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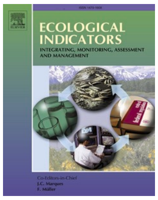

Air quality in urban areas: Comparing objective and subjective indicators in European countries

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ABSTRACT

Urban areas are major consumers of environmental resources and thus often place unsustainable demands on natural resources. As half of the world's population (55%) lives in urban areas, the environmental degradation produced by cities threatens the health and quality of life of a fair share of the world's population. For these reasons, progress towards sustainable urban development must be monitored and measured through suitable indicators. With reference to the assessment of air quality as a specific dimension of environmental quality in urban areas, existing studies have introduced various methodologies that mostly focus on objective measures (typically, exposure to outdoor air pollutants) while neglecting measures based on individual perceptions. Our goal is to contribute to filling this gap. To this end, we explore the relationship between objective and subjective measures of urban air quality in European countries. While the objective indicator is based on concentrations of PM2.5, our subjective indicator is reconstructed from individual perceptions collected through the European Union Statistics on Income and Living Conditions (EU-SILC) sample survey. Finally, through a cluster analysis, we classify the countries into homogeneous groups based on the values of these indicators. Our analysis reveals several differences in the country rankings according to the two indicators. For one group of countries, both approaches converge, thus leading to more definitive conclusions. For other countries, the mismatch between the two indicators suggests that either approach alone is not able to capture the full picture on air quality in urban environments.

1. Introduction

Today, over half of the world's population (55%) lives in urban areas, and it is projected that all regions will urbanize further in the coming decades (United Nations, 2018).

Urban areas are also the territory on which the main issues of sustainable development must be addressed. Indeed, urban areas are major consumers of environmental resources and thus often place unsustainable demands on natural resources in a trade-off between local quality and global sustainability (Alberti, 1996). Environmental degradation produced by cities through the depletion of resources such as water and soil and reduction of air quality not only concerns residents of urban areas: the environmental externalities of cities extend beyond cities' administrative boundaries, thus threatening the health and quality of life of a very large share of the population.

This paper concentrates on air quality in urban areas as a particular dimension of environmental degradation produced by cities. It is well known that high levels of urbanization are associated with severe air pollution and other environmental problems, affecting human health and well-being (Banzhaf et al., 2014). The sources of outdoor air pollution in urban areas are clearly understood. They include transport and the fuels used for transport (particularly road vehicles), as well as industry and emissions from homes and businesses. It is also clear that people are exposed to outdoor air pollution in the places where they live, work and spend their leisure time, and they also assess the air quality of such places from their subjective point of view.

Air quality standards for the protection of health are given in the EU Ambient Air Quality Directive (EU, 2008). A selection of the air pollutants regulated under the EU Directive, such as particulate matter (PM2.5 and PM10), nitrogen dioxide (NO2), ozone (O3) and benzo(a)

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pyrene (BaP), is employed by the European Environment Agency to summarize the national air quality situation in each country (EEA, 2019). Such indicators focus on objective measurements while neglecting those based on individual perceptions. Indeed, the individual self-assessment of air quality (i.e., assessment of whether individuals feel pollution to be a problem in the places where they live) is also an important measure that needs to be taken into account because annoyance due to the perceptions of environmental stressors can impair overall well-being and can be considered an adverse health effect per se. Moreover, in general, measures based on individual perceptions are linked to the social dimension of sustainable development, which interacts with its environmental and economic dimensions (Barbier, 1987; Pulselli et al., 2015; Neri et al., 2017). The perspective of jointly using subjective and objective measures of air quality as important indicators of this particular aspect of urban quality of life can allow for better monitoring of progress towards more sustainable urban development. Nevertheless, the relationship between subjective and objective measures of air quality has not been fully explored; indeed, they are generally viewed as separate in the literature.

Our aim is to contribute towards filling this gap. To gain a more holistic understanding of how urban environments affect air quality, we compare the performance of European countries according to two different indicators of urban air quality, one objective and the other subjective. Then, we classify countries into homogeneous groups based on the values of these indicators using cluster analysis (Everitt et al., 2011).

As an objective indicator, we use particulate matter (PM2.5) concentrations, which are considered to be the best proxy for the “ideal” measure of air pollution (OECD, 2011). Furthermore, among European countries, the estimates of the health impacts attributable to exposure to air pollution indicate that PM2.5 concentrations were responsible, in 2015, for the largest share of premature deaths (EEA, 2018). The subjective indicator is reconstructed from individual perceptions collected through the European Union Statistics on Income and Living Conditions (EU-SILC) sample survey.

Although the analysis is based on large-scale and nationwide data, the methodological contribution is general enough to be easily extended to a more detailed geocoded scale of analysis, such as level 2 or level 3 of the Nomenclature of Territorial Units for Statistics (NUTS).

The remainder of the article is organized as follows: Section 2 presents the literature review, Section 3 illustrates the methodological approach, Section 4 discusses the results, and Section 5 concludes.

2. Background

In the social and economic literature, an objective measurement is based on explicit criteria and is taken by external observers (Veenhoven, 2007), whereas a subjective indicator is often defined as information that includes some kind of subjective component, such as a personal perception or evaluation. As early as the 1990s, Michalos (1992) noticed that several indicators used to observe reality only appear to be neutral. Indeed, the author claimed that objective indicators represent limited aspects of the many facets of reality, and consequently, he argued that objective indicators can be considered a starting point for subsequent studies involving individuals.

There is a consolidated knowledge about the discrepancy between objective and subjective indicators in empirical research related to life domains (Cummins, 2000; McCrea et al., 2006). In a methodological contribution, Maggino and Ruviglioni (2008) examined the issue of integrating objective and subjective measurements in the general context of quality of life research. The authors outlined two different perspectives that can be considered. The first claims that objective indicators of quality of life at the macro level can be considered an antecedent with respect to subjective indicators. Following this perspective, objective indicators can be interpreted in terms of contextual conditions that can explain the subjective indicators (see, for instance, Welsch, 2007).

In contrast, the second perspective claims that objective and subjective indicators of quality of life are independent. According to this perspective, perceptions are influenced by individual characteristics and not by objective living conditions. From this point of view, subjective indicators can be considered an important component driving the improvement of objective conditions (see, for instance, de Vries et al., 2003).

In the specific context of environmental quality, the use of both subjective and objective measures has received increasing attention in different fields of study. With reference to the effect of air pollution, recent applications that make use of both objective and subjective measures have appeared in a fields ranging from epidemiology (Orru et al., 2018) and quality of life (Liao et al., 2015) to housing economics (Berezansky et al., 2010; Mínguez et al, 2013).

However, the issue of subjective perceptions may also be a key element in the specific analysis of urban environments’ quality and sustainability. In assessing the evolution of the urban environment towards sustainability, Alberti (1996) listed human health and well-being as dimensions to be considered, together with the use of natural resources, the release of emissions and waste and the transformation of the physical structure and habitat. Accordingly, in defining urban quality, Alberti (1996) stressed that physical elements and people’s perceptions shape urban quality; however, quantifying people’s perceptions to obtain a complete model of urban sustainability is difficult. In a similar vein, a more recent stream of literature on urban sustainability has stressed the need to integrate top-down assessment tools with “citizen-led, participatory, localized and procedural approaches” (Ahvenniemi et al., 2017). This is supported by the evidence that local stakeholder participation in the definition of the indicators and assessment tools of urban sustainability, the so-called bottom-up approach, is advantageous in terms of correctly defining and successfully achieving priorities (Reed et al., 2006; Berardi, 2013).

Nonetheless, there is a paucity of studies accounting for both objectively measurable dimensions of urban quality and subjectively perceived dimensions. One of the few exceptions is Banzhaf et al. (2014), who provided a conceptual framework to assess environmental quality jointly using qualitative and quantitative data and applied their methodology to the urban area of Santiago de Chile. As for cross-country comparison, Chiarini et al. (2020) provided a novel indicator to measure the performance of European countries in terms of joint perceptions of air quality and noise pollution to find relevant correlations with macro factors.

3. Materials and methods

3.1. Subjective indicator

The subjective indicator of air pollution has been estimated using microdata from the 2013 wave of the European Union Statistics on Income and Living Conditions (EU-SILC) (European Commission, 2013). In particular, we build this subjective indicator of air pollution related to cities (henceforth APIC) by measuring the difference in the predicted probability of reporting environmental discomfort when living in a large urban area compared to living in a rural area. The strategy used is as follows:

i) *Unit of analysis*: The unit of analysis is the household, whose reference person is asked to respond to the specific question, “In the area where you live, do you have pollution, grime or other environmental problems caused, among others, by traffic or industry?”.
ii) *Environmental problem*: The aim is to assess whether the respondent feels pollution is a problem and thus to measure self-reported exposure to pollution and other environmental problems. Although this information is rather general, encompassing

not just air pollution, it is currently used as a subjective indicator in combination with data on the exposure to fine particulate matter in several publications (see, for example, Eurostat, 2019).

iii) *Living areas*: For the measure of urbanization, the EU SILC data identify three types of living areas: densely populated areas (cities/large urban areas), intermediate density areas (towns and suburbs/small urban areas) and thinly populated areas (rural areas).

iv) *Perception in living areas*: The relationship between the degree of urbanization and the perception of environmental problems (POLLUTION = 1) is estimated through a logistic regression (Agresti, 2002) with controls for several socioeconomic and demographic characteristics defined in Table 1[1].

The total sample consists of 178,851 households distributed across the following 25 European countries: Austria (AT), Belgium (BE), Bulgaria (BG), Switzerland (CH), Cyprus (CY), Czech Republic (CZ), Germany (DE), Denmark (DK), Greece (EL), Spain (ES), Finland (FI), France (FR), Croatia (HR), Hungary (HU), Ireland (IE), Italy (IT), Lithuania (LT), Luxembourg (LU), Norway (NO), Poland (PL), Portugal (PT), Romania (RO), Sweden (SE), Slovakia (SK) and United Kingdom (UK). Table 2 shows the descriptive statistics of the variables for every

Table 1

Description of variables used in the logit regressions (Source: EU-SILC 2013).

Variable	Description	Codes
POLLUTION	Pollution problems	=1 if the household states that it has pollution, grime or other environmental problems in the local area; =0 otherwise
URB1	Degree of urbanization	=1 densely populated areas (cities/ large urban areas); =0 otherwise
URB2	Degree of urbanization	=1 intermediate density areas (towns and suburbs/small urban areas); =0 otherwise
HOUSE_PROP1	Tenure status	=1 for outright owner; =0 otherwise
HOUSE_PROP2	Tenure status	=1 for owner paying mortgage; =0 otherwise
INCOME	Annual equivalised disposable household income (as a z-score)	
CHILDREN	Presence of children in the household	=1 if at least one children (aged<16) is in the household; =0 otherwise
HOUSE_FSIZE	Household size	=1 for large household (4 members or more); =0 otherwise
HAPPY	Happiness status	=1 if the household members are happy most or all of the time (within-household median < 3); =0 otherwise
CALM	Calmness status	=1 if the household members are calm most or all of the time (within-household median < 3); =0 otherwise
D_UNEXP	Inability to face unexpected expenses	=1 if the household cannot afford an unexpected expense; =0 otherwise
RATE_RICH	Income from real and financial activities, as a % of total household income (as a z-score)	
EDU	Education level of household reference person	=1 for tertiary education (ISCED level 5 or 6); =0 otherwise
WORK	Work status of household reference person	=1 for employee or self-employed; =0 for unemployed or inactive
AGE	Age (in years) of the household reference person (as a z-score)	

Table 2

Average values of household level variables across countries (Variables are defined in Table 1. Weighted data using cross-sectional weights.)

Country	Sample size	POLLUTION	URB1	URB2	HOUSE_PROP1	HOUSE_PROP2	INCOME	CHILDREN	HOUSE_SIZE	HAPP Y	CALM	D_UNEXP	RATE_RICH	EDU	WORK	AGE
AT	5484	0.11	0.35	0.30	0.32	0.22	24,912	0.23	0.20	0.66	0.70	0.25	0.02	0.22	0.67	50.49
BE	5975	0.17	0.32	0.52	0.34	0.34	22,614	0.25	0.19	0.68	0.56	0.26	0.03	0.37	0.60	51.40
BG	3916	0.13	0.45	0.21	0.94	0.02	3549	0.25	0.29	0.40	0.48	0.65	0.02	0.26	0.66	52.42
CH	6568	0.10	0.30	0.48	0.05	0.35	46,596	0.25	0.20	0.70	0.65	0.20	0.03	0.39	0.75	51.22
CY	3669	0.15	0.55	0.21	0.62	0.20	20,662	0.34	0.35	0.43	0.40	0.53	0.03	0.35	0.78	48.46
CZ	7685	0.16	0.34	0.33	0.66	0.15	8601	0.25	0.22	0.53	0.58	0.43	0.01	0.18	0.67	51.15
DE	11,895	0.23	0.38	0.41	0.25	0.21	21,381	0.19	0.13	0.59	0.65	0.37	0.03	0.31	0.63	52.49
DK	5099	0.06	0.36	0.21	0.15	0.45	29,842	0.25	0.18	0.79	0.72	0.27	0.02	0.34	0.65	50.01
EL	6616	0.09	0.61	0.00	0.74	0.17	7722	0.26	0.20	0.44	0.61	0.41	0.01	0.37	0.73	50.59
ES	10,612	0.27	0.45	0.13	0.63	0.13	9714	0.25	0.26	0.27	0.27	0.47	0.03	0.26	0.55	53.02
FI	10,393	0.10	0.53	0.23	0.51	0.32	16,578	0.28	0.25	0.60	0.50	0.38	0.04	0.32	0.65	51.26
FR	10,427	0.08	0.38	0.28	0.35	0.36	25,744	0.23	0.17	0.80	0.83	0.27	0.03	0.37	0.69	50.51
HR	4606	0.11	0.47	0.20	0.39	0.24	24,988	0.26	0.19	0.64	0.55	0.33	0.07	0.28	0.61	52.13
HU	9497	0.07	0.29	0.28	0.94	0.02	5783	0.26	0.31	0.56	0.59	0.66	0.01	0.20	0.56	53.19
IE	4519	0.14	0.34	0.31	0.76	0.17	5254	0.25	0.25	0.56	0.63	0.72	0.00	0.24	0.62	52.66
IT	15,703	0.05	0.35	0.25	0.42	0.30	22,682	0.36	0.28	0.79	0.73	0.53	0.01	0.42	0.61	49.92
LT	4667	0.10	0.64	0.00	0.17	0.61	23,495	0.37	0.31	0.85	0.86	0.33	0.04	0.32	0.82	49.32
LU	3630	0.17	0.46	0.39	0.64	0.16	18,673	0.24	0.22	0.51	0.57	0.39	0.04	0.15	0.59	54.86
NO	5461	0.16	0.45	0.10	0.90	0.07	5501	0.24	0.21	0.50	0.77	0.58	0.01	0.31	0.63	52.30
PL	10,477	0.12	0.17	0.37	0.33	0.38	40,665	0.29	0.25	0.74	0.61	0.23	0.03	0.28	0.68	49.97
PT	5233	0.18	0.56	0.00	0.78	0.08	5579	0.25	0.21	0.35	0.61	0.71	0.01	0.29	0.67	51.95
RO	7005	0.40	0.90	0.10	0.63	0.18	13,425	0.30	0.29	0.74	0.64	0.23	0.04	0.20	0.67	49.41
SE	5676	0.08	0.53	0.17	0.24	0.63	46,829	0.30	0.22	0.73	0.78	0.10	0.03	0.35	0.75	49.84
SK	5173	0.10	0.38	0.25	0.82	0.10	6290	0.29	0.30	0.70	0.76	0.49	0.01	0.27	0.66	51.15
UK	8865	0.15	0.46	0.28	0.44	0.36	10,788	0.31	0.25	0.57	0.51	0.40	0.02	0.19	0.64	51.05

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[1] It is worth noting that we also control for the so-called one-source bias (Putrik et al., 2015). Indeed, perceptions of pollution can be biased by one's personal views. We mitigate this problem by computing two measures of the average household psychological climate, thus taking advantage of the information available in the ad hoc module of subjective well-being in the standard 2013 EU-SILC core survey (Eurostat, 2013). The estimation procedures have been applied using the software program Stata (StataCorp, 2015).

country.

To derive the subjective indicator, in each country j (j = 1…J) the following logit regression was estimated:

$$\log \frac{P\left(POLLUTION_{i\ j}=1\middle|\mathbf{x}_{\mathbf{i\ j}},URB_{1\ i\ j},URB_{2\ i\ j}\right)}{1-P\left(POLLUTION_{i\ j}=1\middle|\mathbf{x}_{\mathbf{i\ j}},URB_{1\ i\ j},URB_{2\ i\ j}\right)}=$$

$$=\mathbf{x}^{'}_{\mathbf{i\ j}}\boldsymbol{\beta}_{\mathbf{j}}+\beta_{URB1\ j}URB_{1\ i\ j}+\beta_{URB2\ j}\ URB_{2\ i\ j};$$

$$i=1\cdots n_j\ and\ j=1\cdots.J \tag{1}$$

where $\boldsymbol{x}^{'}_{ij}=\left(1,\boldsymbol{x}_{2ij},\ldots,\boldsymbol{x}_{(K)ij}\right)$ is the i$^{\text{th}}$ row vector of the $n_j\times(K)$ model matrix $\mathbf{X}$, which includes all control variables related to each household i, and $\boldsymbol{\beta}_j$ is the corresponding parameter vector to be estimated. β_{URB1j} and β_{URB2j} are the coefficients of two dummy variables, URB1 and URB2, controlling for those households living, respectively, in densely populated areas (cities/large urban areas) and in intermediate density areas (rural areas used as a baseline). Finally, n_j denotes the sample size in the j$^{\text{th}}$ country[2]. The APIC in country j (APIC$_j$) is calculated as the average marginal effect (Hensher and Johnson, 1981) of URB1.

A positive (negative) sign on the APIC for country j means that, on average, across the population of country j, households living in densely populated areas are more likely to feel pollution to be a problem (not to be a problem) than households living in rural areas. The higher the value of APIC$_j$, the worse is the country ranking in terms of air quality.

Fig. 1 shows the ranking of 25 European countries based on our subjective indicator APIC. In particular, the graph reports the estimated 95% confidence intervals of APIC in each country. In almost all countries, the APICs clearly do not intersect the vertical line fixed at zero, which means that, controlling for other covariates, the degree of urbanization has a significant impact on the probability of being exposed to the risk of pollution.

Evidently, Greece emerges as an outlier, showing by far the worst ranking. This result is likely to be influenced by the widespread discontent and the actual hardship of the Greek population in the aftermath of the heavy economic and financial crisis of 2007–2008. We surmise that the adverse economic conditions in Greece influence the evaluation of every single aspect of quality of life. Italy and Germany follow, with much higher values of the indicator than the values of the remaining countries. Furthermore, all the Nordic countries rank below the median, whereas the countries with the highest per capita GDP (namely, Norway, Luxembourg and Switzerland) are found among the low-ranking countries.

3.2. *Objective indicator*

One of the major indicators of air pollution is the concentration of PM. Indeed, the level of PM in cities is an indicator that must be monitored to reduce the adverse per capita environmental impact of cities within the framework of Sustainable Development Goal 11 (United Nations, 2015). Particulate matter is differentiated into PM2.5 and PM10; the diameters of the particles in micrometers (μm) are 2.5 and 10 μm, respectively. Sources of PM pollution can be both anthropogenic and natural. The former are known to produce finer particles (PM2.5) as a result of traffic emissions or combustion activities, whereas the latter (which include soil dust and sea salt) are responsible for producing coarser (PM10) particles (Mukherjee and Agrawal, 2017). The focus of this analysis is on PM2.5. Indeed, PM2.5 is the objective indicator accepted to be of greatest global concern given its relationship with adverse health outcomes from chronic exposure, as also shown by the estimates provided for Europe by the European Environment Agency (EEA, 2018). The most recent available estimates are from 2015 and show that premature deaths originating from long-term exposure to PM2.5 amounted to 422.000, whereas the estimated impacts of exposure to NO2 and O3 concentrations were approximately 79.000 and 17.700 premature deaths per year, respectively.

Based on the population weighted annual mean of PM2.5 in micrograms per cubic meter (source: European Environment Agency, EEA) for 2013, we have derived the ranking of 23 European countries (Fig. 2). The countries that rank highest are Central and Eastern European countries (namely, Bulgaria, Polonia, Croatia and Czechia), followed by Italy. In contrast, the Southern European countries (Spain, Greece and Portugal) rank as low as the Nordic countries. Sweden and Finland show the lowest values of PM2.5 emissions.

4. Results

4.1. *Comparing air quality in cities based on perceptions and objective pollution levels*

Based on the methodology described in Section 3, Fig. 3 compares the ranking of countries according to the subjective APIC indicator of air quality in cities (left-hand panel) with the ranking obtained using the objective measure of pollution, namely, the concentration of PM2.5 (right-hand panel).

The Spearman rank correlation coefficient is slightly positive but not statistically significant (0.224; p-value = 0.304). Indeed, the two rankings show some remarkable differences that are worth noting. For instance, Greece displays the highest subjective indicator of the effect of cities on air quality, whereas when we examine the classification in terms of objective pollution, Greece is classified in the bottom part of the ranking. In addition, by comparing Greece with Denmark and Ireland, we find that despite the very similar level of objective pollution, the perception that the urban environment is a source of poor air quality is by far larger in Greece than in Denmark and Ireland. Conversely, despite the very similar level of the subjective APIC indicator observed in Sweden and Czechia, in the former country, a much lower level of the objective indicator than that in the latter country is observed.

The problem of what generates the gap between the objective and subjective indicators and how this gap is different between the various countries is obviously linked to a series of causes that involve cultural, educational and political aspects (see, within the vast literature, Van Liere and Dunlap, 1980; Allan et al., 2000). The complexity of factors affecting individual perceptions is also very important and involves social acceptance and outcomes derived from acting in accordance with one's deeply held principles. Education, age, gender, socioeconomic status and several properly psychological aspects also affect environmental concerns (see, for instance, Axelrod and Lehman 1993, Swami et al. 2010, and Marquart-Pyatt 2012), as does the placement of countries in the various stages of growth and development. As for the importance of the development stage, we recall the literature on the environmental Kuznets curve (EKC; see, among others, Stern et al., 1996; Dasgupta et al., 2002; Dinda, 2004), which predicts increasing levels of objective pollution in the initial stages of economic development. In general, the empirical literature on the Kuznets curve has not analyzed whether, at different points on the inverted U-shaped curve between pollution and GDP growth, different perceptions of pollution could be experienced. Although this analysis cannot be at the center of this work, it is important to underline that our results on the gap between objective and subjective indicators might be related to this feature of the EKC. For instance, Fig. 3 shows that several European countries that, up to a few decades ago, were in the political orbit of the Soviet Union are today experiencing high objective pollution but a more limited perception of it. This might be consistent with the idea that in the first phase of the Kuznets curve, growth-driven pollution is not perceived as harmful to the same extent as pollution associated with the downward-sloping arm of the Kuznets bell. Finally, information policy and lobbying activity on environmental issues also play an important

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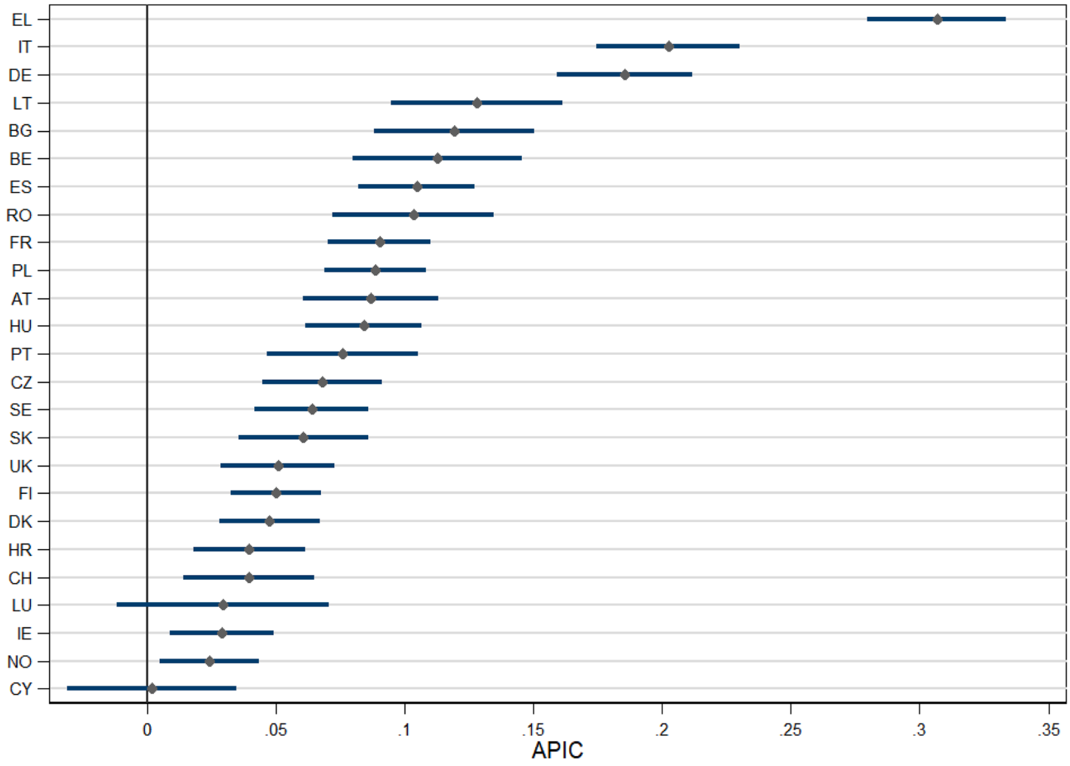
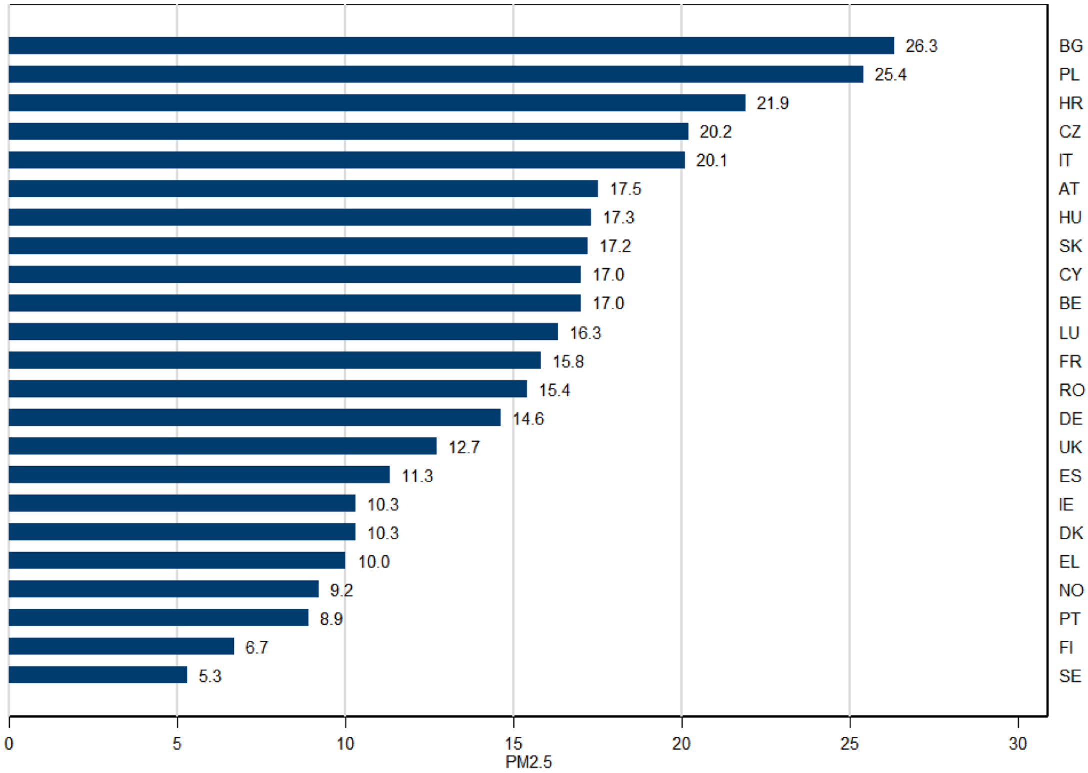
[2] The results of the logit regressions are reported in Appendix, Table A1.



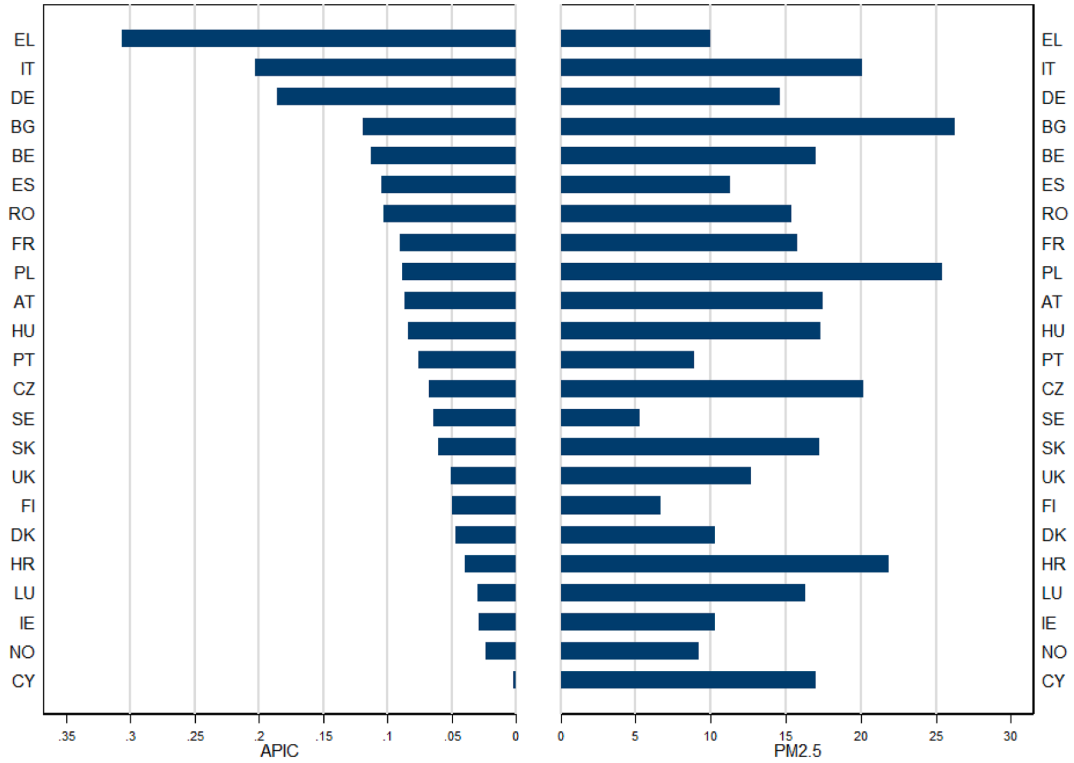
Source: Authors’ elaborations from EU-SILC data

Fig. 1. Country ranking according to the APIC subjective indicator, reference year 2013.



Source: European Environment Agency

Fig. 2. Country ranking according to the PM2.5 objective indicator, reference year 2013.



Source: Authors’ elaborations from EU-SILC data; European Environment Agency

Fig. 3. Country rankings according to the subjective indicator APIC (left panel) and the objective indicator (PM2.5, right panel).

role in shaping individuals’ perceptions and, therefore, influencing the gap between the two indicators. For instance, the Global Climate Coalition (GCC), formed in the United States in 1990 and joined by several European multinationals, represented, until the year of its dissolution in 2001, the major companies that were the main producers and users of fossil fuels (coal, oil, cars, electrical utilities, cement, aluminum, steel, chemicals, etc.). This association (like others representing companies around the world) was particularly active at conferences on climate and the environment, with the aim of spreading skepticism on the scientific literature on climate and pollution by means of press releases, congressional testimonies, academic interventions, and sponsoring of a series of scientific reports (see, for instance, Davis, 1996; Levy and Egan, 2003 for a survey of this literature).

4.2. *Clubs of countries according to subjective and objective indicators*

To go deeper into the analysis of the mismatch between subjective and objective indicators of air quality in European countries, we need to understand the relationship between the two types of measures (Lee and Marans, 1980). From this perspective, we can borrow a conceptual model proposed by Zapf in 1984 and recovered by Maggino and Ruviglioni (2008) and Noll (2013). The relationship between objective and subjective assessments of air quality is summarized in Table 3, which cross-tabulates low and high values of the objective (PM2.5) indicator (rows) with low and high values of the subjective (APIC) indicator (columns), thus identifying four different theoretical situations:

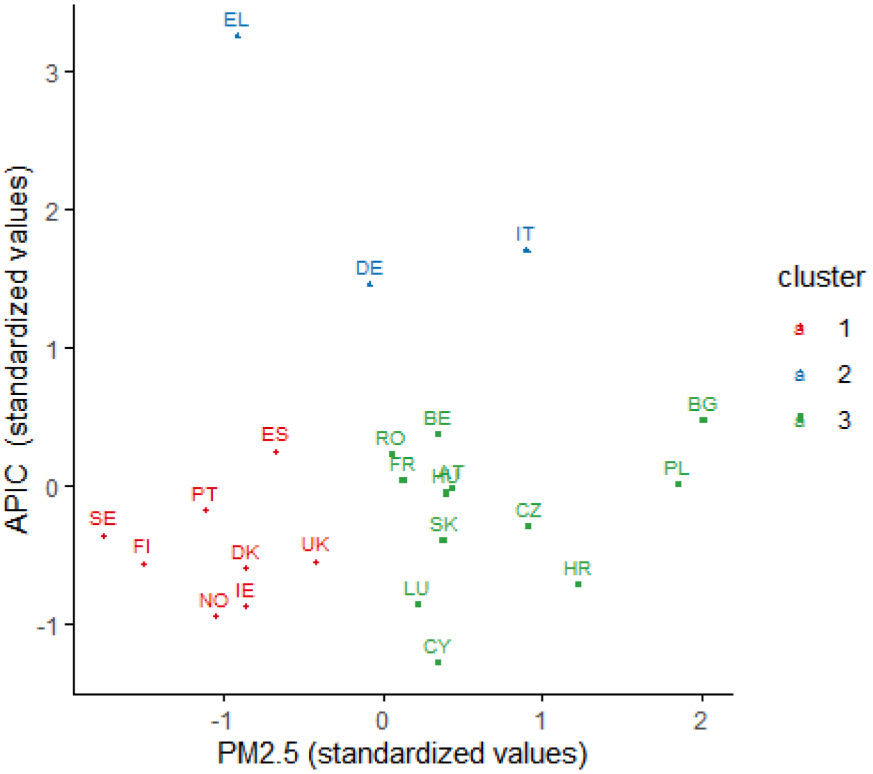
i) the desirable scenario, which here we label as “good air quality”, i.e., low levels of both PM2.5 and perceptions of environmental discomfort when living in a large urban area;
ii) the worst scenario, which we label as “bad air quality”, i.e., high levels of both PM2.5 and self-reported environmental discomfort when living in a large urban area;
iii) the “dissonance” scenario, defined by low levels of PM2.5 and high perceptions of air pollution, also labeled by Noll (2013) as the “satisfaction dilemma”; and
iv) the “adaptation” scenario, defined by high levels of PM2.5 and low levels of the subjective measure, labeled by Noll (2013) as the “satisfaction paradox”.

Table 3
Relationship between objective and subjective components of air quality in European urban environments: a classification based on Zapf’s model.

Level of:		(APIC)	
		LOW	HIGH
(PM2.5)	LOW	Good air quality	Dissonance
	HIGH	Adaptation	Bad air quality

While the first scenarios correspond to a situation of agreement between the objective and subjective indicators, Noll (2013) emphasizes that the two remaining scenarios are the most interesting from a policy-making point of view because the assessments based on objective and subjective information are contradictory rather than consistent.

The four scenarios depicted in Table 3 can be helpful in conducting the next step of the analysis. Exploiting the variability in the indicators retrieved in our dataset, we perform a cluster analysis (Everitt et al., 2011) that allows us to partition the countries under study into a limited number of internally homogeneous groups. The cluster analysis results are robust to different clustering methods (whether hierarchical or partitioning methods) and to different specifications of the same method (whether the k-means or k-medians algorithm in the case of partitioning methods). Fig. 4 shows the composition of the clusters resulting from an analysis through a k-means algorithm. The number of clusters $k = 3$ was



Source: Authors’ elaborations from EU-SILC data; European Environment Agency

Fig. 4. Results of the cluster analysis based on objective and subjective indicators.

chosen as a suitable compromise between achieving a large reduction in the data (from 23 countries to 3 groups) while still explaining a large share of the total variance in the data set by the clustering (68.7%). As a diagnostic tool for assessing the quality of the final cluster solution, we can refer to the silhouette width (Kaufman and Rousseeuw, 1990). For every country, the silhouette width measures the degree of within-cluster homogeneity and between-cluster heterogeneity. A good classification results when the silhouette width takes a value close to 1, that is, when, on average, a given country is close to the other countries in the same cluster and distant from all the countries in the other groups. In contrast, a value close to −1 reflects a misclassification of the country, whereas a value approximately 0 suggests that the country lies between two clusters. Single country widths are then averaged within each cluster and finally across the clusters to produce the overall average index: the higher the overall index, the better the quality of the solution (Rousseeuw,1986). Table 4 summarizes the cluster solution. Cluster 1 comprises Sweden, Finland, Norway, Denmark, Ireland, the United Kingdom, Spain and Portugal. This group reflects the highest degree of both inner cohesion and separation from the other groups, as shown by the largest value of the silhouette width. Cluster 2 is composed of Greece, Germany and Italy, whereas cluster 3 is the largest group and includes the following countries: France, Belgium, Luxembourg, Austria, Hungary, Slovakia, Czechia, Romania, Bulgaria, Poland, Croatia and Cyprus.

The location of the clusters of countries in Fig. 4 shows that cluster 1, at the bottom left-hand side of the graph, achieves the best performance on both indicators, which agree with each other. According to the labeling criteria proposed in Table 3, we might label this cluster the “good air quality” group. As expected, all Northern European countries are part of this cluster.

Cluster 3 includes a large number of countries that stand out for low values of subjective perceptions of air quality, similar to Cluster 1, but higher levels of PM2.5 than those of cluster 1. In other words, these countries seem to suffer from the “satisfaction paradox”, which can be explained by several possible determinants, as addressed in the previous section. Interestingly, Central and Eastern European countries belong to this cluster. In particular, countries such as Bulgaria, Poland, Croatia and Czechia emerge as having the highest levels of pollution due to PM2.5 emissions (including among the other countries in the same cluster), though they show, on average, very similar perceptions of air quality to those of the countries in cluster 1. This result can easily be traced back to the macroeconomic problems relating to the development-pollution relationship mentioned above in the brief review of the determinants of environmental perceptions.

Fig. 4 shows that Cluster 2 is composed of just three countries (Greece, Italy and Germany) that share much higher than average values of the subjective indicator, though they differ quite a lot in PM2.5 concentration. Indeed, the objective measure is at a low level in Greece, whereas in Germany it is very close to the average value across all countries and in Italy takes on a high value. Regardless of the classification based on the clustering algorithm, the three countries display, in

Table 4
Cluster solution.

Cluster	Size	Average values		Silhouette width	Composition
		APIC	PM2.5		
1	8	0.056	9.34	0.57	Sweden, Finland, Norway, Denmark, Ireland, United Kingdom, Spain and Portugal
2	3	0.232	14.90	0.27	Greece, Germany and Italy
3	12	0.074	18.94	0.40	France, Belgium, Luxembourg, Austria, Hungary, Slovakia, Czechia, Romania, Bulgaria, Poland, Croatia and Cyprus
Total	23	0.088	15.07	0.44	

terms of the labeling proposed by Table 3, alternative features of either agreement or disagreement between the objective and subjective indicators of urban air quality.

Italy seems to be the only country for which both indicators (objective and subjective) converge in pointing to poor air quality in urban areas. Whatever the approach, whether based on external observation or individual experiences, there is evidence of a serious degradation of air quality in the Italian large urban areas.

For Greece, the strong dissonance between the two measures may be due to the aftermath of the recent financial and economic crises that sharpened the defeatism and pessimism of the country's inhabitants on many life aspects, including the living environment. From Zapf's perspective, Greece seems to suffer markedly from the "satisfaction dilemma". Indeed, the economic crisis was so grave for Greek people that any political action in that period was not appreciated by citizens.

Interestingly, Germany is in the same cluster as Italy and Greece, showing features of the "satisfaction dilemma", which we surmise to have different roots from that dilemma in Greece. Unlike many other European countries, Germany is a country with a high degree of environmental concern: this is manifested by the fact that it has the largest number of environmental nongovernmental organizations among all European countries (EEB, The European Environmental Bureau, www.eeb.org) and by the Green Party being active there since the early 1980s.

5. Conclusions

This paper contributes to the currently flourishing debate about environmental quality of life in urban areas, examining whether subjective indicators can be used, in combination with objective measures, for its assessment. We investigated a specific aspect of environment quality of life, namely, air quality in urban areas, which can prove useful for informing policy-makers and for helping people with everyday life decisions, such as the choice of where to live. We innovated on existing studies in this area because we derived our country-level indicator as an average marginal effect after conditioning on several household characteristics.

The findings of the analysis conducted across European countries suggest that only in a limited group of countries do the subjective and objective approaches converge and thus lead to straightforward conclusions on the assessment of air quality; these include Northern European countries and some in the Mediterranean area. In contrast, for other countries, the mismatch between the objective and subjective indicators points to the existence of a "satisfaction dilemma" as well as a "satisfaction paradox". We have found Central and Eastern European countries to be among those that suffer from the "satisfaction paradox", thus suggesting that a possible explanation of the diverging assessments, which deserves in-depth analysis, is related to the different stages of development.

Further research may explore the use of different sources of information for defining a subjective indicator of air quality in urban areas; this could help to make our results more robust, considering that the subjective indicator that we chose also includes the assessment of grime and other environmental problems in the living area. Finally, for the classification of countries into homogeneous groups in situations where membership in a given group is not clear-cut and each data point can belong to more than one cluster, traditional cluster analysis may be replaced by a fuzzy clustering technique.

CRediT authorship contribution statement

Bruno Chiarini: Conceptualization, Writing - original draft. **Antonella D'Agostino:** Conceptualization, Methodology, Software, Validation, Formal analysis, Writing - original draft. **Elisabetta Marzano:** Conceptualization, Resources, Methodology, Validation, Writing - original draft, Writing - review & editing. **Andrea Regoli:** Conceptualization, Methodology, Software, Validation, Formal analysis, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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