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Are cities ready to synergise climate neutrality and air quality efforts?

G. Ulpiani [a,*], E. Pisoni [a], J. Bastos [a], F. Monforti-Ferrario [a], N. Vetters [b]

[a] European Commission, Joint Research Centre (JRC), Ispra, Italy
[b] European Commission, Joint Research Centre (JRC), Brussels, Belgium

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ABSTRACT

This study investigates the alignment of climate change mitigation with air quality initiatives in 362 (mostly European) cities eligible under the Climate-Neutral and Smart Cities Mission, hence targeting net-zero greenhouse gas (GHG) emissions by 2030. It examines ambient air quality, particularly $PM_{2.5}$ concentration levels, and GHG emissions, considering physical attributes, policy frameworks, and local authority actions. The research finds a north-to-south gradient in air quality, with northern cities exhibiting better air conditions, and a strong correlation between sectors contributing to GHG emissions and air pollution. Cities' strategies are dominated by cross-sectoral plans and assessing air quality as a co-benefit of climate mitigation is common practice, suggesting potential for synergistic approaches to climate and air quality goals, supported by the political authority that cities typically exert over relevant policy areas. Machine learning analysis (XGBoost) highlights national context, population density, and climate class as significant predictors of $PM_{2.5}$ levels, with policy variables indicating that proactive health and justice measures in city governance may correlate with improved air quality. The study advocates for a co-benefits approach in urban policy-making to effectively address climate change and air quality challenges, and it emphasises the need for transdisciplinary research and governance to optimise outcomes and reduce trade-offs.

1. Introduction

As the global community grapples with the urgent need to tackle climate change and its associated impacts, cities are increasingly recognised as focal points for implementing effective strategies to mitigate climate change and other environmental impacts (IPCC, 2022). Cities concentrate human population and economic activities, which are associated with high energy and resource requirements. It is estimated that, in 2015, core urban areas directly contributed to about one-third of scope 1 global anthropogenic greenhouse gas (GHG) emissions (Crippa et al., 2021), while consumption-based GHG emissions attributable to cities have shown an increasing trend in recent years, reaching a quota of about 70 % in 2020 (IPCC, 2022). Cities are also associated with ambient air pollution, which, due to potentially high population exposure, can have substantial public health impacts (Brauer et al., 2024; Sang et al., 2022; Yu et al., 2024). In Europe, despite the general improvements observed in recent years, concentrations of critical air pollutants such as fine particulate matter and nitrogen oxides ($PM_{2.5}$ and NO_x, respectively) in urban areas are often higher than those considered safe for health. In 2021, 97 % of the European urban population across Europe was exposed to concentrations of $PM_{2.5}$ above the health-based guideline level set by the World Health Organization (EEA, 2023). Similarly, the current pace of GHG emission reductions is far too slow to maintain global temperatures within the agreed-upon warming thresholds and achieve near-term climate stabilisation (Rogelj et al., 2023), with cities called to at least a quadruple effort compared to current mitigation achievements in order to reach a climate-neutral status (Ulpiani et al., 2023). Yet, for most local governments, moving forward on the climate change and air quality agenda requires navigating an intricate tapestry of e.g. political, economic, social, regulatory risks (Ulpiani & Vetters, 2023), while striving to create the necessary multi-level coordination across departments and governance levels (Shtjefni et al., 2024).

The social and economic repercussions of climate change and air pollution are multi-fold. The global social cost of air pollution is estimated at \$3 trillion/year at least, while the magnitude and frequency of weather and climate disasters that are estimated to cost over \$1 billion has been steadily increasing (Erickson, 2017). On the bright side, the

* Corresponding author at: European Commission, Joint Research Centre, Directorate C - Energy, Transport and Climate, Unit 2 - Energy Efficiency and Renewables, Via Fermi 2749, 21027 Ispra (VA), ITALIA.
E-mail address: Giulia.ULPIANI@ec.europa.eu (G. Ulpiani).

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global air quality co-benefits of GHG mitigation can reach 0.4, 1.1 and 1.5 million avoided deaths per year (due to $PM_{2.5}$ emission reduction) by 2030, 2050 and 2100 (West et al., 2013).

Recent scientific research has highlighted the potential benefits of tackling GHG emissions and ambient air pollution together (Pisoni et al., 2023; Vandyck et al., 2020). Integrated strategies can yield multiple benefits, such as reduced GHG emissions, increased public health and enhanced urban liveability (Monforti-Ferrario et al., 2018, 2024; Peduzzi et al., 2020). Benefits of integrating air quality and GHG reduction measures are also observed at city level. For instance, a scenario analysis for the Seoul Metropolitan Area (Chae & Park, 2011) estimated 41–90 % larger reductions in NO_x, PM_{10} and CO_2 emissions could be achieved with integrated measures tackling GHG emissions and air pollution, than with separated measures (Chae & Park, 2011), along with significant cost and health benefits. Encouraging results emerged also from analyses based on GAINS (Greenhouse Gas - Air Pollution Interactions and Synergies), an integrated model for evaluating climate change and air quality policies. For example, Woo et al. (2024) adapted GAINS to the Korean setting and tested three alternative scenarios -Business as Usual (BAU), Air Quality (AQ), and Maximum Feasible Reduction (MFR, incorporative state-of-the art emissions reduction technologies) – to verify the impacts of changes in activity levels resulting from GHG reduction policies on air quality (Woo et al., 2024). The AQ scenario could reduce NO_x by 21 % and SO_2 by 20 % by 2030, compared to a 25 % NO_x increase in the BAU, with the MFR achieving even greater reductions yet at higher cost. In a scenario analysis for Beijing, the GAINS-City model showed that implementing air quality measures could reduce annual air pollutant emissions (NO_x and $PM_{2.5}$) by 37–55 %, SO_2 by 39–48 %, and CO_2 emissions by 5–22 %, highlighting significant co-benefits of air quality policies on GHG reductions (F. Liu et al., 2013). The findings emphasised the need for technological improvements and more ambitious combined urban and regional measures to achieve further reductions. Similar applications, showing co-benefits of air quality and GHG reduction at local scale, have been developed for California (Fournier et al., 2022), Beijing (Liu et al., 2024b) and for 8 big cities located in Europe, Canada, Africa and India (Boyd et al., 2022).

In Europe, an additional pressure towards a combined approach to air quality and climate mitigation derives from the concurrent ambitious targets set by the EU Green Deal, which targets a 55 % reduction both of GHG emissions and of premature deaths caused by air pollution by 2030 (European Commission, 2021). In this context, major European cities like Barcelona, Madrid, Milan, or Paris have paved the way to integrating air quality in climate action plans by adopting a synergistic approach (European Commission, 2024).

Despite increasing evidence on the benefits of integrated action, these two environmental issues (climate change and ambient air pollution) are often still tackled separately, dealt with by different departments, stakeholder groups, and scientific communities, and within different policy frameworks (Maione et al., 2016). Cities might lack awareness of the additional benefits that could be achieved by a policy when designed and implemented to obtain not only GHG emissions reductions, but also improved air quality. Cities might also lack the tools and resources to advance the status quo, to quantify and analyse in detail their specific cases or to maximise the positive impacts of their actions, thus potentially overlooking opportunities to improve public health while fostering GHG mitigation (Roggero et al., 2023). On the other side, cities could be tempted to apply GHG reduction actions potentially harmful for air quality, such as increasing biomass burning in domestic appliances with a low grade of efficiency and pollution emission control (Zauli-Sajani et al., 2024).

This paper explores the importance of and the existing room for aligning climate change mitigation and air quality efforts in cities, particularly within the context of the EU's ambitious 100 Climate-neutral and Smart Cities Mission (hereinafter Cities Mission). The Cities Mission seeks to transform 100+ cities into climate change mitigation leaders, by setting a pioneering target of net-zero emissions by as early as 2030. Mission cities are tasked with developing a Climate Neutrality Action Plan, a portfolio of transformative actions aimed at achieving climate neutrality, while offering opportunities to catalyse climate change adaptation (i.e. enhanced resilience to climate change impacts) and improving ambient air quality and public health. By analysing the questionnaire through which cities expressed their interest in the Mission and combining it with air pollution estimates, we address the following research questions:

- How significantly do cities factor in air quality issues when planning for a climate-neutral future?
- Is there alignment between the sectors targeted for intervention, and can a transformative strategy designed to cut GHG emissions also significantly impact air pollution levels?
- Are cities developing comprehensive, multi-sectoral strategies that foster a synergistic approach to addressing both climate and air quality objectives?
- Have cities established frameworks or mechanisms to evaluate and monitor the impact of GHG reduction measures on air quality?
- To what degree do cities possess the authority to effectively manage the intersection of climate action and air quality initiatives?
- To what extent does air quality hinge on natural conditions, and what role can policy play in mediating these effects?

Addressing these questions necessitates a substantial sample of cities and the collection of specific information through standardised protocols, as described in the Methods section. The results unveil the opportunity space that exists already today for integrating air quality with climate change mitigation, and provide insight on key levers and predictors to guide more targeted and impactful regulatory frameworks.

2. Methods

To explore the potential linkages between urban air quality and GHG emissions from a combined physical and policy-oriented perspective, this study draws on the combination of 3 main datasets, and on specific descriptive and inferential statistical analyses, as described next.

2.1. Datasets

The Cities Mission dataset is composed by the answers that 362 eligible cities provided to 374 questions on their past, present and future in climate change mitigation action, enriched by specific modules on GHG emission inventories, governance, partnerships, financing, and risk anticipation. The questionnaire served as an Expression of Interest (EOI) for the Mission, submitted by cities with the ambition to become climate-neutral by 2030, and can be found in the Supplementary Materials of Ulpiani and Vetters (2023). In total, 35 countries are covered, with 13 countries represented by >10 cities. Numerous governance arrangements are included, which may manifest as different degrees of maturity and integration in climate action. Cities of around 10 thousand inhabitants as well as large conurbations of up to 15 million inhabitants are encompassed. The sample includes a good percentage of coastal cities (19 %) and in terms of climate, all five main classes (A, B, C, D, and E) of the Köppen-Geiger classification (Peel et al., 2007) are represented. The data is elicited in a homogeneous manner and in the context of the same climate target (i.e. climate neutrality by 2030), which provides comparability in terms of ambition. Data quality went through control procedures performed by the Joint Research Centre of the European Commission. A total of 60+ questions from the questionnaire, directly or indirectly relevant to air quality, inform this analysis. It is important to notice that air quality was mentioned in the EOI questionnaire, but no special emphasis was given in comparison with other environmental issues. For this reason, the answers here analysed can be taken as "unbiased", making the Cities Mission dataset an appropriate tool to analyse the grade of interest and awareness of eligible cities. As the EOI questions examined here were not compulsory and could be conditional to the answers provided to preceding questions, the number of respondent cities is always specified in the results. Further, for multiple-choice questions, the total number of entries ("n") is recorded and displayed on all graphical representations. More information on the dataset and the data processing for use in this study can be found in the Supplementary Material (Supplementary Note 1 and Table S2). While offering unprecedented opportunities to investigate the readiness of cities to co-target climate neutrality and air quality, some limitations affect the Cities Mission dataset:

- It derives from an open questionnaire filled by cities, not a systematic registration of data on existing policies, measures, or monitoring setups. This entails that e.g. the presence of a plan is not insightful of its effectiveness.
- The dataset is geographically imbalanced (e.g. not all countries are equally represented).
- The focus on GHG emissions and air quality is not equated, as the Cities Mission generally looks at whether air quality is included in climate mitigation actions, not viceversa.
- It overlooks specific connections between emissions reduction and air quality. Recent studies underscore the positive impact of green digital finance on the combined pursuit of pollution and carbon reduction goals, further amplified by green technology innovation, industrial structure upgrading, and enhanced financial supervision (He et al., 2023; Li et al., 2024; Yin et al., 2024). The favourable role played by digital technological innovation is further stressed in Zhu et al. (2024), while economic acceleration and foreign direct investment are emphasised in Xu et al. (2024) as additional positive driving factors. These cross-sectoral dimensions could not be analysed due to the lack of relevant data covering all the cities.

The air pollutants dataset contains yearly mean concentrations (for $PM_{2.5}$, PM_{10} and NO_2) for the year 2019 for each city, as derived from the Copernicus Atmospheric Service (CAMS). We use the Ensemble CAMS reanalysis product as data source (CAMS, 2023), computed as the median of simulations performed with 9 state-of-the-art air quality models, including assimilation of validated data. As air pollution data comes with a 10 km spatial resolution, it is spatially averaged on the city polygons, to reflect the average urban concentrations.

Finally, *the dataset on sectoral contributions to $PM_{2.5}$ concentrations* is derived from the $PM_{2.5}$ Atlas (Zauli-Sajani et al., 2024). In the $PM_{2.5}$ Atlas, source contributions are computed using the SHERPA air quality model (Pisoni et al., 2019) and applying a brute-force approach (Thunis et al., 2019), simulating once-at-a-time the impacts of reducing emissions for different sectors. The robustness of this approach is showed through comparative analysis with the results of alternative models in Khomenko et al. (2023). More information on the two air quality datasets can be found in the Supplementary Material (Table S1).

2.2. Statistical analyses

Our investigation starts with an assessment of air pollutant concentrations and GHG emissions in the 362 cities before exploring associated policy measures and governance provisions. The data distribution is initially analysed using descriptive statistics, in the form of rankings, boxplots, or raincloud plots. Then, to elucidate which natural, socio-economic or policy-related characteristics of the cities are most strongly correlated with air quality levels (using $PM_{2.5}$ concentrations as a proxy), we constructed a regression model based on the gradient boosting method. This machine learning technique has numerous applications in predictive modelling (Pisoni et al., 2022) and has proven effective in forecasting air quality (Ma et al., 2020; Van et al., 2023). We build and validate the model in R, using the 'XGBoost' algorithm (Chen & Guestrin, 2016). Since the model cannot handle missing values (NaNs), the analysis is performed on the 261 cities for which we have a complete dataset across the physical and policy variables considered. The availability of GHG emission data is the main constraint. XGBoost can account for the co-dependence between independent variables and does not require strict assumptions concerning the model structure and parameters. We ordered categorical inputs according to custom logics to facilitate interpretation: countries were sequenced from northwest to southeast, and climatic classes were arranged from cold and humid to hot and dry, based on the Köppen-Geiger classification. Moreover, per capita emission values higher than 5 tCO2e were kept fixed at 5 (hence the value 5 means >=5) to avoid spurious fittings to outliers in the model.

After the model training and validation, we use the extended interpretative capabilities of SHAP (SHapley Additive exPlanations) values to compute the importance of each model variable considering interactions and allowing the direction of the impact to be visualised. We adopt the 'Shapforxgboost' package (Liu & Just, 2020).

The XGBoost algorithms deepen the investigation on what might be correlated with air quality levels. The analysis focuses solely on $PM_{2.5}$ annual mean concentrations, i.e. a reference ambient air pollutant in terms of public health, implicated in various respiratory and cardiovascular diseases (EEA, 2022; Yue et al., 2024). A total of 46 input variables are fed into the model, out of which 39 are policy-related. These correspond to the 60+ questions extracted from the Expression of Interest, along with additional city attributes (e.g. country, climate), fully described in the Supplementary Material (Tables S1 and S2).

3. Results

The section starts with an analysis focused on air pollutants and GHG emissions, transitions to scrutinising the EOI questionnaire, discusses the co-benefits and municipal powers, and wraps up with an investigation of the potential inter-relationships among variables using the SHAP concept.

3.1. Air pollution and GHG emissions

Fig. 1 summarises the main characteristics of, air pollution indicators and GHG emissions for the 362 cities. The map (Fig. 1**A**) shows their spatial distribution, population density and air quality. The colour code is used to distinguish cities with different air quality levels, in terms of $PM_{2.5}$ annual mean concentrations, while the marker size increases with the population density. Noticeably, $PM_{2.5}$ concentration levels stratify from north to south, with very low $PM_{2.5}$ concentrations (<5 μg/m^3) being a prerogative of Northern Europe, and with the highest $PM_{2.5}$ concentrations (>20 μg/m^3) condensed in South-Eastern regions. With a certain variability, also densely populated areas are associated with higher pollution levels.

The raincloud plots in Fig. 1**B** display the distribution of $PM_{2.5}$, PM_{10} and NO_2 annual mean concentrations. The scatterplot represents each city median value over the year, while the violin and boxplot show the density estimate and the summary statistics, respectively. For each pollutant, the World Health Organization (WHO) air quality guidelines threshold is shown as a red dotted line (5 μg/m^3 for $PM_{2.5}$, 15 μg/m^3 for PM_{10}, and 10 μg/m^3 for NO_2) for reference (WHO, 2024). Similarly, the orange dotted line represents the threshold proposed in the upcoming Revised Ambient Air Quality Directive (European Commission, 2022). It is observed that i) in terms of statistical variability, NO_2 exhibits the largest interquartile range at almost 10 μg/m^3 and is the only pollutant whose median is below the WHO threshold; ii) PM_{10} reaches the highest extremes (exceeding 30 μg/m^3 – twice the threshold – in multiple cases), yet its 25th percentile falls below the threshold; and iii) the 25th percentile of $PM_{2.5}$ is almost twice the WHO threshold indicating potential poor air quality across the vast majority of eligible cities. Indeed, only 17 cities appear to be below the WHO threshold according to CAMS

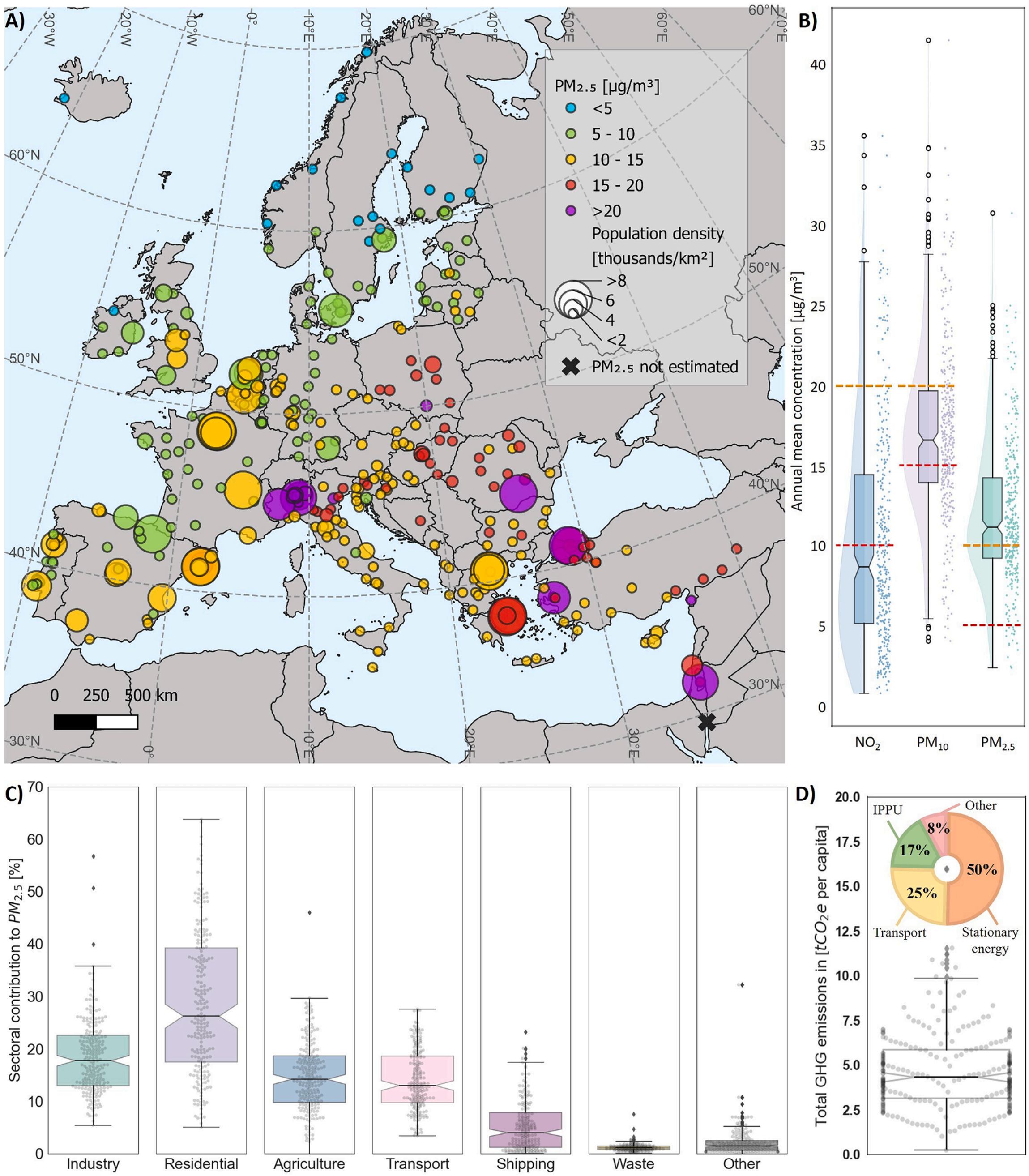

Fig. 1. Air pollution and greenhouse gas emissions across the 362 cities that expressed interest in the 100 Climate-Neutral and Smart Cities Mission. A) Map of the cities and indication of their population density and annual mean concentration of $PM_{2.5}$ (16 cities are not shown for confidentiality reasons); B) Raincloud plots of the air pollutants concentrations distribution; C) Percent contribution of different sectors to total $PM_{2.5}$ concentrations; D) Boxplot of per capita GHG emissions and pie chart of sectoral contributions.

data: 5 in Norway, Sweden and Finland, 1 in Iceland, and 1 in Ireland.

The sectoral attribution of $PM_{2.5}$ is displayed in Fig. 1**C**. The residential sector is by far the greatest contributor, with median at almost 30 % of total $PM_{2.5}$, 75th percentile at 40 %, and maximum at nearly 65 %. This is also the sector with largest interquartile range (over 20 %, more than twice the range of other sectors). The second largest contributor is the industry sector, with median around 20 %, followed by agriculture and transport, both at around 15 %. Shipping can sporadically have an important role; however, together with waste and other sectors, it typically accounts for a small relative contribution. This is in line with evidence from different models based on emission reduction impact methods, including chemical transport model (CTM) simulations and other approaches, such as reduced-complexity CTM or adjoint sensitivity methods (Khomenko et al., 2023).

Interestingly, a similar distribution is observed in terms of GHG emissions (CO_2, CH_4, N_2O and F-gases). This is visualised in Fig. 1**D** where the boxplot of total GHG emissions per capita is accompanied by a pie chart showing the sectoral distribution. For more information on e.g. the variability of these contributions across the cities, refer to (Ulpiani et al., 2023). Due to the use of two data sources with different sectorial structure/classification, the sector names do not correspond between ambient air pollutant and GHG figures. In GHG accounting, the stationary energy sector represents buildings (including industrial buildings), equipment and facilities and is typically dominated by residential emissions and the IPPU sector (Industrial Processes and Product Use) represents industrial processes and product use. While specific emission sources may differ even within the same sector, it is intuitive that by adopting a bold decarbonisation action on highly-emitting sectors, Mission cities are offered the opportunity to co-target climate mitigation and air quality, delivering on both the Paris Agreement objectives and Air Quality targets.

3.2. Action plans

The prime instrument for cities to enforce policies for climate change or air quality action is the design and approval of action plans. Fig. 2 illustrates the distribution of all the plans declared by eligible cities in the EOI questionnaire. The invitation was to describe maximum 5 plans with relevance to climate mitigation. Cities could choose the plan typology from a list of options (x-axis labels in Fig. 2). The option SECAP/SEAP indicates the Sustainable Energy (and Climate) Action Plans that cities and municipalities in the Global Covenant of Mayors initiative develop and implement to outline their actions towards improving energy efficiency, reducing GHG emissions, adapting to climate change, and addressing energy poverty (Melica et al., 2022). Similarly, Sustainable Urban Mobility Plans (SUMPs) are integrated strategic plans designed to ensure that transportation in urban areas is sustainable, efficient, and meets the needs of citizens, while Sustainable Development Action Plans (SuDs) are comprehensive strategies to achieve long-term sustainable development goals, focusing on balancing environmental integrity, economic prosperity, and social equity. SECAPs/-SEAPs, SUMPs, and SuDs are specific plans developed in the context of European Commission initiatives and policies according to specific guidelines. One of the action plan types cities could choose was "Air quality plan". Their inclusion in this specific dataset entails that the city is aware of the relevance of the interplay between climate mitigation and air quality policies. The barplot to the left is insightful of the variety of plans (types are counted only once across the – maximum – 5 plans). Conversely, the barplot to the right contemplates all answers provided by cities and cumulatively accounts for all action plans. This second visualisation is thus informative of the popularity of certain plan types over others.

Expectedly, cross-sectoral plans that tackle the reduction of GHG emissions from different perspectives (SECAPs/SEAPs, SuDs, climate change mitigation plans, and other cross-sectoral plans) dominate the arena of plan types declared by eligible cities, with SUMPs being the only sectoral plans being selected by almost half of the cities. However, a noticeable share of respondents (15 %) included air quality plans in their selection of 5 plans relevant for GHG emission reduction. This suggests that 55 cities (out of which 10 in Germany) have already designed air quality action plans underscoring emissions reduction targets too. This is an encouraging signal towards moving away from a siloed approach to environmental challenges. Nonetheless, the percent cover could be considered low since the cohort of cities here examined is potentially representative of European frontrunner cities in climate action, i.e. cities having a longstanding commitment to addressing the climate crisis and having expressed the highest possible ambition (climate neutrality) in a very tight timeframe (by 2030).

3.3. Co-benefits and powers

Another way cities could demonstrate their awareness of the interplay between air quality and climate change mitigation in the EOI questionnaire was the co-benefits section. Cities were asked whether they assess the possible co-benefits/adverse impacts generated by local scale climate mitigation policies/actions in 4 main categories - economic, social, public health, and environmental impacts – and/or vice versa. In total, 172 cities indicated some level of familiarity with co-benefits/adverse impact assessment.

Fig. 3 shows the ranking of the different options cities could choose from in the public health category. It shows that 95 % of the 172 cities could identify at least one aspect pertaining to public health and well-being among the options provided and that air quality is by far the most commonly mentioned aspect (almost 90 %). The identification of air

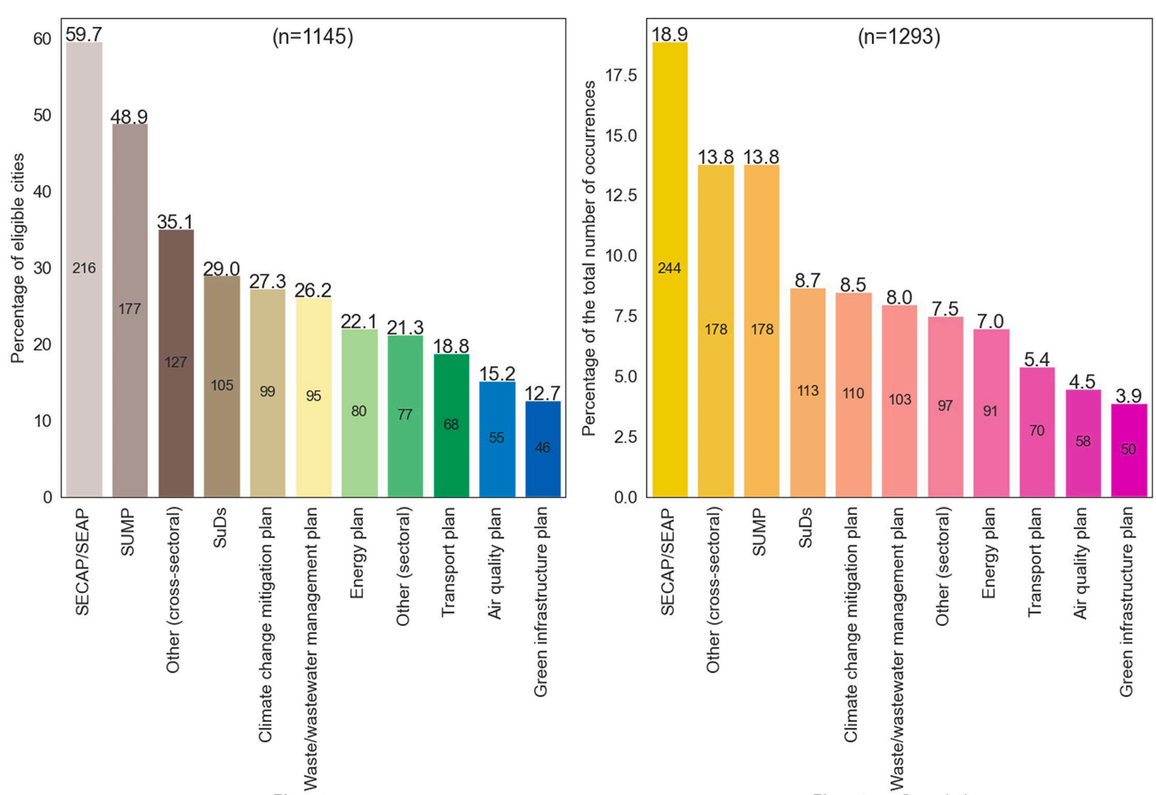

Fig. 2. Thematic distribution across plans – variety and most frequent types. Number of respondent cities: 329.

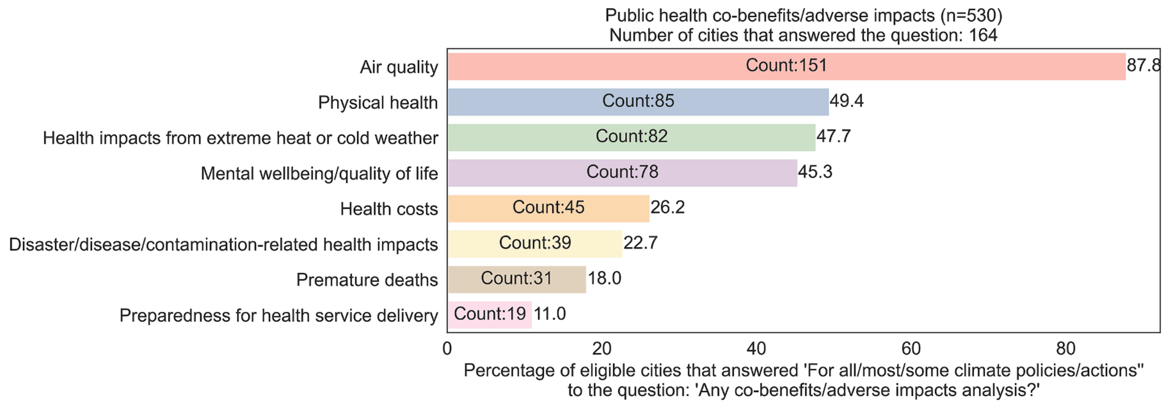

Fig. 3. Ranking of the most common public health co-benefits or adverse impacts assessed by eligible cities in climate action.

quality as the most popular co-benefit for climate mitigation is in line with recent literature (Karlsson et al., 2020; Roggero et al., 2023). All other options (including physical health, health impacts from extreme heat or cold weather, and mental wellbeing/quality of life) were selected by less than half of the cities. Even across the other 3 categories (economic, social, and environmental impacts), with options like "job creation", "mobility and access", and "green space coverage and quality" (top selections in each ranking), the share could not reach as high as 90 %. This may suggest that cities frequently co-monitor or tackle air quality in combination with their climate action. While this does not necessarily reflect integrated action, it may set the groundwork for an evidence-based dual approach.

Another positive indication is that the majority of local authorities acknowledged having the legal powers to act or make policy decisions in the air quality domain. This is shown in Fig. 4, which illustrates the ranking of various action fields cited by cities in the EOI questionnaire, organized from the most to the least controlled or influenced at local level. Almost all eligible cities (353) provided an answer and over 80 % declared that they have the legal powers to act/decide on: 'Green spaces / Green infrastructure', 'Urban land use', 'Waste/wastewater management', 'Buildings & Construction', and 'Transport'. Interestingly, these are among the most important contributors to air pollution and GHG emissions, where faster and bolder action could be prioritised. >50 % of the eligible cities also indicated 'Environment', 'Air quality' (71 %), 'Water Resource Management', 'Disaster risk', 'Economic development', and 'Public health', which is an encouraging indication of the room for co-benefits planning. <20 % of the cities selected 'Industrial emissions' and 'Agricultural emissions', suggesting that IPPU and AFOLU (Agriculture, Forestry and Other Land Use) may require some intermediate steps and increased capacity to speed up the transition to climate neutrality. Most respondents (52 %) ticked between 11 and 14 options with a very homogeneous percent distribution across all possible combinations (10–11 %). This suggests that, on average, cities acknowledge their power to act and decide upon 8 or 9 fields, which bodes well in terms of adopting holistic/integrated approaches.

3.4. *Inter-relationships*

The summary plot in Fig. 5 shows the most relevant predictors for $PM_{2.5}$ concentrations in eligible cities, as obtained through XGBoost. Each point on the summary plot represents the SHAP value of each city per variable, i.e. a metric of importance representing the feature's contribution to the model's output. Overlapping points are jittered in the y-axis direction to get a sense of the distribution. Positive and negative SHAP values indicate that a variable contributes to an increase and decrease in the predicted $PM_{2.5}$ levels, respectively. The numbers along the y-axis, used to perform the ranking, represent the global "feature importance", i.e. the average absolute SHAP value per variable. A larger value means the feature has a stronger influence. Finally, the colour represents the value of the variable from low (yellow) to high (purple).

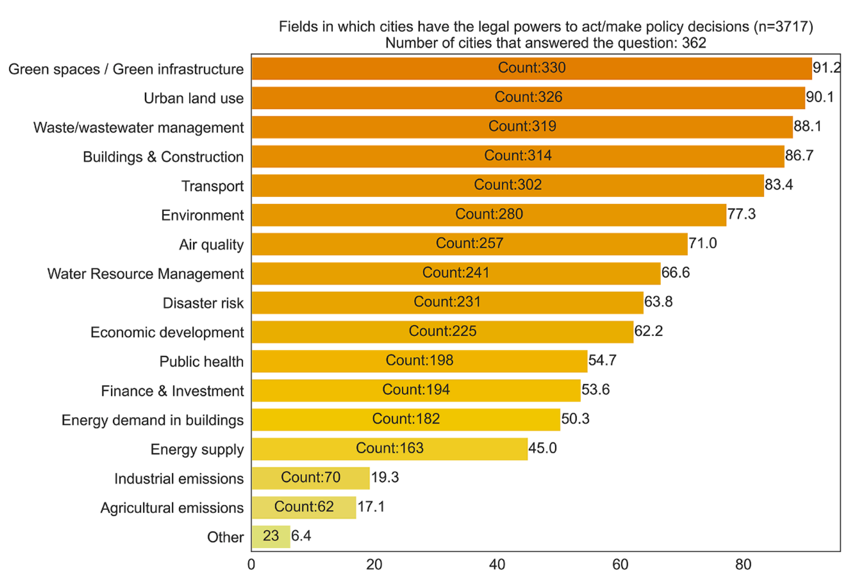

Fig. 4. Ranking of the most common fields over which eligible cities have the power to act or make policy decisions.

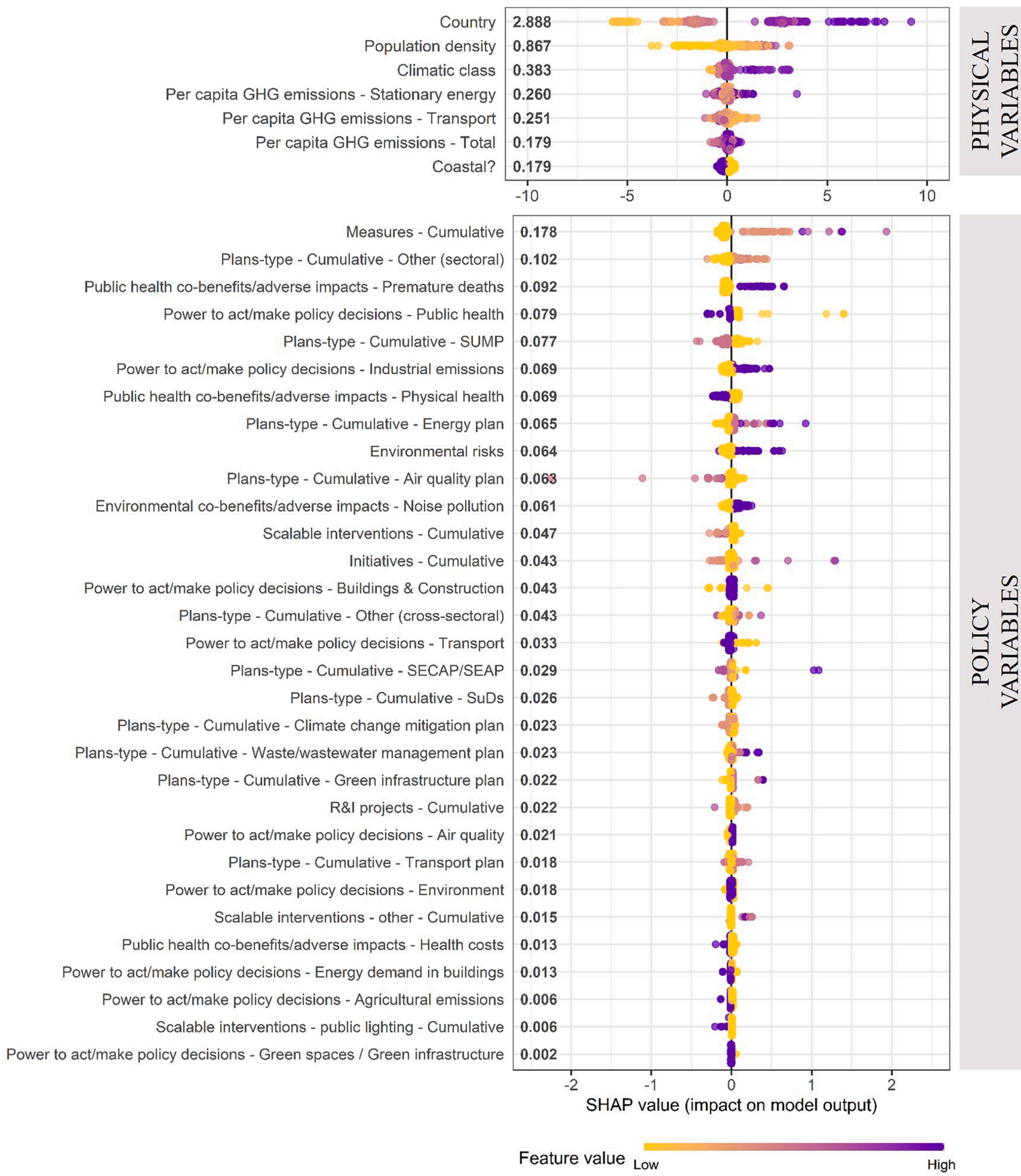

Fig. 5. Ranking of the most important predictors for $PM_{2.5}$ annual concentration levels across 261 eligible cities as returned by the XGBoost model, divided between physical and policy variables.

Countries are ordered from North-West to South-East, and small and high values are assigned accordingly. Similarly, a scale of increasing value is attributed to different climatic classes, with cold humid climates at the lower end and hot dry climates at the higher end. For continuous numerical variables, their value is reflected in the different shades between yellow and purple. For binary variables (e.g. all dummified variables) yellow points represent zeros (i.e. absence of a given feature) and purple points represent ones (i.e. presence of a given feature).

It is important to note that, for legibility and ease of interpretation, in Fig. 5 we retained only those variables whose global importance was greater than zero. Moreover, in case a variable (e.g. "Measures") features both as non-cumulative and cumulative count, we only retained the form having higher importance. Finally, the graph is split in two different blocks that distinguish "physical" from "policy" variables. The x-axis is scaled differently between the two blocks on account of the higher explanatory power of physical variables, to clearly show patterns also across policy variables. It is interesting to notice as the split into two groups of variables occurred "naturally", with the physical variable exhibiting the lowest explanatory power laying just above the policy variable with the highest explanatory power. This picture is consistent with the general vision of air pollution as an issue where geographical and climate aspects play a major role, together with urban features, such as population density.

The analysis on physical variables (top block in Fig. 5) reveals that:

- $PM_{2.5}$ concentrations are most strongly correlated with the national context, as closely analysed in the dependency graph in Fig. 6**A**. As we move from north-western to south-eastern countries, pollution levels tend to increase, possibly due to a combination of climatic and governance characteristics. Notably, being located in Luxembourg or

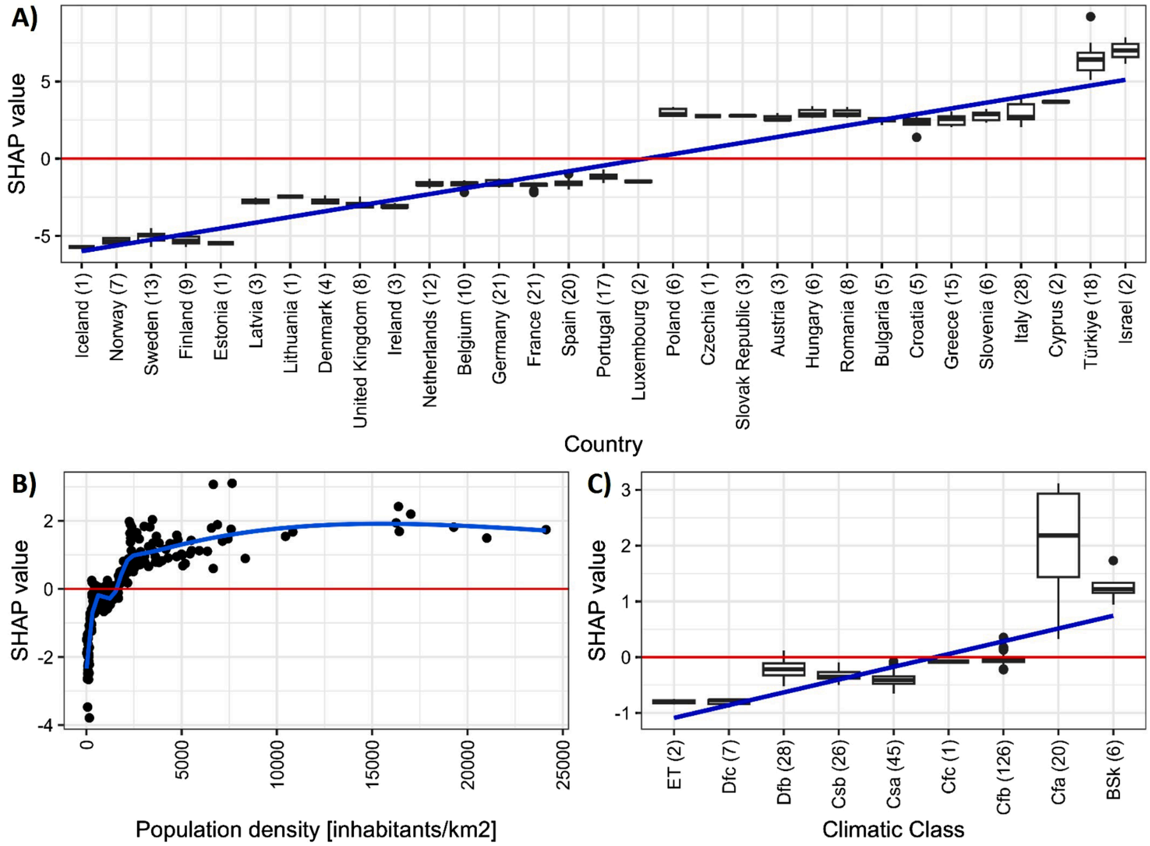

Fig. 6. SHAP Dependency graphs for the following variables: A) country, B) population density, and C) climatic class.

farther north-west is associated with lower pollution levels (below the SHAP=0 line), while for all other countries a significant positive impact on the prediction is observed. Interestingly, SHAP values seem to stratify according to 5 country groups: group 1 includes 5 countries (Iceland, Norway, Sweden, Finland, and Estonia) and exhibits highly negative impact with air pollution with SHAP value frequently below −5, group 2 (from Latvia to Ireland) levels out at roughly −2.5, group 3 (from The Netherlands to Luxembourg) at around −2, group 4 (from Poland to Cyprus) at 2.5 (with greater inter-country variability), and group 5 (Türkiye and Israel) reaches the highest level with SHAP over 6.

- The second most influential variable is population density. As clearly displayed in Fig. 6**B**, the SHAP value increases with the population density following a logarithmic function, thus increasingly very sharply for each increment in population density for low density levels to then flatten out. The curve crosses the SHAP=0 line at around 2000 inhabitants/km^2 and abruptly flattens beyond 2500 inhabitants/km^2. Interestingly, a similar pattern is observed for GHG emissions per capita from ground transportation in Kennedy et al. (2011).
- The third explanatory variable visible in Fig. 5 is the climatic class. As Köppen-Geiger classes are ordered from cold humid to hot dry, the dependency graph in Fig. 6**C** abides by the same logic, hence i) the main class goes from E (polar) to B (dry), ii) within each class, the subclass goes from “no dry season” (f) to “dry summer” (s), and iii) within each sub-class the sequence is from cold (c) to hot summer (a). In this case, an exponential trend can be observed, with the SHAP value increasing more than proportionally with the climatic class. Notably, three main levels can be distinghished: negative impact with SHAP at around −0.8 (classes ET and Dfc), light negative impact with SHAP between −0.5 and 0 (Dfb, Csb, Csa, Cfc, and Cfb classes), and a highly positive impact with SHAP over 1 for two classes (Cfa and BSk). This suggests that $PM_{2.5}$ levels tend, to some extent, to increase as the climate becomes hotter and drier, even if they depend also on emission patterns and on other climatic and meteorological aspects (EEA, 2023). Further, Cfb is the most populous class yet the interquartile range of the SHAP values is very narrow. Conversely, for the class Cfa that represents only 20 cities the variability is by far the highest across all classes.
- The following predictors in the ranking deal with GHG emissions. Notably, higher per capita emissions in the stationary energy sector or across all sectors are associated with higher pollution levels, although a certain variability is observed; while lower per capita GHG emissions in the transport sector seem to increase the prediction (increased $PM_{2.5}$ concentration levels) even though no sharp distinction between low and high variable values can be clearly discerned. This observation may seem counterintuitive, but it could indicate that in cities enjoying lower GHG emissions in the transport sector, there is less emphasis on implementing sustainable transport options, potentially resulting in lower air quality levels.
- The seventh variable in the ranking (and last among non-policy variables) is whether the city is coastal, i.e. located within 10 km of the coastline (Ulpiani et al., 2024). The variable is binary (0 or 1) and so is its relationship with air quality: all coastal cities are assigned a negative SHAP value (i.e. better air quality), while inland cities systematically exhibit a positive SHAP value. This relationship is linked to coastal areas being generally associated with stronger and more frequent wind than inland areas (Lv et al., 2021).

The analysis on policy variables (bottom block in Fig. 5) provides insight on their relative weight as compared to physical variables, and on the weight variability across different policy aspects. It is observed that:

- The explanatory power of policy variables is comparatively lower than that of physical variables. These are intrinsically different features and may rightfully come with different threshold of meaningfulness. Beyond the consideration that having a certain policy in place does not entail effectiveness, policy aspects tend to persist less than physical phenomena, as they may be as shorter-lived as political cycles.
- Interestingly, higher pollution is associated with higher engagement in climate and air quality action (suggested here by a higher number of measures relevant to both aspects and "other" sectoral plans – cumulative count). Hence, cities that mention more interventions addressing air quality, might have air quality as a priority, and they might design and implement more measures to tackle such challenges, i.e., in a reactive manner.
- Sustainable Urban Mobility Plans (SUMPs) are more important than energy or any other plans in the prediction of $PM_{2.5.}$ This reinforces the idea that operating in the transport sector holds promise in the dual challenge of reducing GHG emissions and air pollutants, while also being a typical city scale measure. Further, the analysis suggests that SUMPs are perceived as a way to carry benefits on air quality, although not very pronounced. This is observed even if transport is the fourth sector in order of importance as source of $PM_{2.5}$ and accounts for no >25 % of GHG emissions on average (see Fig. 1**C**).
- Cities experiencing higher air pollution tend to be more concerned with premature mortality. Conversely, cities that have the power to act or make policy decisions on public health or keep track of the effects of their policy on physical health tend to enjoy better air quality. More polluted cities may be more easily plagued by early deaths and be forced to monitor trends over time to maintain a certain control and/or to protect their citizens. On the other hand, cities more directly engaged in the health sector may have already taken a proactive stance in the past and implement stricter regulations or policies, resulting in a successful control of pollution levels to safeguard public wellness. Furthermore, they might be addressing health disparities linked to pollution exposure, particularly affecting vulnerable populations residing in areas with poorer air quality (Della Valle et al., 2023). To verify this interpretation, an additional analysis is performed on the Cities Mission dataset to determine whether the group of cities concerned with premature deaths is more engaged also in terms of i) security/protection for poor/vulnerable populations or ii) social inclusion, equality and justice (co-benefits listed under the social category). Indeed, the Chi-square test reveals a highly significant statistical correlation ($p < 0.001$, see Supplementary Note 2).
- Cities having power over industrial emissions, reporting air quality among environmental risks, or tracking noise pollution are associated with higher pollution levels. These cities are likely home to substantial pollutant sources (industries and traffic).

Any other correlation is characterised by a very limited prediction power and/or does not show a clear-cut trend between low and high variable values. In particular, it is interesting to notice the very low ranking of agriculture-related policies, despite this sector being the third most important source of air pollution according to Fig. 1**C**. Agriculture is often not perceived as a significant contributor to urban pollution, probably because of its non-urban dimension and arguably also because agriculture emissions contribute to urban ambient air pollution mostly in an indirect way, by means of secondary nitrate PM formation (Clappier et al., 2021).

4. Discussion and conclusions

Our results underscore the complexity of the interplay between air quality and GHG emissions in European cities, and the potential linkages between actions to tackle them. As expected, air pollution concentrations are significantly influenced by physical variables, such as national context, population density, climate, GHG emissions, and proximity to coast. The relative ranking of the impact of these variables supports the overall reliability of our approach and confirms some well-established findings on the geography of air pollution across Europe (EEA, 2023). However, it is noted that most recent literature emphasises the relevance of policy aspects especially when climate mitigation and air pollution are seen in conjunction. For instance, in Liu et al. (2024a), environmental regulation emerged as the most influential factor promoting the synergy between emissions and pollution reduction, outranking physical variables.

Our investigation follows this recent stream and questions potentially significant linkages between policymaking, GHG emissions and air quality. The following interpretation emerges from the analysis. Cities may be:

- pro-active in increasing or maintaining ambient air quality (e.g. those actively engaged in lowering air pollutant emissions, improving public health and promoting a more socially-just approach to environmental issues) and therefore be associated with higher air quality. These cities are well placed to continue developing a preventive strategy in their climate mitigation actions; and
- re-active to existing air pollution challenges, which may be associated with high public health and economic burdens, and which tend to engage the most in climate and air quality measures. These cities that have not yet solved their air pollution issues (and possibly need to comply with air quality standards), have the chance to leverage future climate mitigation policies and actions to co-target air quality.

The results from the Cities Mission analysis indicate that cities believe policy actions aimed specifically at the energy and transport sectors could potentially lead to the most substantial effects. Existing literature supports this view. A study by Hanaoka & Masui suggests that strategies involving widespread adoption of renewable energies, substantial electrification in transport, residential, and commercial sectors, increased use of biofuels in transportation, and deployment of carbon removal technologies could effectively mitigate both GHG emissions and air pollutants (Hanaoka & Masui, 2020). The role of electrification is also highlighted in Fournier et al. (2022), where authors caution that local air quality benefits are primarily dictated by the amount of reduced gas consumption, whereas the impacts on ambient air quality are governed by the timing of changes in load profiles. Several studies across diverse global contexts, underscore the critical role of policy interventions in addressing environmental degradation caused by transport and industrial activities (Slovic et al., 2016). These policies often prioritise local needs, advocate for awareness campaigns, and integrate social dimensions like educational programs. Key strategies in the transport sector include promoting active modes like public transportation and biking, enhancing road infrastructure, and adopting cleaner vehicle technologies, such as electric vehicles (Wu et al., 2024). Implementing measures on energy efficiency and renewable energy generation may also have substantial implications for air quality alongside climate benefits. These strategies may reduce emissions of $PM_{2.5}$ and other critical air pollutants (Buonocore et al., 2016). On top of this, urban green (e.g., parks, forests and green roofs) can play an important role in the transition to net-zero GHG and air pollution cities and in delivering a just and equal distribution of benefits (Wolch et al., 2014). In this context, our analysis (see Fig. 4) indicates that green spaces/infrastructure and urban land use are the two fields where cities most commonly have the power to act.

Overall, the results confirm that the sectors where a co-benefit approach is most documented and beneficial, carry the largest contributions to both GHG emissions and $PM_{2.5}$ levels; hence there is a large opportunity space to develop climate neutrality plans that maximise the air quality benefit. Interestingly, our analysis also presents evidence of some misalignment between cities' perceptions (as represented by the prioritisation within sectoral plans) and source apportionment results, although this occurs within the context of an overall consistent picture. Specifically, there appears to be some degree of overestimation regarding the impact of the transport sector on air quality, which is symmetrically coupled with a potential underestimation of agriculture's role.

The analysis also demystifies the fact that cities simply acknowledge air quality as a potential co-benefit of climate mitigation without taking any step to promote a dual-goal approach. Indeed, in almost all respondent cities, there have been attempts to assess the possible co-benefits/adverse impacts generated by local scale climate mitigation policies/actions on atmospheric pollution and/or vice versa. In this direction, a recent narrative meta-review conducted by O'Regan & Nyhan highlights state-of-the-art monitoring and modelling tools that can inform and monitor progress towards both GHG emission and air pollution reduction targets. This includes emission inventories, air quality monitoring and modelling methodologies as well as health impact assessment tools and street-level greenspace quantification (O'Regan & Nyhan, 2023), all of which Mission cities are encouraged to integrate into their Climate Neutrality Action Plans.

Effective monitoring is also crucial to detect potential burden-shifts and trade-offs (i.e., when actions to tackle one aspect inadvertently exacerbate the other) as climate mitigation solutions can be both synergistic and antagonistic with respect to air pollution. A comprehensive review performed by von Schneidemesser in 2015 offers a synopsis of the numerous connections between air quality and climate change, emphasising that policy efforts aimed at addressing either issue should consider their interconnections (von Schneidemesser et al., 2015). Potential benefits and trade-offs can vary with the context, type and location of the intervention. Thus, context-specific assessments, measurements and scenario analyses are important to identify opportunities for improvement, maximise benefits, and avoid overlooking trade-offs (X. Chen et al., 2023). In general, measures targeting CH_4 may generate benefits for both climate and O_3 air quality, and reducing black and organic carbon offers significant air quality and public health benefits and potentially reduces near-term radiative forcing (Fiore et al., 2015). Trade-offs should be then carefully balanced, especially when climate mitigation relies on biofuels, including wood-based biomass burning (Cohen et al., 2021; Tomlin, 2021), and in case of sulphate reductions (Fiore et al., 2015). In a context of ambitious climate mitigation targets, the use of solid biomass for heat and electricity production could be especially tempting, owing to the commonly accepted hypothesis of "carbon neutrality" for bio-based fuels. Nevertheless, biomass use has to be handled by means of appropriate technologies to avoid unintended detriment of air quality (Monforti-Ferrario & Belis, 2018). The Cities Mission analysis reveals that cities are familiar with multi-sectoral action plans, where the impact of specific measures are checked against different sectors and goals. This is a positive signal in view of balancing out potential spill overs. However, more interdisciplinary research is needed to increase our understanding of the interactions between GHG and ambient air pollutant emissions, and regional and global climates (Baklanov et al., 2016).

This study benefits from the uniqueness of the Cities Mission dataset, which offers the possibility to investigate the air quality-climate mitigation nexus from a hybrid physical and policy perspective. In addition, the inclusion of data from the CAMS reanalysis and state-of-the-art modelling results provides a clear and comprehensive picture of background air quality at urban level. Finally, the use of advanced machine learning techniques combined with extended interpretative capabilities makes it possible to evaluate the importance of each different feature (input) on influencing the output in a transparent fashion. On the other hand, the robustness of the results is limited by the self-reported nature of the Cities Mission dataset, its geographic imbalance, the unequal focus on GHG emissions versus air quality, and the lack of cross-sectoral data. Moreover, some important physical variables were not considered (e.g. meteorological variables, economic metrics). Future investigation may incorporate a wider set of input variables to provide a more comprehensive understanding and may explore horizontal domains and more sector-specific nuances.

In conclusion, this investigation helps delineate the opportunity space for a co-benefit approach in policymaking between GHG emissions and air pollutants reduction. It is crucial that in the rush for complying with increasingly stringent GHG reduction targets, air pollution control remains also a key objective. The overlap in sources of GHG and ambient air pollutant emissions creates scope for policy measures to limit global warming and improve air quality simultaneously. This integration offers a promising pathway for cities to achieve their ambitious climate neutrality goals while also protecting public health and the environment. However, the diversity in context and policy effectiveness, and the complexity of urban systems and their environmental impacts, necessitate tailored decision-making approaches. Effective evidence-based policymaking and implementation requires context-specific evaluation and adjustment to optimise outcomes, ensuring both GHG emission reductions and enhanced air quality (and ensuing public health benefits) are fairly distributed. Finally, it should be remembered that not all climate mitigation strategies improve air quality. Developing a more robust and quantitative scientific understanding about these connections can help to reduce undesirable effects.

Data statement

The dataset analysed in the study is not publicly available due to confidentiality reasons.

CRediT authorship contribution statement

G. Ulpiani: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **E. Pisoni:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **J. Bastos:** Writing – review & editing, Methodology, Formal analysis. **F. Monforti-Ferrario:** Writing – review & editing, Supervision. **N. Vetters:** Writing – review & editing, Supervision.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2024.106059.

Data availability

The data that has been used is confidential.

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