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Ports and their influence on local air pollution and public health: a global analysis

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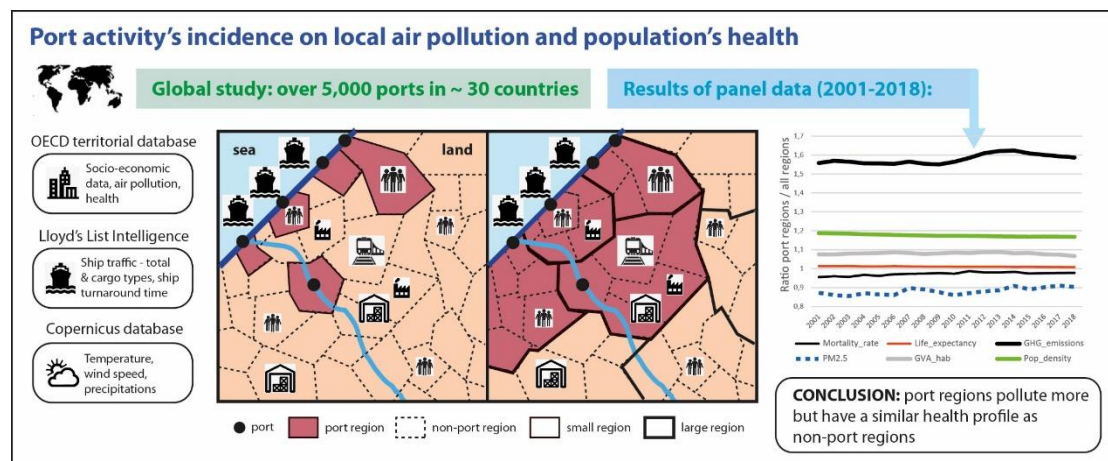
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Abstract

Despite the skyrocketing growth in recent decades of environmental studies on ports and shipping, their local health impacts remain largely under-researched. This article tackles this gap in research by statistically analyzing data on global shipping flows across nearly 5,000 ports in 35 countries between 2001 and 2018. The different traffic types, from containers to bulk and passengers, are analyzed jointly with data on natural conditions, air pollution, socio-economic indicators, and public health. The principal results show that port regions pollute more than non-port regions on average, while health impacts vary according to the size and specialization of the port region. Three types of port regions are clearly differentiated: industrial, intermediate, and metropolitan port regions.

Keywords: health; maritime transport; air pollution; port region; vessel movements

Graphical abstract



1. Introduction

The environmental impacts of ports and shipping have attracted growing attention in recent decades. Already in 1993, the International Association of Cities and Ports titled its fourth international conference “port cities, actors of the environment”. In the early 2000s, new research emerged on the integration of environmental values in port policies (Chédot, 2001) and port legislation (Ansaud, 2006), to name but a few. Pollution (as measured by CO₂ and PM_{2.5}) is also driven by other activities in the port city (Merk and Dang, 2013). The port is a transport node as well as a magnet for industrial and logistic activities, as illustrated by the many growth pole and free-zone policies in the 1970s in Western countries and even more evidently in Asia. Alongside a wide range of technical, technological, spatial, and socio-economic considerations, rising environmental concerns often motivated the separation between port and city by the relocation or closure of ports, and the redevelopment of old port areas for new urban uses such as culture and tourism (Hoyle, 1989). Industrial and port activities now often serve traditional port cities by trucks from peripheral locations, while creating new pressures on suburban settlements.

Since many ports remain urban, research on environmental issues in port cities has been very dynamic in the past two decades (Carpenter and Lozano, 2020; Wagner, 2019; Zheng et al., 2020). Specific aspects have been explored, such as the green transformation of industrial maritime transport (Comtois and Slack, 2005), industrial ecology (Cerceanu et al., 2014), environmental conflicts (Lo Prete, 2012; Bartłomiejski, 2016), urban vulnerability in port cities (Lo Prete, 2015), the sustainability of port and port-city plans (Schipper et al., 2017), and stakeholder perspectives on the sustainable development of port cities (Lam and Yap, 2019).

This surge in interest goes along with increasing efforts at all levels, from institutions such as the International Maritime Organization (IMO), the International Association of Ports and Harbors (IAPH), and the European Seaports Organization (ESPO), to promote sustainability in ports through a broader environmental vision that also encompasses health issues. Port city actors benefit from ever more advanced methods and precise tools of measurement to quantify and map pollutions of all kinds (Azarkamand et al., 2020; Contini and Merico, 2021). In the matter of preventing of seaport pollution and the correlated health impact on the local population, the set of technical and organizational solutions available to the port community is very diverse, from improving the fluidity and safety of the flow of passengers and to tend towards renewable energies and cleaner fuels (Sdoukopoulos et al., 2019; Alamoush et al., 2020).

Nevertheless, two main questions remain largely unanswered: to what extent do ports contribute to local pollution? How much is this contribution detrimental to the health of local populations? The “health” dimension of port impacts/concerns has largely been ignored in the literature. Environmental and health studies are, in fact, drastically different in nearly all aspects (Table 1).

The literature on green ports is so vast that it has been the focus of entire books (Bergqvist and Monios, 2019) and dense review articles (Lam and Notteboom, 2014;

Gonzalez-Aregall et al., 2018; Iris and Lam, 2019). In comparison, we have found only five journal articles dealing explicitly with ports, pollution, and health in the entire literature (Gianicolo et al., 2013; Vigotti et al., 2014; Bauleo et al., 2019; Viana et al., 2020; Gillingham and Huang, 2021). Most of these deal with a port city in Italy, where the interplay between environmental assessment and risks affecting labor is significantly critical (Attardi et al., 2012). Although the recent review of the field by Mueller et al. (2023) includes more papers, most of these are in fact health impact assessments looking at health risk factors without an explicit and direct analysis of the actual health effects on the population (Allen, 2014). More likely are studies about the health impacts of shipping onboard, including on the crew and passengers (Mouchtouri et al., 2010; Akamangwa et al., 2016; Lloret et al., 2021).

Characteristics	Environmental studies	Health studies
Specialization	Transport studies (operations research, social sciences) and environmental sciences	Medical sciences (e.g. public health epidemiology), interdisciplinary
Methodology	Measurement and mapping of pollutions considered as health risks	Cohort studies; model-based analyses; correlation between population exposure to hazards and health; often cross-sectional or ecological design
Data and monitoring	Pollutions and emissions from different sources, geocoding	Hospital admissions, premature deaths, diseases, socioeconomic status, gender, age, habits
Comparability and timeline	Cross-comparisons, static	Monographs, time series
Geographic scope	Port terminal, port-city interface, port hinterland	Intra-urban level (comparison between port and non-port areas)
Support to decision-making	Technical and/or organizational solutions, policy implications	Limited discussion on actors and governance
Health impacts	Health impacts sometimes implicit but mostly not directly discussed	Health impacts explicit

Table 1: Comparison between environmental and health studies in a port context

The concept of “environmental health” (OMS Europe, 1994) encompasses all aspects of the environment that can affect the quality of life, including air pollution and its interaction with the local population. “Vulnerability” pertains to the potential impacts or actual effects experienced by the local community (Lo Prete, 2015). But, while

environmental health focuses mainly on the environmental factors that may affect people's health (e.g., air pollution causing respiratory diseases), the notion of vulnerability focuses also on those who would suffer from the threats or the tangible effects of port development which would therefore affect public health. This distinction is important to understand how, today, the issue of health in a port context cannot be separated from that of the environment and must be considered broadly (Jeanjean et al., 2021).

On the connection between health and ports, there have been global studies on ship emissions and mortality (Corbett et al., 2007). The literature includes several studies on the health impact of industrial activities but they do not make any specific mention of ports (Martuzzi et al., 2014; Mudu et al., 2014; Domingo et al., 2020; Marquès et al., 2020). There are also health studies of port cities and regions that do not mention the port as a factor (on the case of Sydney, Australia, see Broome et al., 2015; for the Campania region in Italy, see Fusco et al., 2020).

Our research innovates in several ways. First, it provides an international perspective of the impact of ports on local air pollution and public health across the OECD area. Second, we use untapped data on global movements of merchant vessels and a full set of environmental, socio-economic, geographic, and demographic indicators to run multivariate analyses of these impacts at the scale of small regions (among which cities) and large regions. The main results demonstrate whether possessing a port increases pollution, is detrimental to life expectancy, and/or aggravates mortality rates. We differentiate traffic types by their uneven effects on environment and health (e.g., passengers, containers, bulks, etc.) and conclude with a typology of port regions. This typology serves to identify critical cases and is a benchmark to pursue more qualitative research on actual environmental and health protection practices.

The remainder of this article is organized as follows. The second section provides a review of the recent literature on pollution and health impacts in port cities. Thirdly, we introduce the data and methodology. The fourth section displays the main results of the statistical analysis and the cartography of the typology. We conclude in the last section on the lessons learned and propose further research paths.

2. Literature review on ports, pollution, and health impacts

Most activities taking place in a port city environment are in some way linked to the shipping activity (Coomber et al., 2016). Yet, some can be found in any city, such as manufacturing, logistics, and heavy industries, while others are specific to ports, such as loading and unloading of goods, oil jetties, shipyards, fishing fleets, marinas, and dredging and building of port infrastructures. Various forms of pollution, including air, noise, visual, olfactory and water pollution, can result from such activities, causing negative consequences for human health and the environment (Sakib et al., 2021).

Port and port-related activities not only consume various resources, such as water, electricity, coal and land, but also inevitably damage the urban environment (Li et al., 2019). Maritime transport noticeably contributes to the degradation of air quality in coastal areas (Ledoux et al., 2018; Mwase et al., 2020; Merico et al., 2020; Gregoris et al., 2021). Air pollutants such as sulphur oxides (SO_x), nitrogen oxides (NO_x),

particulate matter (PM), carbon monoxide (CO), and volatile organic compounds (VOCs) are emitted to the atmosphere as a direct result of shipping activities (Sorte et al., 2020). Exposure to PM and nitrogen dioxide (NO₂) is particularly harmful to health (EEA, 2019). Annual NO_x ship emissions can reach 5-10% of total global emissions, and even 30-40% at the regional level (Ramacher et al., 2020). Before the launch of sulfur limit and emission control areas (SECAs) by the IMO under the Marpol convention, annual SO_x emissions from ships accounted for 4-9% of total global emissions. In Europe, according to Merico et al. (2021), PM_{2.5} and PM₁₀ emissions represented 45% and 28% of shipping-related emissions, respectively. Ultrafine particles from cruise ships and ferries in particular (especially in ports such as Barcelona, Palma de Mallorca, Venice, Civitavecchia, Southampton, Lisbon, etc.) may cause specific problems both regarding the occupational health of dockworkers and of coastal residents. Worldwide, 14,500–37,500 premature deaths were attributed to PM_{2.5} related to shipping, with the highest values in areas recording both high PM concentration and population density.

But such global averages must not hide the fact that pollution from ships is concentrated near the coast and within ports (Jahangiri et al., 2018). In the latter case, ships pollute more at berth than during maneuvering (Fameli et al., 2020), so their turnaround time is a crucial factor in pollution, especially concerning NO_x (Sorte et al., 2019), but also PM concentration, which may culminate at 7-26% in Asian ports (Chen et al., 2019; Zhang et al., 2022). The terminal area itself, as well as port-related industries and logistics also participate in local air pollution, although their contribution is not always clearly measured (Mueller et al., 2023; Rowangould et al., 2020). Merico et al. (2020) and Sorte et al. (2019) multiple emissions' contribution to ambient air quality (i.e., ship, terminal, road traffic, refineries). The latter study found that the combination of trucks, railways, cargo handling equipment and bulk material storage contributed the most to surface PM₁₀ concentrations over the study area. A study on the port of Felixstowe (UK) demonstrated that inland transport emissions were double the size of port emissions (Gibbs et al., 2014).

Air pollution in ports also varies according to traffic types. At liquid bulk terminals, the main concern is the emission of volatile organic compounds (VOCs) during the storage and turnover of oil and chemicals (Yuan et al., 2022). Solid bulks (e.g., grain, coal, ores, cement) may produce dust during ship loading and unloading or when carried via uncovered conveyor belts and unfiltered silos. Cereals in particular are mixed with earth residuals contaminated by agricultural fertilizers and pesticides. The study by Morin et al. (2013) on Rouen, Europe's largest port for cereals, was motivated by the fact that important amounts of PM are released during the loading of food grains onto ships, representing a potential danger for the populations living in the close vicinity to the harbor (e.g., fertilizers, pesticides, mycotoxins and microflora).

Cruise shipping, a fast-growing sector in the past decade or so, produces emissions that harm the health of not only tourists and residents (Chatzinikolau et al., 2015; Perdiguero and Sanz, 2020), but also of crew members (Lloret et al., 2021). In the case of container vessels, not all port cities use rail or river transportation as an alternative to road, which represents 75% of all intra-EU freight movements (Eurostat, 2019). Ports such as Le

Havre in France have a very unbalanced modal split, with more than 90% of hinterland traffic occurring by road. Even in multimodal ports such as Antwerp in Belgium, where barges carry about 40% of hinterland traffic, road congestion may reach extreme levels, due to the combination of transnational and national trucking flows with urban commuting flows, especially at peak hours.

Currently, the methodologies on how ship emissions impact air quality and human health are well established and used in the cost-benefit analyses of policy proposals (Nazmus et al., 2021). The effect of large-scale air pollution emission changes on ecosystems, human health, and their economic impacts can be modelled with reasonable accuracy. However, there is no unified framework to assess the environmental and socioeconomic impacts of ports and shipping (Ytreberg et al., 2021). Existing studies use a wide variety of methods, including experimental observations, numerical modelling, and emission inventory analysis (Merico et al., 2017). Some scholars have conducted on-site sampling campaigns and evaluated quantitatively the impact of ship emissions on port air quality based on the measured data (Wang et al., 2019; Peng et al., 2022). Steffens et al. (2017) used the mobile measurement method to assess the air quality of the port, a tool which is more flexible than the fixed monitoring station. Mainstream methods to estimate ship emissions in ports are either top-down (i.e., fuel-based) or bottom-up (i.e., activity-based) (Nunes et al., 2017a; Yang et al., 2021; Toscano et al., 2021). The bottom-up approach for instance was adopted by Sorte et al. (2021) in their detailed emissions inventory covering shipping and cargo handling (see also Kara et al., 2021; Sorte et al., 2020). The source apportionment literature is vast and diverse, examining ship emissions and air quality alongside the effects of emission regulations (Anastasopoulos et al., 2023).

It is very difficult to untangle the contribution of each source to the overall local pollution, due to complex interactions between these sources and the rapidly changing meteorological conditions (Lang et al., 2017). To simulate urban-scale pollutant concentrations, Ramacher et al. (2020) used the coupled prognostic meteorological and chemistry transport model (TAPM) for measuring the contribution of road traffic and shipping related emissions to overall air quality and the annual mean population exposure in Hamburg. Merico et al. (2019) proposed a system integrating dispersion modelling and measures supplied from both meteorological stations and traffic data within the harbor. Despite their steady improvements, such experiments still have limitations due to the complexity of chemical processes in the atmosphere, the difficulty of source attribution, and limited spatiotemporal data resolution.

Quantitative studies with an explicit focus on health impacts are usually done at the intra-urban level. In Civitavecchia, Bauleo et al. (2019) showed that people living in areas with higher concentrations of PM₁₀ or NO_x were younger and had a lower socioeconomic status than in less polluted areas, while residents near the port had higher mortality rates from all cancers and neurological diseases. In Brindisi, Gianicolo et al. (2013) found that health risks (i.e., unplanned hospital admissions) increased for people living under prevailing winds carrying PM₁₀ and NO₂ and coming from port and industrial areas. In Taranto, the district most affected by the port and steelworks (i.e., young age, low socioeconomic status, high deprivation index, and highest SO₂ mean

concentration) was a distance away due to topography (Vigotti et al., 2014). According to the study of eight Mediterranean cities by Viana et al. (2020), shipping caused fewer premature deaths than vehicular traffic, though emissions from both remained comparable in magnitude. Gillingham and Huang (2021) used vessel tonnage and patient-level administrative data over the 2001-2016 period to make evident that air pollution from U.S. ports affects health outcomes. However, the impact differs by race and respiratory hospital visits, heart-related visits, and psychiatric visits are three times higher for Black people than for whites.

The level of detail and the diversity of measures presented by these studies largely explain the scarcity of comparative analyses either at the global scale or even within the same country. This is also due to the relative uniqueness of port sites, urban morphologies, and climatic conditions from one place to the other. Therefore, in the next section we present the data and methodology that make it possible, for the first time, to run an international and comparative analysis of the environmental and health impacts of ports.

3. Data and methodology for an international study

3.1 Hypotheses

Based on the above, our main hypotheses are as follows:

- H1a: the presence of a port aggravates air pollution and health conditions
- H1b: port regions witness heavier environmental and health impacts than non-port regions

This can be verified by a statistical analysis, first testing whether ports regions exhibit a specific profile compared to other regions. Ports may significantly affect pollution and health, but local environmental and health conditions are influenced by other activities as well as a number of natural and human factors. Impacts may result from activities that are distinct from the port itself (i.e., terminals) but strongly related to it, like industries, logistics, and the concentration of population. However, many new terminals have been developed at the periphery, in greenfield sites, so that a port region is not necessarily more polluting than a non-port region. Given that ports are very diverse across the globe, traffic volume and specialization should also be considered:

- H2: impacts are higher for larger ports than for smaller ports
- H3: impacts are differentiated across traffic types

While the quantity of traffic passing through ports should inevitably result in more air pollution, this is less evident when it comes to different traffic types. Those act as “supply chains” with each having its own rationale. As mentioned above, solid bulks like cereals provoke dust clouds in port cities, while container traffic pollutes mainly when carried onshore between the terminal and the hinterland, especially in a dense

urban environment that trucks go through. The consideration of traffic types is also important because of their particular regional branching and industrial relatedness (Ducruet and Itoh, 2016). Bulks will be produced or consumed more locally by heavy industries, compared to containers that supply more distant customers or are concentrated in dense urban regions (Guerrero, 2014). Cruise shipping, which takes place within port cities, implies long turnaround times for vessels during port stays, as well as important road traffic from tourists (Tichavska and Tovar, 2015).

3.2) Global database

The international perspective proposed here uses the port region as the spatial unit of analysis. The OECD territorial database (OECD, 2023), which covers about 2,000 regions in 36 countries, is the main data source. It provides socio-economic, environmental, and health indicators at two regional levels, namely small regions (TL3) and large regions (TL2). While we are aware that administrative boundaries and port hinterlands are often mismatched, administrative regions remain relevant spatial units as they constitute the “captive” part of the hinterland (Ducruet, 2009; Notteboom et al., 2023). We combine this database with the one from Lloyd’s List on global shipping, whose main advantage is to palliate the absence of a global database on actual port throughput (Lloyd’s List Intelligence, 2023).

As seen in Table 2, Lloyd’s data makes it possible to calculate ship traffic at ports overall and by type of ship, which corresponds to the product between ship capacity (gross registered tons) and number of calls on a yearly basis. We excluded non-commercial vessels, like navy ships and hospital ships for instance. After several trials and errors, it was decided to exclude vessels performing port services (i.e., towage, pilotage, dredging) as well as general cargo, and to keep other categories at an aggregated level, like liquid bulk (i.e., chemicals, crude oil, gas, oil tanker), solid bulk (i.e., coal, cement, grain, ores), and passenger/vehicles (i.e., ferry, cruise, roll-on/roll-off, and vehicles), while containers is a category on its own. Traffic was summed for regions containing more than one port. As high ship turnaround time is considered a factor of pollution in the literature, it was calculated as an average for the whole fleet by region and by year.

OECD data include two main pollutions, namely PM_{2.5} concentration ($\mu\text{g}/\text{m}^3$) and Greenhouse Gases (GHG) emissions (million tons CO₂ equivalent). These PM_{2.5} concentration estimates (outdoor and ambient) were derived “by integrating satellite observations, chemical transport models and measurements from ground monitoring station networks” (OECD, 2023). They were population-weighted using gridded population datasets. Fine particulate matter was chosen as it is the pollutant which poses the greatest risk to health globally, especially as it increases the risk of respiratory and cardiovascular diseases (WHO, 2018). GHG is the sum of seven gases with direct effects on climate change: carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF₆), and nitrogen trifluoride (NF₃). The data are expressed in CO₂ equivalents and refer to gross direct emissions from human activities.

Category	Variable	Description
Port traffic	Total vessel traffic	Gross tonnage (GRT) (LN)
	Containers, liquid bulks, passengers & vehicles, solid bulks	% in regional total
	Average ship turnaround time	Average number of days spent by vessels in ports
	Port dummy	0/1
	Emission Control Area (ECA)	0/1
Geography	Wind speed	Knots
	Precipitations	0.01 inches
	Temperature	Fahrenheit
Pollution	Particulate matter (PM _{2.5}) concentration	Average level experienced by the population ($\mu\text{m}/\text{m}^3$)
	Total CO ₂ equivalent emissions	Metric tons (LN)
Health	Mortality rate	No. deaths per 1,000 people
	Life expectancy at birth	No. years
Socio-economic	Gross Domestic Product (GDP) per capita	\$US per inhabitant (LN)
	Population density	No. inhabitants per km ² (LN)

Table 2: List of regional variables

We also documented local natural conditions. Those were collected from the Copernicus¹ website, a dataset providing daily surface meteorological data for the period from 1979 to the present. Among all possible indicators, we retained those most relevant to the study of port pollution, namely temperature, wind speed, and precipitations. The method was then to calculate the yearly average for each region from individual station data, using QGIS and the shapefiles of regions. While higher temperatures are known to increase pollution (Zhao et al., 2020), wind speed and precipitations reduce it by dispersion and dilution (Liu et al., 2017; Zhang et al., 2023). Such effects were tested via several control variables, scoped to those shown in Table 2. The health indicators that were retained are life expectancy at birth and mortality rate. Among all possible socio-economic variables, population density and Gross Value Added (GVA) per capita are retained as potential factors of increased pollution. Analyses are compared between large and small territorial units to investigate the potential effects of geographic scale on the relationship between vessel activity, pollution, and health. Depending on the scope of the hinterland, relationships between the variables may vary, as shown in a recent study on employment and traffic specialization in French port cities (Amdaoud et al., 2022). Descriptive statistics for the chosen indicators are provided in Appendix 1.

¹ <https://cds.climate.copernicus.eu/>

3.3 Statistical analysis

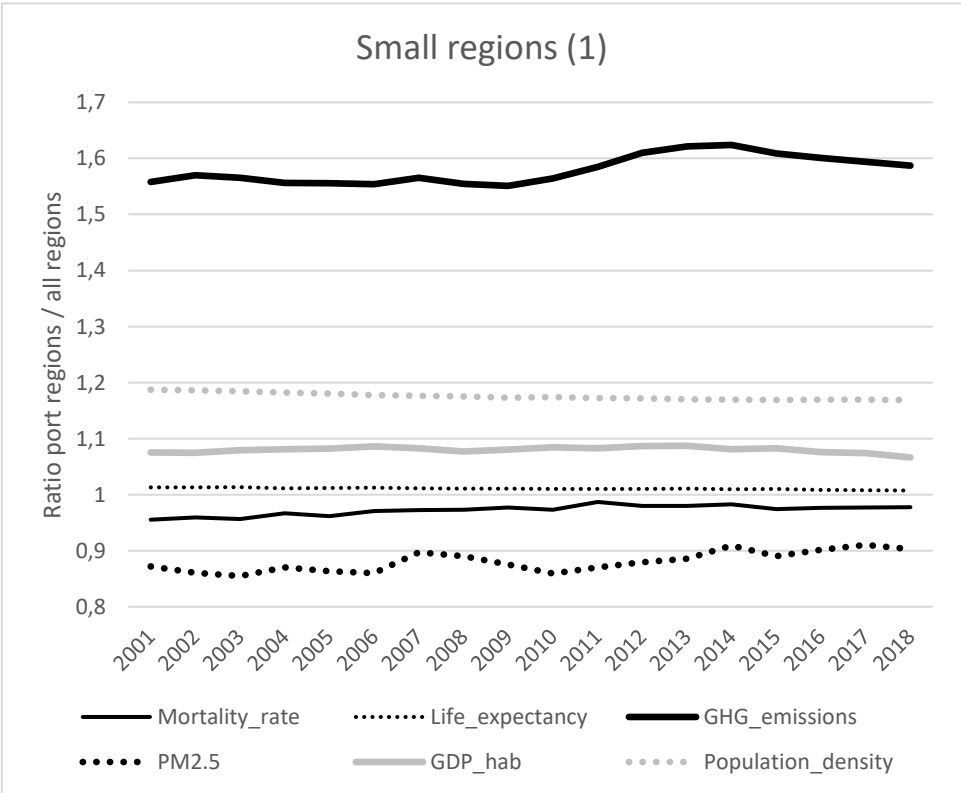
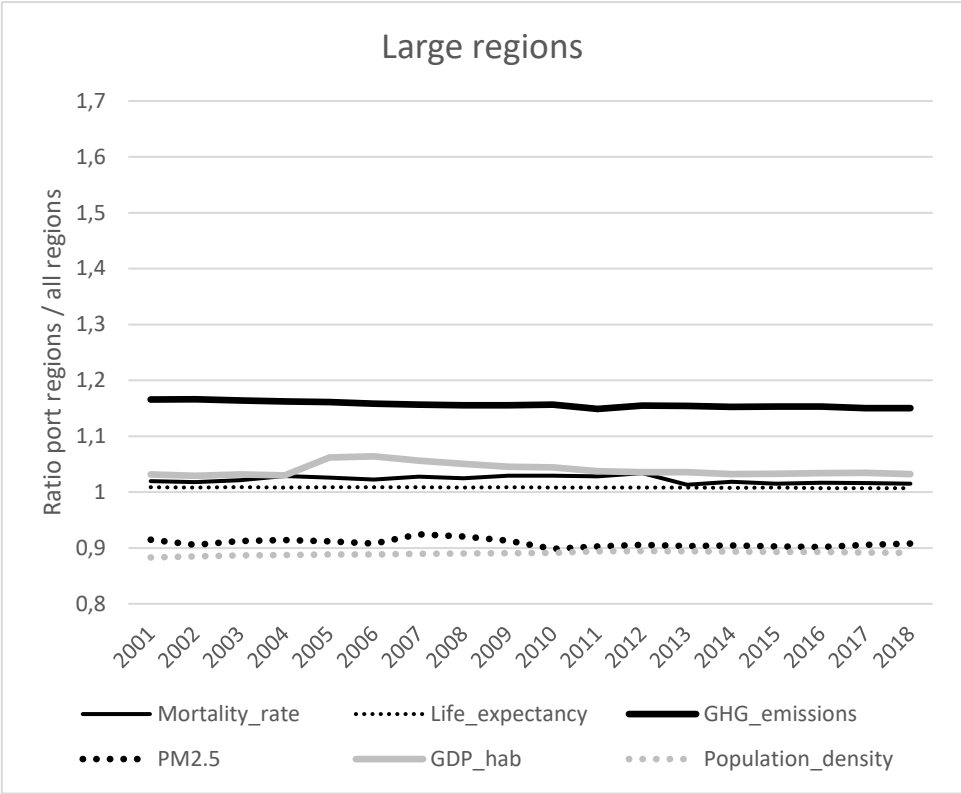
As a cross-sectional and time-series study (2001-2018), the best method to verify our hypotheses was a regression analysis of a panel data. The main reason for this choice was because this model could mitigate the effect of omitted variable bias when there is a lack of information on variables that are associated with both the regressors of interest and the dependent variable, and if these variables are constant in the time dimension or across entities. We ran two models: a) fixed effects regression using time and entity fixed effects and b) random effects. A Hausman test led us to choose the fixed effects model. Due to the inclusion of a time-invariant variable (ECA zone dummy), we selected a variant of the model called the Least-Squares Dummy Variable (LSDV) model, equivalent to the demeaning approach.

A factor analysis as well as a hierarchical cluster analysis (HCA) were applied to the most recent year (2018) in order to describe general (static) trends and delineate distinct classes of port regions. In these analyses, similar to what is done for regressions, several variables were transformed into natural logarithms to attenuate the influence of extreme values (GHG, total traffic, population density, and GVA per capita). For the factor analysis and the HCA, various other variables were converted into location quotients to control for geographic or national bias during regional comparisons (mortality rate, life expectancy, PM_{2.5}, wind speed, temperature, precipitation). Location quotients are calculated as the regional value divided by the national average.

4. Results

4.1 The effect of having a port

Our first analysis focuses on the port dummy to verify its effect on environmental and health conditions. We calculated the ratio between the average score of port regions and the average score of all regions for the main environmental, health, and socio-economic variables (Figure 1). This provides a positive answer to the fundamental question of whether port regions are more polluted than non-port regions, in terms of GHG emissions. This is the case for both large and small regions, but the gap between port and non-port regions is much wider in the case of small regions (1.5-1.6 compared with 1.1-1.2). Although such results cannot prove a direct and causal effect of ports, environmental issues are more critical in smaller territories with a port. This is not the case for the exposure to PM_{2.5} emissions, given that the ratios are lower than 1 for both large and small regions. Small port regions are also characterized by a higher population density and GDP per capita on average, which accentuate GHG emissions and at the same time, increases the exposure to such emissions.



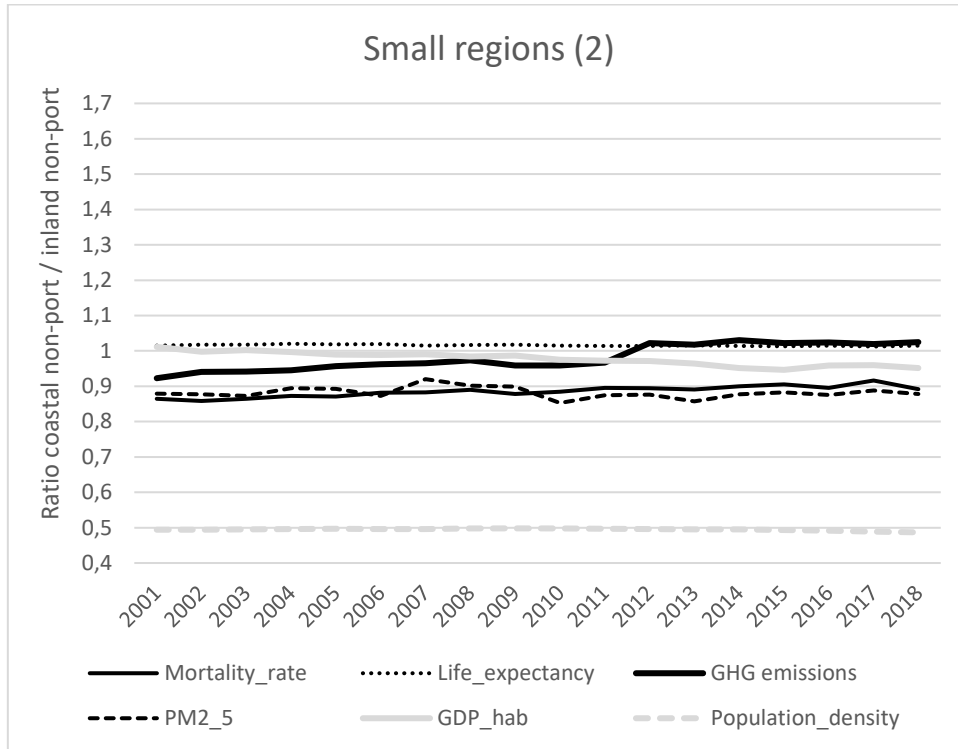


Figure 1: Comparison of port and non-port regions, 2001-2018

However, health indicators show no specificity, except for the mortality rate that is lower than average for small port regions, while life expectancy is more or less the same in port and non-port regions. At this stage, we can only confirm the links between GHG emissions and the concentration of population and economic activities when a region has a port. The relationship with health outcomes needs further investigation with different methodologies.

Interestingly, the bottom part of Figure 1 shows that in maritime countries², non-port coastal regions are nearly identical to non-port inland regions in all aspects (ratio around 1), except for population density. The latter is much lower in non-port coastal regions, and this is principally due to the specialization of these regions in other activities than trade, like agriculture, culture and tourism. The mortality rate is also slightly lower (around 0.9 on average) in coastal non-port regions, as verified in earlier studies comparing coastal vs. inland areas as well as densely vs. sparsely populated areas (Fusco et al., 2020).

The model results show that the port dummy is significant and has the expected sign for GHG emissions, for both large and small regions (Table 3)³. However, it is significant and negative for PM_{2.5} concentration. This may be explained by the fact that despite the high absolute emissions of PM_{2.5} in port cities, inland regions may have even greater concentration of such particulates. One reason is that PM_{2.5} emissions in

² This specific analysis is applied to France, Italy, New Zealand, and Portugal only.

³ See appendices 2 and 3 for full statistical results.

port regions are, at least partly, blown away by stronger winds along the coast⁴. This is quite apparent in Table 3 as wind speed significantly and negatively influences PM_{2.5} concentration. Higher temperatures foster GHG emissions, as stated in the literature (Zhao et al., 2020). Lastly, population density amplifies GHG emissions and PM_{2.5} concentration at both territorial levels. The concentration of population, especially in port regions, amplifies the probability of port-related traffic (e.g., heavy-duty vehicles) and urban traffic creating bottlenecks, especially at peak hours along the most frequented roads.

		GHG emissions	PM2.5 concentration	Mortality rate	Life expectancy	
Large regions	Wind_speed	0.125535***	-0.694115***	0.278587***	-0.119548***	
	Precipitation	-0.006289**	0.016242.	-0.030303***	-0.035758***	
	Temperature	0.054194***	-0.002949	-0.086327***	-0.093318***	
	GVA_hab	0.676815***	-5.061351***	-0.121710*	2.348268***	
	Pop_density	0.080267***	1.312576***	0.367839***	0.533219***	
	Port_dummy	0.177783***	-2.495459***	0.022665	0.757635***	
	GHG	-	-	-0.048595***	-0.118959***	
	PM2.5	-	-	0.237101***	0.089194***	
Small regions	Wind_speed	0.113926***	-0.696420***	-0.073804***	-0.227293***	
	Precipitation	0.001914.	0.024260***	0.005412*	0.016223***	
	Temperature	0.027560***	-0.062909***	0.049757***	0.113059***	
	GVA_hab	0.326368***	-3.172859***	-1.106091***	4.759666***	
	Pop_density	0.273825***	2.059841***	-0.484786***	0.147506***	
	Port_dummy	0.363207***	-2.497721***	0.066642	0.492263***	
	GHG	-	-	0.033233***	-0.105425***	
	PM2.5	-	-	-0.271965***	0.075019**	
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Table 3: Model results with port dummy

Secondly, the port dummy is confronted with health indicators. It is positive but not significant for mortality rate, while it is always positive and significant for life expectancy. What looks like a contradiction could mean that the port effect differs according to phenomena that are more complex than just the presence or absence of such an infrastructure. Besides, Gross Value Added (GVA) per capita lowers mortality and increases life expectancy at both regional scales. Including air pollution indicators in the model is worthy of investigation. GHG emissions significantly lower life expectancy, while PM_{2.5} concentration has the opposite effect⁵. The respective influences of GHG emissions and PM_{2.5} concentration on mortality rates are opposed between large and small regions. This shows that GHG's worsening effect on health is more "local" (small regions) while PM_{2.5}'s one is spread more inland (large regions). These results can be connected to the fact that wind speed significantly reduces mortality in small regions. However, the unavailability of additional data, such as facts about medical care (e.g., number of doctors, hospital beds), hampers the models' results. This motivates us to enrich the analysis with more information about ports, which can be differentiated by their traffic size and specialization.

⁴ We calculated that wind speed, on average, is 1.3 to 1.4 faster in port regions than in non-port regions.

⁵ It should be noted that GHG emissions and PM_{2.5} concentration are used both as dependent and independent variables in our analyses. Therefore, it is not possible to directly compare the parameters of other variables, such as GVA per capita, as their influence on health is underestimated due to the inclusion of GHG and PM_{2.5}.

4.2 The effect of traffic size and specialization

As shown in Table 4, total port traffic has a significant and positive effect on GHG emissions for both small and large regions. The quantity of cargo and number of passengers⁶ handled in ports thus contributes to local air pollution. This is not the case for PM_{2.5}, which confirms the prior findings of Table 3. Interestingly, the average ship turnaround time (ATT) significantly and positively accentuates both GHG emissions and PM_{2.5} concentration at all territorial levels. For all regions, this goes along with a significant and positive effect of population density and GVA per capita on GHG emissions, and a negative effect of belonging to an ECA zone for small regions only. This confirms the findings of Ducruet and Itoh (2022) about the evolution and determinants of ATT at world container ports between 1977 and 2016, whereby city size accentuates ship times and therefore pollution. On the offshore side, solutions such as virtual arrival, vessel speed reduction, inter-terminal barge shuttles, and berth allocation systems are used to lower ATT (Alamouh et al., 2020), just like underground transport, urban area bypass, modal split, automated door systems, truck appointment systems, and connectivity platforms on the onshore side to avoid queuing and congestion. Like for the port dummy analysis (Table 3), wind speed significantly reduces PM_{2.5} concentration in small and large regions, while GVA per capita decreases it.

The use of cold ironing⁷ is a widely used remedy to air pollution (Gonzalez-Aregall et al., 2018), alongside improvements in the productivity of cargo handling vehicles. The results by traffic types are quite contrasted according to the territorial level and the type of air pollution. Solid bulk traffic raises GHG emissions in small and large regions, however, despite it being seen more as a source of PM_{2.5} in the literature and in practice. Liquid bulk and passenger traffic reinforce PM_{2.5} concentration in small regions only. This aligns with practice, since such traffic produce Volatile Organic Compounds (VOCs) like those emitted from bulks during handling and storage. VOCs (methane and nonmethane) contribute especially to GHG emissions during the loading and unloading of tanker ships. Among them, the heavier components (nonmethane VOCs) contribute to low-level photochemical oxidants, such as ozone, which affect human health, food production and the environment. Additional pollutants include oil itself (accidental discharge, loss from deposit tankers and pipeline), oil and rubber (spill from bulk-handling device), oily and toxic sludges (fuel deposits), as well as polychlorinated biphenyls (PCBs), hydrofluorocarbons (HFCs) and hydrocarbons (updated from Trozzi and Vaccaro, 2000).

⁶ In this study, the use of ship tonnage capacity allows to measure cargo and passenger traffic based on the same unit (Gross Registered Tons, GRT).

⁷ Cold ironing is known by a variety of names, including shore power, shore-side power, shore-side electricity (SSE), high-voltage shore connection (HVSC), onshore power supply (OPS), shore-to-ship power, and alternative maritime power.

		GHG emissions	PM2.5 concentration	Mortality rate	Life expectancy		
Large regions	Wind_speed	0.0006725	-0.729059	0.069464	-0.051666		
	Precipitation	0.0085060	0.022319	-0.018353	-0.029037		
	Temperature	0.0472279	0.067562	-0.057228	-0.116917		
	GVA_hab	0.5945499	-3.432197	-0.182014	2.512340		
	Pop_density	0.1349703	0.997147	0.364617	0.413543		
	GHG	-	-	0.110870	-0.122558		
	PM2.5	-	-	-0.084933	-0.021639		
	Traffic	0.1617540	-0.329578	0.059351	0.308154		
	Container	-0.0098377	-0.022529	-0.032374	-0.021119		
	Solid	0.0031901	-0.018293	-0.016977	-0.022979		
	Liquid	-0.0030430	-0.019803	-0.013236	-0.019587		
	Passenger	-0.0135757	-0.009753	-0.008179	-0.006435		
	ECA_zone	0.4390171	-2.033973	0.190262	-1.869046		
	ATT	0.0299926	0.119471	0.013710	-0.023097		
	Small regions	Wind_speed	0.1001921	-0.278101	-0.1337066	-0.1233779	
		Precipitation	0.0030555	0.016450	0.011547	0.0091722	
Temperature		0.0445778	-0.032416	0.0323943	0.0865502		
GVA_hab		0.2570628	-3.403801	0.3522157	2.7539112		
Pop_density		0.1753421	1.592619	-0.2528487	0.2029227		
GHG		-	-	0.1057549	-0.0769772		
PM2.5		-	-	-0.3482413	0.3718072		
Traffic		0.1416695	-0.234005	0.0907745	-0.0542379		
Container		-0.0008921	-0.016615	-0.0153747	-0.0016169		
Solid		0.0098657	-0.001918	0.0033517	0.0005865		
Liquid		-0.0004921	0.008263	0.0001795	0.0012346		
Passenger		-0.0062564	0.006876	-0.0057670	0.0060897		
ECA_zone		-0.2510929	-0.888024	0.7678478	-1.1687847		
ATT		0.0524138	0.004915	0.0104663	-0.0413447		
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Table 4: Model results with traffic size and specialization

Cruise shipping is one notable cause of PM_{2.5} emissions (Lloret et al., 2021). It increased by 25% between 2019 and 2023 in Europe, compared with 9% in SO_x and 18% in NO_x emissions (Day, 2023). The EU has made it mandatory for Member States to install shore power facilities in ports by 2025. There are many initiatives in several port cities: cold ironing for ferries (Gothenburg, Hamburg), cruise liners (Amsterdam, Barcelona, Marseille, Le Havre, Livorno), passenger service vessels (Oslo, Venice), barges and other cargo vessels (Antwerp) (Bergqvist and Monios, 2019). As underlined by Iris and Lam (2019), cold ironing can play a crucial role given that numerous passengers stay onboard large cruise ships during hoteling.

Regarding health, total traffic accentuates mortality as well as life expectancy in large regions, while it accentuates mortality and reduces life expectancy in smaller regions, which is a reasonable result since populations are more exposed to ports in small regions. Average turnaround time increases mortality and decreases life expectancy, which also aligns with experience. GVA per capita and population density increase life expectancy, but the results for mortality are divergent between large and small regions. This indicates that economic development may promote environmental awareness and access to medical care, thereby improving health. Another important result is that GHG emissions reduce life expectancy generally, and only increase mortality in large regions. All traffic types lower both mortality and life expectancy in large regions, while for small regions, bulks (solid and liquid) increase mortality. The same holds true for container traffic, the only category to lower life expectancy in small regions. Thus, and based on the literature, the role of specific transport chains seems to be more apparent at a smaller geographic scale.

4.3 Developing a typology of port regions

4.3.1 General trends

A factor analysis provides a global view of all regions and variables (Figure 2). Interestingly, the scatter plot of variables along the two main factor is highly similar between large and small regions. This is important, as it demonstrates the quality and robustness of data and trends, which are stable across geographic scales. Groups of variables emerge, like in the upper-right quadrant with total traffic, container share, GDP per capita, and ATT, together with GHG emissions and population density. This confirms that container traffic is concentrated in large port-city regions as they are key nodes in the supply chain notably from the demand side (Ducruet and Itoh, 2016). PM_{2.5} concentration, especially for small regions, is also projected on the right/positive side of the first axis (horizontal), thereby consolidating this profile of “port metropolis”.

Natural elements only marginally affect pollution and health in the figure. In terms of health, mortality rate and life expectancy are logically opposed. Moreover, mortality is close to liquid and solid bulks in the upper-left quadrant. Although it is not possible to establish a causal relationship, this result confirms that bulks produce VOCs during cargo handling (coal, grain, ores, oil) that spread throughout the city’s atmosphere and get mixed in with urban pollution. Without protection, conveyor belts carrying coal or iron ore between port and plants provoke leaks and emissions during loading and unloading. VOCs (methane and nonmethane) from tankers contribute to GHG emissions. Among these VOCs, the heavier components (nonmethane) contribute to photochemical oxidants like ozone, which affects human health, food production, and the environment.

Despite the intermodalism made possible by containerization, container traffic generates important flows of heavy-duty vehicles within the port, across the city, and with the hinterland. In Europe, 75% of cargo flows occur by road (Eurostat, 2019), due to the geographic, logistical, and political difficulties of implementing a modal shift towards short-sea shipping. These flows generate congestion which can be addressed through the use of various systems to track trucks and better regulate traffic, but also with booking systems, automated door systems, as well as inter-terminal barge or rail shuttles (Gonzalez-Aregall et al., 2018). In the case of inland navigation, modal shift is an important option, as is the bypass of urban areas with a dedicated freight line or underground freight transport (Visser, 2018). At container terminals, “green concessions” (Notteboom and Lam, 2018) between port and operators may include modal split obligations to choose green modes (van den Berg and de Langen, 2014).

Locally, average ship turnaround time (ATT) is close to total traffic and GHG emissions, since the higher the demand (population density, GVA per capita), the more traffic and pollution. This explains the launch of automated mooring systems to reduce ATT, during which ships continue to burn fuel. In the case of ro-ro terminals, Alamoush et al. (2020) estimated that such systems reduce CO₂ emissions due to mooring by 97%. In addition, berth allocation and planning can also contribute to lower ATT. According to Styhre and Winnes (2019), this reduction applies well to containerships, which operate on a regular basis contrary to bulk ships (Styhre et al., 2017).

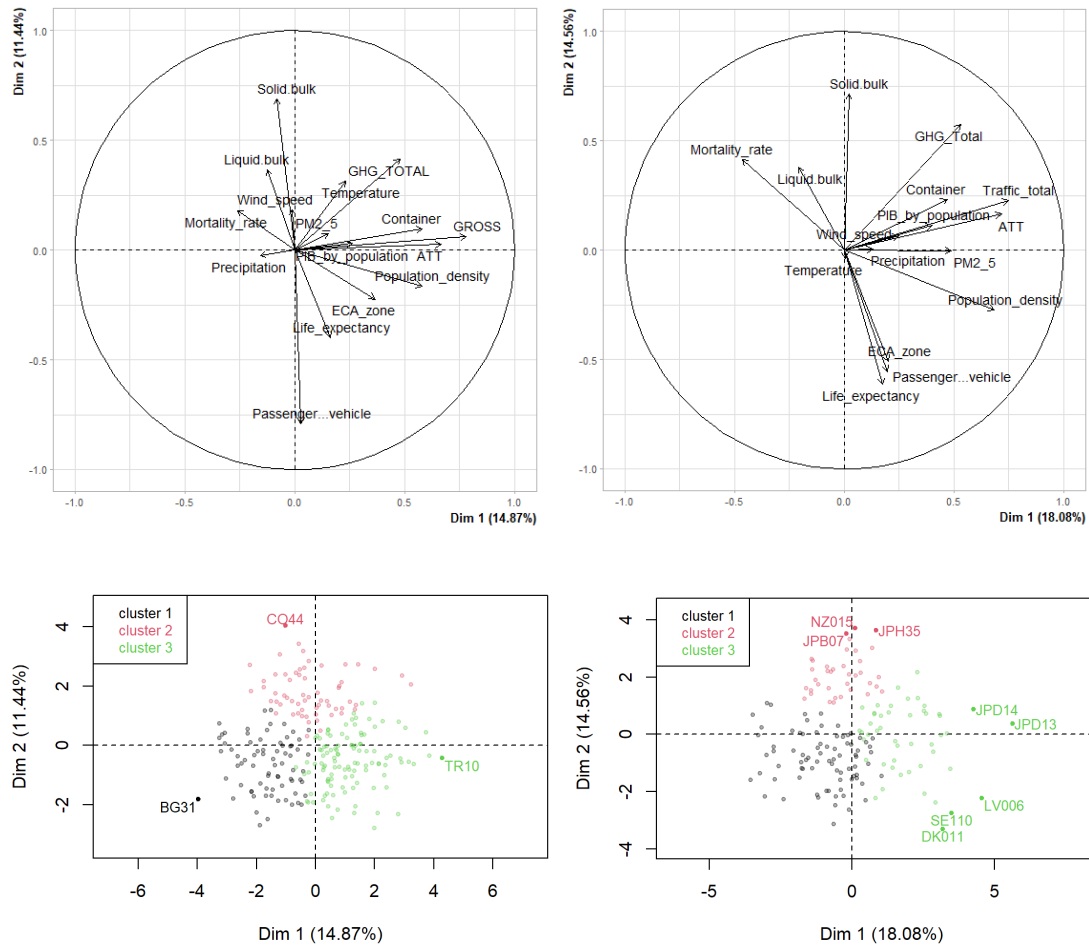


Figure 2: Factor analysis and classification in 2018
 N.B. 245 large regions (left) and 164 small regions (right)

Lastly, life expectancy is grouped with ECA zone and passenger/vehicle traffic. This makes sense if we consider that North Europe and North America are old industrial countries with mature healthcare systems. The importance of passenger traffic can be explained by the density of short-sea shipping in Northern Europe for instance (i.e., the Baltic Sea). A disaggregation by traffic subtypes is necessary to check the specific role of cruise ships compared to ferries, ro-ro, and vehicle traffic, as an avenue for further research.

4.3.2 Clusters of port regions

The great similarity in our results for small and large regions allowed us to categorize them in the same way, regardless of small differences (Table 5). We define as “metropolitan port regions” the ones with the lowest mortality rate and highest life expectancy. They rank high for population density and GDP per capita, carry the largest traffic volumes, and specialize in the most valued traffic, i.e., containers, far ahead of other regions. Their ATT is the longest, probably due to their role as market concentration hubs and important urban settlements, and they have the highest average number of regions belonging to an ECA zone.

	(2)	Large regions			Small regions		
		Metropolitan port regions	Intermediate port regions	Industrial port regions	Metropolitan port regions	Intermediate port regions	Industrial port regions
GHG_emissions	LQ	3.31	2.35	3.60	2.28	1.38	2.57
PM2.5	LQ	0.94	0.92	0.95	1.01	0.87	0.94
Mortality_rate	LQ	0.99	1.06	1.09	0.99	1.09	1.22
Life_expectancy	LQ	1.00	1.00	0.98	1.00	0.99	0.98
Density_population	LQ	1.14	0.65	0.69	1.01	0.40	0.28
GDP_capita	LQ	1.00	0.85	1.02	1.02	0.79	0.97
Total_traffic	LN	17.64	13.27	16.29	17.01	13.60	15.61
Containers	%	24.95	6.31	9.48	22.45	1.58	9.96
Liquid_bulks	%	12.64	16.57	27.24	12.33	14.25	24.05
Passengers_vehicles	%	49.16	43.60	12.29	47.64	51.56	21.93
Solid_bulks	%	7.99	8.50	41.76	9.04	3.62	34.01
ATT	RN	12.74	7.22	10.49	11.50	6.71	8.41
ECA_zone	RN	0.46	0.27	0.20	0.32	0.28	0.05
Wind_speed	LQ	1.00	0.93	1.13	1.21	1.06	1.04
Precipitations	LQ	0.91	1.14	0.96	1.25	0.90	0.90
Temperature	LQ	1.01	0.96	1.06	1.01	1.02	1.00

Table 5: Results of the hierarchical clustering analysis, 2018

(1) highest values for each regional scale / indicator are in bold and italics

(2) unit: location quotient (LQ)⁸, natural logarithm (LN), share (%), raw number (RN)

On the other side of the coin, “industrial port regions” have the most important GHG emissions and mortality rates, together with the lowest life expectancy. They do handle large volumes of traffic, but these are mainly composed of solid and liquid bulks, i.e., lower-value and more polluting items. What is more, such regions are not as much part of ECA zones, given their lowest score in this category. Industrial port regions are also characterized by low population density, given the location of plants and factories away from major urban settlements. They rank relatively high in GVA per capita given their role as transformation and production centers.

These two regional types can both be considered “critical” for two main reasons. First, it is important to note that be they small or large, metropolitan port regions score only slightly under industrial ones in terms of pollution; they even exceed them for PM_{2.5} concentration when considering small spatial units. Thus, while environmental impacts should be more severe in industrial regions, a lot more population is exposed to pollution in metropolitan port regions due to high density. This is particularly salient when considering that container traffic reinforces congestion within and across large agglomerations.

Between those two types, intermediate port regions do not have a specific profile. They rank high on a few variables only, such as passenger and vehicle traffic. More

⁸ Location quotient: regional share / national share was used to avoid the country bias when comparing regions.

importantly, they have the lowest GHG and PM_{2.5} emissions, traffic volume, GDP per capita, and ATT of all regions. Given their low population density, it is possible to infer that such a profile corresponds to peripheral regions using passenger transport to connect with the “core” regions. However, their relatively high score for mortality may be related to a specific activity like cruise shipping. Compared with other regions, this also means that health impacts are clearly associated with the concentration of populations and economic activities. The following cartography allows us to identify which regions compose these clusters on the map, as well as possible spatial regularities.

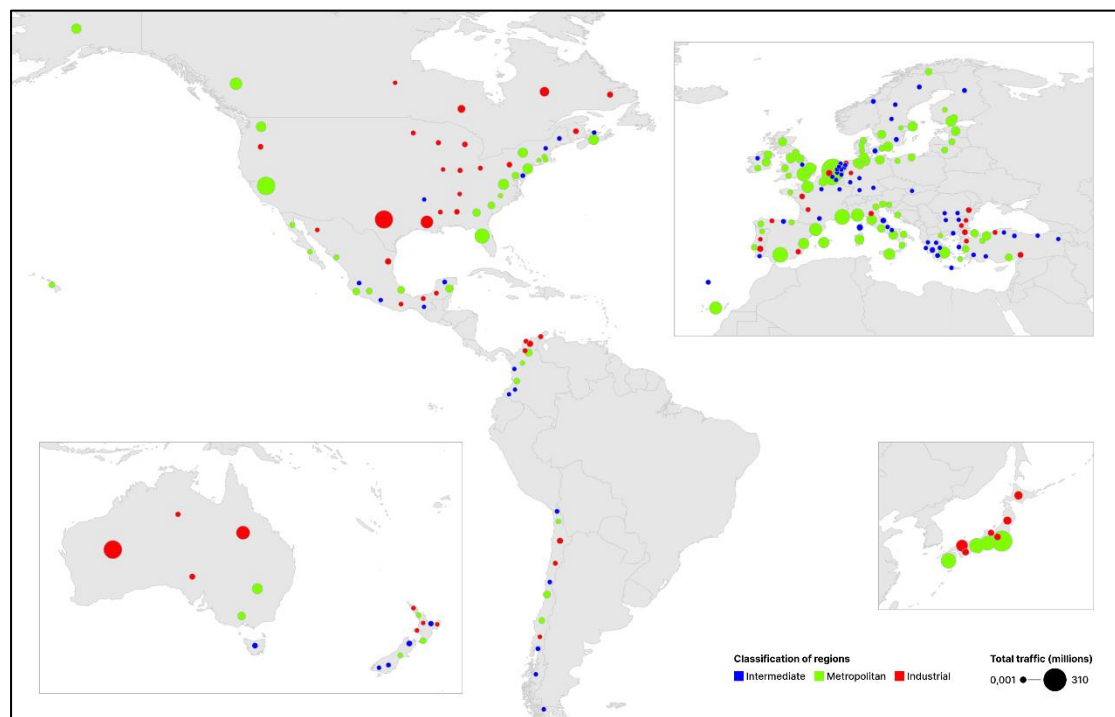


Figure 3: Typology of large port regions in 2018

The typology of large regions (Figure 3) reveals interesting spatial patterns across the globe. First of all, metropolitan port regions are concentrated in Europe. Globally, Europe is recognized as a fertile ground for actions promoting port city sustainability. As Gonzalez-Aregall et al. (2018) observed, Europe is the most advanced region by the number of projects seeking to improve the environmental performance of the hinterland. Another global review of the literature on emission reduction and energy efficiency improvement concluded that European ports are ahead of North American and Asian ones (Alamouh et al., 2020). As Iris and Lam (2019) emphasized, most of the small number of world ports that are certified as meeting the international standard for energy management (ISO 50001) are European; furthermore, the proportion of European ports that have energy efficiency programs increased from 57% to 75% between 2014 and 2016. In North America, such regions are found along the Eastern seaboard (Halifax – Miami) and the Pacific coast (Alaska – Mexico), comprising the most urbanized states like New York, Florida, California, as well as British Columbia

in Canada.

Comparatively, industrial port regions in Europe are concentrated along the Atlantic Ocean and the Black Sea, with only a couple of them in Northern Europe and in Italy. Elsewhere, this category includes the mining regions of Australia, the periphery of Japan (e.g., Hokkaido), and the interior regions of the USA and Canada. As is the case in Australia, two large regions specialized in bulks also belong to this category, namely Texas and Louisiana.

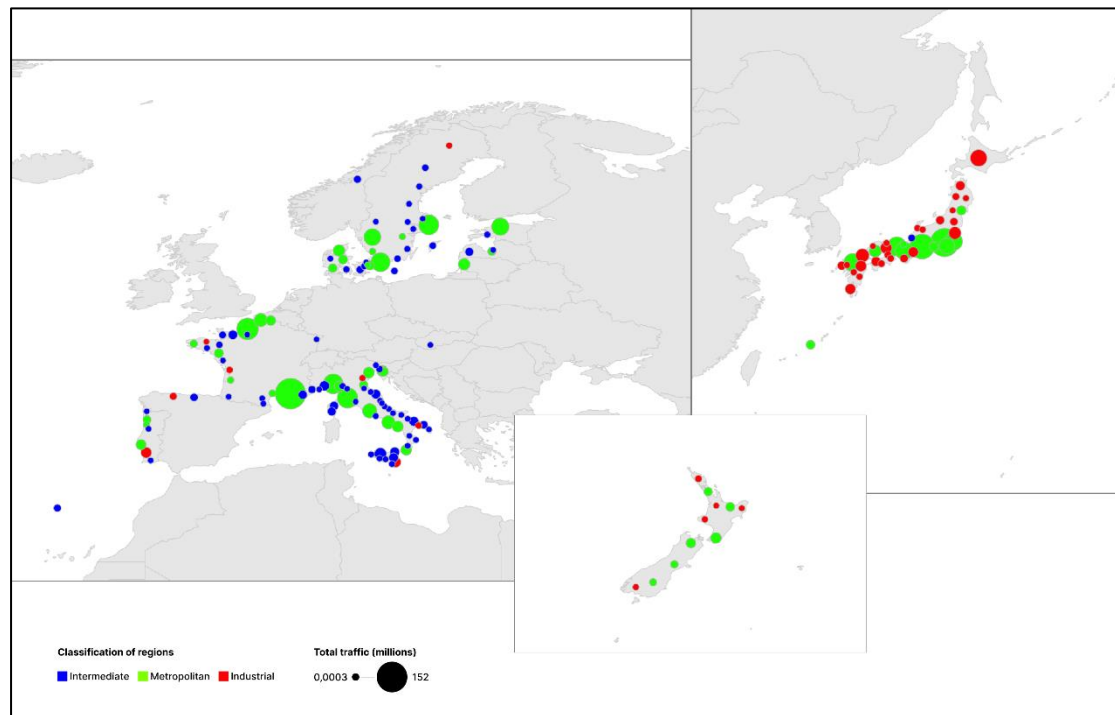


Figure 4: Typology of small port regions in 2018

For small regions (Figure 4), data was only available for parts of Europe, New Zealand, and Japan. This explains at least in part the country bias whereby most industrial port regions are in Japan. The rest of Japan is composed of metropolitan port regions situated along the so-called megalopolis from Fukuoka to Tokyo. This pattern is likely explained by the ageing population, which accentuates mortality rates outside of the megalopolis. In Europe, the industrial port region with the most traffic is Alejento in Portugal, with its port of Sines who developed a container hub in 2004 out of a heavy industrial growth pole. Most traffic goes to metropolitan regions, such as Marseille-Fos (Bouches-du-Rhône), Le Havre and Rouen (Seine-Maritime), France's two largest industrial and container ports. Other cases include Gothenburg (Västra Götaland), Malmö and Stockholm in Sweden, Tallinn in Estonia, and Klaipeda in Lithuania. Italy concentrates an important number of metropolitan port regions, containing the large ports of Genoa, Savona and La Spezia (Liguria), but also Lazio (Civitavecchia), Naples and Salerno.

5. Discussion and conclusion

This research provides the first-ever empirical analysis of the relationships between port activities, the environment, and health from an international perspective. A thorough review of the existing literature revealed that only a few studies actually measured the health impacts of ports (and their industrial areas) at the local level, compared with studies of their environmental impacts. This work is difficult due to the fact that it does not measure actual port pollution, but rather, considers the presence of port(s) and the level and diversity of port activities. Local measures of pollution are, in turn, not specific to ports, as they encompass the entire territory around the port rather than the port itself. Identifying a link between port activities and local pollution/health outcomes thus makes this study a success.

By way of combining data from the OECD and the Lloyd's List at the level of subnational regions, our main results confirm that port regions pollute more than non-port regions, in particular with GHG emissions. The analysis based on the port dummy confirms that the presence of port(s) increases GHG emissions but not PM_{2.5} emissions, mainly due to winds. Beyond the port dummy, traffic size and longer ship turnaround time increase pollution, in line with expectations. Belonging to an Emission Control Area (ECA) lowers local pollution as predicted, a trend which is valid at both territorial levels.

The analysis of pollutions (GHG and PM_{2.5}) alongside traffic volume and types, substantiates many practical observations, as GHG emissions increase mortality in all cases, and PM_{2.5} lowers life expectancy, although nothing proves that such pollutions come from the port itself. A future objective of further research is to enhance traffic data with information on ship pollution, contingent upon accessing additional facts on ship engines and fuel types.

This research detected similar types of regions at both territorial levels, small and large regions, thereby confirming the robustness of data and spatial patterns. The category of "metropolitan port regions" represents areas with a concentration of population, socio-economic activities, traffic volume (notably containers), and GHG emissions. These regions also witness the lowest mortality rates and are often situated within Emission Control Areas (ECAs), namely in Europe and North America. They stand in direct opposition to "industrial port regions", which specialize in bulk traffic, have the worst health scores, and pollute the most. Such a category includes Australian mining regions and U.S. regions specialized in the oil and agri-food business (Gulf of Mexico and Great Lakes / Midwest). The "intermediary port regions" stand in between both previous categories with no particular profile except for a specialization in vehicle and passenger traffic.

The main implication of these findings is that the port factor is an essential component of local socio-economic activity, pollution, and public health despite the high level of aggregation (i.e., subnational regions) and the administrative – rather than functional – nature of the spatial units under consideration. Given the limited literature on ports and health, and the fact that over 80% of world trade volumes are carried via sea transport, this calls for further research in this particular field, which is still small and scattered. We propose three principal avenues for improvement aimed at refining and deepening

the scope of the current findings.

First, the population under study could be described in more detail. One possibility is to look at social fragility and deprivation (Allen, 2014). But related data like the unemployment rate in particular was not available across the entire OECD area. This dimension is important, as the social and economic insecurity engendered by port development affects the precarious classes above all (De Lara, 2018), and the impact of air pollution is stronger among the poorest (Suarez-Castillo, 2023). As health indicators are very sensitive to the age structure of population, their deconstruction by age groups would be a prerequisite to a better assessment of the impact of air pollution. Data about access to and availability of medical care, such as the number of doctors and hospital beds, would greatly enhance the analysis.

Second, Lloyd's List Intelligence data on vessel movements may be combined with engine and fuel type data to calculate actual port/shipping pollution and compare it with OECD figures. As more precise pollution and health data is provided by the OECD, we shall also run separate analyses by GHG emission source (i.e., transport in general, road transport, and industry) and by cause of mortality (i.e., respiratory system, circulatory system, and transport). Port activities can be further disaggregated by ship types to have a clearer view of traffic specialization (i.e., crude oil, chemicals, tanker, general cargo, port services, cruise, ferries, etc.).

Third, another avenue of research is to work at the level of metropolitan areas. The OECD metropolitan database includes socio-economic and environmental indicators at this particular level, which is more functional than the administrative region. This would make it possible to integrate new variables on port city topography and morphology, wind direction for instance, and use data on urban congestion, such as the Tom-Tom Index⁹. At this level, information on environmental-friendly measures and equipment (ISO certifications, cold ironing, modal split) can be made available through a survey addressed to the relevant local authorities.

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⁹ <https://www.tomtom.com/traffic-index/>

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Appendix 1: Descriptive statistics for the year 2018

Variable	Unit	Large regions					Small regions				
		Mean	Median	Max.	Min.	Std. Dev.	Mean	Median	Max.	Min.	Std. Dev.
Mortality_rate	LQ	1.04	1.03	1.86	0.51	0.17	1.95	1.80	4.91	0.28	0.92
Life_expectancy	LQ	1.00	1.00	1.04	0.87	0.02	0.93	0.92	1.41	0.58	0.16
GHG_emissions	LQ	3.09	2.97	6.49	0.68	1.15	1.09	1.08	1.55	0.70	0.16
PM2.5	LQ	0.94	0.94	1.86	0.28	0.17	0.99	0.99	1.02	0.94	0.01
Density_pop	LQ	0.88	0.71	3.35	0.01	0.62	0.57	0.40	3.74	0.05	0.54
GDP_hab	LQ	0.96	0.89	3.51	0.34	0.34	0.91	0.88	3.51	0.51	0.29
ATT	days	10.49	10.90	15.50	1.00	3.58	8.66	8.94	15.19	0.50	3.70
Containers	%	15.39	4.88	77.43	0.00	20.13	10.32	2.64	75.86	0.00	16.06
Liquid_bulks	%	17.48	11.99	97.00	0.00	19.80	15.96	6.91	100.00	0.00	21.17
Passengers_vehic	%	38.28	34.27	100.00	0.00	31.13	43.25	42.25	100.00	0.00	32.54
Solid_bulks	%	16.56	7.17	100.00	0.00	23.32	12.60	4.73	100.00	0.00	17.74
Total_traffic	LN	15.97	16.74	19.55	6.95	2.61	15.18	15.72	18.84	5.82	2.53
ECA_zone	Dummy	0.33	0.00	1.00	0.00	0.47	0.24	0.00	1.00	0.00	0.43
Wind_speed	Knots	1.01	1.00	2.72	0.45	0.28	1.10	1.09	1.87	0.34	0.30
Precipitations	0.01 inch	1.00	0.88	5.77	0.00	0.71	1.01	0.84	6.75	0.03	0.86
Temperature	F°	1.01	1.01	1.53	0.42	0.12	1.01	1.01	1.31	0.66	0.10

Appendix 2: Model results for port dummy

	GHG emissions						PM2.5 concentration									
	Residuals:	Min	IQ	Median	3Q	Max	Residuals:	Min	IQ	Median	3Q	Max				
Large regions		-4.1687	-0.7190	0.0567	0.8063	3.0170		-12.794	-3.313	-0.954	2.562	44.102				
	Coefficients:	Estimate	Std.	Error	t value	Pr(> t)	Coefficients:	Estimate	Std.	Error	t value	Pr(> t)				
	(Intercept)	-1.615653	0.108341	-14.913	<2e-16	***	(Intercept)	30.514284	0.487398	62.606	<2e-16	***				
	Wind_speed	0.125535	0.009261	13.556	<2e-16	***	Wind_speed	-0.694115	0.041661	-16.661	<2e-16	***				
	Precipitation	-0.006289	0.001935	-3.249	0.00116	**	Precipitation	0.016242	0.008707	1.865	0.0622					
	Temperature	0.054194	0.002410	22.489	<2e-16	***	Temperature	-0.002949	0.010841	-0.272	0.7856					
	GVA_hab	0.676815	0.023381	28.947	<2e-16	***	GVA_hab	-5.061351	0.105187	-48.118	<2e-16	***				
	Pop_density	0.080267	0.007837	10.241	<2e-16	***	Pop_density	1.312576	0.035259	37.227	<2e-16	***				
	Port_dummy	0.177783	0.028142	6.317	2.82e-10	***	Port_dummy	-2.495459	0.126602	-19.711	<2e-16	***				
	Residual standard error:	1.146 on 7265 degrees of freedom						Residual standard error:					5.155 on 7265 degrees of freedom			
Multiple R-squared:	0.2169						Multiple R-squared:					0.4328				
Adjusted R-squared:	0.2162						Adjusted R-squared:					0.4324				
F-statistic:	335.4 on 6 and 7265 DF						F-statistic:					924 on 6 and 7265 DF				
p-value:	<2.2e-16						p-value:					<2.2e-16				
Small regions	Residuals:	Min	IQ	Median	3Q	Max	Residuals:	Min	IQ	Median	3Q	Max				
		-3.2371	-0.5175	0.0058	0.5012	2.8486		-11.8980	-2.9785	-0.5204	2.2358	20.4907				
	Coefficients:	Estimate	Std.	Error	t value	Pr(> t)	Coefficients:	Estimate	Std.	Error	t value	Pr(> t)				
	(Intercept)	-2.224041	0.110160	-20.19	<2e-16	***	(Intercept)	22.424035	0.577597	38.823	<2e-16	***				
	Wind_speed	0.113926	0.005746	19.83	<2e-16	***	Wind_speed	-0.696420	0.030129	-23.114	<2e-16	***				
	Precipitation	0.001914	0.001063	1.80	0.0719	.	Precipitation	0.024260	0.005574	4.353	3.6e-05	***				
	Temperature	0.027560	0.002345	11.75	<2e-16	***	Temperature	-0.062909	0.012297	-5.116	2.0e-07	***				
	GVA_hab	0.326368	0.027713	11.78	<2e-16	***	GVA_hab	-3.172859	0.145305	-21.836	<2e-16	***				
	Pop_density	0.273825	0.008900	31.12	<2e-16	***	Pop_density	2.059841	0.046138	44.645	<2e-16	***				
	Port_dummy	0.363207	0.022059	16.47	<2e-16	***	Port_dummy	-2.497721	0.115658	-21.596	<2e-16	***				
Residual standard error:	0.837 on 7031 degrees of freedom						Residual standard error:					4.389 on 7031 degrees of freedom				
Multiple R-squared:	0.2955						Multiple R-squared:					0.3651				
Adjusted R-squared:	0.2989						Adjusted R-squared:					0.3645				
F-statistic:	500.9 on 6 and 7031 DF						F-statistic:					673.8 on 6 and 7031 DF				
p-value:	<2.2e-16						p-value:					<2.2e-16				
Signif. Codes:	0 '***'	0.001 '**'	0.01 '*'	0.05 '.'	0.1 ''	1										

	Mortality rate						Life expectancy									
	Residuals:	Min	IQ	Median	3Q	Max	Residuals:	Min	IQ	Median	3Q	Max				
Large regions		-6.1596	-1.7834	-0.1721	1.4440	13.1859		-13.1968	-1.5876	0.0699	1.6550	8.7966				
	Coefficients:	Estimate	Std.	Error	t value	Pr(> t)	Coefficients:	Estimate	Std.	Error	t value	Pr(> t)				
	(Intercept)	8.543170	0.289289	29.532	<2e-16	***	(Intercept)	72.652938	0.293276	247.729	<2e-16	***				
	Wind_speed	0.278587	0.020398	13.658	<2e-16	***	Wind_speed	-0.119548	0.020679	-5.781	7.2e-09	***				
	Precipitation	-0.030303	0.004144	-7.313	2.89e-13	***	Precipitation	-0.035758	0.004201	-8.512	<2e-16	***				
	Temperature	-0.086327	0.005331	-16.194	<2e-16	***	Temperature	-0.093318	0.005404	-17.267	<2e-16	***				
	GVA_hab	-0.121710	0.059502	-2.045	0.0408	*	GVA_hab	2.348268	0.060322	38.929	<2e-16	***				
	Pop_density	0.367839	0.018448	19.940	<2e-16	***	Pop_density	0.533219	0.018702	28.512	<2e-16	***				
	Port_dummy	0.022665	0.051894	0.366	0.7142	.	Port_dummy	0.757635	0.062747	12.074	<2e-16	***				
	PM2.5	-0.048595	0.005585	-8.701	<2e-16	***	PM2.5	-0.118959	0.005662	-21.010	<2e-16	***				
GHG	0.237101	0.025126	9.436	<2e-16	***	GHG	0.089194	0.025472	3.502	0.00465	***					
Residual standard error:	2.451 on 7263 degrees of freedom						Residual standard error:					2.485 on 7263 degrees of freedom				
Multiple R-squared:	0.1785						Multiple R-squared:					0.482				
Adjusted R-squared:	0.1776						Adjusted R-squared:					0.4814				
F-statistic:	197.3 on 8 and 7263 DF						F-statistic:					844.6 on 8 and 7263 DF				
p-value:	<2.2e-16						p-value:					<2.2e-16				
Small regions	Residuals:	Min	IQ	Median	3Q	Max	Residuals:	Min	IQ	Median	3Q	Max				
		-10.8065	-1.2509	-0.0621	1.1813	7.4418		-10.4545	-0.7793	0.3411	1.1733	5.0284				
	Coefficients:	Estimate	Std.	Error	t value	Pr(> t)	Coefficients:	Estimate	Std.	Error	t value	Pr(> t)				
	(Intercept)	14.970709	0.286870	52.186	<2e-16	***	(Intercept)	63.609645	0.270958	234.759	<2e-16	***				
	Wind_speed	-0.073804	0.014088	-5.239	1.66e-07	***	Wind_speed	-0.227293	0.013306	-17.081	<2e-16	***				
	Precipitation	0.005412	0.002445	2.213	0.0269	*	Precipitation	0.016223	0.002309	7.025	3.4e-12	***				
	Temperature	0.049757	0.005451	9.128	<2e-16	***	Temperature	0.113059	0.005149	21.959	<2e-16	***				
	GVA_hab	-1.106091	0.066503	-16.632	<2e-16	***	GVA_hab	4.759666	0.062815	75.773	<2e-16	***				
	Pop_density	-0.484786	0.023911	-20.275	<2e-16	***	Pop_density	0.147506	0.022584	6.531	9.7e-11	***				
	Port_dummy	0.066642	0.053393	1.248	0.2120	.	Port_dummy	0.492263	0.050432	9.761	<2e-16	***				
PM2.5	0.033233	0.005232	6.352	2.26e-10	***	PM2.5	-0.105425	0.004942	-21.335	<2e-16	***					
GHG	-0.271965	0.027431	-9.914	<2e-16	***	GHG	0.075019	0.025910	2.895	0.0038	**					
Residual standard error:	1.922 on 7029 degrees of freedom						Residual standard error:					1.815 on 7029 degrees of freedom				
Multiple R-squared:	0.2029						Multiple R-squared:					0.6014				
Adjusted R-squared:	0.202						Adjusted R-squared:					0.6009				
F-statistic:	223.7 on 8 and 7029 DF						F-statistic:					1326 on 8 and 7029 DF				
p-value:	<2.2e-16						p-value:					<2.2e-16				
Signif. Codes:	0 '***'	0.001 '**'	0.01 '*'	0.05 '.'	0.1 ''	1										

Appendix 3: Model results for traffic size and specialization

	GHG emissions						PM2.5 concentration						
	Residuals:	Min	1Q	Median	3Q	Max	Residuals:	Min	1Q	Median	3Q	Max	
		-3.1663	-0.6714	0.0233	0.6355	4.1861		-12.736	-3.200	-0.801	2.382	42.852	
Large regions	Coefficients:	Estimate	Std.	Error	t value	Pr(> t)	Coefficients:	Estimate	Std.	Error	t value	Pr(> t)	
	(Intercept)	-3.1836675	0.1520125	-20.943	<2e-16	***	(Intercept)	28.292401	0.779266	36.306	<2e-16	***	
	Wind_speed	0.0006725	0.0116219	0.058	0.95386	.	Wind_speed	-0.723059	0.059578	-12.237	<2e-16	***	
	Precipitation	0.0085060	0.0020915	4.067	4.85e-05	***	Precipitation	0.022319	0.010722	2.082	0.037431	*	
	Temperature	0.0472279	0.0029103	16.228	<2e-16	***	Temperature	0.067562	0.014919	4.528	6.11e-06	***	
	GVA_hab	0.5945499	0.0317151	18.747	<2e-16	***	GVA_hab	-3.492197	0.162582	-21.480	<2e-16	***	
	Pop_density	0.1349703	0.0102057	13.225	<2e-16	***	Pop_density	0.997147	0.052318	19.059	<2e-16	***	
	Traffic	0.1617540	0.0106468	15.193	<2e-16	***	Traffic	-0.329578	0.054579	-6.039	1.69e-09	***	
	Container	-0.0098377	0.0012821	-7.673	2.07e-14	***	Container	-0.022529	0.006572	-3.428	0.000614	***	
	Solid	0.0031901	0.0010279	3.104	0.00192	**	Solid	-0.018293	0.005269	-3.472	0.000522	***	
	Liquid	-0.0030430	0.0010521	-2.892	0.00384	**	Liquid	-0.019803	0.005393	-3.672	0.000244	***	
	Passenger	-0.0135757	0.0009786	-13.872	<2e-16	***	Passenger	-0.009753	0.005017	-1.944	0.051952	.	
	ECA_zone	0.4390171	0.0381922	11.495	<2e-16	***	ECA_zone	-2.033973	0.195786	-10.389	<2e-16	***	
	ATT	0.0299926	0.0053068	5.652	1.69e-08	***	ATT	0.119471	0.027204	4.392	1.15e-05	***	
	Residual standard error:	0.9821 on 4204 degrees of freedom						Residual standard error:	5.035 on 4204 degrees of freedom				
Multiple R-squared:	0.3953						Multiple R-squared:	0.3528					
Adjusted R-squared:	0.3936						Adjusted R-squared:	0.351					
F-statistic:	229 on 12 and 4204 DF						F-statistic:	191 on 12 and 4204 DF					
p-value:	<2.2e-16						p-value:	<2.2e-16					
Small regions	Residuals:	Min	1Q	Median	3Q	Max	Residuals:	Min	1Q	Median	3Q	Max	
		-2.66529	-0.46280	0.00408	0.53912	4.60591		-10.2336	-2.1376	-0.3489	1.5072	19.8245	
	Coefficients:	Estimate	Std.	Error	t value	Pr(> t)	Coefficients:	Estimate	Std.	Error	t value	Pr(> t)	
	(Intercept)	-3.3539896	0.1624382	-20.648	<2e-16	***	(Intercept)	15.028584	0.694146	21.967	<2e-16	***	
	Wind_speed	0.1001921	0.0084630	11.839	<2e-16	***	Wind_speed	-0.278101	0.035644	-7.802	8.45e-15	***	
	Precipitation	0.0030555	0.0014618	2.090	0.0367	*	Precipitation	0.016450	0.006157	2.672	0.007584	**	
	Temperature	0.0445778	0.0043677	10.206	<2e-16	***	Temperature	-0.032416	0.018396	-1.762	0.078147	.	
	GVA_hab	0.2570628	0.0493709	5.207	2.06e-07	***	GVA_hab	-3.403801	0.207937	-16.369	<2e-16	***	
	Pop_density	0.1753421	0.0128535	13.642	<2e-16	***	Pop_density	1.1532619	0.054136	29.419	<2e-16	***	
	Traffic	0.1416695	0.0010253	14.131	<2e-16	***	Traffic	-0.234005	0.042224	-5.542	3.26e-08	***	
	Container	-0.0006921	0.0011810	-0.755	0.4501	.	Container	-0.016615	0.004974	-3.340	0.000848	***	
	Solid	0.0098657	0.0008833	11.169	<2e-16	***	Solid	-0.001918	0.003720	-0.516	0.606217	.	
	Liquid	-0.0004921	0.0009077	-0.542	0.5878	.	Liquid	0.008263	0.003623	2.162	0.030738	*	
	Passenger	-0.0062564	0.0007814	-8.006	1.70e-15	***	Passenger	0.006876	0.003291	2.089	0.036775	*	
	ECA_zone	-0.2510329	0.0466908	-5.378	8.15e-08	***	ECA_zone	-0.888024	0.196849	-4.516	6.56e-06	***	
ATT	0.0524136	0.0053244	9.844	<2e-16	***	ATT	0.004915	0.022425	0.219	0.826521	.		
Residual standard error:	0.7901 on 2876 degrees of freedom						Residual standard error:	3.328 on 2876 degrees of freedom					
Multiple R-squared:	0.4662						Multiple R-squared:	0.3635					
Adjusted R-squared:	0.4641						Adjusted R-squared:	0.361					
F-statistic:	226.8 on 12 and 2876 DF						F-statistic:	149.1 on 12 and 2876 DF					
p-value:	<2.2e-16						p-value:	<2.2e-16					
Signif. Codes: 0 '***'	0.001***	0.01**	0.05*	0.1*	1								

	Mortality rate						Life expectancy						
	Residuals:	Min	1Q	Median	3Q	Max	Residuals:	Min	1Q	Median	3Q	Max	
		-5.8112	-1.4972	-0.0618	1.2101	12.8848		-12.819	-1.351	0.125	1.610	7.505	
Large regions	Coefficients:	Estimate	Std.	Error	t value	Pr(> t)	Coefficients:	Estimate	Std.	Error	t value	Pr(> t)	
	(Intercept)	9.831382	0.419425	23.440	<2e-16	***	(Intercept)	71.485056	0.404302	176.811	<2e-16	***	
	Wind_speed	0.069464	0.027620	2.515	0.01940	*	Wind_speed	-0.051666	0.026624	-1.941	0.05238	.	
	Precipitation	-0.018353	0.004897	-3.748	0.000181	**	Precipitation	-0.029037	0.004720	-6.152	8.37e-10	***	
	Temperature	-0.057228	0.007030	-8.140	5.15e-16	***	Temperature	-0.116917	0.006777	-17.253	<2e-16	***	
	GVA_hab	-0.182014	0.080507	-2.261	0.023819	*	GVA_hab	2.512340	0.077604	32.374	<2e-16	***	
	Pop_density	0.364617	0.025405	14.352	<2e-16	***	Pop_density	0.413543	0.024489	16.887	<2e-16	***	
	Traffic	0.059351	0.025609	2.318	0.020520	*	Traffic	0.008154	0.024686	12.483	<2e-16	***	
	Container	-0.032374	0.003020	-10.719	<2e-16	***	Container	-0.021119	0.002911	-7.254	4.78e-13	***	
	Solid	-0.016977	0.002406	-7.056	1.99e-12	***	Solid	-0.022979	0.002319	-9.908	<2e-16	***	
	Liquid	-0.013236	0.002464	-5.373	8.18e-08	***	Liquid	-0.019587	0.002375	-8.248	<2e-16	***	
	Passenger	-0.008179	0.002339	-3.497	0.000476	**	Passenger	-0.006435	0.002255	-2.854	0.004034	**	
	ECA_zone	0.190262	0.091545	2.078	0.037739	*	ECA_zone	-1.869046	0.088245	-21.180	<2e-16	***	
	ATT	0.013710	0.012473	1.099	0.271741	.	ATT	-0.023097	0.012023	-1.921	0.05479	.	
	GHG	0.10870	0.036091	3.072	0.002140	**	GHG	-0.122558	0.006786	-18.059	<2e-16	***	
PM2.5	-0.084933	0.007040	-12.064	<2e-16	***	PM2.5	-0.021639	0.034789	-0.622	0.53397	.		
Residual standard error:	2.293 on 4202 degrees of freedom						Residual standard error:	2.211 on 4202 degrees of freedom					
Multiple R-squared:	0.1802						Multiple R-squared:	0.4989					
Adjusted R-squared:	0.1775						Adjusted R-squared:	0.4972					
F-statistic:	65.98 on 14 and 4202 DF						F-statistic:	298.8 on 14 and 4202 DF					
p-value:	<2.2e-16						p-value:	<2.2e-16					
Small regions	Residuals:	Min	1Q	Median	3Q	Max	Residuals:	Min	1Q	Median	3Q	Max	
		-4.3546	-1.2461	-0.1479	1.1108	7.2897		-7.8477	-0.5659	0.2722	0.9664	4.2429	
	Coefficients:	Estimate	Std.	Error	t value	Pr(> t)	Coefficients:	Estimate	Std.	Error	t value	Pr(> t)	
	(Intercept)	8.758015	0.3999640	21.891	<2e-16	***	(Intercept)	77.3356651	0.3517493	219.860	<2e-16	***	
	Wind_speed	-0.1337066	0.018923	-7.077	1.84e-12	***	Wind_speed	-0.1233779	0.0166149	-7.426	1.47e-13	***	
	Precipitation	0.0115457	0.0031673	3.645	0.000272	**	Precipitation	0.0091722	0.0027855	3.293	0.00100	**	
	Temperature	0.0323943	0.0096149	3.369	0.000764	**	Temperature	0.0865502	0.0084558	10.236	<2e-16	***	
	GVA_hab	0.3522157	0.119134	3.147	0.001665	**	GVA_hab	2.7539112	0.0984225	27.981	<2e-16	***	
	Pop_density	-0.2528487	0.0327082	-7.730	1.47e-14	***	Pop_density	0.2029227	0.0287653	7.054	2.16e-12	***	
	Traffic	0.0907745	0.0224939	4.036	5.59e-05	***	Traffic	-0.0542379	0.0197823	-2.742	0.00615	**	
	Container	-0.0163747	0.0025589	-6.408	2.11e-09	***	Container	-0.0016169	0.0022504	-0.718	0.47253	.	
	Solid	0.0033517	0.0019508	1.718	0.085893	.	Solid	0.0005865	0.0017157	0.342	0.73250	.	
	Liquid	0.0001795	0.0019641	0.091	0.927170	.	Liquid	0.0012346	0.0017274	0.715	0.47483	.	
	Passenger	-0.0057670	0.0017089	-3.375	0.000749	**	Passenger	0.0060897	0.0015029	4.052	5.22e-05	***	
	ECA_zone	0.7678478	0.0187000	7.538	6.38e-14	***	ECA_zone	-1.1687847	0.0895898	-13.046	<2e-16	***	
ATT	0.0104663	0.0117057	0.894	0.371334	.	ATT	-0.0413447	0.0102946	-4.016	6.07e-05	***		
GHG	0.1057549	0.0095923	11.025	<2e-16	***	GHG	-0.0769772	0.0084360	-9.125	<2e-16	***		
PM2.5	-0.3482413	0.0404003	-8.620	<2e-16	***	PM2.5	0.3718072	0.0355301	10.465	<2e-16	***		
Residual standard error:	1.708 on 2874 degrees of freedom						Residual standard error:	1.502 on 2874 degrees of freedom					
Multiple R-squared:	0.1464						Multiple R-squared:	0.4953					
Adjusted R-squared:	0.1423						Adjusted R-squared:	0.4928					
F-statistic:	35.21 on 14 and 2874 DF						F-statistic:	2014 on 14 and 2874 DF					
p-value:	<2.2e-16						p-value:	<2.2e-16					
Signif. Codes: 0 '***'	0.001***	0.01**	0.05*	0.1*	1								