exchanges with installations registered elsewhere.

This reduction in exchanges may have been possible thanks to an increase in the total amount of allowance units distributed by European institutions to the national registries at the beginning of each legal year. However, a second interpretation for this decreasing trade trend is that **installations may have decreased their allowances "import/export" activity due to reduced emissions on their side with the beginning of Phase III**, which thus would explain the lower need for them to resort to external permit transfers to achieve annual compliance and their increased portfolio self-sufficiency.

The centrality statistics calculated also revealed us that a more polarized structure is specific to Phase I and to the early years of Phase II.
The depolarization of the EU ETS system over the years may be due to a dispersion of power among EU countries following the introduction of incentives apt to attract installations (fiscal, monetary, and financial) by new other countries respect to the central ones dominating the early phases (like DE, GB or FR). Next, this trend may be the result of the EU ETS network expansion itself, being the enlargement of the EU membership the cause of new states entrance in the system, and thus, of the centrality dispersion. Finally, this downward trend could be the consequence of an increasing tendency by installations to risk-diversify their permits exchanges with other ones registered in national platforms characterized by different level of centrality.

It is interesting to note how, following a perspective already outlined by Flori and Borghesi as in reference (6), there is a common foundation of efficacy about the EU ETS project underlying these hypotheses. Indeed:

- The potential increase in the number of allowances distributed to national registries portfolios at the beginning of each legal year by the European Union could certainly be justified by a higher demand from the registries to ensure compliance of their installations due to their increased emissions. However, concurrently, an augmenting allocation of funds in the form of more emission certificates to emitting entities could be interpreted as a major commitment by European policymakers and decision-makers to ensure their compliance, and thus an increased focus on EU energy sustainability matters over the years.

- The effectiveness of the EU ETS system in encouraging emitting entities to progressively reduce emission levels over the three phases would be demonstrated by the second hypothesis. This outcome would align with the original purpose of the EU ETS project since its conception: reducing emissions within the borders of the Union and thereby contributing to international environmental and energy sustainability goals.
- The fact that more and more nodes have gained a prominent position in permit transactions over time, ceasing to be marginal nodes and becoming equally significant hubs in the allowances' trade, would indicate that these registries have realized the gains of being active nodes in the network, being then more prompt to host a higher number of installations.
- The entry of new nodes into the network in the form of new coming national registries upon the acquisition of the EU membership would still align with confirming the success of the EU ETS project.

Final considerations on research question 2: Increased network polarization and non-formally regulated agents' influence

In the attempt to answer to research question 2, it has been decided to adopt a broader perspective that incorporates the registration of non-formally regulated entities into the definition of "registries". This comprehensive approach yielded us a more accurate portrayal of the actual centrality of registries within the EU ETS and their geographic distribution, encompassing both installations and non-installations registering any type of accounts.

This second centrality analysis conducted on both the directed and undirected network topology revealed results that deviate significantly from those obtained while addressing research question 1. In particular, the second "main trend" identified in the previous study addressing research question 1 is not confirmed here, but it is practically the opposite. As evident from the generated histogram plots (Figure 7), the centrality distribution among nodes becomes progressively more heterogeneous and polarized over time: contrary to the study at the sole installation level, when considering registries as platforms for any account owned by any kind of agent, a progressive polarization of the system is revealed, rather than a gradual homogenization of the nodes' overall centrality.

This second scenario leads us to new important considerations about the relative influence held by different players. If over the years the hub of DE, FR, GB, NL and IT has become more structured, gradually marginalizing the remaining nodes to minimal centrality positions, it is because in these pivotal countries the role played by non-formally regulated entities (banks, individual non-emitting entities, and in general any third-party agents

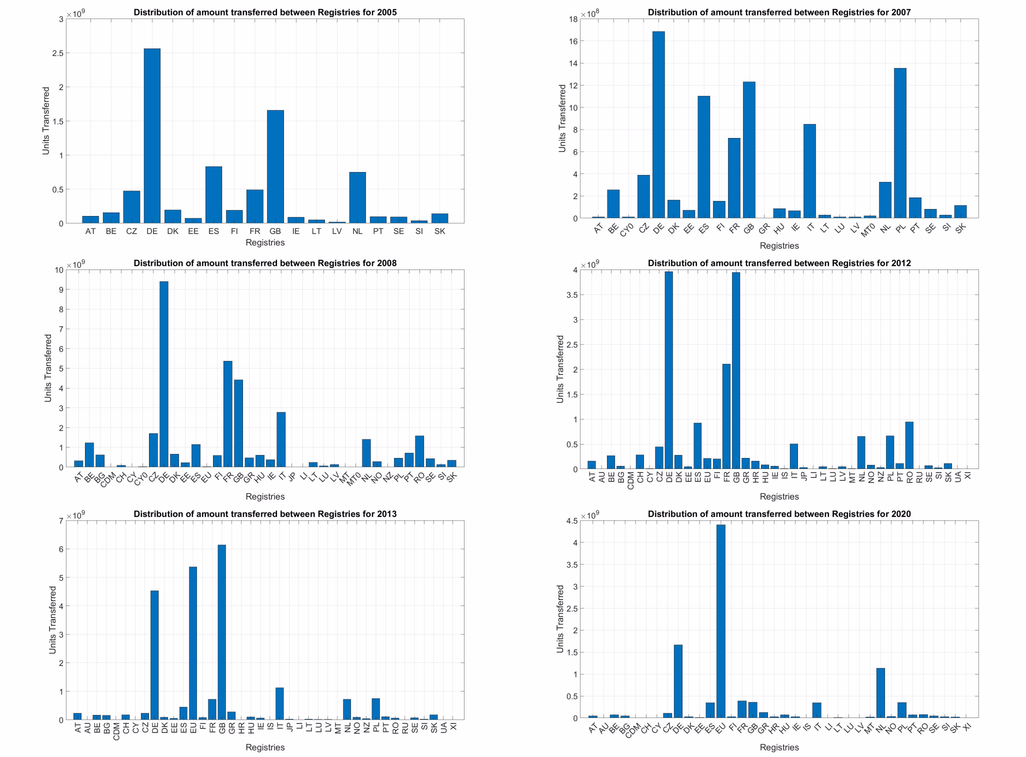

Figure 7: Distribution of amounts transferred between Registries

other than installations engaged in permit exchanges not for compliance but for profit) is relatively stronger than the one played by installations. By side, this should lead us to reflect on the concept of "centrality" and that the influence held by specific national registries in the EU ETS system is not necessarily proportional to their contribution to the system's annual compliance goals. Indeed, the majority of this centrality appears to be the direct result of the choice made by non-emitting entities not concerned with compliance to establish therein and conduct transactions for monetary gain, a choice that may be explained by the presence there of structures and institutions (fiscal, monetary, financial, etc.) apt to attract non-regulated entities.

Final considerations on research question 3: depolarization and loss of internal structure further confirmed

By using the values resulting from the following statistics *i.* number of clusters, *ii.* size of the largest cluster and *iii.* modularity value at each year, we can assess whether the hypotheses advanced so far can be further confirmed or not.

Examining the evolution of data related to the first statistics, we observe that from 2005 to 2020 the values have generally increased, with the highest ones associated to Phase II (2008-2012), which further underscores the centrality dispersion experienced by the network over time. It comes out quite natural now to complement this information with the results obtained from the calculation of the third statistics, namely the modularity value. Overall, it remained relatively constant over the years, ranging between 0.5 and 0.6; nonetheless, a significant increase is noticeable during the transition from Phase I to Phase II, followed by a slight but constant decline starting from the middle of Phase

II until 2015. After this year, the values show a modest increase again. Theoretically, modularity increases with greater internal connectivity within clusters and simultaneous decreased connectivity between clusters.

Combining the results from these two measures, the centrality dispersion experienced by the network over time can be seen in the transition from a structure with few solid clusters well-connected internally around main reference hubs (in the early years) to a structure characterized by numerous clusters organized around new nodes with acquired centrality (in the years between Phase II and III); a transition that essentially results in the increase in the number of clusters, complemented by the slight decline in the modularity value. (Paolella, 2024)

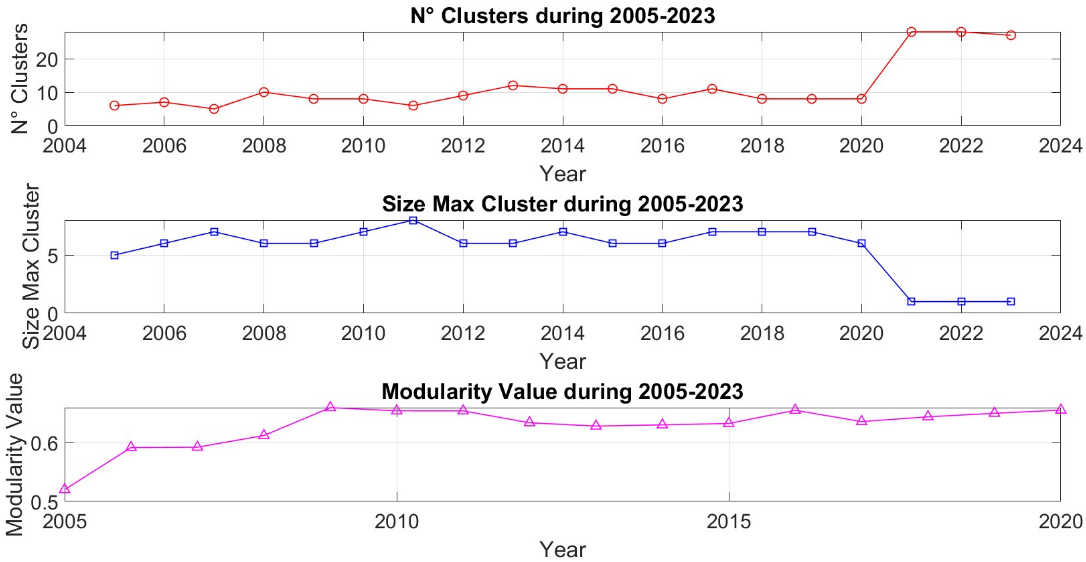

Figure 8: Evolution of Clusters and Modularity

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Declarations

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  Data is available at

- Authors' contributions

  B. Paolella: Methodology, Software, Writing-Reviewing and Editing.
  T. Araújo: Methodology, Software, Supervision, Writing-Reviewing and Editing.

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