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

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Abstract

Despite the skyrocketing growth of environmental studies in recent decades about ports and shipping, the local health impacts of ports remain largely under-researched. This article wishes to tackle this lacuna 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 bulks and passengers, are analyzed jointly with data on natural conditions, air pollution, socio-economic features, and public health. Main results show that port regions pollute more than non-port regions on average, while health impacts vary according to the size and specialization of port regions. Three types of port regions are clearly differentiated, of which industrial, intermediate, and metropolitan port regions.

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

1. Introduction

The environmental impacts of ports and shipping have attracted a growing attention in recent decades. In 1993 already, the International Association Cities and Ports entitled 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. Rising environmental concerns often motivated, alongside a wide range of other technical, technological, spatial, and socio-economic considerations, 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).

Pollution (such 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, but also a magnet for industrial and logistic activities, as illustrated by numerous growth pole and free-zone policies in the 1970s in Western countries and more evidently in Asia. Industrial and port activities serve traditional port cities by trucks at distance, while creating new pressures on suburban settlements.

As numerous ports remain urban, research on environmental issues in port cities has been very dynamic in the last two decades (Carpenter and Lozano, 2020; Wagner, 2019; Zheng et al., 2020). Specific aspects were explored, such as green industrial maritime transport transformation (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), sustainability of port and port-city plans (Schipper et al., 2017), and stakeholder perspectives on port city sustainable development (Lam and Yap, 2019).

This surge of 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 measurement tools to quantify and map pollutions of all kinds (Azarkamand et al., 2020; Contini and Merico, 2021). For seaport pollution and the correlated health concerns on the local population prevention, the set of technical and organizational solutions available to the port community is very diverse, to improve the fluidity and safety of passenger and goods flows and to lean 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 left aside 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 them deal with a port city in Italy, where the interplay between environmental assessment and risk for 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 them are in fact health impact assessments looking at health risk factors but without an explicit and direct analysis of actual health effects on the population (Allen, 2014). More likely are studies about the health impacts of shipping onboard, including the crew and passengers (Mouchtouri et al., 2010; Akamangwa et al., 2016; Lloret et al., 2021).

The concept of “environmental health” (OMS Europe, 1994) includes all environmental concerns that can influence *life quality* such as air pollution (interconnection between local population and their environment), and the one of “vulnerability” refers to

potential impacts or tangible effects on the local population (Lo Prete, 2015). But, while environmental health focuses mainly on environmental factors that may affect health (e.g., air pollution causing respiratory diseases), the notion of vulnerability also focuses on people who would suffer from the threats or tangible effects of port development as a potential or real effect which would therefore affect public health. This distinction is important to understanding how, today, the health question in a port context cannot be separated from the environmental question and must be considered in an encompassing manner (Jeanjean 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

When it comes to health and ports, studies were conducted at the global scale dealing with ship emissions and mortality (Corbett et al., 2007). The literature includes several health impact studies of industrial activities but with no specific mention of ports (Martuzzi et al., 2014; Mudu et al., 2014; Domingo et al., 2020; Marquès et al., 2020). The same applies to 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 proposed 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 merchant vessel movements and a full set of environmental, socio-economic, geographic, and demographic indicators to run multivariate analyses of such impacts at the scale of small regions (of which cities) and large regions. 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 as a benchmark to pursue more qualitative research at thinner scales on actual environmental and health protection practices.

The remainders of this article are 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 about the lessons learned and propose further research pathways.

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

Most activities taking place in the 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, bringing 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 designed under Marpol convention, annual SO_x emissions from ships accounted for 4-9% of the 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. In particular, ultrafine particles from cruise ships and ferries (especially at ports such as Barcelona, Palma de Mallorca, Venice, Civitavecchia, Southampton, Lisbon, etc.) may cause specific problems both to occupational health for dockworkers and for 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 that pollution from ships concentrates 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 that their turnaround time is a crucial factor of pollution, especially concerning NO_x (Sorte et al., 2019), but also PM

concentration, which may culminate to 7-26% in Asian ports (Chen et al., 2019; Zhang et al., 2022). The terminal area itself, port-related industries and logistics also participate to 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) quantified the contribution of these emissions to ambient air quality (i.e., ship, terminal, road traffic, refineries), and in the latter study it was 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 ship loading with food grains emits important amounts of PM, representing potential danger for populations living in the close vicinity of the harbor (e.g., fertilizers, pesticides, mycotoxins and microflora).

Cruise shipping, which has been a fast-growing sector in the last 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 crew members (Lloret et al., 2021). When it comes to container vessels, not all port cities use rail or river 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 much imbalanced 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, methodologies on how ship emissions impact air quality and human health are well established and used in cost-benefit analyses of policy proposals (Nazmus et al., 2021). The effect of large-scale air pollution emission changes on ecosystem, human health, and 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 conducted on-site sampling campaigns and quantitatively evaluated 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, 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 effects of emission regulations (Anastasopoulos et al., 2023). There is a strong difficulty to disentangle the contribution of each source to total local pollution, due to complex interactions among them and 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) to measure the contribution of road traffic and shipping related emissions to total air quality and annual mean population exposure in Hamburg. Merico et al. (2019) proposed a system integrating dispersion modelling and measures issued from both meteorological stations and traffic data inside the harbor. Despite their regular advances, 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 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) located at distance due to topography (Vigotti et al., 2014). According to Viana et al. (2020) in their study of eight Mediterranean cities, 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 period 2001-2016 to demonstrate that air pollution from U.S. ports affects health outcomes but differ by race, as respiratory hospital visits, heart-related visits, and psychiatric visits are three times higher for Black people than for whites.

The level of detail and diversity of measures offered by these studies largely explain the rarity of comparative analyses internationally and 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, we present in the next section the data and methodology capable, for the first time, of running 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 willing to test whether ports regions exhibit a specific profile compared with other regions. Ports may significantly affect pollution and health, but local environmental and health conditions are influenced by other activities and a number of natural and human factors. Impacts may come from activities distinct from the port itself (i.e., terminals) but strongly related to it, like industries, logistics, and the concentration of population. However, numerous new terminals have been developed in the periphery, at 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 differentiate traffic types. Those act as “supply chains” 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 for trucks to go through. The consideration of traffic types is also important because of their particular regional branching and industrial relatedness (Ducruet and Itoh, 2016). Bulks shall be produced or consumed more locally by heavy industries, compared with containers that feed more distant customers or concentrate in dense urban regions (Guerrero, 2014). Cruise shipping, which takes place within port cities, implies long turnaround times for vessels during port stay, as well as important road traffic for tourists (Tichavska and Tovar, 2015).

3.2) Global database

The proposed international perspective 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, which 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, which 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 allows calculating ship traffic at ports in total 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 recognized as 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 (µm/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 natural conditions locally. Those were collected from the website Copernicus¹, a dataset providing daily surface meteorological data for the period from 1979 to present. Among all possible indicators, we retained the most relevant to study port pollution, namely temperature, wind speed, and precipitations. The method has been to calculate the yearly average for each region from individual station data, using QGIS and the shapefiles of regions. While temperature is known to increase pollution (Zhao et al., 2020), wind speed and precipitations reduce it by dispersion and dilution

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

(Liu et al., 2017; Zhang et al., 2023). Such effects were tested via several control variables, scoped to those shown in Table 2. The retained health indicators 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 may vary between the variables, as shown in a recent study on employment and traffic specialization in French port cities (Amdaoud et al., 2022). Descriptive statistics for the retained indicators are provided in Appendix 1.

3.3 Statistical analysis

As a cross-sectional and time-series study (2001-2018), the best method to verify the hypotheses was a regression analysis of panel data. The main reason 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. The detailed statistical results are provided in the appendices, while in-text tables provide the estimates and significance only.

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 and like 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, a number of other variables were transformed into location quotients to avoid the

geographic or national bias when comparing regions (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

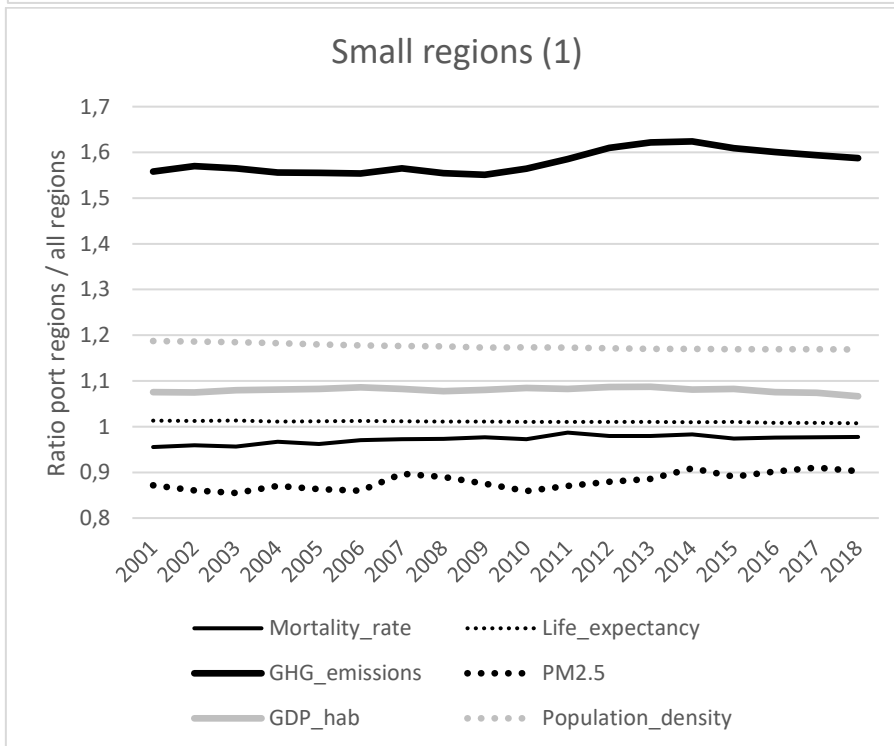
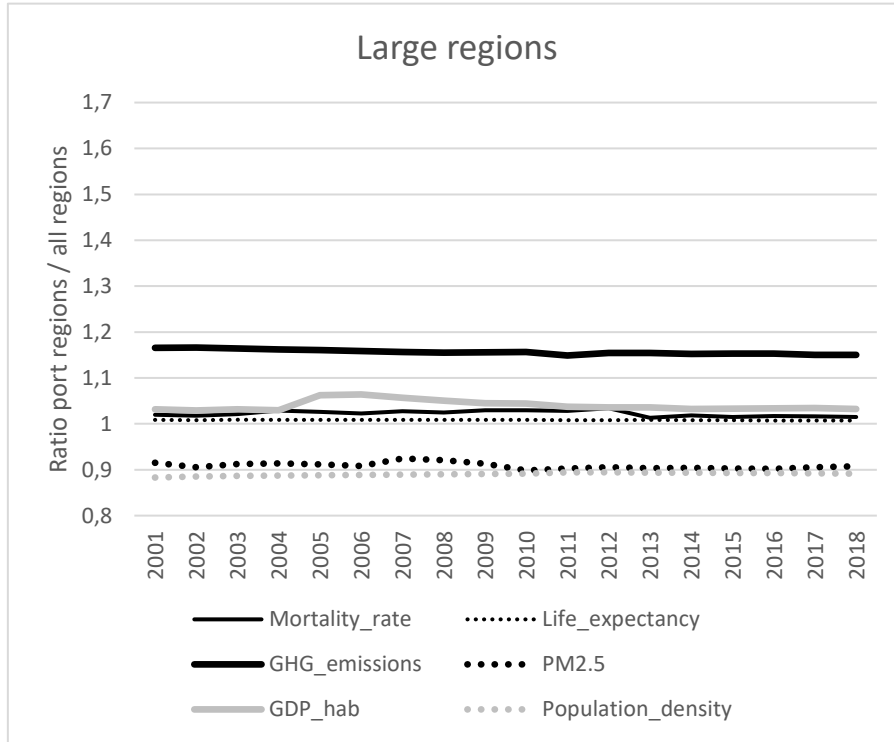
4.1 The effect of having a port

The first analysis focuses on the port dummy to verify its effect on environmental and health conditions. For the main environmental, health, and socio-economic variables, we calculated the ratio between the average score of port regions and the average score of all regions (Figure 1). This allows to answer positively the fundamental question about 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 account for a direct and causal effect of ports, environmental issues are more critical for smaller territories having a port. This is not the case of 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, the exposure to such emissions.

However, health indicators show no specificity, except the mortality rate that is lower than average for small port regions, while life expectancy is more or less the same between port and non-port regions. At this stage, it is only possible to establish links between GHG emissions and the concentration of population and economic activities when a region has a port. The relationship with health conditions needs further investigation using other 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

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

specialization of these regions in other activities than trade, like agriculture, culture and tourism. 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).



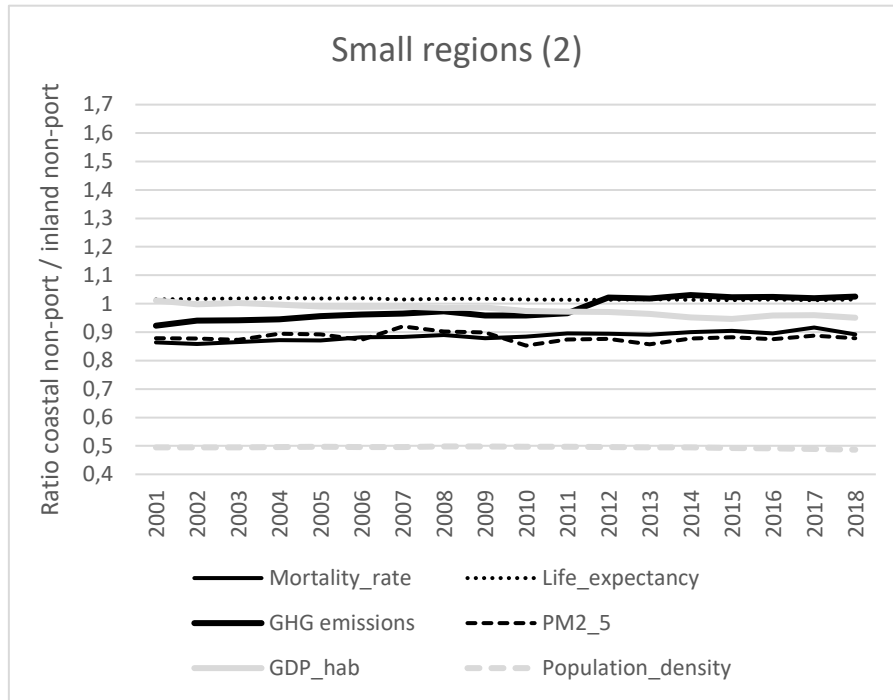


Figure 1: Comparison of port and non-port regions, 2001-2018

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 sources. One reason is that PM_{2.5} emissions in port regions are, at least partly, blown away by stronger winds along the coast⁴. This is well apparent in Table 3 as wind speed is significantly and negatively influencing PM_{2.5} concentration. Higher temperatures foster GHG emissions, in accordance with 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 for port-related traffic (e.g., heavy-duty vehicles) and urban traffic to create bottlenecks, especially at peak hours along the most frequented road arteries.

³ See appendices 2 and 3 for full statistical results.

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

		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 ***
	PM2.5	-	-	-	0.237101 ***
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 ***
	PM2.5	-	-	-	-0.271965 ***
Signif. Codes: 0 '* 0.001'***' 0.01 '**' 0.05 '.'				1	

Table 3: Model results with port dummy

Secondly, the port dummy is confronted with health indicators. For mortality rate, it is positive but not significant, while for life expectancy it is always positive and significant. What looks like a contradiction could signify that the port effect will differ according to more complex phenomena 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. It is worthy of investigation to include air pollution indicators in the model. 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. It shows that the aggravating effect of GHG on health is more “local” (small regions) while the one of PM_{2.5} is more spread inland (large regions). Such results can be linked with the fact that wind speed significantly reduces mortality at small regions. However, the unavailability of additional data, such as 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.

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 passengers⁶ handled at ports is thus contributing to local air pollution. It 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 the 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 at small and large regions, while GVA per capita decreases it.

The use of cold ironing⁷ is a widely applied remedy to air pollution (Gonzalez-Aregall et al., 2018), alongside improvements in the productivity of cargo handling vehicles. The results by traffic types are much contrasted according to the territorial level and the type of air pollution. Solid bulk traffic fosters GHG emissions in small and large regions, however, although it is more recognized as a source of PM_{2.5} in the literature and in practice. Liquid bulk and passenger traffic reinforce PM_{2.5} concentration in

⁶ In this study, the use of ship tonnage capacity allows measuring 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.

small regions only. This is in accordance with practice, since such traffics produce Volatile Organic Compounds (VOCs) like from bulks during handling and storage. Especially during the loading and unloading of tanker ships, VOCs (methane and nonmethane) contribute to GHG emissions. 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).

		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 ***	-3.492197 ***	-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 **	0.0115457 ***	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 ***
	Signif. Codes: 0 '***'	0.001 '**'	0.01 '*'	0.05 '.'	0.1 ''

Table 4: Model results with traffic size and specialization

Cruise shipping is one notable cause of PM_{2.5} emissions (Lloret et al., 2021), which 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 have a crucial role given that numerous passengers stay onboard large cruise ships during hoteling.

When it comes to health, total traffic accentuates mortality and life expectancy for large regions, while it accentuates mortality and reduces life expectancy for smaller regions, which is a reasonable result since populations in small regions are more exposed to ports. Average turnaround time increases mortality and decreases life expectancy, which is also conform with experience. GVA per capita and population density increase life expectancy, but for mortality the results are opposed between large and small regions. This indicates that economic development may promote environmental awareness and medical levels, thereby improving health. Another important result is that GHG emissions generally reduce life expectancy, and increase mortality in large regions only.

All traffic types lower both mortality and life expectancy in large regions, while for small regions, bulks (solid and liquid) increase mortality. The same goes 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 thinner geographic scale.

4.3 Towards 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 sis highly similar between large and small regions. It 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 concentrates in large port-city regions as 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 comforting this profile of “port metropolis”.

Natural elements only have a marginal role on pollution and health in the figure. In terms of health, mortality rate and life expectancy are opposed in a logical manner. Moreover, mortality is close to liquid and solid bulks in the upper-left quadrant. Although there is no possibility to establish a causal relationship, such a result confirms that bulks produce VOCs during cargo handling (coal, grain, ores, oil) that spread throughout the city’s atmosphere and get mixed with urban pollution. Without protection, conveyor belts carrying coal or iron ore between port and plants provoke leaks and emissions during loading and unloading. For tankers, VOCs (methane and nonmethane) contribute to GHG emissions. Among them, the heavier components (nonmethane) contribute to photochemical oxidants like ozone, which affects human health, food production, and the environment.

Despite intermodalism permitted 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 implementing a modal shift towards short-sea shipping. These flows generate congestion, against which it is possible to fight through the use of various systems to track trucks and better regulate traffic, but also booking systems, automated door systems, as well as inter-terminal barge or rail shuttles (Gonzalez-Aregall et al., 2018). For inland navigation, modal shift is an important option, but also 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 favor green modes (van den Berg and de Langen, 2014).

Average ship turnaround time (ATT) is close to total traffic and GHG emissions in a logical way, since the bigger the demand (population density, GVA per capita), the bigger the 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,

Alamouh et al. (2020) estimated that such systems allow to 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).

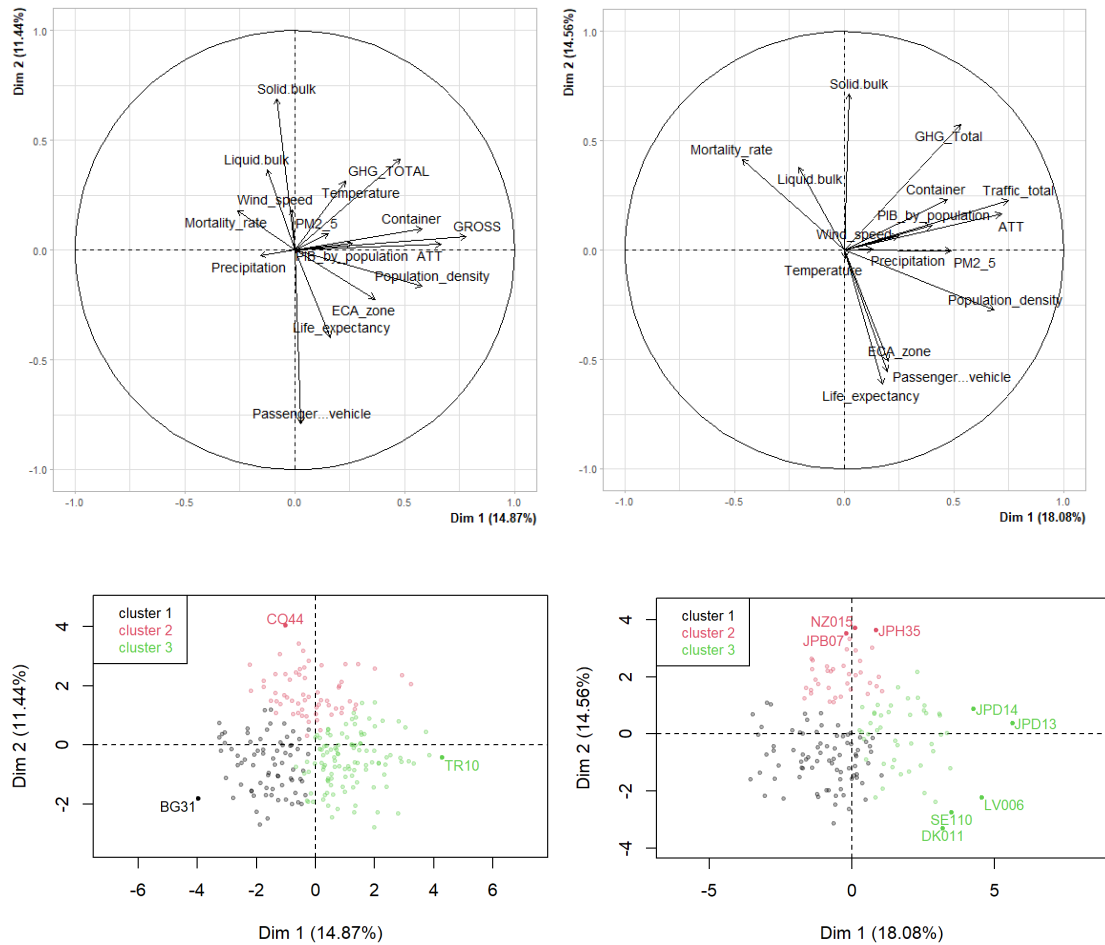


Figure 2: Factor analysis and classification in 2018

N.B. 245 large regions (left) and 164 small regions (right)

At last, 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 benefiting from 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., Baltic Sea). A disaggregation by traffic subtypes is necessary to check the

specific role of cruise compared with ferries, ro-ro, and vehicle traffic, as a path for further research.

4.3.2 Clusters of port regions

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

At the opposite 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 important traffic volumes, but this traffic is mainly composed of solid and liquid bulks, i.e., lower-valued and more polluting traffic. What is more, such regions are not so much part of ECA zones, given their lowest score in this category. Industrial port regions are also characterized by a low population density, given the location of plants and factories away from major urban settlements. They rank relatively high for GDP 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.

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

Between those two types, intermediate port regions do not witness a specific profile. They rank high only for a few variables, such as passenger and vehicle traffic. More 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, and possible spatial regularities.

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

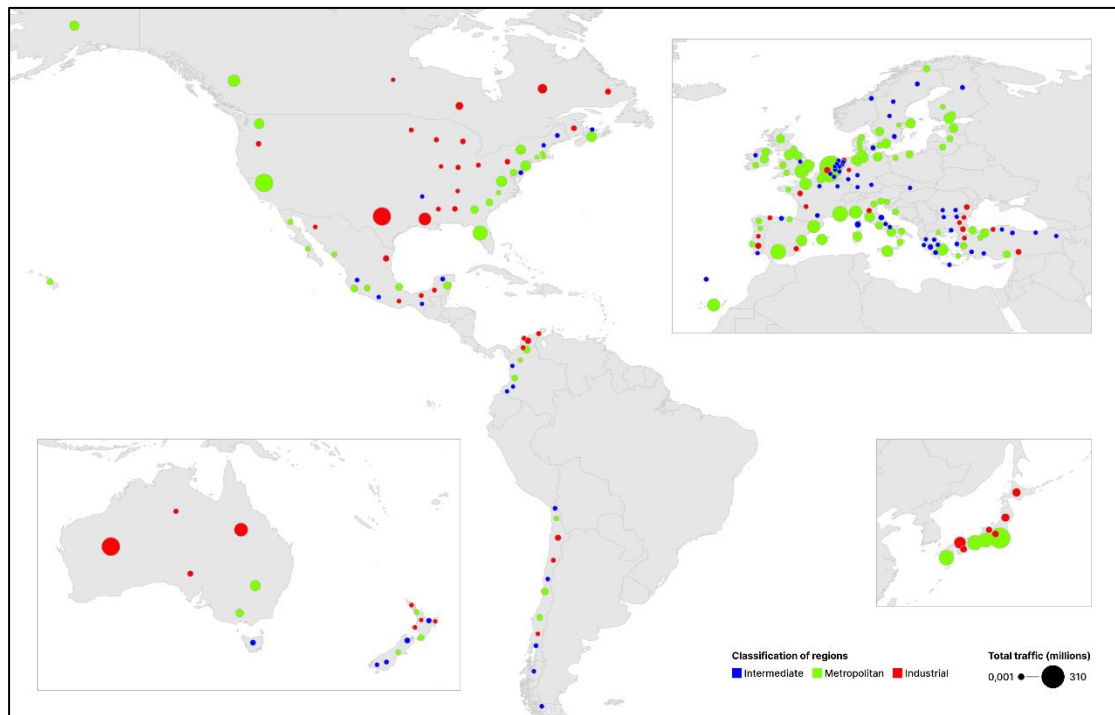


Figure 3: Typology of large port regions in 2018

The typology of large regions (Figure 3) reveals interesting spatial patterns across the globe. First of all, metropolitan port regions concentrate 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 willing to improve the environmental performance of their hinterland. Another global review on emission reduction and energy efficiency improvement concluded that European ports prevail in the literature, before North American and Asian ports (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 of the most urbanized states like New York, Florida, California, as well as British Columbia in Canada.

Comparatively, industrial port regions in Europe concentrate along the Atlantic Ocean and the Black Sea, with only a couple of them in North 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 USA and Canada. Like for Australia, two large regions specialized in bulks also belong to this category, namely Texas and Louisiana.

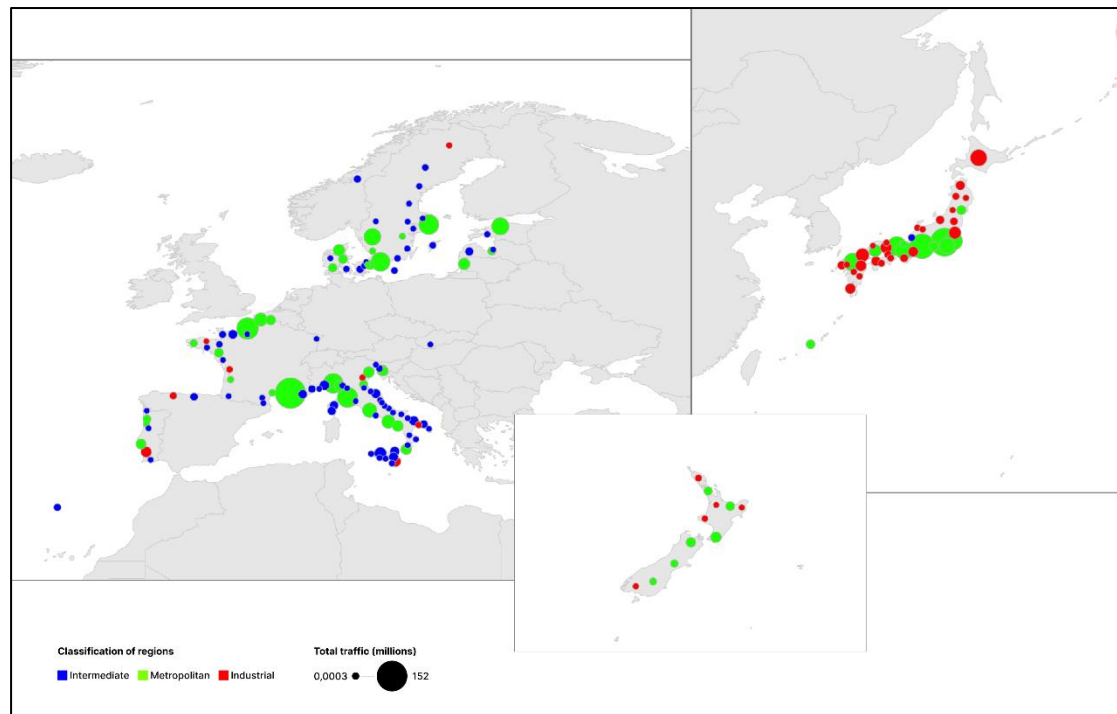


Figure 4: Typology of small port regions in 2018

For small regions (Figure 4), data was available only for parts of Europe, New Zealand, and Japan. This explains at least in part the country bias whereby most industrial port regions concentrate in Japan. The rest of Japan is composed of metropolitan port regions situated along the so-called megalopolis from Fukuoka to Tokyo. Such a pattern for Japan is likely to be explained by the ageing population, which accentuates mortality rates outside of the megalopolis.

In Europe, the industrial port region with the maximum traffic is Alejento in Portugal, with the port of Sines having 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 a sheer 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, 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 environmental impacts. This work is challenging 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 whole territory around the port rather than the port itself. Finding a link between port activities and local pollution/health thus makes the study successful in many ways.

By putting together data from the OECD and the Lloyd's List at the level of subnational regions, main results confirm that port regions pollute more than non-port regions, in particular for 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 accordance 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}) together with traffic volume and traffic types corroborate practice in many ways, as GHG emissions increase mortality in all cases, and PM_{2.5} lowers life expectancy, although it is not proved that such pollutions come from the port itself. It is one future task of further research to complement traffic with ship pollution data, at the condition that we access additional information 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 class of “metropolitan port regions” depicts the concentration of population, socio-economic activities, traffic volume (notably containers), and GHG emissions. Such regions also witness the lowest mortality rates and often situate within Emission Control Areas (ECAs), namely in Europe and North America. They stand in direct opposition with “industrial port regions”, which specialize in bulk traffic, have the worst sanitary 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 with no particular profile except from a specialization in vehicle and passenger traffic.

The main implication of those 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. Three main directions for improvement are proposed to refine and deepen current results.

First, the population under study may 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 whole OECD area. This dimension is important, as the social and economic insecurity engendered by port development concerns above all the precarious classes (De Lara, 2018), and the impact of air pollution is larger among the poorest (Suarez-Castillo, 2023). As health indicators are very sensitive to the age structure of population, their decomposition by age groups would be a prerequisite to better check the impact of air pollution. Data about the access to and availability of medical healthcare, 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 shall make it possible to integrate new variables on port city topography and morphology for instance, wind direction, 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 towards 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	1Q	Median	3Q	Max	Residuals:	Min	1Q	Median	3Q	Max	
		-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	0.0016	**	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				
	Residuals:	Min	1Q	Median	3Q	Max	Residuals:	Min	1Q	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	0.008800	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:	0.2995						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	1Q	Median	3Q	Max	Residuals:	Min	1Q	Median	3Q	Max	
		-6.1596	-1.7834	-0.1721	1.4440	13.1853		-13.1968	-1.5876	0.0639	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	0.004444	-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	0.061894	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				
	Residuals:	Min	1Q	Median	3Q	Max	Residuals:	Min	1Q	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	0.432263	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
Large regions		-3.1663	-0.6714	0.0233	0.6355	4.1861		-12.736	-3.200	-0.801	2.382	42.852
	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	0.016219	0.058	0.95386	.	Wind_speed	-0.729059	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	0.0361922	11.495	<2e-16	***	ECA_zone	-2.033973	0.195786	-10.389	<2e-16	***
	ATT	0.0239926	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	2.60591		-10.2336	-2.1376	-0.3489	1.5072	19.6245
	Coefficients:	Estimate	Std.	Error	t value	Pr(> t)	Coefficients:	Estimate	Std.	Error	t value	Pr(> t)
	(Intercept)	-3.353896	0.1624382	-20.648	<2e-16	***	(Intercept)	15.028584	0.684146	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	1.532619	0.054136	23.419	<2e-16	***
	Traffic	0.1416695	0.0100253	14.131	<2e-16	***	Traffic	-0.234005	0.042224	-5.542	3.26e-08	**
	Container	-0.0008921	0.0018910	-0.755	0.4501	.	Container	-0.016615	0.004974	-3.340	0.000848	**
	Solid	0.0098857	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	0.003823	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	-0.2510929	0.0466908	-5.378	8.15e-08	***	ECA_zone	-0.888024	0.196649	-4.516	6.56e-06	**
ATT	0.0524138	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:	0.4862						Multiple R-squared:	0.3835				
Adjusted R-squared:	0.4841						Adjusted R-squared:	0.381				
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
Large regions		-5.6112	-1.4972	-0.0618	1.2101	12.8848		-12.819	-1.351	0.125	1.610	7.505
	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	-0.018253	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	0.308154	0.024686	12.483	<2e-16	***
	Container	-0.032374	0.003020	-10.719	<2e-16	***	Container	-0.021189	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	0.002484	-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	0.00434	*
	ECA_zone	0.190262	0.039145	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	0.110870	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)	8.7558015	0.3999640	21.891	<2e-16	***	(Intercept)	77.3356651	0.3517493	219.860	<2e-16	***
	Wind_speed	-0.1337066	0.0188923	-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	2.753912	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	-0.0153747	0.0025589	-6.008	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	0.47493	.
	Passenger	-0.0057670	0.0010789	-3.375	0.000749	**	Passenger	0.0060897	0.0015029	4.052	5.22e-05	**
	ECA_zone	0.7678478	0.018700	7.838	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	-0.0769372	0.0064360	-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							