

# Lack of Correlation Between Land Use and Pollutant Emissions: The Case of Pavia Province

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**Abstract.** Air quality is a major concern in highly urbanised and industrialised regions, as well as rural areas. Air pollutant concentrations often exhibit significant spatial and temporal variability, depending on local sources, climate conditions and the characteristics of the built and natural environment. The strong relationship between emissions and human activities is well known: residential functions, infrastructure systems and industrial plants are the main emission sources of different pollutants, especially for PM2.5. Agriculture also produces pollutants. By contrast, forests usually act as adsorption sinks, reducing the pollution concentration. Therefore, pollutant emissions and concentration patterns present significant spatial variability due to different land uses. Moreover, the correlation between urban and territorial functions and pollution varies, sometimes by a significant amount, with different regions and scales leaving a significant gap for urban planning. The presented research aims at describing the potential correlation between different land uses and the emissions and concentrations of air pollutants, as a starting point for more in-depth studies in relation to urban and territorial transformations, the sustainable renewal of dismissed areas and the revitalisation of rural areas. By considering a territorial scale for the analysis (Pavia Province in northern Italy), we intend to underline the links (linear, direct, indirect) between land uses (residential, agricultural, and industrial) and the main air pollutants (CO2eq), as well as the degree of intensity.

**Keywords:** Land Use · Pollutant emissions · Correlation analysis

## 1 Introduction

The United Nations Framework Convention on Climate Change states that land use plays a key role in the production of greenhouse gases, indeed human activities can lead to the production of pollutants in the atmosphere, or their absorption [1].

In both developed and developing countries, air pollution causes significant threats to human health, the environment, social and economic activities. The issue of air quality is receiving increasing attention in an urban context, as well as in less urbanised contexts, such as the so-called rural-urban areas and the countryside regions [2–7].

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The variations in spatial distribution of air pollutants have become a widespread concern in several fields such as urban and rural planning, environmental science, and medicine [8–11].

In 2018, global emissions from agriculture were 4 billion tons of CO2eq from agricultural and livestock activities; land use change CO2eq emissions are mainly from deforestation and the burning of organic soils [12]. Moreover, agricultural activities contribute to increasing $CH_4$ and $N_2O$ emissions [13–15].

In the last 5 years, in Italy, the interaction between pollution, fuel consumption and weather conditions has been particularly accentuated. In 2017, there was an increase for both PM10 and PM2.5, exceeding the WHO reference thresholds: PM2.5 annual limit = 10 μg/cbm; PM10 annual limit = 20 μg/cbm - $O_3$: 8 h limit = 100 μg/cbm [16, 17].

The authors have focussed on analysing the role played by land use and, therefore, human activities on the production of pollutants in the Lombardy Region (Italy). In particular, the chosen study area is Pavia province, in the southwestern part of the Lombardy Region. It is a highly urbanised plain with a high population density and small to middle size cities (only two cities have more than 60,000 inhabitants, one has almost 40,000 inhabitants, and a few have 10–15 thousand inhabitants, but most municipalities have less than 1000 inhabitants). Importantly, there is little settlement sprawl, intensive agriculture and livestock management, and high emission levels of different pollutants.

Air pollution levels in Lombardy remain high and above the European average. Some pollutants have slightly increased their concentrations in the last two years due to meteorological and climatic variations. The meteorological situation of this area is peculiar (atmospheric stability with low winds and thermal inversion) and this affects the concentration levels, the diffusion and dispersion of pollutants in the air [18].

This phenomenon is particularly relevant in the cities of the Po Valley, in which the Province of Pavia is part of the study [19].

The paper aims to verify, at a local level, the provincial/regional trends of the relationship between land use and polluting emissions using correlation analysis of demographic, economic, environmental, and territorial indicators at a provincial level and in the most emissive municipalities.

### 1.1 Study Area: Pavia Province

The choice of the study area fell on the Lombardy Region and on Pavia province, which covers an area of 2,964.7 sqkm. Its geographical and physical characteristics make it one of the most disadvantaged areas in Europe, in terms of air quality: the closed geographic conformation, the poor ventilation of the area, the frequent thermal inversions and the modest mixing height all favour the stagnation of pollutants and hinder their dispersion [20]. The high anthropisation and the high rate of industrialisation of the region further contribute to the degree of pollution.

The most active emission sources in Lombardy appear to be civil combustion processes, production processes and agriculture [21].

The Lombard industrial system is characterised by a wide variety of economic activities and industry is a significant emissive source of volatile organic compounds (VOC) and particulates (PM2.5 and PM10), in quantities that vary according to the processing.

In the residential sector in Lombardy there are about 3.3 million installations, the majority being fuelled by methane gas and resulting in emissions of sulphur dioxides $SO_2$, carbon oxides CO and nitrogen oxides NOx, which are the main causes of the heavy pollution characteristics, especially of large cities in the winter period [22]. Moreover, Lombardy ranks as one of the main agricultural regions of Europe and the progress that this sector has seen has led to great growth in agriculture and, consequently, caused an impact on the environment, making it one of the main causes of pollution in the Po Valley [23]. Figure 1 represents the emission contributions, in terms of CO2eq, of the provinces of Lombardy.

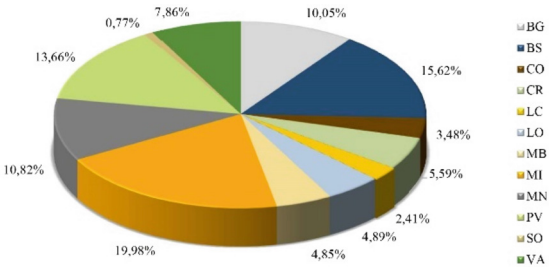


**Fig. 1.** CO2eq contribution of each province in the Lombardy Region ( source: authors)

The provinces that produce the largest quantities of $CO_2$ equivalent emissions and, therefore, contribute the most to the greenhouse effect are those of Milan (20%), Brescia (16%) and Pavia (14%). The province of Milan is characterised by a medium-high territorial extension and the highest population density in the region. The province of Brescia is the province with the largest extension in the region. The province of Pavia is characterised by medium-high territorial extension and by minimal sources of absorption, being a mainly agricultural territory.

Figure 2 shows the estimates of the emissions produced by each macrosector. The 11 macrosectors considered by INEMAR are: public power plants, cogeneration and district heating, energy production (electricity, cogeneration and district heating) and transformation of fuels; non-industrial combustion plants (commercial, residential, agriculture); combustion in industry; production processes; extraction and distribution of fossil fuels; use of solvents; road transport; other moving sources and machinery; waste treatment and disposal; agriculture; other sources and absorption percentage in each province [24]. Pavia province is characterised by a high emission contribution of macrosector 1, a low emission contribution of macrosector 2 and a medium-high emission contribution of macrosector 10, being a mainly agricultural territory. It has minimal absorption because there is scarcely any vegetation in the territories.

In high-density urban environments, the soil is an important regulator of climate and microclimate and is related to air quality. Knowledge of the dynamics relating to land uses is strategic for territorial planning: it allows a fully understanding of the current situation of the territory and, at the same time, allows monitoring the in-progress changes and predicting the possible future changes.

Land use status indicators are obtained with a quantitative geographic approach.

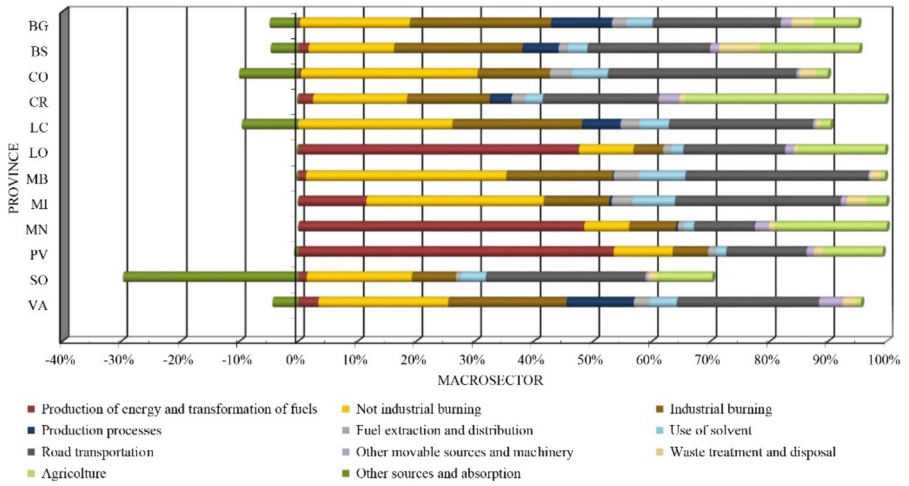


**Fig. 2.** CO2eq contribution of each province in the Lombardy Region for each macrosector ( source: authors)

Geographical elements in an urban context are surfaces, perimeters and percent-age distributions on an overall area: they are objective values that can be used as quantitative indicators and analysed through the theme of land use in Lombardy (Fig. 3), which is concretised in the database DUSAF [25].

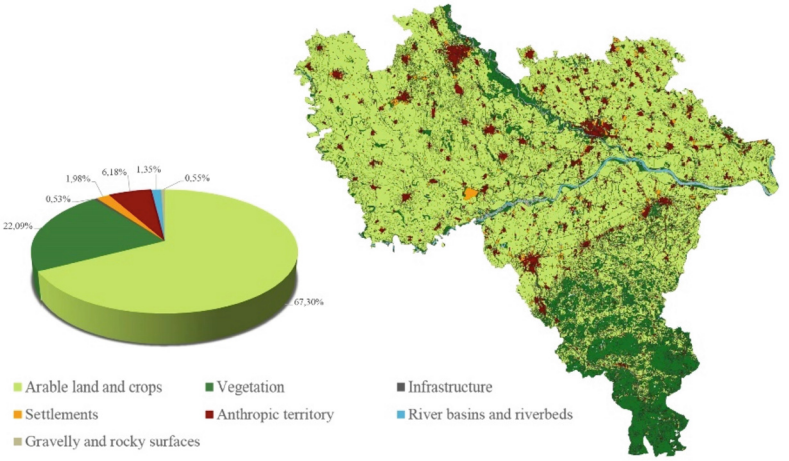


**Fig. 3.** Pavia province land use ( source: authors)

The surface of the province of Pavia:

– 67.30% is occupied by arable land and has a percentage of emissions from agriculture of 10.4% (1,105 kt/year);

– 22.09% is occupied by vegetation and has an absorption rate of -0.7%;
– it has the lowest percentage of territory used for infrastructure in the region (0.53%), producing 13.8% of the total road transport emissions (1460 kt/year), the lowest percentage in Lombardy.

## 2 Data and Methodology

The population of Pavia province forms 5% of the Lombard population; its 534,691 inhabitants are concentrated mostly in the cities of Pavia, Voghera and Vigevano (31% of the total); in 10 of the 186 municipalities there is the 50% of the entire population, while the rest is spread over the remaining municipalities. The municipalities that do not have a population exceeding 5,000 inhabitants account for 88% and only 13 of these are cities. The average population density of the province of Pavia is about 184 inhabitants/sq km and is below the regional average (422 inhabitants/sq km).

Economic growth and, therefore, the growth of GDP (Gross Domestic Product, the most used indicator to evaluate the wealth produced by a country) consequently leads to an increase in emissions due to production activities, construction and transport. It is necessary to combine economic growth with an improvement in environmental quality, thus creating the so-called decoupling between the growth of a country's wealth and its negative impacts on the environment. The province of Pavia is one of the provinces that contributes the least to the growth of Lombardy's GDP, in fact its contribution is only 4%.

The definition of 'emission' given by INEMAR is "the quantity of pollutant introduced into the atmosphere, from a certain polluting source and over a certain period of time; generally, it is expressed in tons/year" [26]. To evaluate the contribution of the various pollutants emitted from various sources, the inventories of the emissions are used which allow us to identify, for each source, the type of pollutant, the quantity emitted and the location. The Lombardy Region inventory of atmospheric emissions INEMAR of ARPA LOMBARDIA, is currently available for the year 2017. Consequently, all of the data in this research is derived from this database [26].

For diffuse emissions it is not possible to obtain a direct measurement and it is, therefore, necessary to estimate them from statistical data and appropriate emission factors, in accordance with the methodologies adopted at national (ENEA-ANPA) and international (Corinair) level [27]. INEMAR makes these estimates on the basis of an indicator that characterises the activity of the source and an emission factor, specific to the type of source, industrial process and purification technology adopted. Therefore, this method is based on a linear relationship between the activity of the source and the emission, according to a relationship that, at a general level, can be traced back to the following [28]:

$$Ei = A \times FEi \tag{1}$$

where:

– Ei = emission of the pollutant i (t/year);
– A = activity indicator;

– FEi = pollutant emission factor I.

The Lombardy Emissions Inventory considers the following air pollutants: sulphur dioxide ($SO_2$), nitrogen dioxide ($NO_2$), nitrogen monoxide (NO), Volatile Organic Compounds (VOCs), carbon monoxide (CO), ammonia ($NH_3$), and fine particulate matter (PM10 and PM 2.5). In addition, there are also aggregate pollutants, obtained from the combination of the emission data of individual pollutants, and one of these is $CO_2$ equivalent: the emissions of 'CO2eq' represents the total emissions of greenhouse gases, weighted based on their contribution to the greenhouse effect. The estimate of aggregate greenhouse gas emissions is based on the following equation [29]:

$$\mathrm{CO2eq} = \Sigma \mathrm{i}\ \mathrm{GWPi} \times \mathrm{Ei} \tag{2}$$

where:

– CO2eq = $CO_2$ equivalent emissions in kt/year;
– GWPi = 'Global Warming Potential', coefficient IPCC equal to 1.000, 0.025 and 0.298 for $CO_2$, $CH_4$ and $N_2O$, respectively [26];
– Ei = $CO_2$ emissions (in kt/year), $CH_4$ and $N_2O$ (in t/year).

For the presented research, we consider all the previous pollutants, as well as $CO_2$, PAH, PTS, $N_2O$, and $CH_4$ as well as the most common elements derived from combustion phenomena and anthropogenic activities.

Moreover, correlation analysis is used to establish a relationship or an association between two quantitative variables [29–31]. For the presented research, we used it to highlight (if present) the relations between air pollution (considering greenhouse gases and other pollutants) and human activities (mainly agricultural and industrial activities, and urban settlements as a whole).

## 3 Correlation Analysis Output

### 3.1 Provincial Level

The first analysis was performed on the entire Province, considering the different air pollutants [26], the population, the population density, and GDP. The correlation analysis was then completed (Fig. 4).

| | PAHs | PM10 | PTS | PM2.5 | $SO_2$ | $N_2O$ | $NH_3$ | NOx | VOCs | $CH_4$ | CO | $CO_2$ | $CO_2$ eq. | Population | Population Density | GDP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PAHs | | 0.65 | 0.59 | 0.68 | 0.98 | 0.30 | 0.18 | 0.87 | 0.59 | 0.17 | 0.48 | 0.59 | 0.59 | 0.10 | 0.07 | 0.08 |
| PM10 | | | 0.99 | 1.00 | 0.55 | 0.54 | 0.42 | 0.78 | 0.93 | 0.51 | 0.90 | 0.50 | 0.52 | 0.68 | 0.41 | 0.65 |
| PTS | | | | 0.98 | 0.48 | 0.57 | 0.48 | 0.74 | 0.95 | 0.60 | 0.90 | 0.45 | 0.47 | 0.72 | 0.42 | 0.69 |
| PM2.5 | | | | | 0.58 | 0.53 | 0.39 | 0.79 | 0.91 | 0.49 | 0.89 | 0.52 | 0.53 | 0.65 | 0.38 | 0.61 |
| $SO_2$ | | | | | | 0.23 | 0.09 | 0.83 | 0.49 | 0.06 | 0.40 | 0.60 | 0.60 | 0.03 | 0.04 | 0.02 |
| $N_2O$ | | | | | | | 0.62 | 0.64 | 0.58 | 0.51 | 0.53 | 0.69 | 0.71 | 0.37 | 0.18 | 0.34 |
| $NH_3$ | | | | | | | | 0.28 | 0.49 | 0.63 | 0.39 | 0.11 | 0.13 | 0.33 | 0.19 | 0.30 |
| NOx | | | | | | | | | 0.73 | 0.28 | 0.68 | 0.84 | 0.84 | 0.35 | 0.22 | 0.33 |
| VOCs | | | | | | | | | | 0.67 | 0.87 | 0.46 | 0.48 | 0.72 | 0.37 | 0.69 |
| $CH_4$ | | | | | | | | | | | 0.45 | 0.12 | 0.16 | 0.44 | 0.20 | 0.41 |
| CO | | | | | | | | | | | | 0.43 | 0.45 | 0.80 | 0.49 | 0.77 |
| $CO_2$ | | | | | | | | | | | | | 1.00 | 0.18 | 0.10 | 0.16 |
| $CO_2$ eq. | | | | | | | | | | | | | | 0.20 | 0.11 | 0.19 |
| Population | | | | | | | | | | | | | | | 0.69 | 0.99 |
| Population Density | | | | | | | | | | | | | | | | 0.68 |
| GDP | | | | | | | | | | | | | | | | |

**Fig. 4.** Correlation Analysis among air pollutants and territorial descriptors at province level ( source: authors)

All the results show a direct correlation among the elements.

Moreover, in order to obtain an effective visualisation, the elements were classified using their correlation index (Fig. 5).

| | PM10 | PTS | PM2.5 | VOCs | CO | NOx | Population | $N_2O$ | Population Density | $CO_2$ eq. | PAHs | $CO_2$ | $SO_2$ | $CH_4$ | $NH_3$ | GDP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PM10 | | 0.99 | 1.00 | 0.93 | 0.90 | 0.78 | 0.68 | 0.54 | 0.41 | 0.52 | 0.65 | 0.50 | 0.55 | 0.51 | 0.42 | 0.65 |
| PTS | | | 0.98 | 0.95 | 0.90 | 0.74 | 0.72 | 0.57 | 0.42 | 0.47 | 0.59 | 0.45 | 0.48 | 0.60 | 0.48 | 0.69 |
| PM2.5 | | | | 0.91 | 0.89 | 0.79 | 0.65 | 0.53 | 0.38 | 0.53 | 0.68 | 0.52 | 0.58 | 0.49 | 0.38 | 0.61 |
| VOCs | | | | | 0.87 | 0.73 | 0.72 | 0.58 | 0.37 | 0.48 | 0.59 | 0.46 | 0.49 | 0.67 | 0.49 | 0.69 |
| CO | | | | | | 0.68 | 0.80 | 0.53 | 0.49 | 0.45 | 0.49 | 0.43 | 0.40 | 0.45 | 0.39 | 0.77 |
| NOx | | | | | | | 0.35 | 0.64 | 0.22 | 0.84 | 0.87 | 0.84 | 0.83 | 0.28 | 0.27 | 0.33 |
| Population | | | | | | | | 0.37 | 0.69 | 0.20 | 0.10 | 0.18 | 0.03 | 0.44 | 0.33 | 0.99 |
| $N_2O$ | | | | | | | | | 0.18 | 0.70 | 0.30 | 0.69 | 0.23 | 0.51 | 0.63 | 0.35 |
| Population Density | | | | | | | | | | 0.11 | 0.07 | 0.10 | 0.04 | 0.20 | 0.19 | 0.68 |
| $CO_2$ eq. | | | | | | | | | | | 0.59 | 1.00 | 0.60 | 0.16 | 0.13 | 0.19 |
| PAHs | | | | | | | | | | | | 0.59 | 0.98 | 0.17 | 0.18 | 0.08 |
| $CO_2$ | | | | | | | | | | | | | 0.60 | 0.12 | 0.11 | 0.16 |
| $SO_2$ | | | | | | | | | | | | | | 0.06 | 0.08 | 0.02 |
| $CH_4$ | | | | | | | | | | | | | | | 0.63 | 0.41 |
| $NH_3$ | | | | | | | | | | | | | | | | 0.30 |
| GDP | | | | | | | | | | | | | | | | |

**Fig. 5.** Correlation analysis among air pollutants and territorial descriptors at province level. Classification based on correlation coefficient ( source: authors)

Figure 6 highlights the massive presence of strong positive correlations. Few pairs of elements show a mild positive correlation (which means there is not so strong a dependence between them, e.g. $NH_3$ and PTS or $CO_2$ and PM10).

Moreover, as expected, it can be seen that, as emissions increase, income also increases; as the population and population density increase, emissions also increase.

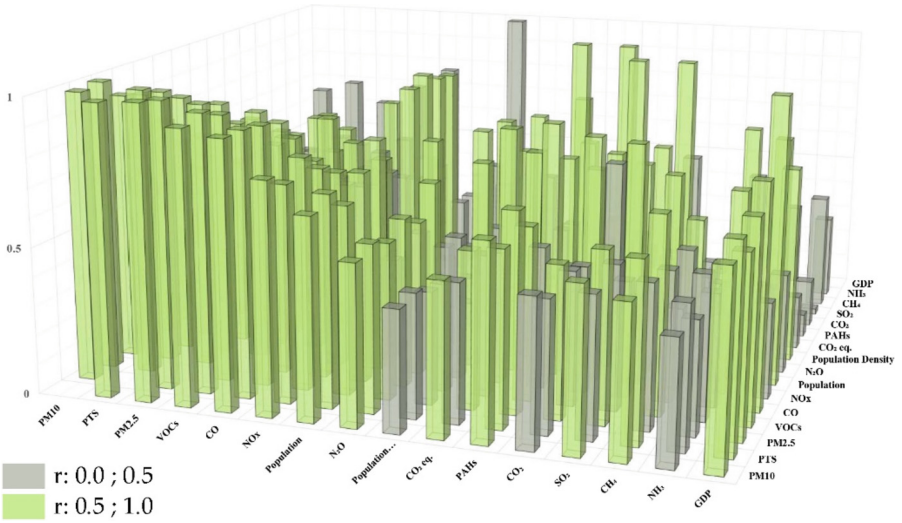


**Fig. 6.** Graphic visualisation of correlation outputs at province level ( source: authors)

### 3.2 Municipal Level

Considering the municipal dimension, as a first step, we analysed the most emissive (in relation to CO2eq) municipalities and highlighted seven realities that were far away from all the others (the next municipality only produced 9.28 kiloton/year of CO2eq). The main features of each municipality are different, with respect to population density, spatial dimension, and GDP. Due to the distribution of their urban functions, they are the most emissive entities in the province.

As already performed for the entire province, we correlated all of the air pollutants, population, population densities and GDP (Table 1, Table 2 and Fig. 7).

**Table 1.** Data on pollutants of the seven most emissive municipalities ( source: authors)

| Municipality | PAHs (kg/year) | PM10(t/year) | PTS(t/year) | PM2.5 (t/year) | $SO_2$(t/year) | $N_2O$(t/year) | $NH_3$(t/year) | NOx(t/year) | VOCs (t/year) | $CH_4$(t/year) | CO(t/year) | $CO_2$(kt/year) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ferrera Erbognone | 6.0 | 14.3 | 17.5 | 13.6 | 15.1 | 68.6 | 36.8 | 863.1 | 242.5 | 400.6 | 82.3 | 2.838.8 |
| Mortara | 117.8 | 44.8 | 60.3 | 38.4 | 24.0 | 29.7 | 247.1 | 588.1 | 637.3 | 1,251.6 | 464.4 | 81.2 |
| Parona | 66.2 | 12.4 | 15.4 | 9.5 | 171.4 | 20.7 | 24.8 | 447.4 | 235.6 | 192.4 | 166.9 | 229.2 |
| Pavia | 20.1 | 53.6 | 74.9 | 44.5 | 4.9 | 22.6 | 109.7 | 468.0 | 924.2 | 1,151.9 | 695.7 | 290.0 |
| Sannazzaro De'Burgondi | 601.1 | 75.9 | 82.1 | 70.8 | 3,380 | 29.2 | 82.6 | 1,918.9 | 1,105 | 449.0 | 667.4 | 2,223.6 |
| Vigevano | 24.6 | 50.8 | 65.0 | 42.9 | 11.7 | 20.4 | 107.7 | 382.7 | 980.3 | 1,161.0 | 645.3 | 230.5 |
| Voghera | 8.9 | 40.4 | 45.7 | 36.4 | 7.1 | 34.3 | 83.9 | 448.1 | 538.0 | 289.2 | 880.6 | 855.2 |

**Table 2.** Data on $CO_2$ eq. and territorial descriptors of the 7 most emissive municipalities ( source: authors)

| Municipality | $CO_2$ eq. (kt/year) | Population (inhab.) | Population Density (inhab./kmq) | GDP (€) |
|---|---|---|---|---|
| Ferrera Erbognone | 2.869,72 | 1.171,00 | 59,90 | 15.442.841,00 |
| Mortara | 126,62 | 15.543,00 | 298,20 | 228.606.170,00 |
| Parona | 240,81 | 1.975,00 | 211,50 | 26.400.225,00 |
| Pavia | 350,58 | 71.297,00 | 1.134,20 | 1.502.659.302,00 |
| Sannazzaro De'Burgondi | 2.245,46 | 5.533,00 | 237,30 | 77.957.469,00 |
| Vigevano | 287,35 | 63.268,00 | 768,00 | 970.129.252,00 |
| Voghera | 886,22 | 39.356,00 | 621,90 | 637.341.042,00 |

| | PAHs | PM10 | PTS | PM2.5 | $SO_2$ | $N_2O$ | $NH_3$ | NOx | VOCs | $CH_4$ | CO | $CO_2$ | $CO_2$ eq. | Population | Population Density | GDP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PAHs | | 0.66 | 0.52 | 0.72 | 0.98 | -0.14 | 0.03 | 0.94 | 0.53 | -0.17 | 0.19 | 0.41 | 0.40 | -0.40 | -0.33 | -0.38 |
| PM10 | | | 0.97 | 0.99 | 0.65 | -0.44 | 0.41 | 0.53 | 0.96 | 0.42 | 0.76 | -0.03 | -0.02 | 0.38 | 0.40 | 0.36 |
| PTS | | | | 0.95 | 0.49 | -0.49 | 0.52 | 0.37 | 0.97 | 0.60 | 0.75 | -0.17 | -0.16 | 0.52 | 0.54 | 0.51 |
| PM2.5 | | | | | 0.71 | -0.38 | 0.36 | 0.60 | 0.93 | 0.34 | 0.74 | 0.06 | 0.07 | 0.30 | 0.32 | 0.28 |
| $SO_2$ | | | | | | -0.09 | -0.12 | 0.95 | 0.53 | -0.26 | 0.20 | 0.49 | 0.49 | -0.36 | -0.30 | -0.34 |
| $N_2O$ | | | | | | | -0.27 | 0.20 | -0.51 | -0.35 | -0.49 | 0.80 | 0.80 | -0.46 | -0.53 | -0.43 |
| $NH_3$ | | | | | | | | -0.12 | 0.35 | 0.77 | 0.31 | -0.46 | -0.46 | 0.21 | 0.18 | 0.18 |
| NOx | | | | | | | | | 0.39 | -0.28 | 0.03 | 0.70 | 0.69 | -0.49 | -0.44 | -0.46 |
| VOCs | | | | | | | | | | 0.54 | 0.71 | -0.12 | -0.12 | 0.54 | 0.54 | 0.52 |
| $CH_4$ | | | | | | | | | | | 0.28 | -0.51 | -0.50 | 0.62 | 0.56 | 0.60 |
| CO | | | | | | | | | | | | -0.29 | -0.29 | 0.66 | 0.68 | 0.61 |
| $CO_2$ | | | | | | | | | | | | | 1.00 | -0.53 | -0.55 | -0.50 |
| $CO_2$ eq. | | | | | | | | | | | | | | -0.52 | -0.54 | -0.49 |
| Population | | | | | | | | | | | | | | | 0.97 | 0.98 |
| Population Density | | | | | | | | | | | | | | | | 0.99 |
| GDP | | | | | | | | | | | | | | | | |

**Fig. 7.** Correlation analysis among air pollutants and territorial descriptors for the seven most emissive municipalities ( source: authors)

Moreover, we defined the ranking of the correlation index (Fig. 8).

| | PM10 | PM2.5 | PTS | VOCs | CO | $SO_2$ | PAHs | NOx | $CO_2$ | $CH_4$ | Population Density | GDP | Population | $NH_3$ | $CO_2$ eq. | $N_2O$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **PM10** | | 0.99 | 0.97 | 0.96 | 0.76 | 0.65 | 0.66 | 0.53 | -0.03 | 0.42 | 0.40 | 0.36 | 0.38 | 0.41 | -0.02 | -0.44 |
| **PM2.5** | | | 0.95 | 0.93 | 0.74 | 0.71 | 0.72 | 0.60 | 0.06 | 0.34 | 0.32 | 0.28 | 0.30 | 0.36 | 0.07 | -0.38 |
| **PTS** | | | | 0.97 | 0.75 | 0.49 | 0.52 | 0.37 | -0.17 | 0.60 | 0.54 | 0.51 | 0.52 | 0.52 | -0.16 | -0.49 |
| **VOCs** | | | | | 0.71 | 0.53 | 0.53 | 0.39 | -0.12 | 0.54 | 0.54 | 0.52 | 0.54 | 0.52 | -0.12 | -0.51 |
| **CO** | | | | | | 0.20 | 0.19 | 0.03 | -0.29 | 0.28 | 0.68 | 0.61 | 0.66 | 0.31 | -0.29 | -0.49 |
| **$SO_2$** | | | | | | | 0.98 | 0.95 | 0.49 | -0.26 | -0.30 | -0.34 | -0.36 | -0.12 | 0.49 | -0.09 |
| **PAHs** | | | | | | | | 0.94 | 0.41 | -0.26 | -0.33 | -0.38 | -0.40 | 0.03 | 0.40 | -0.14 |
| **NOx** | | | | | | | | | 0.70 | -0.28 | -0.44 | -0.46 | -0.49 | -0.12 | 0.69 | 0.20 |
| **$CO_2$** | | | | | | | | | | -0.51 | -0.55 | -0.50 | -0.53 | -0.46 | 1.00 | 0.80 |
| **$CH_4$** | | | | | | | | | | | 0.56 | 0.60 | 0.62 | 0.77 | -0.50 | -0.35 |
| **Population Density** | | | | | | | | | | | | 0.99 | 0.97 | 0.18 | -0.54 | -0.53 |
| **GDP** | | | | | | | | | | | | | 0.18 | 0.18 | -0.49 | -0.43 |
| **Population** | | | | | | | | | | | | | | 0.18 | -0.52 | -0.46 |
| **$NH_3$** | | | | | | | | | | | | | | | -0.46 | -0.27 |
| **$CO_2$ eq.** | | | | | | | | | | | | | | | | 0.80 |
| **$N_2O$** | | | | | | | | | | | | | | | | |

**Fig. 8.** Correlation analysis among air pollutants and territorial descriptors for the seven most emissive municipalities. Classification based on correlation coefficient ( source: authors)

Figure 9 shows the different correlation indexes obtained. There are different kinds of correlations: strong positive (i.e. NOx and PAH), mild positive (i.e. $SO_2$ and $CO_2$), mild negative ($SO_2$ and population density) and strong negative (i.e. population density and $N_2O$).

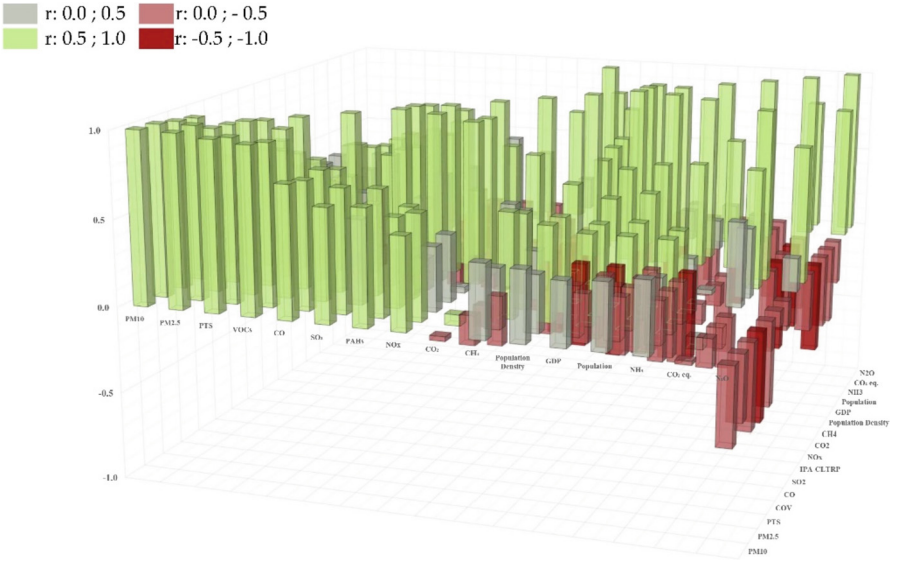


**Fig. 9.** Graphical visualisation of correlation outputs for the seven most emissive municipalities ( source: authors)

**Agricultural Areas.** For each municipality, we assumed that CO2eq was the most representative pollution parameter in the context of the real pollution situation, in relation to

the agricultural function (expressed in square metres). As shown in Table 3 and Fig. 10, there is a negative correlation between agricultural area and CO2eq.

**Table 3.** Correlation between CO2eq and agricultural area for the seven most emissive municipalities

| Municipality | Agricultural area (sqm) | $CO_2$ eq. (kt/year) | r |
|---|---|---|---|
| Ferrera Erbognone | 11,155,741.44 | 2.869.72 | −0.44 |
| Mortara | 38,189,181.16 | 126.62 | |
| Parona | 4,129,459.89 | 240.81 | |
| Pavia | 29,322,650.69 | 350.58 | |
| Sannazzaro de' Burgondi | 11,615,745.83 | 2,245.46 | |
| Vigevano | 28,626,280.19 | 287.35 | |
| Voghera | 46,643,247.56 | 886.22 | |

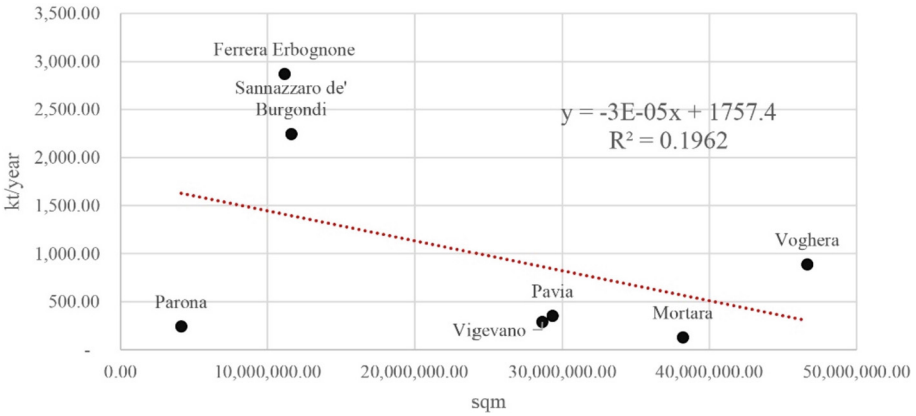


**Fig. 10.** Scatterplot of correlation between CO2eq and agricultural area for the seven most emissive municipalities ( source: authors)

Moreover, we performed the correlation with all of the air pollutants, starting from specific data related to each function. The results shown in Table 4 are in line with those expected, particularly for $NH_3$ and $CO_2$.

**Urban Settlements.** For each municipality, we assumed CO2eq as the pollution parameter representative of the context and of the real pollution situation, in relation to urban settlement areas (expressed in square metres). Residential, tertiary, and commercial functions and public services and facilities were included. As shown in Table 5 and Fig. 11, there is a negative correlation between areas of urban settlement and CO2eq.

**Table 4.** Correlation coefficients between air pollutants and agricultural area for the most emissive municipalities ( source: authors)

| Municipality | Agricultural area (sqm) | PAHs (kg/year) | PM10 (t/year) | PTS(t/year) | PM2.5 (t/year) | $SO_2$(t/year) | $N_2O$(t/year) | $NH_3$(t/year) | NOx(t/year) | VOCs (t/year) | $CH_4$(t/year) | CO(t/year) | $CO_2$(kt/year) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ferrera Erbognone | 11.155.741,4 | 6 | 14,3 | 17,5 | 13,6 | 15,1 | 68,6 | 36,8 | 863,1 | 242,5 | 400,6 | 82,3 | 2.838,8 |
| Mortara | 38.189.181,1 | 117,8 | 44,8 | 60,3 | 38,4 | 24,0 | 29,7 | 247,1 | 588,1 | 637,3 | 1.251,6 | 464,4 | 81,2 |
| Parona | 4.129.459,9 | 66,2 | 12,4 | 15,4 | 9,5 | 171,4 | 20,7 | 24,8 | 447,4 | 235,6 | 192,4 | 166,9 | 229,2 |
| Pavia | 29.322.650,7 | 20,1 | 53,6 | 74,9 | 44,5 | 4,9 | 22,6 | 109,7 | 468,0 | 924,2 | 1.151,9 | 695,7 | 290 |
| Sannazzaro De'Burgondi | 11.615.745,8 | 601,1 | 75,9 | 82,1 | 70,8 | 3.380 | 29,2 | 82,6 | 1.918,9 | 1.105 | 449 | 667,4 | 2.223,6 |
| Vigevano | 28.626.280,2 | 24,6 | 50,8 | 65 | 42,9 | 11,7 | 20,4 | 107,7 | 382,7 | 980,3 | 1.161 | 645,3 | 230,5 |
| Voghera | 46.643.247,6 | 8,9 | 40,4 | 45,7 | 36,4 | 7,1 | 34,3 | 83,9 | 448,1 | 538,0 | 289,2 | 880,6 | 855,2 |
| Correlation between Agricultural land and indicator | | Correlation coefficient | | | | | | | | | | | |
| | Agricultural area | -0,34 | 0,30 | 0,38 | 0,26 | -0,38 | -0,19 | 0,63 | -0,43 | 0,24 | 0,46 | 0,71 | -0,45 |

**Table 5.** Correlation between CO2eq and urban settlements area for the seven most emissive municipalities

| Municipality | Agricultural land (sqm) | CO2eq (kt/year) | r |
|---|---|---|---|
| Ferrera Erbognone | 734,689.37 | 2,869.72 | −0.45 |
| Mortara | 4,181,058.73 | 126.62 | |
| Parona | 627,983.42 | 240.81 | |
| Pavia | 11,352,391.73 | 350.58 | |
| Sannazzaro de' Burgondi | 4,566,901.56 | 2,245.46 | |
| Vigevano | 12,430,334.36 | 287.35 | |
| Voghera | 46,643,247.56 | 886.22 | |

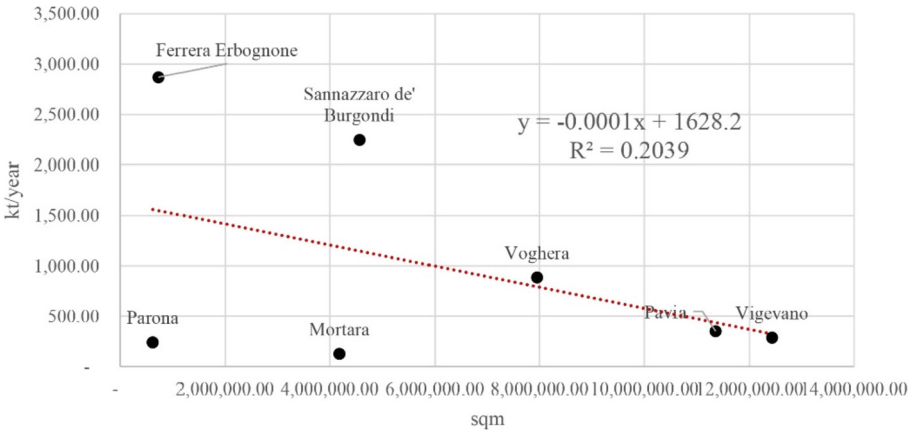


**Fig. 11.** Scatterplot of correlation between CO2eq and urban settlement areas for the seven most emissive municipalities ( source: authors)

Correlation was performed for all the air pollutants. The results, shown in Table 6, are quite peculiar because they show that direct or indirect correlations were not in line with what was expected (i.e. $CO_2$ or PM2.5 and PM10, for which strong direct correlations were expected).

**Table 6.** Correlation coefficients between air pollutants and urban settlement areas for the seven most emissive municipalities ( source: authors)

| Municipality | Urban settlements area (sqm) | PAHs (kg/year) | PM10 (t/year) | PTS(t/year) | PM2.5 (t/year) | $SO_2$(t/year) | $N_2O$(t/year) | $NH_3$(t/year) | NOx(t/year) | VOCs (t/year) | $CH_4$(t/year) | CO(t/year) | $CO_2$(kt/year) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ferrera Erbognone | 734.689,37 | 6 | 14,3 | 17,5 | 13,6 | 15,1 | 68,6 | 36,8 | 863,1 | 242,5 | 400,6 | 82,3 | 2.838,8 |
| Mortara | 4.181.058,73 | 117,8 | 44,8 | 60,3 | 38,4 | 24,0 | 29,7 | 247,1 | 588,1 | 637,3 | 1.251,6 | 464,4 | 81,2 |
| Parona | 627.983,42 | 66,2 | 12,4 | 15,4 | 9,5 | 171,4 | 20,7 | 24,8 | 447,4 | 235,6 | 192,4 | 166,9 | 229,2 |
| Pavia | 11.352.391,73 | 20,1 | 53,6 | 74,9 | 44,5 | 4,9 | 22,6 | 109,7 | 468,0 | 924,2 | 1.151,9 | 695,7 | 290 |
| Sannazzaro De'Burgondi | 4.566.901,56 | 601,1 | 75,9 | 82,1 | 70,8 | 3.380 | 29,2 | 82,6 | 1.918,9 | 1.105 | 449 | 667,4 | 2.223,6 |
| Vigevano | 12.430.334,36 | 24,6 | 50,8 | 65 | 42,9 | 11,7 | 20,4 | 107,7 | 382,7 | 980,3 | 1.161 | 645,3 | 230,5 |
| Voghera | 46.643.247,56 | 8,9 | 40,4 | 45,7 | 36,4 | 7,1 | 34,3 | 83,9 | 448,1 | 538,0 | 289,2 | 880,6 | 855,2 |
| Correlation between Agricultural land and indicator | | Correlation coefficient | | | | | | | | | | | |
| | Urban settlements area area | -0,42 | 0,20 | 0,40 | 0,10 | -0,51 | -0,53 | 0,70 | -0,59 | 0,30 | 0,84 | 0,32 | -0,81 |

**Industrial Sites.** For each municipality, we assumed CO2eq as the pollution parameter most representative of the context and of the real pollution situation in relation to the industrial sites (expressed in square metres). As shown in Table 7 and Fig. 12, there is an irrelevant negative correlation between industrial sites and CO2eq.

**Table 7.** Correlation between CO2eq and industrial sites for the seven most emissive municipalities

| Municipality | Industrial sites | CO2eq (kt/year) | r |
|---|---|---|---|
| Ferrera Erbognone | 1,913,019.42 | 2,869.72 | −0.018 |
| Mortara | 2,003,151.37 | 126.62 | |
| Parona | 999,895.96 | 240.81 | |
| Pavia | 2,577,443.08 | 350.58 | |
| Sannazzaro de' Burgondi | 2,248,542.33 | 2,245.46 | |
| Vigevano | 3,135,846.70 | 287.35 | |
| Voghera | 2,863,940.06 | 886.22 | |

Moreover, we performed the correlation with all the air pollutants. The results, shown in Table 8, are quite peculiar because they show some direct or indirect correlation, which is not in line with what was expected.

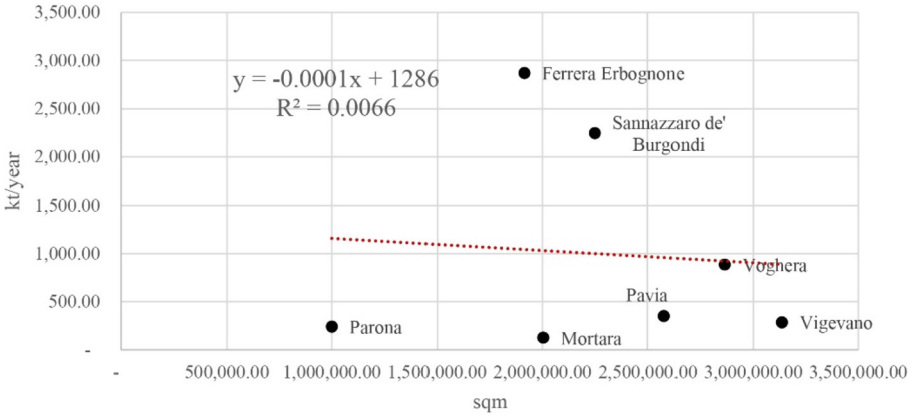


**Fig. 12.** Scatterplot of correlation between CO2eq and industrial sites for the seven most emissive municipalities ( source: authors)

**Table 8.** Correlation coefficients between air pollutants and industrial sites for the seven most emissive municipalities ( source: authors)

| Municipality | Industrial settlements area (sqm) | PAHs (kg/year) | PM10 (t/year) | PTS(t/year) | PM2.5 (t/year) | $SO_2$(t/year) | $N_2O$(t/year) | $NH_3$(t/year) | NOx(t/year) | VOCs (t/year) | $CH_4$(t/year) | CO(t/year) | $CO_2$(kt/year) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Ferrera Erbognone | 1.913.019,42 | 6 | 14,3 | 17,5 | 13,6 | 15,1 | 68,6 | 36,8 | 863,1 | 242,5 | 400,6 | 82,3 | 2.838,8 |
| Mortara | 2.003.151,37 | 117,8 | 44,8 | 60,3 | 38,4 | 24,0 | 29,7 | 247,1 | 588,1 | 637,3 | 1.251,6 | 464,4 | 81,2 |
| Parona | 999.895,96 | 66,2 | 12,4 | 15,4 | 9,5 | 171,4 | 20,7 | 24,8 | 447,4 | 235,6 | 192,4 | 166,9 | 229,2 |
| Pavia | 2.577.443,08 | 20,1 | 53,6 | 74,9 | 44,5 | 4,9 | 22,6 | 109,7 | 468,0 | 924,2 | 1.151,9 | 695,7 | 290 |
| Sannazzaro De'Burgondi | 2.248.542,33 | 601,1 | 75,9 | 82,1 | 70,8 | 3.380 | 29,2 | 82,6 | 1.918,9 | 1.105 | 449 | 667,4 | 2.223,6 |
| Vigevano | 3.135.846,70 | 24,6 | 50,8 | 65 | 42,9 | 11,7 | 20,4 | 107,7 | 382,7 | 980,3 | 1.161 | 645,3 | 230,5 |
| Voghera | 2.863.940,06 | 8,9 | 40,4 | 45,7 | 36,4 | 7,1 | 34,3 | 83,9 | 448,1 | 538,0 | 289,2 | 880,6 | 855,2 |
| Correlation between Agricultural land and indicator | | Correlation coefficient | | | | | | | | | | | |
| | Industrial settlements area area | -0,09 | 0,59 | 0,62 | 0,56 | -0,04 | -0,13 | 0,26 | -0,10 | 0,65 | 0,46 | 0,80 | -0,09 |

## 4 Discussion and Conclusion

The presented correlation analysis aimed to highlight evidence among the human activities and pollutant emissions in the Province of Pavia and in the most polluted Municipalities of the selected territory, in terms of equivalent $CO_2$. The human activities were synthesised with the extension (in sqm) of land use: agricultural land, urban settlement areas and industrial areas. The source of territorial data is the Geoportale of Lombardy Region (open source data) that considers groups of activities based on their similarity (i.e. industrial land and artisan areas are combined).

The correlation between the global pollutants for the whole province territory (Fig. 4), allows us to be confident about the research hypothesis. At the moment, open source

data is not available (at municipality level) that is able to combine every single activity with the specific emissions. These data are only available at the Province level.

It is well known that the total pollutant emissions depend on the intensity of land use and on. Specific uses that the GIS data may not trace, e.g. certain industrial activities in Sannazzaro de' Burgondi have very high emissions even if the extension of the industrial area is not huge. So, it is foreseeable that the relation analysis among parameters could have some nonlinear behaviour.

What emerged as a novelty in the analysis is the total lack of correlation between land uses and total emissions (Fig. 10, Fig. 11, and Fig. 12). The correlation is not only weak, but also negative, and this result is absolutely surprising. The reasons for this could depend on the low sensitivity of the single activity extension with the global data (Table 3, Table 5, and Table 7). At the Lombardy Region scale, agriculture is the driving force for the 6% of PM10, and industrial activities are driving forces for around 10% of PM10. In Table 4, the correlation index r between agricultural land and PM10 is positive but low ($r = 0.3$) and, in Table 8, the correlation index between industrial settlements and PM10 is 0.59. The behaviour of these two parameters makes sense, considering the linear impact of correlation and the global emissions. It is quite surprising that the correlation among various settlements and the total equivalent CO2 is always negative.

The next steps of the research will be: a) analysis of the regression index; b) comparison between correlation indexes and regression indexes; c) comparison among global data coming from different provinces of the Lombardy Region, in order to check the strength of the results.

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