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Review article

Atmospheric corrosion maps as a tool for designing and maintaining building materials: A review

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HIGHLIGHTS

- Systematic review of atmospheric corrosion maps produced around the world.
- Most important authors, keywords, and parameters in the construction of corrosion maps.
- Methodology to create atmospheric corrosion maps.

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ABSTRACT

Atmospheric corrosion maps can be used to conduct a fast and graphical assessment of material deterioration in specific geographic environments. These maps are a key tool for selecting the most adequate materials in terms of corrosion resistance, maintenance, and cost-efficiency in outdoor constructions. Several studies have evaluated the effects of environmental factors and pollutants on building materials at local, regional, national, and international levels. However, not enough atmospheric corrosion maps are readily available, possibly due to the complexity of the variables that should be considered to construct them, which include weather, meteorological, and pollution-related factors that vary in space and time. This article presents a thorough literature review of atmospheric corrosion maps published between 1971 and 2021 mainly indexed in the Scopus database. It is complemented with a detailed review of books, journals, and projects by research centers that focuses on the methodologies, parameters, and tools that have been used to construct said maps. Most of the available maps are outdated, which highlights the need for new maps that reflect recent global changes in atmospheric pollution and temperature that can intensify metal deterioration in some places.

1. Introduction

It has been reported that one of the most common types of corrosion is atmospheric corrosion, since more than 80% of metallic materials exposed to the aggressive action of the atmosphere are affected by corrosion. The corrosion process in the atmosphere is mainly electrochemical, where the layer of moisture that eventually covers the metal surface constitutes the electrolyte. This layer may range from having a monomolecular thickness to clearly visible and defined water films [1]. On the other hand, on the metal surface, the anodic and cathodic areas present great variability and alternation, which enables corrosion to spread across the surface. Humidity, temperature, time of wetness of the metallic surface and atmospheric constituents such as Sox, Cl^-, and NOx are the factors that most influence atmospheric corrosion [2], [3]

The most common anodic and cathodic reactions can be seen in Eqs. (1) and (2) [4]:

$$Me \rightarrow Me^{n+} + ne^- \text{ (anodic reaction)} \quad (1)$$

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \text{ (cathodic reaction)} \quad (2)$$

In atmospheres with a high degree of contamination by acid pollutants, the main cathodic process is the formation of hydrogen gas as shown in Eq. (3):

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$$2H^+ + 2e^- \rightarrow H_2 \quad (3)$$

A film of corrosion products precipitates when the moisture layer evaporates. The kinetics of the corrosion reactions and the nature of the corrosion products depend on the characteristics of the electrolyte [5], [6].

In addition, the moisture layer is extremely sensitive to the environmental characteristics of the atmosphere. These characteristics constitute what is known as a "macroclimate" (oxygen, humidity, atmospheric agents, wind, and global radiation from the sun) and a "microclimate" (dew formation, time of wetness, and accumulation of acidic ions nature in the moisture layer) [7].

Depending on the level of pollutants and aggressiveness, atmospheric environments can be classified into rural, urban, industrial, marine, marine-urban, and marine-industrial [8].

The most important aggressive agents in atmospheric corrosion are chloride ions and sulfur dioxide [4], [7], [9]. Chlorides coming from marine atmospheres, mainly as aerosols, reach metal surface, thus participate directly in corrosion reactions [4], [10].

Road deicers, coal burning, municipal incinerators, and bleaching plants in the pulp and paper industries are also important sources of chlorides [4], [11].

Sulfur dioxide is the most important gaseous precursor of atmospheric corrosion in industrial and urban atmospheres. It is produced from anthropogenic and natural sources, such as the combustion of fossil fuels (e.g., crude oil and coal) and the emissions of petrochemical, metal, paper, and other industries. Once incorporated into the moisture layer, SO_2 oxidizes to sulfites and sulfates, acidifying and hence increasing the aggressiveness of the electrolyte layer [4], [7]. The corrosivity of chlorides and sulfur dioxide is high because they are easily incorporated into moisture layers formed on metals. On the ither hand, in marine-urban and marine-industrial atmospheres, the greater incidence of chlorides and sulfur dioxide depends on their respective concentrations [7]. Nitrogen oxides (NOx), which are produced by road traffic and energy production, have become more relevant as corrosive agents [12]. NO_2 is less aggressive than sulfur or chloride compounds. Nevertheless, it has a synergistic effect with SO_2 in the corrosion of several metals. In recent decades, the SO_2 concentration in many industrial and urban areas of developed countries has shown a significant decrease, while NO_2 emissions have presented a continuous increase [4]. Ozone is another potentially aggressive atmospheric agent, although relatively less important [13].

The metals used in the construction industry must meet different design and mechanical resistance requirements, and, at the same time, they should be easy to make and low-cost. However, most of these metals present atmospheric corrosion when they are put into service. Some of the most common metals used in the construction industry are carbon steel [11], [14] galvanized steel [5], and aluminum [15].

Due to the great diversity of meteorological conditions and pollutants, the three metals exposed to the atmosphere can show corrosion rates tens and even hundreds of times greater in some places than in others. Among these materials, carbon steel usually corrodes the fastest, with a corrosion rate between 5 and 20 times higher than that of galvanized steel depending on the type of atmosphere [7]. In turn, carbon steel can corrode approximately between 130 and 200 times faster than aluminum in highly-aggressive environments [16].

Corrosion maps provide information about the atmospheric corrosivity of a given geographic environment, which guides the selection of the most adequate materials for outdoor construction projects in those places, as well as their maintenance [17]. Such maps make it easier to identify less or more corrosive environments in a given geographic space in order to select more effective corrosion protection solutions in different sectors, such as: commercial and industrial mining [18]. Thus, the data contained in the maps can support real decision-making strategies regarding the durability of materials.

This literature review covers historical and geographic data of different atmospheric corrosivity maps constructed around the world, particularly those of carbon steel, galvanized steel, and aluminum. This article also reviews the activities, tests, analyses, and tools required to construct this kind of maps.

2. Methodology

First, a systematic literature review was carried out to study the main aspects, methodologies, and rules for the construction of corrosion maps addressed by different authors. Second, a bibliometric analysis was conducted using the Scopus database, and bibliometric networks were constructed to understand author and country trends in the field of atmospheric corrosion maps. We also focused on aspects such as tests, meteorological measurements, statistical treatment, and modeling investigated by some authors. The searches in Scopus were conducted on January 1, 2021, and the results were limited to publications between 1987 and 2021. The search included only atmospheric corrosivity maps and excluded terms related to accelerated corrosion tests. Other corrosion maps constructed throughout history were not found in Scopus, although many of them were included in the references. Therefore, we complemented the search with a detailed review of books, journals, proceedings, and projects by research centers in order to find most atmospheric corrosivity maps constructed throughout history. These maps were published from 1971 to 2021. VOSviewer software (version 1.6.13) was used to analyze co-authorship and keywords in the fields discussed here [19]. Table 1 details the results of each search in Scopus, Table 2 presents the maps found in Scopus between 1987 and 2021, and Table 3 lists the maps found in other sources.

3. Constructing atmospheric corrosion maps

To create a corrosion map, meteorological variables should be measured in the field to establish the deposition rate of the most influential atmospheric pollutants and calculate the corrosion rate of the metals of interest. These data are then statistically processed to categorize the aggressiveness of the environments, obtain correlations, and create the maps using an array of digital tools.

Table 1. Advantages and limitations of statistical procedures in the construction of corrosion maps.

Statistical procedure	Advantages	Limitations	Reference
Multivariable linear regression model	Different types of variables can be included to make predictions of corrosion rates.	• It considers an equal variability in all the sampling locations. • Special attention should be paid to the number of independent variables included in the model.	[47]
Spearman's rank correlation coefficient	It reduces the number of variables.	• Influencing variables in the model could be eliminated.	[48]
Random Forest Analysis (RFA)	It can process a large number of variables and reduce their dimensionality.	• Results interpretation is affected. • The information necessary to construct the model is difficult to obtain. • The model to be implemented is complex.	
Artificial Neural Networks (ANNs)	Competitive learning is based on available information.	• The more variables, the longer the learning time. • Sufficient information must be available to feed the model.	[49]

Table 2. Results of the systematic search.

Search string	Number of publications found		
	Unfiltered	Filter 1	Filter 2
"Atmospheric corrosion" AND "map*" AND "aluminum"	47	23	10
"Atmospheric corrosion" AND "map*" AND "carbon steel" OR "mild steel"	66	45	20
"Atmospheric corrosion" AND "map*" AND "galvanized steel" OR "galvanised steel"	35	31	9
Filter 1: Search string match and abstract reading. Filter 2: Full-text reading.			

For example, in the conservation of cultural heritage is becoming an important topic monitoring and modeling air pollution, allowing reductions in maintenance and restoration costs [20]. Atmospheric corrosion maps are a valuable tool for this purpose.

Table 3. Atmospheric corrosion maps found in Scopus classified by continent.

Location	Year of publication	Reference
ASIA		
India (construction steel)	2021	[63]
Karachi, Pakistan	2020	[64]
Shandong, China	2020	[17]
Industrial zone, Indonesia (construction steel)	2019	[65]
Guangdong Province, China	2019	[66]
Transmission towers, Japan	2017	[67]
Oil refinery, Teheran, Iran	2013	[68]
Iran	2012	[69]
India	2011	[70]
India	2009	[71]
India (update)	2008	[72]
Vietnam	2007	[73]
Kuwait	2007	[74]
Hainan Province, China	2003	[75]
Chengdao, China	2001	[76]
EUROPE		
Slovakia	2019	[77]
Continental mainland, Russia	2019	[78]
Slovakia (construction steel)	2016	[79]
Czech Republic	2015	[80] [81]
Athens, Greece	2013	[82]
Sweden	2012	[83]
Spain (zinc)	2010	[84]
Northern area and border with Russia, Norway	2002	[85]
Catalonia, Spain	1987	[86]
AMERICA		
Chile	2012	[87]
Northern coast of Brazil (steel, galvanized steel, aluminum, and copper)	2007	[88]
Venezuela	2000	[89]
Venezuela	1998	[90]
North Carolina, United States (galvanized steel)	1994	[91]
OCEANIA		
New Zealand	2013	[92]
New Zealand	1990	[93]
AFRICA		
South Africa	2019	[94]
ANTARCTICA		
Antarctica (steel, galvanized steel, aluminum, and copper)	2004	[95]

The most direct and convenient form for users to analyze regional atmospheric corrosion evaluation results is by using atmospheric corrosion maps.

The atmospheric corrosion maps are graphical methods that allow to describe the corrosivity of a regional environment, which can help engineers and users to select the most appropriate anticorrosive materials and suitable anticorrosion coatings [17].

Tidblad [21] reported that atmospheric corrosion of metals could be strongly influenced by the effect of chlorides in coastal areas, as a consequence of climate change. It has been shown that SO_2, Cl^- deposition and temperature changes will have the strongest influence on the increase in corrosivity categories. Corrosion rates will increase especially in areas of high precipitation, despite a decrease in the influence of acid pollutants [22].

3.1. Field evaluations

In field evaluations, metallic specimens are placed on atmospheric test racks for pre-established periods of time to calculate their corrosion rates. The evaluations include the obtention of meteorological data and the pollutant deposition in the places of interest, meeting the requirements of standards such as ISO/TC 156 [23], ISO 8565 [24], and ASTM G50 [25].

No standard defines an exact period of time for field evaluations because material deterioration depends on the aggressiveness of the environment and the material being tested.

However, the tets should last at least one year to be able to classify the atmospheres according to the ISO 9223 standard and let the corrosion process stabilize in order to evaluate the corrosion rate more accurately [8].

Atmospheric corrosion studies use meteorological parameters that include temperature, wind speed and direction, radiation, precipitation and relative humidity.

These data can be provided by universities or nearby meteorological stations. This information can also be measured directly by installing systems such as hygrometers (to evaluate temperature and relative humidity data), pluviometers (to measure precipitation), and anemometers (to measure wind speed and direction). Additionally, pollutant monitoring can be used to characterize the aggressiveness of the atmosphere at each testing location applying ISO 9223 standard [8]. This information can be provided by organizations in charge of this kind of studies or obtained using collectors (or samplers) designed for each type of pollutant.

Samplers are generally simple and hand-made. They can be active or passive: active samplers are employed to take specific measurements in situ, while their passive counterparts are used to monitor a pollutant for a given period.

The collection of air pollutants in passive samplers is based on the permeation or diffusion of the pollutant into an absorbent medium.

The driving force is the concentration gradient between the absorbing surface and the surrounding air, where the pollutants concentration is initially zero [26], [27].

The deposition rate of chlorides in the atmosphere is usually measured using the wet candle method [28] in accordance with the NBR 6211 [29] or the ISO 9225 [30] standards. Similarly, the deposition rate of substances that contain sulfur (SO_2, SO_3, H_2S, and SO_4^{2-}) is evaluated in accordance with the NBR 6921 [31] or the ASTM D 2010 [32] standards. Atmospheric NOx can be measured employing passive samplers [33], which are highly portable and low-cost [34].

In all these cases, the results are expressed in mg of pollutant deposited on the surface of the samplers over a given period of time (mg/m^2day).

In recent years, different studies have explored pollutant monitoring using global information systems. A big challenge for this approach to the development of satellite instruments that provide precise and accurate measurements close to the surface of the earth.

For example, the TROPOMI (Tropospheric Monitoring Instrument) was launched on October 13, 2017, to improve the spatial precision and temporal resolution of SO_2, NO_2, and ozone measurements [35].

3.2. Calculating corrosion rate

Corrosion rate is usually calculated in accordance with the ISO 9226 [36] and the ASTM G-1 [37] standards. The plates made of the metallic material are weighed and then exposed to the environment. After the exposure, the plates are etched (to remove the corrosion products that were generated) and weighed again. Using the two weights, the corrosion rate can be determined employing the following Eq. (4):

$$r_{corr} = \frac{\Delta m}{A^{*}t^{*}\rho} \quad (4)$$

Where:

r_{corr} = corrosion rate (μm/years)
Δm = mass difference (g)
A = area of the sample exposed to the corrosive medium (m^2)
t = time of exposure of the sample to the corrosive medium (years)
ρ = material density (g/cm^3)

3.3. Statistical processing of experimental data

Statistical analyses of corrosion rates, pollutant quantifications, and meteorological data can be used to formulate predictive equations to create corrosion maps and correlate corrosion rates with environmental and pollutant data collected at different exposure locations. These equations help to predict the behavior of different materials regarding corrosion, and they can even be used to extrapolate information obtained in one place to others where field studies have not been conducted.

Different models, known as dose–response functions (DRFs), have been developed in large-scale corrosion exposure projects, including ISOCORRAG and MICAT, to correlate corrosion rates to environmental parameters and pollutants [22] [38]. Nowadays, there are a lot of DRFs for different regions of the world.

They include variables such as time of wetness, relative humidity, rainfall, temperature, sulfur dioxide content and chloride content [39] [40], [41], [97]. These empirical functions can be useful for predictive purposes, as well as constructing and updating atmospheric corrosion maps.

ISO 9223 standard [5] includes DRFs for the first year of exposure and different metals. For example, the DRF of carbon steel in this standard is shown in Eq. (5):

$$r_{corr} = 1.77\,[SO_2]^{0.52}\exp(0.02\,RH + f_{cs}) + 0.102\,[Cl^-]^{0.62}\exp(0.03\,RH + 0.04T) \quad (5)$$

where:

r_{corr} is the corrosion rate (μm/year)
f_{cs} = 0.150 (T-10) when T ≤ 10 °C, otherwise f_{cs} = -0.054 (T-10)
SO_2 is the sulphur dioxide (mg/(m^2 day))
T is the temperature (°C)
RH is the relative humidity (%)
Cl^- is the chloride deposition rate (mg/m^2. day)).

The reliability of corrosion damage prediction by DRFs is currently estimated using statistical methods suggested in ASTM G16 standard [ASTM G16]. Panchenko et al [41] developed other statistical indicators for this purpose and used data on steel and zinc corrosion obtained in continental territories. Several authors [42], [43] have pointed out that, due to the complexity of the relationship between different factors influencing atmospheric corrosion, DRFs are useful to a certain extent.

Multiple statistical procedures are employed to analyze corrosion rates. For instance, Randomized Complete Block Design (RCBD) classifies the experimental units into blocks, selecting the corrosion rate as the response or independent variable, the degree of corrosion as the factor, and the exposure time as the block [44]. Regression models are also used to predict corrosion rate [40], but, when they are implemented, the dimensionality of the variables must be reduced if it is too high.

Some of the methodologies used to reduce these variables are Spearman's rank correlation coefficient, which measures the correlation between two variables of interest, principal component analysis, which reduces a large number of variables to a small one based on their vectors; cluster analysis, which groups variables; and Random Forest Analysis (RFA) [45].

RFA is a learning algorithm that consists of a random number of simple trees that are used to obtain an estimation of a dependent variable, whether continuous or categorical. An advantage of RFA is its capacity to detect the variables that make the largest contributions to the prediction of the dependent variable of interest, which can be used to identify the most important predictor in a group of factors in a study [46].

Artificial Neural Networks (ANNs) are computer structures that model the properties and behavior of brain structures. ANNs are composed of different elements: artificial neurons, links, layers, weights, threshold, and activation functions. Among other purposes, ANNs are used to model experimental data of atmospheric corrosion. To apply this methodology, some steps should be followed: preprocessing the original dataset; dividing the preprocessed dataset into training, validation, and test datasets, establishing, training and testing the architecture of the model, and implementation [79, 80]. However, in corrosion field tests, the sample size is generally not big enough to guarantee a high prediction accuracy when an ANN model is used [42]. In view of the above, it can be said that there is no standard statistical methodology to analyze corrosion rate; hence, the process depends on the objectives that have been set in each particular study, as well as the factors and variables of interest.

In recent years, some researchers have worked on the construction of novel corrosion maps thanks to the different statistical procedures that currently exist for the analysis and prediction of corrosion rates. The selection of these statistical procedures will depend on the number of variables that should be included. In addition, the advantages or disadvantages of each of these methodologies must be taken into account, which will influence the type of corrosion map to be obtained (See Table 1).

For example, Wanida Pongsaksawad et al. [47] built a web application of the corrosion map of Thailand derived from a multivariate linear regression model, which included the distribution function of mean relative humidity, temperature, amount of total chloride deposition and rainfall (https://thaicorrosionmap.mtec.or.th). This web application allows users to observe the corrosion rate of carbon steels and corrosion resistant steels in any location in Thailand. In addition, the authors included a calculator on the website so that users can estimate corrosion resistance and service life by manually entering a corrosion rate.

These authors are using machine learning to investigate big data of atmospheric corrosion monitoring sensor output in correlative with weather data and to construct future corrosion maps.

In this sense and thanks to current technological advances, machine learning models are being used more frequently to construct corrosion maps employing the large amount of geographic information that is collected daily at different locations. Machine learning uses statistical models—i.e., regression vector models, RFAs, ANNs, Support Vector Machines (SVMs), Spearman's correlation analysis, and simple and multiple regression models in order to impute or reduce the number of variables involved in a model, which can improve predictions [1], [2],[43].

Considering current technological advances, future corrosion maps will be constructed using (1) machine learning tools that incorporate statistical models of spatial interpolation, which include the dispersion of the variables (e.g., ordinary and universal Kriging models for interpolation [4]) and (2) a combination of data analysis tools such as those mentioned above.

Another methodology for modeling atmospheric corrosion data is Bayesian statistics because it can include a priori distributions to analyze the information. In these models, technological advances facilitate simulation processes, and the assumptions are based on the convergence of Markov chains, which can be done quickly thanks to different statistical software such as R and Python. Bayesian models can also be applied to atmospheric corrosion data using an a priori distribution that models

the variability in each area where measurements are taken in order to analyze the random effect in each one and obtain concrete results.

3.4. Types of atmospheric corrosion maps

There are different types of maps: corrosion or atmospheric corrosivity maps of a specific place, pollutant maps, climatic maps, heritage climate maps and heritage risk maps [50]. Figure 6 shows three types of maps of different places and conditions. In addition, there are corrosion maps of individual materials and years, as well as those covering an entire period of time. These maps are constructed based on corrosion rates or mass loss data, which are directly obtained or calculated using DRFs [51]. It is also possible to construct mean concentration maps of specific pollutants and thus visualize the distribution of such pollutants in a place of interest [52], [53]. To present the information (corrosion rate, corrosivity category, and sulfur or chlorides content, etc.), some maps use isolines, contours, legends, colors, or tags showing values or ranges of values associated with a particular place or region.

3.5. Software used to construct corrosion maps

Several tools can be used to generate corrosion maps. ArcGIS®, which is geostatistical analysis software, can construct corrosion distribution and superficial pollution maps based on Geographic Information Systems (GIS) [54]. It uses graphical interpolation methods such as IDW, kriging, Topo to Raster, or Natural Neighbor to obtain prediction maps of large areas based on the relationships between the data measured in the field and the distance between them [55], [56].

Surfer® is another application used for this purpose. The mesh of this program enables users to produce different types of maps, including contours, vectors, pictures, shaded reliefs, hydrographic basins, 3D surfaces, and 3D metallic structure maps [57], [58]. Other authors have implemented it to generate level curves by means of statical methods and calculation algorithms, which can be used to represent the trend of each variable and extrapolate its magnitude to areas where data are not available [59].

Surfer® is widely used terrain modelling, bathmetric modeling, analysis, landscape visualization, contour mapping and 3D surface mapping [60], [61].

ArcMap 10 is another geostatistical analysis tool that can be used to construct corrosion maps and manage geographic data [62]. It is the main application of ArcGIS, and it is employed to perform many of the routine tasks of a GIS, representing geographic information as a collection of layers and other elements on a map.

4. Bibliometric analysis and networks

A systematic search was conducted to find publications about atmospheric corrosion maps, specifically regarding metallic materials of special interest for the construction industry, aluminum, carbon steel and galvanized steel. The search strings in Table 2 were used for this purpose.

Table 3 lists the maps found in the literature search conducted in Scopus classified by continent. It includes atmospheric corrosion maps of countries, cities, regions, and industries. It shows that in Asian (such as India) and European countries, these maps have been constructed even for specific industries. Nevertheless, this search did not retrieve maps from other countries, which were possibly published as part of projects, publications that are not indexed in Scopus, or studies conducted by associations and corrosion centers.

As shown below, other maps have been developed even before 1987; however, they are not indexed in Scopus. Consequently, the results of a detailed complementary search are shown in Table 4. Because these maps were found in other sources, we gathered all the publications in Mendeley and imported them into VOSviewer software to construct keyword

Table 4. Atmospheric corrosion maps found in other publications.

Study/Project	Year(s)	Reference
Mexico City, Mexico (zinc)	2021	[96]
Zhejiang Province, China (steel, zinc, and copper)	2020	[97]
Thailand (steel)	2020	[98]
Coimbra and Aveiro, Portugal (steel, zinc, and copper)	2019	[99]
Slovakia (zinc)	2018	[100]
Iran (copper)	2016	[101]
Cyprus (steel)	2016	[102]
Costa Rica (steel)	2015	[103]
Abu Dhabi, United Arab Emirates (zinc)	2013	[104]
Bogotá, Colombia (steel)	2012–2013	[105]
Vietnam (steel, zinc, and copper)	2012	[106]
Korea (steel, galvanized steel, copper, and aluminum)	2011	[107]
Bogotá, Colombia (steel)	2011	[62]
EDELCA's Trunkline Transmission System, Venezuela	2011	[108]
Oahu, Hawaii, United States (9 metals)	2008	[109]
Ceará, Brazil (steel, copper, bronze, galvanized steel, and aluminum)	2008	[110]
Mexico City, Mexico	2002	[111]
Zulia, Venezuela (steel and copper)	2001	[112]
Canary Islands, Spain	2001	[113]
China (zinc)	2001	[114]
Auckland, New Zealand (zinc)	2000	[115]
North Island, New Zealand (zinc)		
Wellington, New Zealand (zinc)		
Christchurch, New Zealand (zinc)		
South Island, New Zealand (zinc)		
Las Palmas, Canary Islands, Spain (steel)	1999	[116]
Thailand (steel)	1999	[117]
Melbourne metropolitan area, Southeast Melbourne, Newcastle, Hunter Valley, and State of South Australia		
Colombia (according to Brooks' deterioration index)	1999	[7]
Brazil (according to Brooks' deterioration index)		
Uruguay (according to Brooks' deterioration index)		
Venezuela (according to Brooks' deterioration index)		
Spain (according to Brooks' deterioration index)		
Portugal (according to Brooks' deterioration index)		
Rural atmospheres in Spain (steel, zinc, and copper)		
Spain (steel, zinc, copper, and aluminum)		
Cuba (steel, zinc, copper, and aluminum)		
Argentina (steel, zinc, copper, and aluminum)		
Rural atmospheres in Argentina (steel, zinc, copper, and aluminum)		
Brazil (steel, zinc, copper, and aluminum)		
Costa Rica (galvanized steel, copper, and aluminum)		
Ecuador (steel, galvanized steel, copper, and aluminum)		
Mexico (steel, zinc, copper, and aluminum)		
Panama (steel, zinc, copper, and aluminum)		
Venezuela (steel, zinc, and copper)		
Peru (steel, zinc, copper, and aluminum)		
Uruguay (steel, zinc, galvanized steel, copper, and aluminum)		
Portugal (steel, zinc, copper, and aluminum)	1993	[118]
North America (for vehicles and roadside applications)	1991	[119]
South Africa	1991	
Great Britain	1991	[120]
United States	1985	
African continent (steel and zinc)	1985	[121]
Melbourne, Australia	1982	[122]
United Kingdom and Ireland (zinc)	1971	[123]

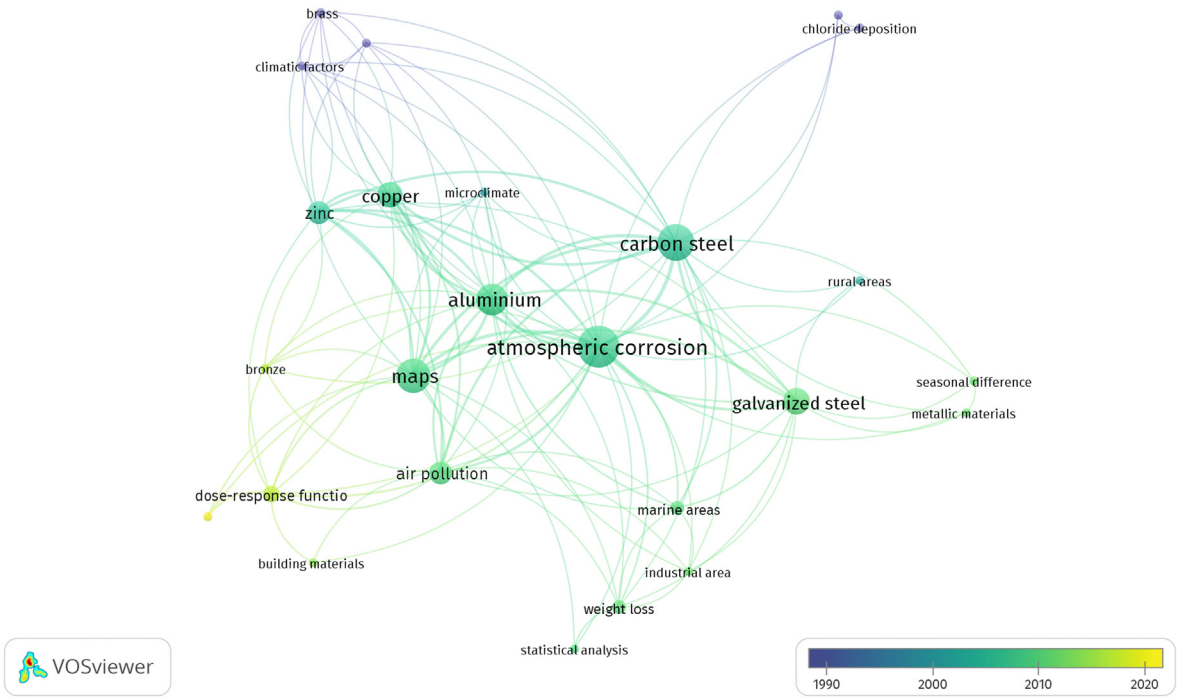


Figure 1. Keyword network of atmospheric corrosion maps of aluminum.

networks of the three materials (Figures 1, 2, and 3), where author keywords were analyzed with full counting. Keyword networks show keywords that are mentioned in articles at least once. Therefore, these networks show all the keywords that the authors have mentioned.

The number of available corrosion maps is quite small, and many of them were constructed as part of international projects. This is probably due to their costs and the exposure times required to build them; furthermore, the logistics associated with this type of study can be complex in countries or regions with complicated geography or transportation difficulties.

VOSviewer software was used to construct three separate keyword networks with the terms found in the publications about atmospheric corrosion maps of aluminum, carbon steel and galvanized steel. The general search in scopus was carried out with the filters shown in Table 1. From the results, we individually selected the documents that presented atmospheric corrosion studies and highlighted the importance of constructing corrosion maps. The publications listed in Tables 2 and 3 were used to construct the keyword networks in VOSviewer. It is important to mention that the search in Scopus was restricted to publications between 1987 and January 2021 because the first article found in said database was

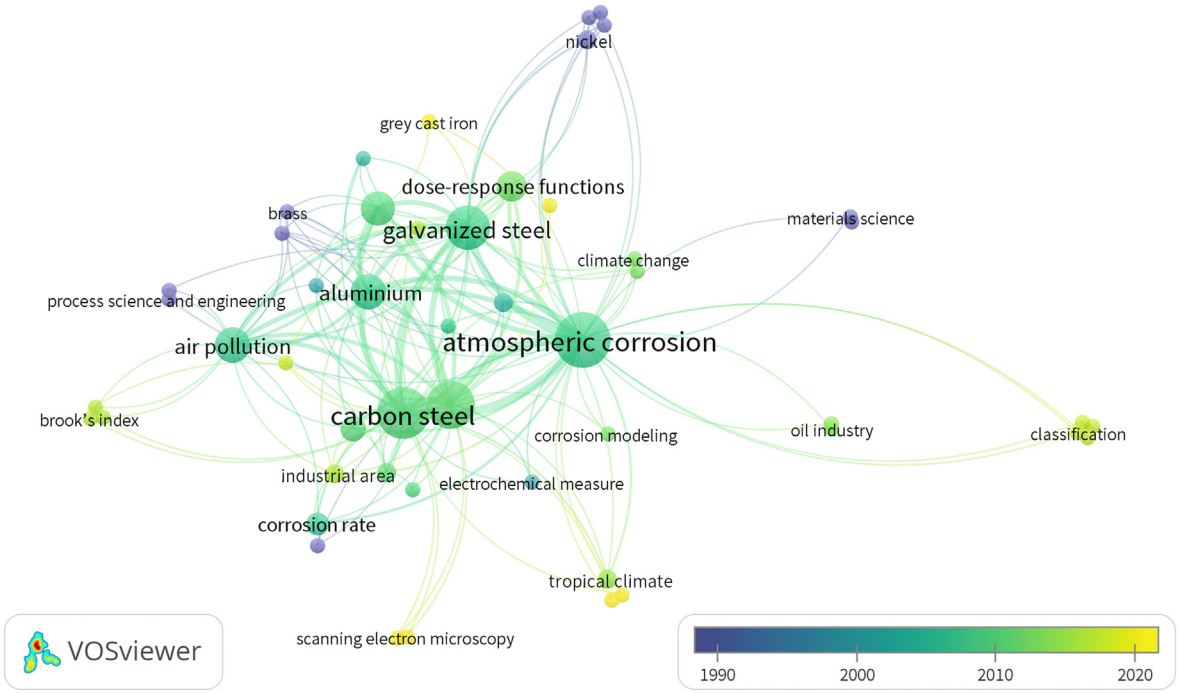


Figure 2. Keyword network of atmospheric corrosion maps of carbon steel.

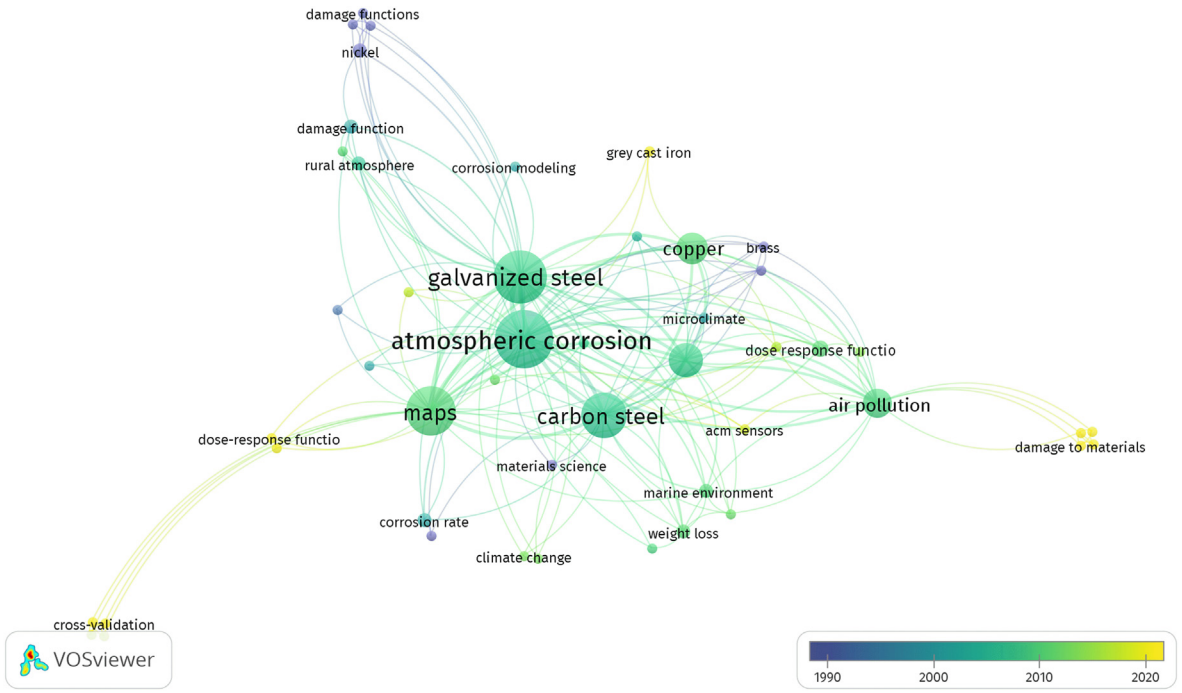


Figure 3. Keyword network of atmospheric corrosion maps of galvanized steel.

published in 1987. In the last six years, there have been 2 publications about aluminum (both in 2019), 4 about galvanized steel (2 in 2019 and 2 in 2020), and 7 about carbon steel (5 in 2019, 1 in 2020, and 1 in 2021).

As expected, the keyword network of atmospheric corrosion maps of aluminum presented some general terms such as "atmospheric corrosion," "maps," and "air pollution" (Figure 1). In this network, "carbon steel" is a recurrent keyword, which indicates that many studies include both metals. Other important terms such as "climatic factors," "industrial area," "marine areas," "rural areas," and "chloride deposition" are included in Figure 1. The minimum number of occurrences selected here was one.

Figure 2 presents the keywords found in the selected publications about atmospheric corrosion maps of carbon steel. This is the biggest network among the three metals; hence, it can be said that this material has been investigated and documented more in depth than its counterparts. In this network, the main terms are "atmospheric corrosion," "maps," and "carbon steel." In addition, it shows a relationship with aluminum and galvanized steel. Some other important terms in this network are "corrosion rate," "climate change," "corrosion modeling," and "materials science."

The keyword network of galvanized steel (Figure 3) contains less terms, which suggests that more corrosion studies should investigate this material. As in the two previous cases, the main terms are "atmospheric corrosion" and "maps," and there is a connection with other materials such as steel and aluminum. Additionally, it contains the term "marine environment," which enables us to deduce that many of these studies and maps are focused on coastal areas.

In Figures 1, 2, and 3, the large circles represent the keywords that are repeated the most in the publications reviewed here, while the small ones

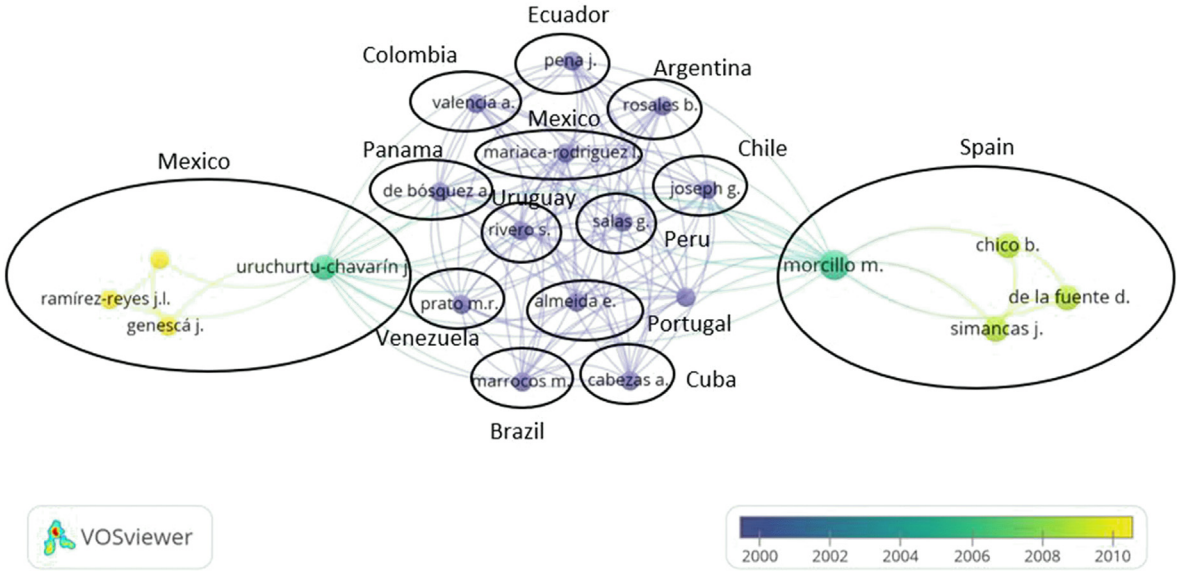


Figure 4. Co-authorship network of atmospheric corrosion maps of aluminum.

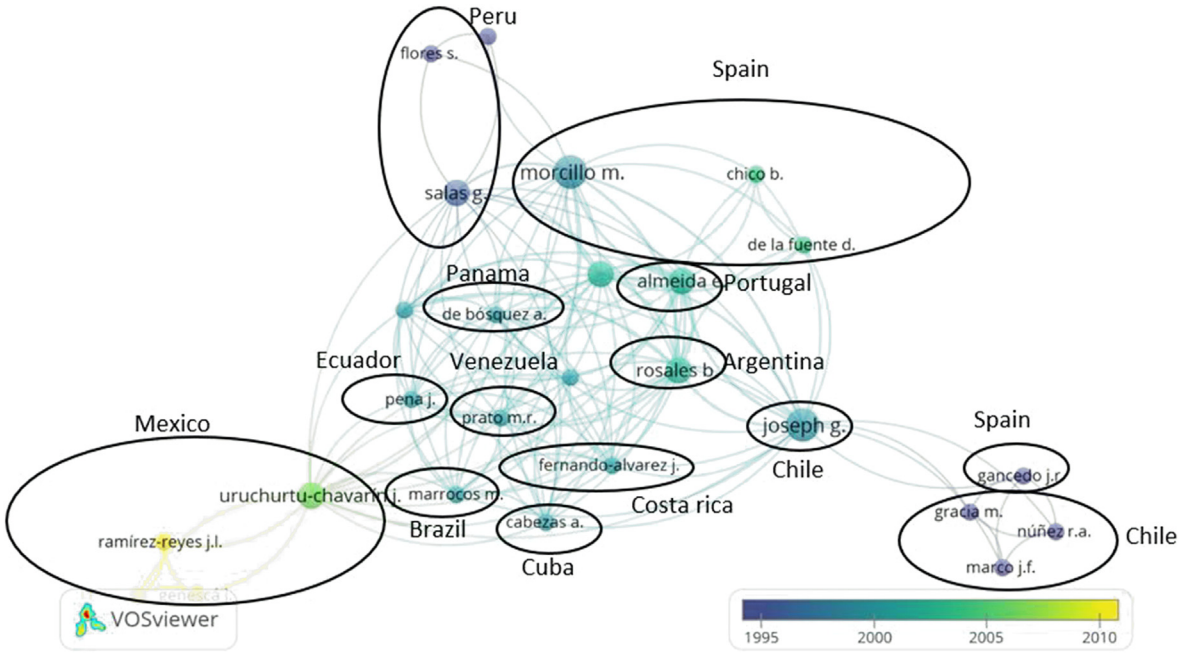


Figure 5. Co-authorship network of atmospheric corrosion maps of carbon steel.

denote those that appear less times. In turn, the colors correspond to the timeline on the right side.

Therefore, it can be noted that, in the past, atmospheric corrosion studies focused on "corrosion rate; " "maps; " and materials such as "brass", "steel" and "copper". With the passage of time, more attention has been devoted to the influence of atmospheric parameters and the time of wetness. Since 2014, the authors in this area have shown an interest in particles for statistical models, as can be seen in the figures above. Although to a small extent, they have started to explore "dose response function," using data that have already been obtained to predict the behaviors of the materials.

When they study the effects of deterioration of materials considering local atmospheric conditions instead of exposure time (which is the other way to study them), many authors use damage functions, such as dose-

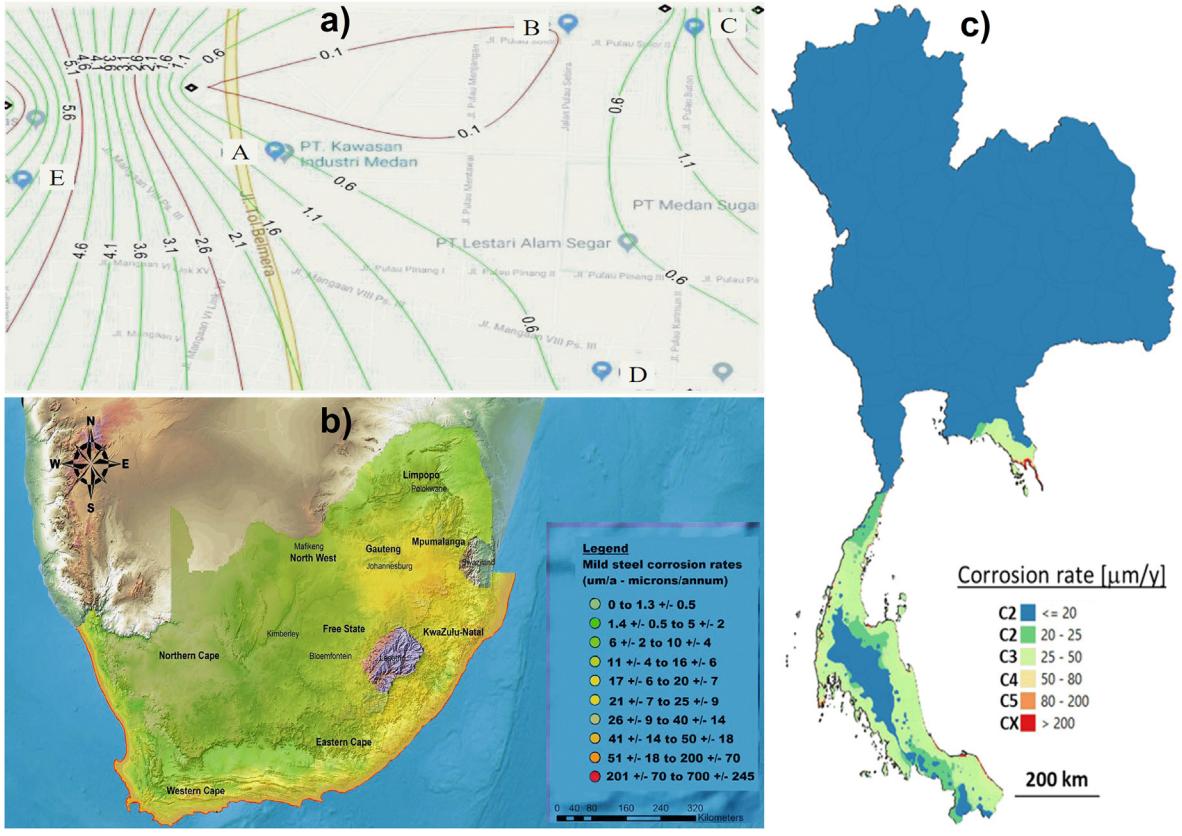


Figure 6. Examples of corrosion maps: (a) isoline map of an industrial area [57], (b) atmospheric corrosion map of South Africa [94], and (c) corrosion rate map of carbon steel (SS400) for tropical climate in Thailand [129].

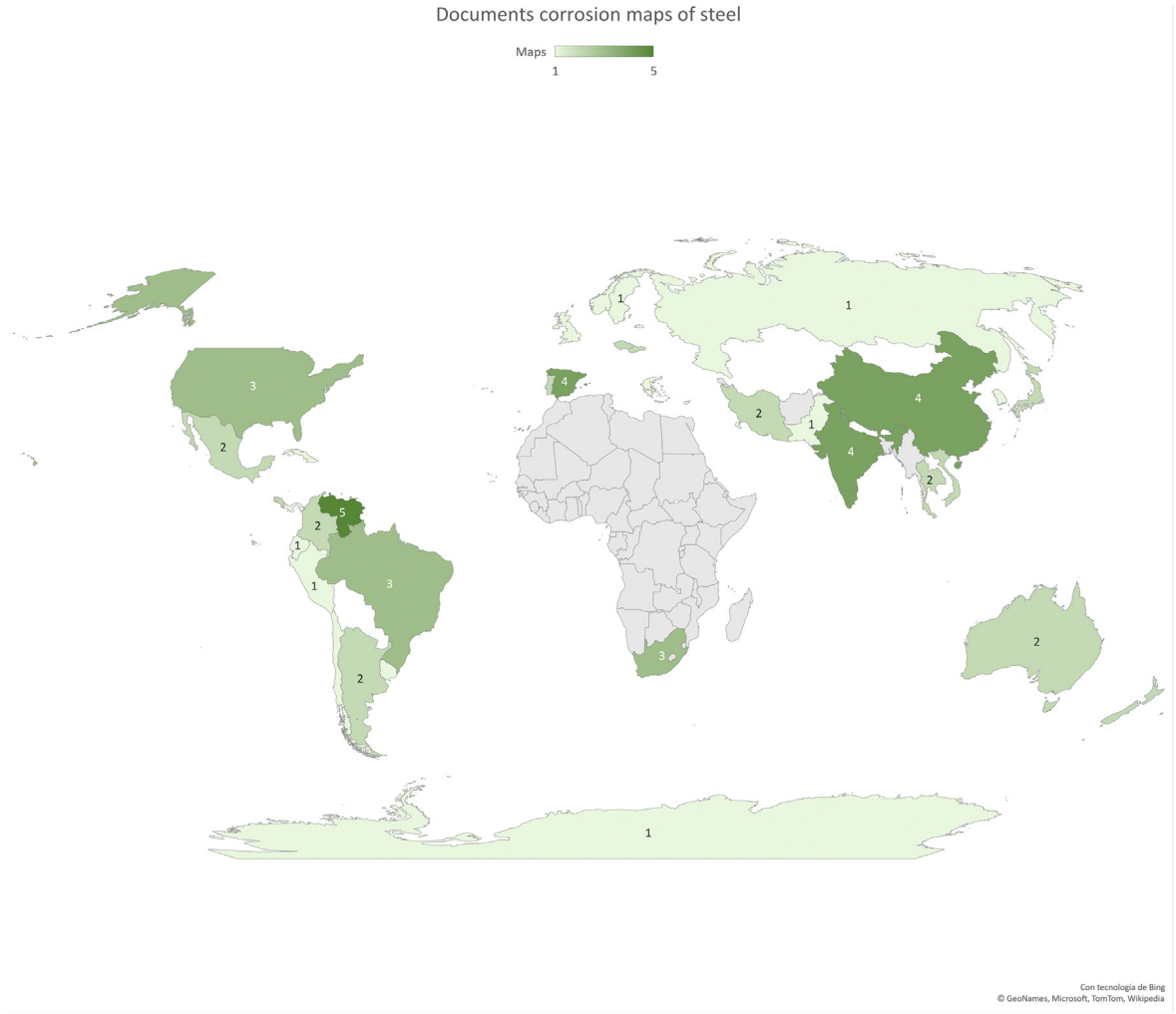


Figure 7. Number of atmospheric corrosion maps of carbon steel by country of origin.

response functions (DRFs). A damage function generally refers to a quantitative relationship between exposure to environmental variables and their effects, while a DRF is a type of damage function that encompasses the effects of one or more pollutants [6].

It is also important to mention that many of the publications analyze, in parallel, several types of materials. Therefore, the same materials "carbon steel", "galvanized steel", "aluminum", and "copper", appear in Figures 1, 2, and 3. Terms such as "climate change" and "corrosion rate" also appear in them because the focus of these studies is on characterizing the atmospheres they investigate, which can be marine, urban, and industrial. Finally, "climatic parameters," "chlorides," and "sulfur" appear in the networks because they are the most influential factors atmospheric corrosion. The network of carbon steel (Figure 2) includes some terms related to materials characterization, such as "electrochemical measure" and "scanning electron microscopy." These keywords are not found in the other networks despite the fact that these characterization techniques are widely employed in materials science to gather information on corrosion mechanisms and the corrosion products that are formed.

The circle of "industrial area" is smaller in Figure 1 than in Figure 2 because the most important damage to aluminum is produced by chloride ions (Cl^-), which are absorbed in the imperfections of the passive layer which generates the formation of complexes that cause pitting corrosion.

In industrial atmospheres, the corrosion rate aluminum is very low, which is mainly due to the protection of the passive layer [7].

These keyword networks give us an idea of the most important resources to construct atmospheric corrosion maps. They also show us the current focus of research in this area, i.e., climate change. As a result, more attention has been paid to the damage caused by atmospheric corrosion and pollutants (such as ozone and NOx) due to their gradual increase and the decrease in SOx emissions in some developed countries. Nevertheless, due to the deterioration of the ozone layer in the stratosphere, more attention should be paid to the effect of increased radiation.

The co-authorship networks only correlate authors who have worked in collaboration. The software emphasizes the period between 2000 and 2010 because the highest density of articles is found in those years, when most studies were conducted in the frame of three international collaborative programs: ISOCORRAG, ICP/UNECE, and MICAT. These networks also show that independent studies have been conducted in recent years. However, they have not included the collaboration of authors from different countries. On the contrary, they have been carried out for particular environments and not as part of systematic research into corrosion maps.

This review also analyzed the co-authorship networks in the field discussed here and their evolution over time. Figures 4 and 5 are the co-authorship networks of the selected publications about corrosion maps of aluminum and carbon steel, respectively. The co-authorship network of galvanized steel was not included here because the number of publications about corrosion maps of this material is remarkably low and does not enable an in-depth exploration of the topic. Their authors apparently publish independently; as a result, they do not form a specific network, and this map presented isolated points only.

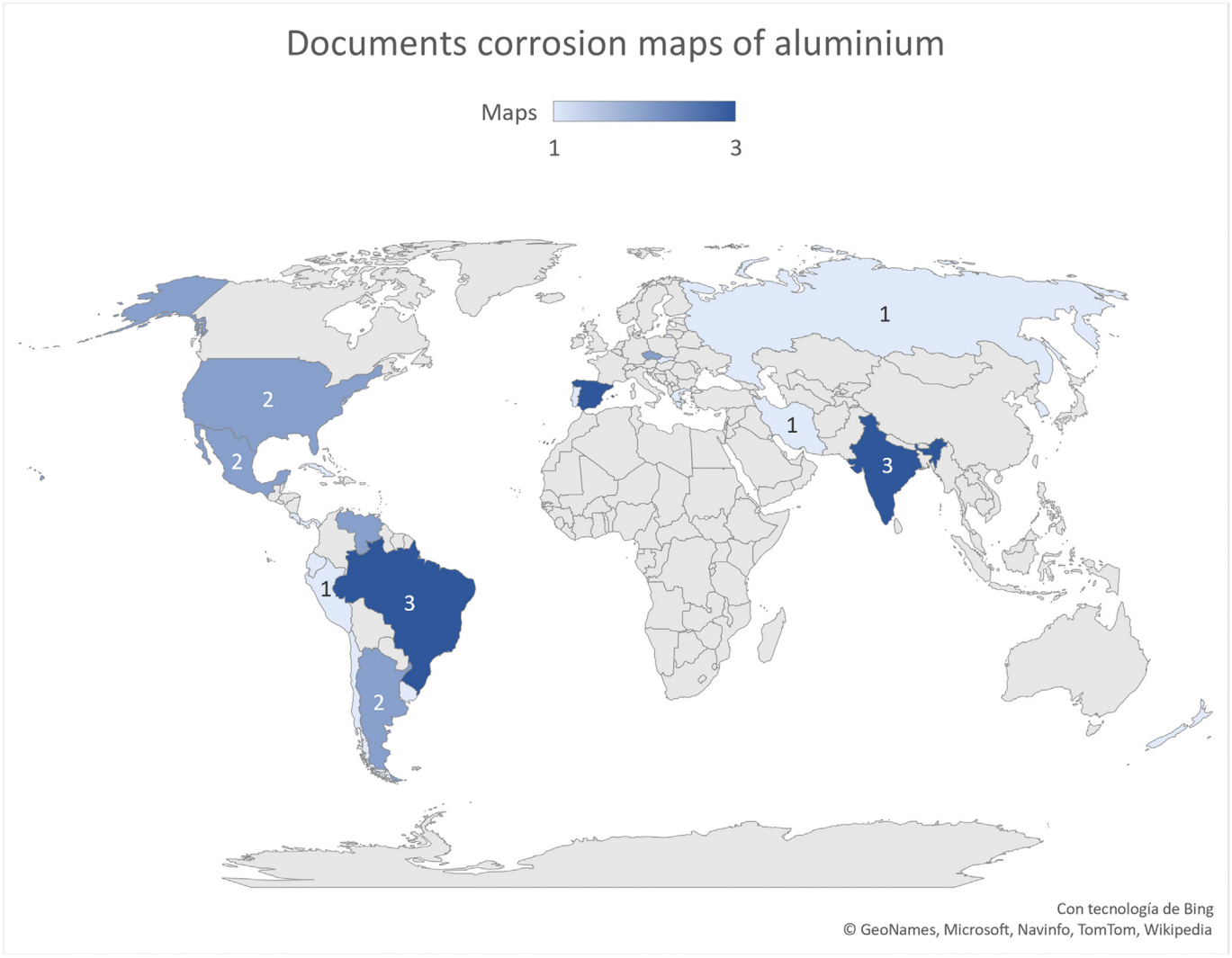


Figure 8. Number of atmospheric corrosion maps of aluminum by country of origin.

A line connecting two authors means that they co-authored a publication. The names in yellow indicate that the authors have recently published papers on the topic, while those in dark blue represent not-so-recent publications. In the co-authorship networks, the authors' countries of origin are marked to highlight the places where this topic has been collaboratively studied. These two co-authorship networks show a relationship between authors in Spain, Mexico, and South America. The most recent publications are from Mexico, followed by Spain. There are several authors in South America who have participated in the construction of atmospheric corrosion maps of their countries; most of them have collaborated in the MICAT project [124].

The first recorded atmospheric map was published in the British Isles in 1971. The following decade brought four new maps from Catalonia (Spain), Australia, the United States, and the African continent. In the 1990s, the oil, chemical, and construction industries (among others) started to appreciate the importance of corrosion maps, which resulted in the construction of around 30 maps worldwide. In this decade, most maps were constructed as part of the MICAT project, mainly in Latin America. After 2000, Asia became an important leader in the construction of such maps, producing around 15. Remarkably, only a few maps (16) have been created in the last five years.

Although corrosion maps were commonly aimed at studying the characteristics of atmospheric corrosion in certain continents or small areas. In the 1980s, three important programs dedicated to measuring atmospheric corrosion emerged, such as: MICAT, ISOCARRAG an ICP/UNECE.

A total of 38 countries in Europe, America, Asia, and Oceania participated in them [23]. These programs included corrosion rate measurements, construction of climatic maps, and maps of testing stations. Their main objective was constructing atmospheric corrosion maps of the participating countries, as shown in Table 3. Combining updated datasets derived from these international projects with the application of DRFs, new maps can be calculated and produced considering the current situation of multiple pollutants [125].

It has been reported that the atmospheric corrosivity of a region has increased the concern for major industries that require knowing the behavior against atmospheric corrosion of materials such as aluminum, copper, carbon steel and galvanized steel [126].

Studying atmospheric corrosion maps is remarkably important for companies that use metals in their infrastructure and/or activities open to the environment. For example, in the United States, corrosion causes losses equivalent to 0.3% of its GDP, impacting its industrial (50%), infrastructure (8.2%), services (17.35%), transportation (10.76%), and manufacturing (6.37%) sectors [127]. Corrosion maps have also been constructed in Cuba. They show that long periods of durability and useful life can be achieved in coastal areas of the country with a high construction potential. This extends the time between costly repairs to the infrastructure and represents a significant contribution to economic savings for the industry [128].

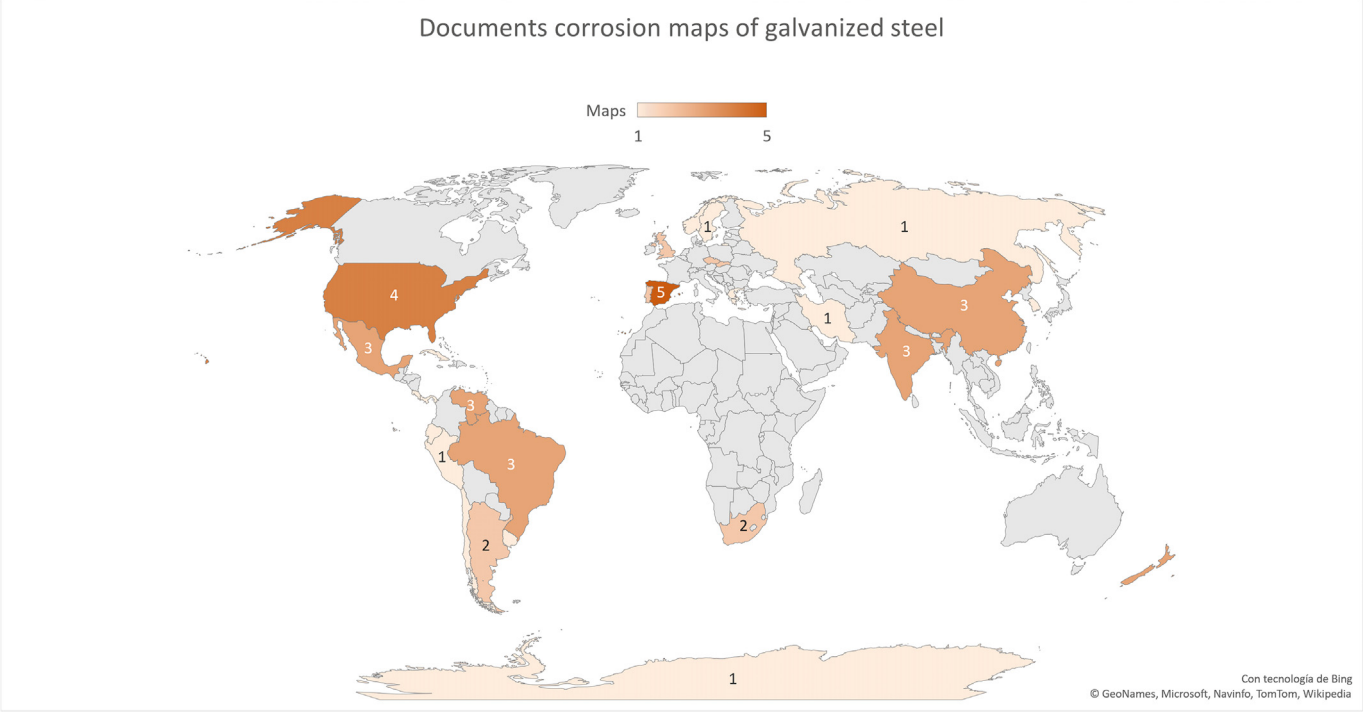


Figure 9. Number of atmospheric corrosion maps of galvanized steel or zinc by country of origin.

Corrosion maps have been presented in different ways and adapted to the places or properties they characterize. Figure 6a shows a map with isolines, which is used in corrosion maps of different industries, for instance, the corrosion map of structural steel in an industrial area [57]. Figure 6b presents an updated corrosion map of carbon steel in South Africa (Figure 6b), one of the most recently published, which was produced using interpolation methods [94]. Finally, Figure 6c is a corrosion rate map for tropical climate Thailand (a geographical information system GIS), with different ranges of corrosion rates of carbon steel (SS400) [129].

The information in Tables 2 and 3 was used to determine the number of atmospheric corrosion, deterioration, or durability maps of the three materials constructed in each country. Figure 7 presents the number of maps of carbon steel constructed in each nation; similar maps were created for aluminum (Figure 8) and galvanized steel or zinc (Figure 9).

The distribution of articles in the world maps (Figures 7, 8, and 9) shows that, in the last 50 years, most of them have been written in Asia and Europe. America has also contributed some papers, although to a lesser degree. Some nations have only one publication, which generally means that a corrosion map of the biggest cities in the country was constructed. Meanwhile, countries such as Spain, China, and India have produced more than three maps each.

5. Conclusions

This bibliometric analysis found 88 corrosion maps around the world. Some countries have produced two or more maps, which could represent different cities, industries, and years. Considering that there are 193 countries in the world, it is clear that more countries should conduct this kind of studies because corrosion maps can hardly be extrapolated to other places since they depend on factors such as time of wetness, rainfall, relative humidity, temperature, and pollutants (which are different in every area).

Many countries have outdated corrosion maps (United Kingdom and Ireland (zinc), 1971; Melbourne, Australia, 1982, among others), which highlights the need for constructing new ones that reflect current real conditions of atmospheric pollution and climate change. They could be used to determine the durability of the metallic materials currently employed in infrastructures and implement possible methods to preserve them.

The keyword networks of atmospheric corrosion maps of aluminum, carbon steel, and galvanized steel indicate that the most common topics in these publications are meteorological parameters, polluting agents, durability prediction using statistical analyses (such as DRFs), and characterization of the products of corrosion.

The co-authorship networks above show that, between 1999 and 2004, a number of international collaborative projects regarding atmospheric corrosion were undertaken. However, recent years have seen a decline in the collaboration between authors in this field. Since 2004, research into corrosion maps has been independent and for particular environments, not systematic.

Finally, it was found that, in most of the publications reviewed here, the data collected in different areas were often analyzed using fixed-effects experimental designs, which consider the variability in the measurements to be equal in all areas. However, this assumption is not always satisfied because environmental conditions may vary from place to place. Therefore, future studies can apply designs based on Bayesian statistics that include random effects in the model, which would enable us to model atmospheric corrosion more efficiently.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

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Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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