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► To cite this version:

Xavier Morelli, Stephan Gabet, Camille Rieux, H el ene Bouscasse, Sandrine Mathy, et al.. Which decreases in air pollution should be targeted to bring health and economic benefits and improve environmental justice?. *Environment International*, 2019, 129 (August 2019), pp.538-550. 10.1016/j.envint.2019.04.077 . hal-02145954

HAL Id: hal-02145954

<https://hal.science/hal-02145954>

Submitted on 26 Oct 2021

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1 **Title**

2 Which decreases in air pollution should be targeted to bring health and economic benefits and
3 improve environmental justice?
4

5 **Author names and affiliations**

6 Xavier Morelli^{*,1}, Stephan Gabet^{*,1}, Camille Rieux², H el ene Bouscasse^{3,4}, Sandrine Mathy³,
7 R emy Slama¹
8

9 *Co-first authorship;

10 ¹ Team of Environmental Epidemiology Applied to Reproduction and Respiratory Health,
11 Inserm, CNRS, and Grenoble-Alpes Univ., U1209, Institute for Advanced Biosciences (IAB),
12 Grenoble, France;

13 ² Atmo Auvergne-Rh one-Alpes, Grenoble, France;

14 ³ Grenoble Applied Economics Lab (GAEL), CNRS and Grenoble-Alpes Univ., Grenoble,
15 France;

16 ⁴ CESAER, Agrosup Dijon, INRA, Bourgogne Franche-Comt e Univ., Dijon, France.
17

18 **Corresponding author**

19 R emy Slama

20 IAB, Inserm/CNRS/UGA

21 Site Sant e

22 All e des Alpes

23 38700 La Tronche

24 France

25 tel: +33 4 76 54 94 02

26 e-mail: remy.slama@univ-grenoble-alpes.fr
27

28 **Abstract**

29 *Background*

30 Fine particulate matter (PM_{2.5}) exposure entails large health effects in many urban areas.
31 Public measures aiming at decreasing air pollution are often designed without targeting an
32 explicit health benefit. Our objective was to investigate the health and economic benefits and
33 the social inequalities in exposure resulting from several scenarios of reduction of PM_{2.5}
34 exposure, in order to support decisions about urban policies.

35 *Material and Methods*

36 In the French conurbations of Grenoble and Lyon (0.4 and 1.4 million inhabitants,
37 respectively), PM_{2.5} yearly average exposure was estimated on a 10-m grid by coupling a
38 PM_{2.5} dispersion model to population density. Changes in death cases, life expectancy, lung
39 cancer and term low birth weight incident cases as well as associated health economic costs
40 were estimated for ten PM_{2.5} reduction scenarios differing in terms of amplitude of reduction
41 and spatial extent. Changes in social differences in PM_{2.5} exposure were also assessed.

42 *Results*

43 During the 2015-2017 period, PM_{2.5} average exposure was 13.9 µg/m³ in Grenoble and
44 15.3 µg/m³ in Lyon conurbations. Exposure to PM_{2.5} led to an estimated 145 (95%
45 Confidence Interval, CI, 90–199) and 531 (95% CI, 330–729) premature deaths, 20 (95% CI,
46 9–30) and 83 (95% CI, 39–123) incident lung cancers, and 49 (95% CI, 19–76) and 193 (95%
47 CI, 76–295) term low birth weight cases each year in Grenoble and Lyon conurbations,
48 respectively, compared to a situation without PM_{2.5} anthropogenic sources, i.e. a PM_{2.5}
49 concentration of 4.9 µg/m³. The associated costs amounted to 495 (Grenoble) and 1,767
50 (Lyon) M€/year for the intangible costs related to all-cause non-accidental mortality and 33
51 and 134 M€ for the tangible and intangible costs induced by lung cancer. A PM_{2.5} exposure
52 reduction down to the WHO air quality guideline (10 µg/m³) would reduce anthropogenic
53 PM_{2.5}-attributable mortality by half while decreases by 2.9 µg/m³ (Grenoble) and 3.3 µg/m³
54 (Lyon) were required to reduce it by a third. Scenarios focusing only on the most exposed
55 areas had little overall impact. Scenarios seeking to reach a homogeneous exposure in the
56 whole study area were the most efficient in alleviating social inequalities in exposure.

57 *Conclusions*

58 Reduction scenarios targeting only air pollution hotspots had little expected impact on
59 population health. We provided estimates of the PM_{2.5} change required to reduce PM_{2.5}-
60 attributable mortality by one third or more. Our approach can help targeting air pollution
61 reduction scenarios expected to entail significant benefits, and it could easily be transposed to
62 other urban areas.

63

64 **Highlights**

- 65 • We considered several PM_{2.5} reduction scenarios and the associated health and economic
66 benefits
- 67 • We also assessed the resulting changes in social inequalities in air pollution exposure
- 68 • Decreasing PM_{2.5} exposure by about 3 µg/m³ was expected to reduce PM_{2.5} attributable
69 mortality by a third
- 70 • Urban area scale measures (as opposed to measures restricted to pollution hotspots) were
71 required to significantly improve public health

72

73 **Keywords**

74 Dispersion model; economic costs; health impact assessment; lung cancer; fine particulate
75 matter (PM_{2.5}); social deprivation.

76

77 **Abbreviations**

78 95% CI: 95% Confidence Interval

79 Δ_{NAC}: difference in the number of attributable cases

80 EDI: European Deprivation Index

81 LEZ: low emission zones

82 NO₂: nitrogen dioxide

83 PM: particulate matter

84 PM_{2.5}: Fine particulate matter

85 RR: risk ratio

86 SDHC: social deprivation heterogeneity coefficient

87

88 **Acknowledgments**

89 We thank Atmo Auvergne-Rhône-Alpes, and in particular Marie-Blanche Personnaz,
90 Florence Troude, and Cécile Fontagné, for providing air pollution and population density
91 data, the Epidemiology center on causes of death (CépiDC, Inserm) for providing mortality
92 data, the National methodological platform for the study and reduction of social inequalities
93 in oncology (ERISC; Univ. of Caen) and the French national Cancer League for providing
94 social deprivation data, Marc Colonna and all contributors of the Cancer Register of the
95 French Department of Isère, and the Urban planning agency of the Grenoble region (AURG)

96 and the Urban planning agency for the development of the Lyon urban area (UrbaLyon) for
97 providing population structure data. We also thank Grenoble Alpes Metropole for its support.

98

99 **Funding**

100 The present study is part of the QAMECS and MobilAir research projects, funded by the
101 French Environment and Energy Management Agency (ADEME) and by the IDEX Program
102 of Grenoble-Alpes University ComUE in the framework of the “Investing for the future”
103 Program of the French National Research Agency (ANR-15-IDEX-02). It was carried out as
104 part of the “Breathable city in 5 years” Program of the French Ministry of Ecological and
105 Solidarity Transition for Grenoble conurbation.

106

107 **Declaration of interest**

108 None.

109

110 **Word count**

111 5,600

112

113 **Number of Tables/Illustrations**

114 4 tables and 4 figures (in color).

115

116 **Supporting information**

117 1 figure.

118

119 **1 Introduction**

120

121 Atmospheric pollution exposure increases mortality risk, cardiovascular and respiratory
122 morbidity, including through lung cancer incidence (Raaschou-Nielsen et al., 2013; Hamra et
123 al., 2014). An effect on low birth weight risk and on several other diseases such as metabolic
124 disorders is also likely or very likely (Wilhelm et al., 2012; Pedersen et al., 2013; World
125 Health Organization, 2013). In industrialized countries, a large part of the health impact of
126 atmospheric pollutants is likely to be driven by fine particulate matter (PM_{2.5}) exposure
127 (Martenies et al., 2017; World Health Organization, 2014; Lelieveld et al., 2015). This impact
128 tends to be larger in urban areas, where pollution levels, number of pollution sources, and
129 population density are higher. Worldwide, it has recently been estimated that 3.2 (95%
130 Confidence Interval, CI: 1.5–4.6) million people prematurely die every year due to exposure
131 to PM_{2.5} (Lelieveld et al., 2015). The *Aphekom project*, focusing on nearly 40 million persons
132 across 25 European cities, has estimated that in the situation of 2004–2006 PM_{2.5} exposure
133 levels, 18.8 thousand deaths (95% CI: 6.6–32.4) could be prevented yearly through
134 compliance with the 10 µg/m³ WHO air quality guideline for PM_{2.5} (Pascal et al., 2013). In
135 France, the number of attributable deaths amounts to 48.3 (CI: 41.8–192.6) thousand, when
136 focusing on anthropogenic PM_{2.5} exposure levels in 2007–2008 (Pascal et al., 2016).
137 Therefore, in industrialized countries, atmospheric pollution is one of the main factors on
138 which it is possible to act at the population level to improve public health.

139 Several policies are targeted towards reducing traffic-related emissions. These include
140 regulating emission limits for new vehicles (the *Euro* standard in the EU), developing public
141 transportation, supporting biking and walking as transportation means as well as
142 implementing low emission zones (LEZ). In Europe, 227 LEZ have been implemented across
143 12 countries since the mid-1990's. France is lagging behind with only 2 LEZ recently created
144 in Paris (2015) and Grenoble (2017, for commercial vehicles) (Forestier and Cape, 2018).
145 Other measures targeting energy consumption, heating, building insulation or industrial
146 emissions have also been implemented.

147 Plans improving air quality do not always set explicit targets in terms of air pollution
148 emissions or atmospheric levels reduction; even when explicit targets are set, the values are
149 rarely justified. Since the ultimate goal of such plans is to improve public health, it would be
150 helpful for policymakers to know which reduction in air pollution levels should be targeted in
151 order to significantly improve health. In addition, an estimation of the expected avoided

152 economic costs associated with the air pollution emission, level, or health changes targeted
153 would be useful, for example to compare them with the expected cost of the planned
154 measures.

155 Previous urban planning health impact assessment studies sometimes encompassed an
156 estimate of prevented health costs or a cost-benefit analysis (Abe and Miraglia, 2016;
157 Martenies et al., 2017; Mueller et al., 2018, 2017a). In 25 European cities, the *Aphekom*
158 *project* estimated that the monetary gain of a decrease in PM_{2.5} exposure down to the 10
159 µg/m³ WHO guideline could amount to 31 billion Euros per year (Pascal et al., 2013).

160 Several studies quantified the effect of attaining specific air quality levels in terms of
161 health impact, mostly expressed as premature mortality: for instance, in Barcelona (Pérez et
162 al., 2009), Mexico City (Riojas-Rodríguez et al., 2014), and in a panel of European cities
163 (Ballester et al., 2008). In Grenoble and Lyon urban areas, Morelli et al. (2016) quantified the
164 gain in death cases, in lung cancer and term low birth weight incidence expected from a
165 fulfillment of the WHO PM_{2.5} level guideline (10 µg/m³). Scenario targets other than
166 corresponding to the compliance with air quality guidelines were sometimes considered in
167 counterfactual studies. Abe & Miraglia (2016) and Pascal et al. (2013) estimated the number
168 of annually avoided premature deaths for a 5 µg/m³ decrease in São Paulo and in 25 European
169 Cities, respectively. Interim scenarios gradually decreasing PM_{2.5} concentrations to the WHO
170 air quality guideline were built in some Chinese studies (Fang et al., 2016; Maji et al., 2018;
171 Liu et al., 2016; Song et al., 2017). A nationwide French study also proposed scenarios
172 targeting specific PM_{2.5} levels (Pascal et al., 2016) such as the situation “without
173 anthropogenic particulate matter”, the “level of the least polluted municipalities of the same
174 urbanization degree”, and “compliance with the EU regulatory value of 20 µg/m³ on 3-year
175 average” (French Republic (Official Journal), 2010). Boldo et al. (2011) considered a 10.7%
176 PM_{2.5} level reduction over Spain, corresponding to the expected decrease after
177 implementation of intended public policies. Health gains related to lower PM_{2.5} levels
178 resulting from scenarios that combined traffic reduction and transportation mode shift policies
179 (from car to bicycle and/or public transportation) were also evaluated, e.g. by Rojas-Rueda et
180 al. (2012, 2013) in Barcelona and its suburbs, by Woodcock et al. (2013) for the UK, by Xia
181 et al. (2015) in Adelaide urban area, and by Mueller et al. (2018) across 167 European cities.
182 Finally, Williams et al. (2018) recently quantified the health consequences of PM_{2.5} and NO₂
183 exposure changes of four power transition scenarios in the UK. Contrary to mortality metrics,
184 birth outcomes have rarely been considered in health impact assessment studies (Morelli et
185 al., 2016; Rojas-Rueda et al., 2013; Malley et al., 2017; Mueller et al., 2017b).

186 Finally, social inequalities with regard to air pollutant exposure have been previously
187 documented by, e.g., Padilla et al. (2014), Morelli et al. (2016) and Hajat et al. (2015). It
188 would be relevant to contrast pollution reduction scenarios in terms of their social justice, i.e.,
189 to identify *a priori* whether specific social classes would benefit more than others from a
190 given reduction scenario, or whether a plan would allow decreasing social inequalities in air
191 pollution exposure. Yet, to the best of our knowledge, no study scrutinized whether
192 hypothetical scenarios of PM_{2.5} reduction could modify social inequalities facing air pollution
193 exposure.

194
195 The main aim of this work was to estimate how various hypothetical scenarios of
196 reduction of PM_{2.5} exposure in urban areas would translate in terms of health benefits. We
197 considered avoided death cases, gain in life expectancy, and lung cancer and term low birth
198 weight prevented cases as well as associated health costs. We also studied to which extent the
199 expected benefit associated with each scenario varied between neighborhoods with varying
200 degrees of social deprivation. We took the example of Grenoble and Lyon, two middle and
201 large-size French urban areas.

202

203 **2 Material and Methods**

204

205 **2.1 Study areas and PM_{2.5} exposure assessment**

206 The study areas corresponded to Grenoble and Lyon conurbations, which include 49 and 59
207 municipalities, have surfaces of 541 and 534 km², and had 444 and 1,355 thousand
208 inhabitants in 2014, respectively (Figure 1). Grenoble and Lyon urban areas are located in the
209 South-East of France and they are the 11th and 2nd largest in France in terms of population,
210 respectively (Insee, 2017a).

211 Population exposure to air pollution was assessed with a fine-scale spatial resolution,
212 as described previously (Morelli et al., 2016). Atmospheric pollutant concentrations were
213 modeled combining two air pollution dispersion models, CHIMERE, a mesoscale chemistry
214 transport model (Menut et al., 2013) and SIRANE, a proximity scale model (Soulhac et al.,
215 2011). Validation of SIRANE model has been previously demonstrated (Soulhac et al., 2012).
216 Routine validation of the model estimates is conducted with Delta Tool (EU's Joint Research
217 Centre, aqm.jrc.ec.europa.eu/index.aspx). This allowed estimating PM_{2.5} levels for the years
218 2015 to 2017 with a 10-meter spatial resolution, over the whole study areas; the average
219 exposure for the 2015-2017 period was taken as a reference in the present study. In order to
220 estimate PM_{2.5} population exposure, concentrations in PM_{2.5} were coupled with information
221 on population density by five-year age classes at the same spatial resolution, based on the
222 latest available data from the National Institute of Statistics and Economic Studies (Insee,
223 2017a) and the National Institute of Geographic and Forestry Information (IGN, 2017).

224

225 **2.2 Considered scenarios**

226 In each study area, the PM_{2.5} baseline (2015-2017) exposure was hypothetically modified
227 according to ten different scenarios summarized in Table I. Scenarios S1 corresponded to a
228 decrease of PM_{2.5} levels down to the 10 µg/m³ WHO guideline in the whole study area.
229 Further scenarios consisted in a decrease down to the 5th percentile of PM_{2.5} concentration
230 distribution in the rural towns from the whole country (S2), as done by Pascal et al. (2016), or
231 down to the 10th percentile of PM_{2.5} exposure by census block in the study area (S3).
232 Scenarios S4 to S8 consisted in an absolute and spatially homogeneous decrease in PM_{2.5}
233 exposure levels with various amplitudes: S4 and S5 targeted decreases by 1 and 2 µg/m³ of
234 the PM_{2.5} yearly average exposure, respectively, while scenarios S6, S7, and S8 aimed for an
235 exposure decrease set to achieve specific health objectives: decreases by 33% (S6), 50% (S7),

236 and 67% (S8) in the non-accidental death cases attributable to PM_{2.5} exposure, where the
237 attributable fraction was expressed with respect to the gain under scenario S2. Finally,
238 scenarios S9 and S10 were inspired by the 2008/50/EU Directive transposed in French law in
239 2010 (French Republic (Official Journal), 2010), which targeted relative PM_{2.5} yearly
240 decreases to be attained by 2020. The decrease depends on the average exposure for the last
241 three years (here, 2015-2017), and corresponded to 15% in the case of Grenoble and Lyon
242 conurbations. Specifically, S9 estimated the PM_{2.5} exposure if the present Directive was
243 enforced at the whole conurbation scale whereas S10 assumed that the target 15% decrease
244 was restricted to “pollution hotspots”, defined as the locations above the 90th percentile of
245 PM_{2.5} average exposure in 2015-2017. In all scenarios, grid points already below the targeted
246 level were assumed to remain unchanged.

247

248 **2.3 Attributable risk characterization**

249 We considered three long-term health effects: all-cause non-accidental mortality
250 (ICD10: A00-R99), lung cancer incidence (ICD10: C33-34), and term low birth weight
251 incidence. All-cause non-accidental mortality data were obtained from the Epidemiology
252 center on causes of death (CépiDC, Inserm) for people aged 30 years and older, at the
253 municipality scale for Grenoble conurbation and the city of Lyon, and at the regional scale for
254 Lyon suburbs. Lung cancer incidence in the study areas were estimated thanks to regional
255 data from the French National Cancer Institute (data 2008-2010) (INCa, 2017a). Term low
256 birth weight case estimates were based combining the local number of births and the national
257 prevalence of term low birth weight, which was 3.1% in France in 2014 (Ministry of
258 Solidarity and Health, 2017).

259 For each health outcome, we selected a dose-response function from the literature,
260 aiming at robust studies such as meta-analyses and studies with limited potential for
261 confounding (Table II).

262 For each scenario, we quantified expected health benefits as the difference in the
263 number of attributable cases (Δ_{NAC}) between the baseline period (2015-2017) and a
264 counterfactual situation corresponding to the same area assuming that the scenario had been
265 implemented. The difference $\Delta_{NAC_{i,j}}$ was estimated at each grid point i,j with a 10-m spatial
266 resolution as described previously (Morelli et al., 2016). The values of $\Delta_{NAC_{i,j}}$ were then
267 added for all grid points to obtain the Δ_{NAC} for the whole area.

268 We also assessed the changes attributable to each scenario in terms of gain in number
269 of life-years in people aged 30 years and older, and the gain in life expectancy at 30 years,

270 applying the method recommended by the French national public health agency (Ung et al.,
271 2013) and used in *Aphekom project* (Pascal et al., 2013). Analyses were performed using
272 Stata version 14.2 (Stata Corp., College Station, TX, USA) and R software version 3.2.2 (R
273 Foundation for Statistical Computing, Vienna, Austria); geographical data were handled with
274 QGIS (OSGeo Foundation, Beaverton, OR, USA).

275

276 **2.4 Economic costs associated with each scenario**

277 For each scenario, we assessed the economic benefit corresponding to the cost of death and
278 disease cases Δ_{NAC} , as well as years of life lost (see 2.3) avoided by the scenario (Tables IIIa
279 and IIIb). Benefits are expressed in Euros (2017) per year, with the hypothesis that the
280 scenarios have produced the effects presented in Tables IIIa and IIIb.

281 For all-cause non-accidental mortality reduction, economic benefits were evaluated
282 using the *Aphekom project* methodology and values (Chanel, 2011), taking into account the
283 intangible costs, i.e., the costs due to grief and loss of quality of life. These intangible costs,
284 based on a literature review of contingent valuations, corresponded to €99,786 per year of life
285 saved (66,517–133,045; the range of values being calculated assuming variations of $\pm 33\%$
286 around the unit value) (Chanel, 2011).

287 For lung cancer incidence, intangible but also tangible costs were estimated; the latter
288 included direct medical costs and indirect costs due to loss of productive work. These three
289 cost components (intangible costs, direct tangible costs, and indirect tangible costs) are borne
290 by different economic entities: the patient and family, the health system, and the society,
291 respectively. For intangible costs, we estimated the number of years of life lost using the
292 number of new lung cancer cases and assuming 100% lung cancer lethality (INCa, 2017b);
293 we also assumed an average age of lung cancer onset of 65 years (INCa, 2017c), an average
294 life expectancy of 82.35 years (Insee, 2017b), and that the 1-, 3-, and 5-year survival rates
295 were 46, 22, and 17%, respectively (INCa, 2017b), which corresponded to an average loss of
296 15.6 years of life for each case. Medical cost estimates were based on a recent French study
297 (Cortaredona and Ventelou, 2017). With the hypothesis that the median age of diagnosis is 65
298 years (INCa, 2017c), the mean value of a year of treatment for the year of diagnosis
299 corresponded to €54,695 (\pm €14,757) for men and €49,844 (\pm €13,533) for women. Finally, we
300 considered that lung cancer incidence entails 120 work days off each year after diagnosis for
301 non-retired people (Rafenberg et al., 2015), with a mean value of €96 per day of work
302 (Chanel, 2011). For tangible costs, we took into account new cases from the year under

303 consideration but also, based on the expected survival, new cases from the previous five
304 years.

305 Due to a lack of reliable data on costs associated with low-birth weight, no economic
306 valuation was provided for this outcome.

307

308 **2.5 Socio-economic inequalities in air pollution exposure**

309 Area-level social deprivation was estimated as previously explained (Morelli et al., 2016)
310 through the European Deprivation Index (EDI, latest available version: 2011) (Pornet et al.,
311 2012). The EDI unitless quantitative value characterizes the deprivation status and relies on
312 ten characteristics available at the IRIS level (Pornet et al., 2012). IRIS represent
313 homogeneous neighborhoods and are the finest geographical census unit available; they are
314 similar to the US census block group and contain on average 2,000 inhabitants (Insee, 2016).
315 Grenoble and Lyon study areas are divided into 201 and 512 IRIS, respectively. The EDI
316 variables cover various socio-economic characteristics such as overcrowded home proportion,
317 occupational class, employment status, and basic amenities presence (Pornet et al., 2012).

318 IRIS were ranked according to their EDI value and then were split into ten equally-
319 sized groups. The PM_{2.5} distribution in each of these EDI deciles was then plotted. To identify
320 the scenarios allowing the largest decrease in environmental inequalities across social
321 deprivation levels, we estimated a social deprivation heterogeneity coefficient (SDHC) for
322 each hypothetical scenario. This coefficient was defined as the average difference between the
323 population average exposure in each EDI decile and the lowest population average exposure
324 among all EDI deciles, or:

$$325 \quad \text{SDHC}_s = \frac{1}{10} \times \left(\sum_{d=1}^{10} E_d - 10 \times \min(E_d) \right)$$

326 where s is the air pollution reduction scenario, d represent EDI deciles, and E_d the population
327 density-weighted PM_{2.5} exposure average in decile d .

328 Thus, a SDHC of 0.5 is indicative of an average difference of 0.5 µg/m³ between each EDI
329 decile and the area in which air pollution exposure is the lowest.

330 We also compared the variance of PM_{2.5} exposure levels by EDI decile under each
331 hypothetical scenario to that of the baseline situation (2015-2017), using modified Pitman
332 variance comparative test for paired samples (Grambsch test).

333

334 **3 Results**

335

336 **3.1 Study population and baseline situation**

337 On average, 2,601 and 8,284 people aged 30 years and more died non-accidentally yearly
338 during the 2006-2015 period in Grenoble and Lyon conurbations, respectively; there were 269
339 and 963 new lung cancer cases as well as 187 and 657 term low birth weight newborns,
340 respectively, each year.

341 Before implementation of any hypothetical scenario, the population density-weighted
342 PM_{2.5} exposure levels (corresponding to the 2015-2017 average) were 13.9 µg/m³ (5th-50th-
343 95th percentiles: 10.2-14.6-16.2 µg/m³) in Grenoble and 15.3 µg/m³ (12.5-15.4-17.6 µg/m³)
344 in Lyon conurbations (Figures 1 and 2). Illustrations of the spatial contrasts in exposure are
345 provided by West-East cross-sections of the study areas in Figure S1.

346

347 **3.2 Impact of scenarios on air pollution, health, and health-related costs**

348 The expected distributions of PM_{2.5} exposure under each scenario are displayed in Figure 3
349 and Table IIIa. Scenario S10 (“2020 target, in hotspots”) had the lowest impact on PM_{2.5}
350 exposure, with decreases of 0.2 µg/m³ in both conurbations. As expected, decreases in PM_{2.5}
351 yearly average were the strongest for scenario S2 (“No anthropogenic PM_{2.5}”), for which the
352 target exposure was 4.9 µg/m³.

353 Under scenario S2 (“No anthropogenic PM_{2.5}”), 145 (95% Confidence Interval, CI,
354 90-199) and 531 (95% CI, 330-729) deaths, 20 (95% CI, 9-30) and 83 (95% CI, 39-123)
355 new lung cancers, and 49 (95% CI, 19-76) and 193 (95% CI, 76-295) term low birth weight
356 cases would be prevented each year in Grenoble and Lyon conurbations, respectively
357 (Tables IIIa and IIIb). In terms of life expectancy at 30 years, this corresponded to gains of
358 4,963 (S2-Grenoble) and 17,708 (S2-Lyon) years of life in the population for all-cause non-
359 accidental mortality – or a gain of 10 and 10.7 months of life expectancy, respectively – and
360 of 313 (S2-Grenoble) and 1,287 (S2-Lyon) years of life for lung cancer. The corresponding
361 economic costs (intangible), which can be interpreted as an estimate of the cost of PM_{2.5}-
362 related deaths in the baseline situation (2015-2017), were 495 (S2-Grenoble) and 1,767 M€
363 (S2-Lyon). For lung cancer, intangible costs amounted to 31 (S2-Grenoble) and 128 M€ (S2-
364 Lyon), while total tangible costs (direct and indirect) amounted to 1.4 (S2-Grenoble) and 5.6
365 M€ (S2-Lyon).

366 A PM_{2.5} exposure reduction down to the WHO air quality guideline of 10 µg/m³
367 (scenario S1) would lower the mortality rate in Grenoble and Lyon areas by 25 (95% CI, 15–
368 34) and 35 (95% CI, 22–48) for 100,000 person-years, respectively; this corresponded to
369 gains of 4.5 (95% CI, 2.8–6.3) and 5.5 (95% CI, 3.4–7.7) months of life expectancy at 30
370 years. For all-cause non-accidental mortality, reaching the WHO target values would lead to
371 save 226 M€ (S1-Grenoble) and 918 M€ (S1-Lyon). In both areas, this scenario was close in
372 terms of health benefits to the scenario aiming to decrease by 50% the mortality linked to
373 PM_{2.5} exposure (scenario S7). A reduction by one-third in PM_{2.5}-attributable mortality
374 (scenario S6) would be reached by a decrease in yearly average exposure by 2.9 µg/m³
375 in Grenoble and 3.3 µg/m³ in Lyon urban areas.

376 A PM_{2.5} level reduction targeting only air pollution “hotspots” (i.e., the locations
377 above the 90th percentile of the air pollution exposure distribution) would avoid 4 (S10-
378 Grenoble; 95% CI, 2–5) and 13 (S10-Lyon; 95% CI, 8–18) death cases per year, while a
379 homogeneous decrease by 1 µg/m³ would prevent 16 (S4-Grenoble; 95% CI, 10–23) and 53
380 (S4-Lyon; 95% CI, 32–73) death cases per year.

381

382 **3.3 Impact of scenarios on social inequalities in air pollution exposure**

383 In both areas, baseline population density-weighted PM_{2.5} average exposure differed between
384 the EDI deciles (Figure 4). Indeed, in the baseline situation, our measure of social
385 heterogeneity in air pollution exposure (SDHC) was 2.62 µg/m³ in Grenoble and 1.53 µg/m³
386 in Lyon conurbations; moreover, the variances of exposure distribution were 1.50 and 0.51,
387 respectively (Chi-square test on variance comparison to zero, *p*-value <10⁻¹⁶; Figure 4 and
388 Table IV).

389 Six out of the ten intervention scenarios were not expected to change the distribution
390 of PM_{2.5} exposure according to social deprivation. Only scenarios targeting a spatially
391 homogeneous value in the whole area (S1–S3), and to a lesser extent the “2020 target”
392 scenario (S9), led to a decrease in social inequalities with respect to PM_{2.5} exposure. All other
393 scenarios, corresponding to less ambitious homogeneous decreases (S4–S8) or to a decrease
394 spatially very limited (S10), did not significantly decrease social inequalities regarding PM_{2.5}
395 exposure.

396

397 **4 Discussion**

398

399 **4.1 Summary of the main findings**

400 We investigated the expected health and economic impacts of ten hypothetical reduction
401 scenarios in PM_{2.5} air concentrations implemented in two French urban areas. In comparison
402 to a situation with no anthropogenic PM_{2.5} emissions, the current (2015-2017) situation was
403 associated with a decrease in about 10 months in life expectancy at 30 years and a total
404 economic cost of 2.3 billion Euros over the two areas. This estimate can be put in regard to
405 the cost of tobacco smoking in Grenoble and Lyon which, assuming that they are proportional
406 to the population size, may be about 3.3 billion Euros in 2010 (Kopp and Ogrodnik, 2017). A
407 decrease down to the WHO air quality guideline for PM_{2.5} (10 µg/m³) would entail a decrease
408 in all-cause mortality from 5.6 to 6.4%, according to the area, and would save 1.14 billion
409 Euros over both cities. A homogeneous decrease in PM_{2.5} yearly average exposure in the
410 whole area down to the WHO guideline of 10 µg/m³ would allow to prevent about half of the
411 mortality attributed to anthropogenic PM_{2.5} exposure.

412

413 **4.2 Strengths and limitations**

414 Our study is one of the first health impact assessment studies to simultaneously consider
415 premature mortality, life expectancy, lung cancer incidence, and term low birth weight as
416 outcomes. It is also unique by the variety of scenarios considered and by the estimation of the
417 potential decrease of social inequalities and economic gains associated with the scenarios. We
418 relied on a fine-scale (10 m grid) exposure model integrating population data at the same
419 scale, which is important as the spatial resolution of models influences health impact
420 estimations (Morelli et al., 2016; Kulhánová et al., 2018).

421 Health impact estimates depend on input parameters, in particular health outcome
422 incidence and dose-response functions. The latter were assumed linear, which seems to be a
423 reasonable assumption in the 5-18 µg/m³ exposure range covered in this study (Crouse et al.,
424 2012; Pope et al., 2015). We chose relative risks from meta-analyses for mortality and lung
425 cancer. In order to limit fluctuations in mortality rates, we used a ten-year average at the
426 municipality scale. Lung cancer incidence data were available for the latest 3-year period
427 (2008-2010) and term low birth weight incidence cases for 2014 (i.e. matching the population
428 density data), both at the regional scale, which might give more weight to random spatial
429 fluctuations than for mortality. Few studies quantified the medical costs associated with lung

430 cancer, and the related sick leave durations, which possibly limited the accuracy of our
431 estimates of the tangible costs associated with lung cancer.

432 We also estimated tangible costs specifically for lung cancer; these represented
433 approximately 4% of the total costs of air pollution related to lung cancer. Given this small
434 proportion, and keeping in mind that the entities bearing the tangible and intangible costs
435 differ, one can consider that the total costs were well approximated by the intangible costs.
436 While this is true for lung cancer, the calculation has not been done for the other causes of
437 death. However, we believe that the ratio of tangible to intangible costs would be even lower
438 for the other diseases, the cost of treating lung cancer being particularly high.

439

440 **4.3 Which air pollution change should be targeted to entail benefits?**

441 The impact of air pollution reduction in Europe has been considered in several former studies.
442 Among the largest studies, the *Apheis project* (Ballester et al., 2008) and *Aphekom project*
443 (Pascal et al., 2013), which involved more than twenty European cities, showed that all-cause
444 mortality could be reduced by 3.0 to 6.2%, according to city, if the considered cities complied
445 with the WHO guideline for PM_{2.5} (10 µg/m³) using the same dose-response relation as we
446 did (RR, 1.06 for a 10 µg/m³ increase in PM_{2.5}). We estimated that 2.5 (S1-Grenoble) and
447 3.3% (S1-Lyon) of all-cause mortality could be avoided if the PM_{2.5} WHO guideline was
448 observed, a value in the lower range of the *Apheis* and *Aphekom* results. This can be explained
449 by the lower PM_{2.5} exposure levels modeled in our study areas during the period 2015-2017 in
450 comparison with the levels reported in these two studies with exposure data before 2000 and
451 from 2004-2006, respectively. To our knowledge, only one other study has investigated
452 hypothetical scenarios of air pollution reduction in France (Pascal et al., 2016). Authors relied
453 on a national, municipality scale (2-km grid) model (Bentayeb et al., 2014) combined to a
454 dose-response function issued from the French Gazel cohort, which was much steeper than
455 ours (RR 1.15; 95%CI, 1.05–1.25, for a 10 µg/m³ increase in PM_{2.5}), and reported that around
456 6.2% of long-term mortality attributable to PM_{2.5} could be avoided by complying with the 10
457 µg/m³ WHO guideline value. The steeper dose-response relation (15% excess relative risk,
458 compared to 6.6% in our study) and the more remote time period considered by Pascal et al.
459 (2007-2008, when PM_{2.5} levels were higher than in 2015-2017) could explain the difference
460 between results.

461 We had previously estimated (Morelli et al., 2016) that, compared to the air pollution
462 levels from 2012, reaching the WHO PM_{2.5} yearly guideline would lead to a decrease by 5.1
463 and 6.0% in mortality in Grenoble and Lyon urban areas, respectively. In comparison to this

464 former study, the lower PM_{2.5} exposure levels during the period 2015-2017 explain the lower
465 health gains reported in our current study (median exposures of 14.6 and 15.4 *versus* 18.1 and
466 19.6 µg/m³ in Grenoble and Lyon urban areas, respectively). These substantial decreases in
467 PM_{2.5} exposures result from a) the trend for decreasing of atmospheric particulate matter
468 concentrations in the study areas and b) the recent extension of Grenoble and Lyon
469 conurbations (in 2015), with the integration of municipalities farther from the city center and
470 with less atmospheric pollution.

471 The economic valuation of the deaths attributable to PM_{2.5} in the baseline situation,
472 compared to the situation without PM_{2.5} anthropogenic emissions, corresponded to 1,115
473 (Grenoble) and 1,304 (Lyon) Euros/inhabitant/year, while comparing the current situation to
474 the WHO levels (10 µg/m³) corresponded to 509 and 678 Euros/inhabitant/year, respectively.
475 In *Aphekom project*, the costs associated with PM_{2.5} exposure, compared to the WHO
476 guideline compliance in four French cities (Paris, Marseille, Lille, and Strasbourg) ranged
477 between 686 (Strasbourg) and 840 (Paris) Euros/inhabitant/year (Corso et al., 2011). The
478 slightly higher estimated costs in *Aphekom project* compared to ours is explained by the
479 higher PM_{2.5} concentrations monitored in the four cities during the studied period (2004–
480 2006): from 16.6 (Strasbourg) to 18.5 (Marseille) µg/m³.

481 Our study confirms that in areas complying with the EU PM_{2.5} regulation, the health
482 and economic impact of PM_{2.5} atmospheric pollution is large. Indeed, a decrease in yearly
483 average exposure by about 3 µg/m³ in the considered urban areas would reduce the PM_{2.5}-
484 attributable mortality by one third, which would correspond to nearly 400
485 Euros/inhabitant/year. Focusing on “hotspots” (scenario 10) was unlikely to entail significant
486 health benefits at the urban scale. Conversely, trying to bring the whole area down to the level
487 encountered in the least polluted neighborhoods of the area (scenario S3) improved health,
488 confirming that interventions affecting a large proportion of the study population should be
489 targeted. As far as homogeneous decreases are concerned, one can keep in mind the
490 approximate dose-response function of a 1 month gain in life expectancy at 30 years for each
491 decrease by 1 µg/m³ in the PM_{2.5} average level in the study area. Consequently, plans aiming
492 an average reduction lower than 1 µg/m³ in the PM_{2.5} average concentration will probably be
493 perceived as without real ambition by the population, although social perceptions on this
494 matter may vary.

495 Depending on the way the PM concentrations reductions are achieved, changes in
496 other environmental factors can be expected; measures targeting traffic may also entail
497 reductions in noise levels, greenhouse gas emissions, road accidents, and could lead to

498 increases in physical activity if car users switch to more active transportation modes. Most of
499 these effects are expected to lead to additional health benefits. In an assessment of the impact
500 of high walking and cycling transport scenarios in English and Welsh urban areas, Woodcock
501 et al. (2013) estimated that, if a large proportion of car users switched to active transportation
502 modes, a greater part of the expected health benefits would stem from increased physical
503 activity, compared to benefits stemming from PM concentration reductions.

504

505 **4.4 Impact of air pollution interventions on environmental justice**

506 Contrarily to what may sometimes be thought, a scenario focused on so-called air pollution
507 « hotspots » (above the 90th PM_{2.5} exposure percentile) and targeting a 15% air pollution
508 reduction in these areas would only very marginally improve health at the urban scale (a 2 to
509 3% improvement compared to the attributable impact of anthropogenic sources in the two
510 study areas), but it would also very little decrease social inequalities in air pollution exposure.
511 These results are respectively explained by the facts a) that decreasing the average exposure
512 by acting only on a small population subgroup can only be achieved through a very strong
513 change in this subgroup (Slama and Siroux, 2012) and b) that in the studied areas, social
514 inequalities in air pollution exposure were not restricted to a small very disfavored subgroup
515 but expanded over the whole continuum of social categories (Figure 4).

516 Very few studies investigated the impact of air pollution intervention policies on social
517 deprivation or socioeconomic status, or considered the future impact of hypothetical scenarios
518 on environmental justice. Tonne et al. (2008) estimated the health benefits expected from the
519 London low emission zone (LEZ) with a dispersion model, and stratified the exposure
520 according to socio-economic data. Inside the LEZ perimeter, the authors found an increase of
521 years of life gained, while the impact at the urban area scale was rather limited. The most
522 deprived areas were exposed to higher NO₂ and PM₁₀ levels and benefited more of the
523 reductions of air pollution, and hence of the associated increase in years of life. In Rome,
524 Cesaroni et al. (2012) also observed that the LEZ reduced exposure among all socio-economic
525 groups and in particular the least deprived ones, who were also the most exposed, but it
526 increased social inequalities in NO₂- and PM₁₀-attributable mortality. The authors reported
527 similar figures in terms of years of life gained at the city scale compared to the LEZ
528 perimeter. To our knowledge, no other study investigated the socioeconomic inequalities
529 following an enforced low emission zone. A recent study estimated that, whilst much health
530 benefit could be expected, social inequalities with regard to atmospheric pollution exposure
531 would not be lessened by the *UK Climate Change Act* scenarios (Williams et al., 2018). This

532 latter study emphasizes that such social inequalities deserve to be looked at the stage of the
533 design of policy planning.

534

535 **4.5 Applicability of our approach to other areas**

536 Although some of our results are area specific (e.g. the $PM_{2.5}$ decrease leading to a reduction
537 by half in the $PM_{2.5}$ -attributable mortality), the approach could in principle be transposed to
538 other cities where fine-scale air pollution models are available. From this, the mortality could
539 be estimated using simple tools and methods, such as those developed by WHO
540 (who.int/hia/tools/en). Not relying on fine-scale information on $PM_{2.5}$ would entail some bias
541 – likely towards an underestimation of health impacts (Morelli et al., 2016; Kulhánová et al.,
542 2018) – but will nevertheless provide a relevant estimate of the magnitude of the $PM_{2.5}$
543 impact, from which an approximation of the $PM_{2.5}$ exposure level reduction needed to target a
544 given health improvement could be estimated.

545

546

547

548

549 **5 Conclusions**

550 Our assessment of a large range of contrasted scenarios provides indications of the air quality
551 improvement to target in order to significantly improve public health. Reductions of at least
552 $1 \mu\text{g}/\text{m}^3$ in $\text{PM}_{2.5}$ exposure for all citizens are expected to allow a public health gain of about
553 one month in life expectancy, while focusing on hotspots has a limited value at the population
554 scale. The current impact of $\text{PM}_{2.5}$ exposure in the two urban areas considered is substantial in
555 spite of their compliance with the EU $\text{PM}_{2.5}$ regulation. The European current limit value for
556 $\text{PM}_{2.5}$ of $25 \mu\text{g}/\text{m}^3$ was set in 2008, three years after the 2005 WHO Global Update providing
557 a guideline value of $10 \mu\text{g}/\text{m}^3$. The $25 \mu\text{g}/\text{m}^3$ limit value from the 2008 EU directive was
558 supposed to be amended in 2013 with the introduction of more severe $\text{PM}_{2.5}$ limit values to be
559 attained by 2020, but this disposition was eventually withdrawn (Brunekreef et al., 2015). Our
560 assessment of this scenario (S9) showed that it would entail health benefits and improve
561 environmental justice, although much more weakly than those expected from fulfilling the 10
562 $\mu\text{g}/\text{m}^3$ WHO guideline. The example of Tokyo metropolitan area (Hara et al., 2013) shows
563 that strong improvements in air quality likely to entail a large public health benefit can be
564 achieved in large urban areas without compromising mobility.

565 In our eyes, the public health (and possibly economic) estimates associated with air
566 pollution reduction scenarios could be used by decision makers to choose between possible
567 scenarios, and justify their decisions to the local population on the basis of this expected
568 public health impact (or rely on such results in public consultations), which may be more
569 telling than an air pollution concentration change. We are not aware of decision-makers
570 having already explicitly used such a framework to select among air pollution reduction
571 scenarios, but this approach is easily transferable in other Western cities.

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7 Tables and Figures

Table I. Description of the ten hypothetical scenarios of fine particulate matter (PM_{2.5}) exposure reduction considered.

| Scenario number | Scenario description | Scenario name | PM _{2.5} yearly level reduction |
|-----------------|---|---|---|
| S1 | Spatially homogeneous target value in the whole area | “WHO guideline” | Down to WHO yearly guideline (10 µg/m ³) |
| S2 | | “No anthropogenic PM _{2.5} emissions” | Down to lowest nation-wide levels (4.9 µg/m ³) ^a |
| S3 | | “Quiet neighborhood” | Down to lowest study area district levels (10 th percentile of exposure) ^b |
| S4 | Homogeneous PM _{2.5} decreases in the whole area | “-1 µg/m ³ ” | Baseline ^c -1 µg/m ³ |
| S5 | | “-2 µg/m ³ ” | Baseline ^c -2 µg/m ³ |
| S6 | | Targeted reduction in PM _{2.5} -related mortality in the whole area ^d | “-1/3 of mortality” |
| S7 | “-1/2 of mortality” | | |
| S8 | “-2/3 of mortality” | | |
| S9 | 2008/50/EU Directive ^f “2020 target” | In the whole study area” | Baseline ^c -15% |
| S10 | | Restricted to PM _{2.5} exposure hotspots” | Baseline ^c -15%, only if baseline ≥90 th centile of PM _{2.5} levels ^g |

^a Corresponding to the 5th percentile of PM_{2.5} concentration distribution among French rural towns (Pascal et al., 2016).

^b The 10th percentile of PM_{2.5} exposure by Housing Block Regrouped for Statistical Information (IRIS) in the study area (corresponding to 10.3 and 12.4 µg/m³ in Grenoble and Lyon conurbations, respectively).

^c Baseline corresponds to the PM_{2.5} exposure average for the 2015-2017 period, taken as a reference in the present study.

^d Mortality reduction targets expressed as a proportion of the non-accidental death cases attributable to PM_{2.5} exposure that can be prevented under the scenario S2: “No anthropogenic PM_{2.5} emissions”.

^e S6: -2.9 and -3.3 µg/m³ in Grenoble and Lyon conurbations, respectively; S7: -4.4 and -5.1 µg/m³; S8: -6.0 and -6.9 µg/m³.

^f Inspired by the 2008/50/EU Directive, which targets relative PM_{2.5} yearly average decreases to obtain by 2020. The decrease value depends on the exposure average for the last three years (2015-2017): -15% in the case of Grenoble and Lyon conurbations.

^g The 90th percentile corresponded to 16.0 and 17.4 µg/m³ in Grenoble and Lyon conurbations, respectively.

Table II. Dose-response functions used to estimate the long-term effects of air pollution exposure to fine particulate matter (PM_{2.5}) on health.

| Health event | Study | Relative risk (95% CI) for a 10 µg/m³ increase in PM_{2.5} exposure | |
|------------------------------------|---|---|------------------------------|
| Non-accidental mortality | World Health Organization (2014) ^a | 1.066 | (1.040 – 1.093) |
| Lung cancer incidence | Hamra et al. (2014) ^a | 1.09 | (1.04 – 1.14) |
| Term low birth weight ^b | Pedersen et al. (2013) | 1.392 | (1.124 – 1.769) ^c |

^aMeta-analysis based relative risk.

^bOccurrence of low birth weight birth cases (<2500 g) among term births (those occurring after the end of the 37th gestational week).

^cThe original odds-ratio was reported for a 5 µg/m³ increase in exposure and was 1.18 (1.06–1.33).

Table IIIa. Estimated effects of the scenarios in terms of population exposure to fine particulate matter (PM_{2.5}) and all-cause non-accidental mortality.

| PM _{2.5} exposure reduction scenarios | Population PM _{2.5} exposure | | Health benefits concerning all-cause non-accidental mortality | | | | | | | | | | Economic costs associated with life year loss | | |
|---|---------------------------------------|--|---|---------|----------------------|----------------------------------|----------|------------------------------------|--------|---|----------|---------------------------------|---|------------------------------|-----------------------|
| | Yearly average (µg/m ³) | 5 th –50 th –95 th percentiles (µg/m ³) | Δ _{NAC} ^{a,f} | 95% CI | % of S2 ^b | % of baseline cases ^c | 95% CI | Mortality rate gain ^{d,f} | 95% CI | Gain in life expectancy months ^e | 95% CI | Gain in life years ^f | 95% CI | Intangible costs (in M€2017) | Low–high ^g |
| Grenoble conurbation (444,000 inhabitants) | 13.9 | 10.2–14.6–16.2 | | | | | | | | | | | | | |
| S1: “WHO guideline” | 10.0 | 10.0–10.0–10.0 | 65 | 40–90 | 45% | 2.5% | 1.5–3.5% | 25 | 15–34 | 4.5 | 2.8–6.3 | 2,263 | 1,384–3,158 | 226 | 92–420 |
| S2: “No anthropogenic PM _{2.5} ” | 4.9 | 4.9–4.9–4.9 | 145 | 90–199 | Ref. | 5.6% | 3.5–7.7% | 55 | 34–76 | 10.0 | 6.1–13.9 | 4,963 | 3,027–6,950 | 495 | 201–925 |
| S3: “Quiet neighborhood” | 10.3 | 10.2–10.3–10.3 | 61 | 38–84 | 42% | 2.3% | 1.5–3.2% | 23 | 14–32 | 4.3 | 2.6–5.9 | 2,120 | 1,297–2,958 | 212 | 86–394 |
| S4: “-1 µg/m ³ ” | 12.9 | 9.2–13.6–15.2 | 16 | 10–23 | 11% | 0.6% | 0.4–0.9% | 6 | 4–9 | 1.1 | 0.6–1.5 | 522 | 320–727 | 52 | 21–97 |
| S5: “-2 µg/m ³ ” | 11.9 | 8.2–12.6–14.2 | 33 | 20–45 | 23% | 1.3% | 0.8–1.7% | 12 | 8–17 | 2.1 | 1.3–2.9 | 1,046 | 641–1,457 | 104 | 43–194 |
| S6: “-1/3 of mortality” | 11.0 | 7.3–11.7–13.3 | 47 | 29–66 | 33% | 1.8% | 1.1–2.5% | 18 | 11–25 | 3.0 | 1.9–4.2 | 1,518 | 930–2,115 | 151 | 62–281 |
| S7: “-1/2 of mortality” | 9.6 | 5.8–10.2–11.8 | 71 | 44–98 | 50% | 2.7% | 1.7–3.8% | 27 | 17–37 | 4.6 | 2.8–6.4 | 2,300 | 1,407–3,209 | 230 | 94–427 |
| S8: “-2/3 of mortality” | 8.0 | 4.9–8.6–10.2 | 95 | 59–132 | 67% | 3.7% | 2.3–5.1% | 36 | 22–50 | 6.3 | 3.8–8.7 | 3,119 | 1,906–4,356 | 311 | 127–580 |
| S9: “2020 target, in whole area” | 11.8 | 8.6–12.4–13.8 | 34 | 21–48 | 23% | 1.3% | 0.8–1.8% | 13 | 8–18 | 2.3 | 1.4–3.1 | 1,120 | 686–1,560 | 112 | 46–208 |
| S10: “2020 target, in hotspots” | 13.7 | 10.2–14.1–15.9 | 4 | 2–5 | 3% | 0.2% | 0.1–0.2% | 1 | 1–2 | 0.3 | 0.2–0.5 | 167 | 102–233 | 17 | 7–31 |
| Lyon conurbation (1,355,000 inhabitants) | 15.3 | 12.5–15.4–17.6 | | | | | | | | | | | | | |
| S1: “WHO guideline” | 10.0 | 10.0–10.0–10.0 | 274 | 169–378 | 52% | 3.3% | 2.0–4.6% | 35 | 22–48 | 5.5 | 3.4–7.7 | 9,204 | 5,629–12,851 | 918 | 374–1,710 |
| S2: “No anthropogenic PM _{2.5} ” | 4.9 | 4.9–4.9–4.9 | 531 | 330–729 | Ref. | 6.4% | 4.0–8.8% | 68 | 42–93 | 10.7 | 6.5–14.9 | 17,708 | 10,800–24,795 | 1,767 | 718–3,299 |
| S3: “Quiet neighborhood” | 12.4 | 12.4–12.4–12.4 | 152 | 94–211 | 29% | 1.8% | 1.1–2.5% | 19 | 12–27 | 3.2 | 2.0–4.5 | 5,314 | 3,254–7,410 | 530 | 216–986 |
| S4: “-1 µg/m ³ ” | 14.3 | 11.5–14.4–16.6 | 53 | 32–73 | 10% | 0.6% | 0.4–0.9% | 7 | 4–9 | 1.0 | 0.6–1.4 | 1,631 | 1,000–2,270 | 163 | 67–302 |
| S5: “-2 µg/m ³ ” | 13.3 | 10.5–13.4–15.6 | 105 | 65–146 | 20% | 1.3% | 0.8–1.8% | 13 | 8–19 | 2.0 | 1.2–2.7 | 3,266 | 2,002–4,550 | 326 | 133–605 |
| S6: “-1/3 of mortality” | 12.0 | 9.2–12.1–14.3 | 173 | 107–240 | 33% | 2.1% | 1.3–2.9% | 22 | 14–31 | 3.3 | 2.0–4.5 | 5,400 | 3,307–7,527 | 539 | 220–1,001 |
| S7: “-1/2 of mortality” | 10.2 | 7.4–10.3–12.5 | 266 | 164–367 | 50% | 3.2% | 2.0–4.4% | 34 | 21–47 | 5.0 | 3.1–7.0 | 8,366 | 5,120–11,674 | 835 | 341–1,553 |
| S8: “-2/3 of mortality” | 8.4 | 5.6–8.5–10.7 | 357 | 221–493 | 67% | 4.3% | 2.7–6.0% | 46 | 28–63 | 6.8 | 4.2–9.5 | 11,345 | 6,935–15,848 | 1,132 | 461–2,108 |
| S9: “2020 target, in whole area” | 13.0 | 10.6–13.1–15.0 | 120 | 74–167 | 23% | 1.4% | 0.9–2.0% | 15 | 9–21 | 2.3 | 1.4–3.2 | 3,824 | 2,344–5,328 | 382 | 156–709 |
| S10: “2020 target, in hotspots” | 15.1 | 12.5–15.1–17.3 | 13 | 8–18 | 2% | 0.2% | 0.1–0.2% | 2 | 1–2 | 0.3 | 0.2–0.4 | 514 | 315–716 | 51 | 21–95 |

^a Difference in the number of attributable cases before and after scenario implementation.

^b Gain (in %) compared to the number of avoided cases under the scenario S2, taken as a reference.

^c Proportion (in %) of all-cause non-accidental yearly death cases in Grenoble and Lyon conurbations, corresponding to 2,601 and 8,284 deaths, respectively.

^d For 100,000 person-years.

^e In people aged 30 years (population average).

^f In people aged 30 years and older (global estimate for the whole population).

^g The low and high values are calculated with the hypothesis that the unit value (in euros / life year) varies by plus or minus 33%.

Table IIIb. Estimated effects of the scenarios in terms of health benefits related to lung cancer incidence and term low birth weight cases.

| PM _{2.5} exposure reduction scenarios | Health benefits related to lung cancer cases | | | | | | | | | | Health benefits related to term low birth weight cases | | | | | |
|---|--|--------|----------------------|----------------------------------|-----------|------------------------------|-----------------------|----------------------------|-----------------------|-----------------------|--|------------------------------------|--------|----------------------|----------------------------------|------------|
| | Δ_{NAC} ^{a,c} | 95% CI | % of S2 ^b | % of baseline cases ^c | 95% CI | Intangible costs (in M€2017) | Low-high ^f | Tangible costs (in M€2017) | Low-high ^f | All costs (in M€2017) | Low-high ^f | Δ_{NAC} ^a | 95% CI | % of S2 ^b | % of baseline cases ^d | 95% CI |
| Grenoble conurbation (444,000 inhabitants) | | | | | | | | | | | | | | | | |
| S1: “WHO guideline” | 9 | 4–14 | 45% | 3.4% | 1.5–5.1% | 14 | 4–28 | 0.6 | 0.2–1.2 | 15 | 5–29 | 24 | 9–39 | 49% | 12.9% | 4.8–21.0% |
| S2: “No anthropogenic PM _{2.5} ” | 20 | 9–30 | Ref. | 7.5% | 3.5–11.1% | 31 | 10–62 | 1.4 | 0.5–2.6 | 33 | 10–65 | 49 | 19–76 | Ref. | 26.3% | 10.2–40.8% |
| S3: “Quiet neighborhood” | 8 | 4–13 | 42% | 3.1% | 1.4–4.7% | 13 | 4–26 | 0.6 | 0.2–1.1 | 14 | 4–27 | 23 | 8–37 | 46% | 12.1% | 4.5–19.8% |
| S4: “-1 µg/m ³ ” | 2 | 1–4 | 11% | 0.9% | 0.4–1.3% | 4 | 1–7 | 0.2 | 0.1–0.3 | 4 | 1–8 | 6 | 2–10 | 12% | 3.3% | 1.2–5.5% |
| S5: “-2 µg/m ³ ” | 5 | 2–7 | 23% | 1.7% | 0.8–2.6% | 7 | 2–14 | 0.3 | 0.1–0.6 | 7 | 2–15 | 12 | 4–20 | 24% | 6.4% | 2.3–10.8% |
| S6: “-1/3 of mortality” | 7 | 3–10 | 33% | 2.5% | 1.1–3.7% | 10 | 3–21 | 0.4 | 0.1–0.9 | 11 | 3–22 | 17 | 6–28 | 33% | 9.1% | 3.3–15.2% |
| S7: “-1/2 of mortality” | 10 | 5–15 | 50% | 3.7% | 1.7–5.6% | 15 | 5–31 | 0.7 | 0.2–1.3 | 16 | 5–32 | 25 | 9–41 | 50% | 13.5% | 5.0–22.1% |
| S8: “-2/3 of mortality” | 13 | 6–20 | 67% | 4.9% | 2.3–7.4% | 21 | 6–41 | 0.9 | 0.3–1.7 | 22 | 7–43 | 33 | 12–53 | 67% | 17.8% | 6.7–28.6% |
| S9: “2020 target, in whole area” | 5 | 2–7 | 24% | 1.8% | 0.8–2.7% | 7 | 2–15 | 0.3 | 0.1–0.6 | 8 | 2–16 | 13 | 5–21 | 26% | 6.8% | 2.4–11.4% |
| S10: “2020 target, in hotspots” | 1 | 0–1 | 3% | 0.2% | 0.1–0.3% | 0.8 | 0.2–2 | 0.03 | 0.01–0.1 | 0.8 | 0.2–2 | 1 | 1–2 | 3% | 0.8% | 0.3–1.3% |
| Lyon conurbation (1,355,000 inhabitants) | | | | | | | | | | | | | | | | |
| S1: “WHO guideline” | 43 | 20–65 | 52% | 4.5% | 2.1–6.7% | 67 | 21–134 | 2.9 | 1.0–5.6 | 70 | 22–140 | 108 | 40–173 | 56% | 16.4% | 6.1–26.4% |
| S2: “No anthropogenic PM _{2.5} ” | 83 | 39–123 | Ref. | 8.6% | 4.0–12.8% | 128 | 40–254 | 5.6 | 1.9–10.6 | 134 | 42–265 | 193 | 76–295 | Ref. | 29.4% | 11.5–44.9% |
| S3: “Quiet neighborhood” | 24 | 11–37 | 29% | 2.5% | 1.2–3.8% | 38 | 12–76 | 1.6 | 0.5–3.2 | 39 | 12–79 | 63 | 23–104 | 33% | 9.6% | 3.5–15.8% |
| S4: “-1 µg/m ³ ” | 8 | 4–13 | 10% | 0.9% | 0.4–1.3% | 13 | 4–26 | 0.6 | 0.2–1.1 | 13 | 4–27 | 21 | 8–36 | 11% | 3.3% | 1.2–5.5% |
| S5: “-2 µg/m ³ ” | 16 | 8–25 | 20% | 1.7% | 0.8–2.6% | 26 | 8–52 | 1.1 | 0.4–2.2 | 27 | 8–54 | 42 | 15–71 | 22% | 6.4% | 2.3–10.8% |
| S6: “-1/3 of mortality” | 27 | 12–41 | 33% | 2.8% | 1.3–4.2% | 42 | 13–84 | 1.8 | 0.6–3.5 | 44 | 13–88 | 68 | 25–113 | 33% | 10.3% | 3.8–17.2% |
| S7: “-1/2 of mortality” | 41 | 19–62 | 50% | 4.3% | 2.0–6.5% | 64 | 20–129 | 2.8 | 0.9–5.4 | 67 | 21–134 | 102 | 38–166 | 50% | 15.5% | 5.8–25.2% |
| S8: “-2/3 of mortality” | 56 | 26–83 | 67% | 5.8% | 2.7–8.6% | 86 | 27–172 | 3.7 | 1.2–7.2 | 90 | 28–179 | 134 | 51–214 | 67% | 20.4% | 7.7–32.5% |
| S9: “2020 target, in whole area” | 19 | 9–29 | 23% | 2.0% | 0.9–3.0% | 29 | 9–59 | 1.3 | 0.4–2.5 | 31 | 9–62 | 48 | 18–81 | 25% | 7.4% | 2.7–12.4% |
| S10: “2020 target, in hotspots” | 2 | 1–3 | 3% | 0.2% | 0.1–0.3% | 3 | 1–7 | 0.1 | 0.05–0.3 | 3 | 1–7 | 5 | 2–9 | 3% | 0.8% | 0.3–1.3% |

^a Difference in the number of attributable cases before and after scenario implementation.

^b Gain (in %) compared to the number of avoided cases under the scenario S2, taken as a reference.

^c Proportion (in %) of the estimated incident lung cancer cases in Grenoble and Lyon conurbations, corresponding to 269 and 963, respectively.

^d Proportion (in %) of the estimated total yearly number of term low birth weight cases in Grenoble and Lyon conurbations, corresponding to 187 and 657, respectively.

^e In people aged 30 years and older (global estimate for the whole population).

^f The low and high values are calculated with the hypothesis that the unit value (in euros / life year) varies by plus or minus 33%.

Table IV. Impact of each scenario on social differences in PM_{2.5} exposure.

| PM _{2.5} exposure reduction scenarios | SDHC ^a (µg/m ³) | Variance | p-value ^b |
|--|--|----------|----------------------|
| Grenoble conurbation baseline (2015-2017) | 2.62 | 1.50 | - |
| S1: "WHO guideline" | 0.25 | 0.01 | 0.019 |
| S2: "No anthropogenic PM _{2.5} " | 0.00 | 0.00 | 0.019 |
| S3: "Quiet neighborhood" | 0.23 | 0.01 | 0.019 |
| S4: "-1 µg/m ³ " | 2.62 | 1.50 | 1 |
| S5: "-2 µg/m ³ " | 2.53 | 1.45 | 0.26 |
| S6: "-1/3 of mortality" | 2.53 | 1.45 | 0.26 |
| S7: "-1/2 of mortality" | 2.45 | 1.39 | 0.19 |
| S8: "-2/3 of mortality" | 2.13 | 1.12 | 0.086 |
| S9: "2020 target, in whole area" | 2.24 | 1.13 | 0.028 |
| S10: "2020 target, in hotspots" | 2.41 | 1.32 | 0.12 |
| Lyon conurbation baseline (2015-2017) | 1.53 | 0.51 | - |
| S1: "WHO guideline" | 0.00 | 0.00 | 0.026 |
| S2: "No anthropogenic PM _{2.5} " | 0.00 | 0.00 | 0.026 |
| S3: "Quiet neighborhood" | 0.08 | 0.00 | 0.026 |
| S4: "-1 µg/m ³ " | 1.53 | 0.51 | 1 |
| S5: "-2 µg/m ³ " | 1.53 | 0.51 | 1 |
| S6: "-1/3 of mortality" | 1.53 | 0.51 | 0.46 |
| S7: "-1/2 of mortality" | 1.53 | 0.51 | 0.32 |
| S8: "-2/3 of mortality" | 1.53 | 0.49 | 0.28 |
| S9: "2020 target, in whole area" | 1.35 | 0.37 | 0.018 |
| S10: "2020 target, in hotspots" | 1.38 | 0.43 | 0.077 |

^a Social Deprivation Heterogeneity Coefficient (SDHC). A larger SDHC corresponds to an increased heterogeneity in PM_{2.5} exposure across social categories. Cf. Section 2.5 for details. A low p-value is in favor of a change in social inequalities as a result of the scenario implementation.

^b Grambsch test used to compare the variance of PM_{2.5} exposure by decile of European Deprivation Index (EDI) of the scenario to that of the baseline.

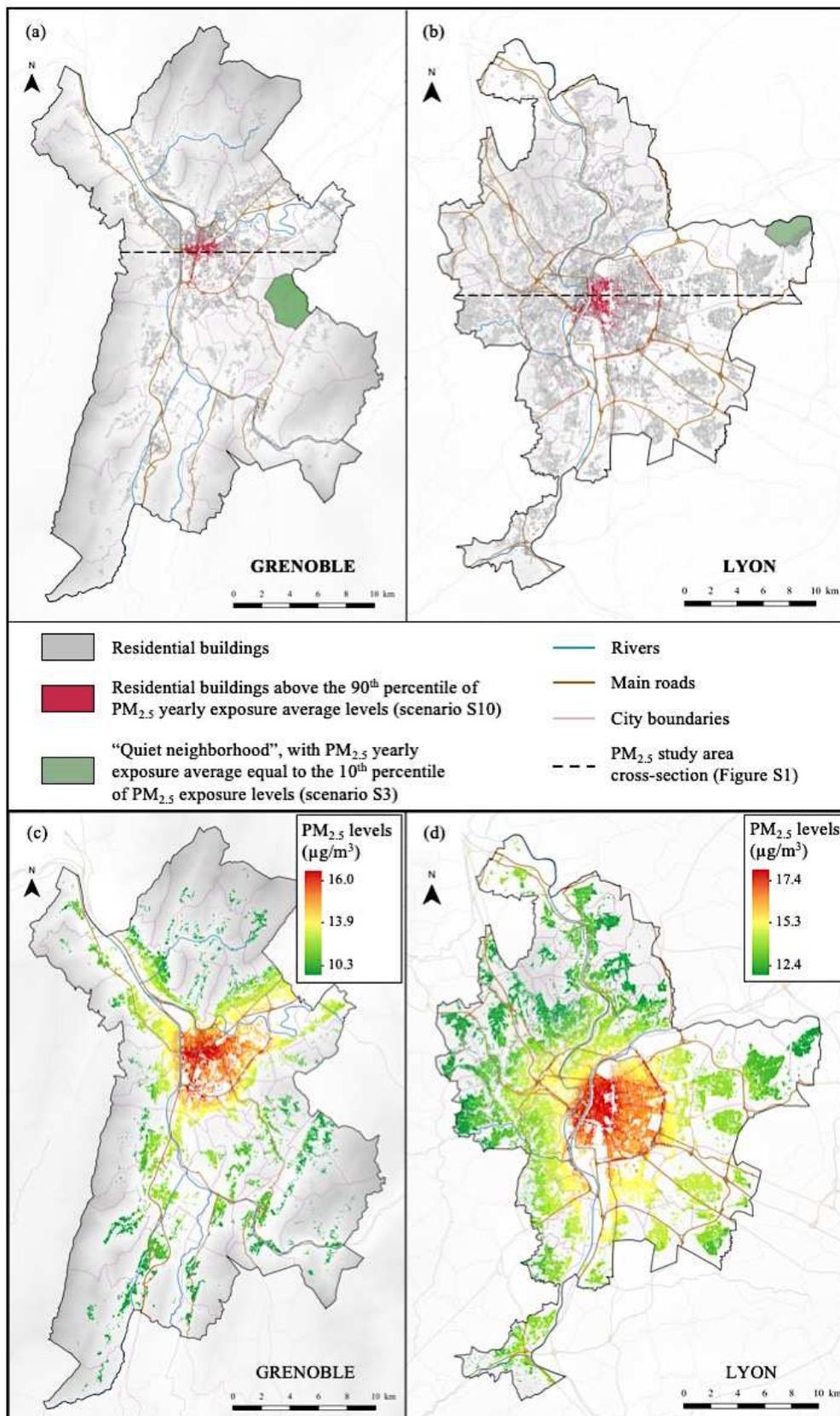
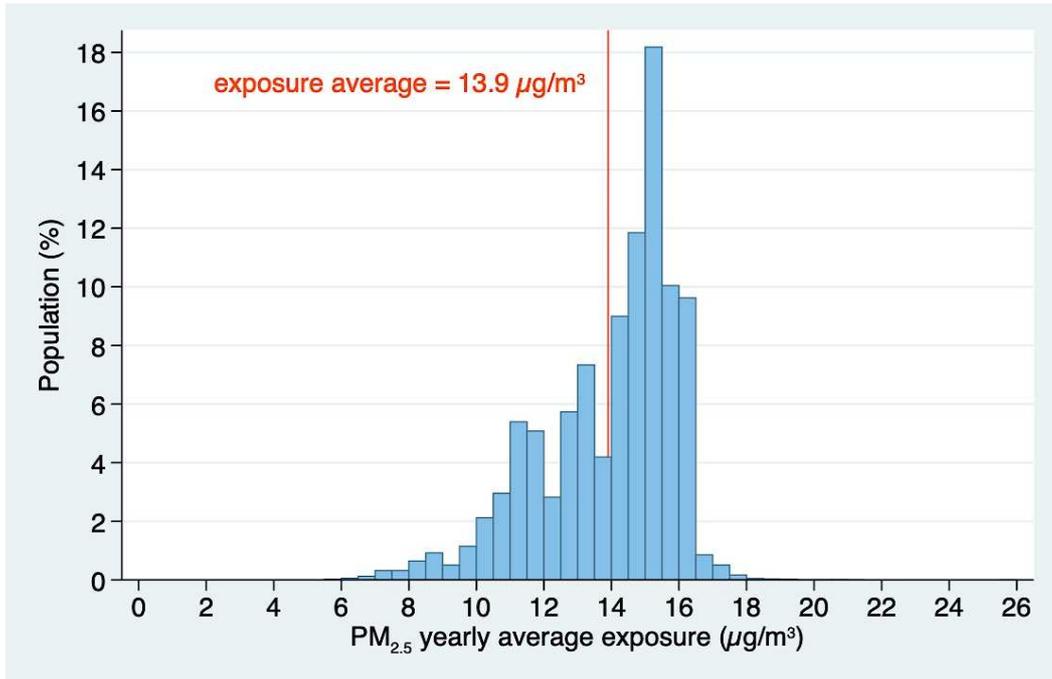


Figure 1. (a and b) Geographical illustration of Grenoble and Lyon urban areas, and (c and d) population exposure to fine particulate matter (PM_{2.5}; yearly average exposure during the period 2015-2017, in µg/m³; uninhabited zones appear in shades of grey). (2-column fitting image)

(i) Grenoble conurbation



(ii) Lyon conurbation

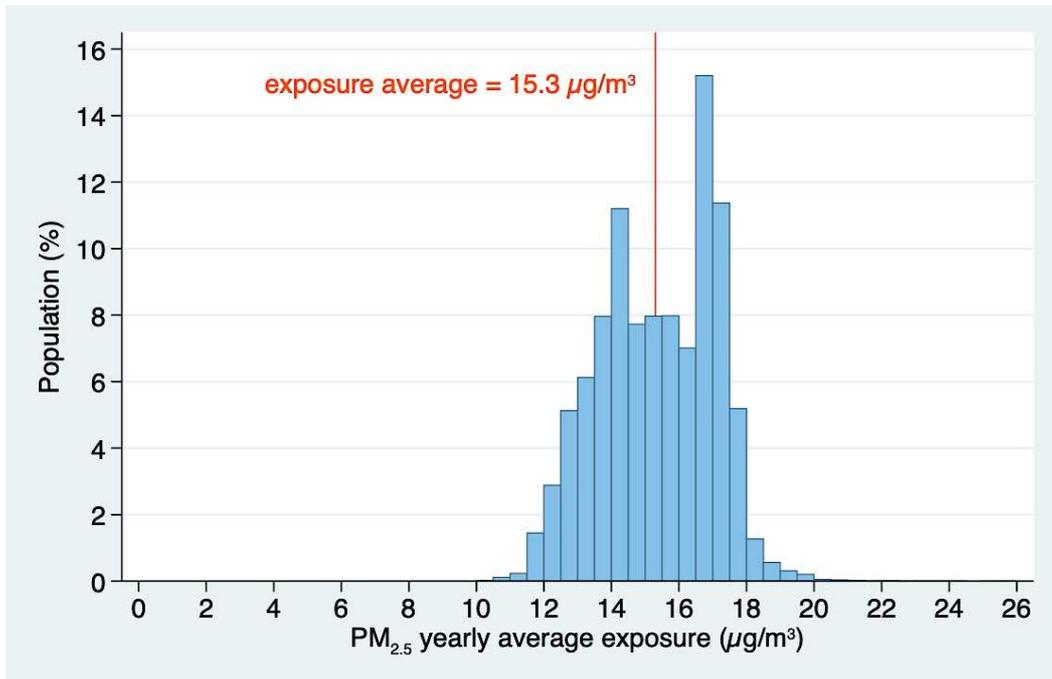
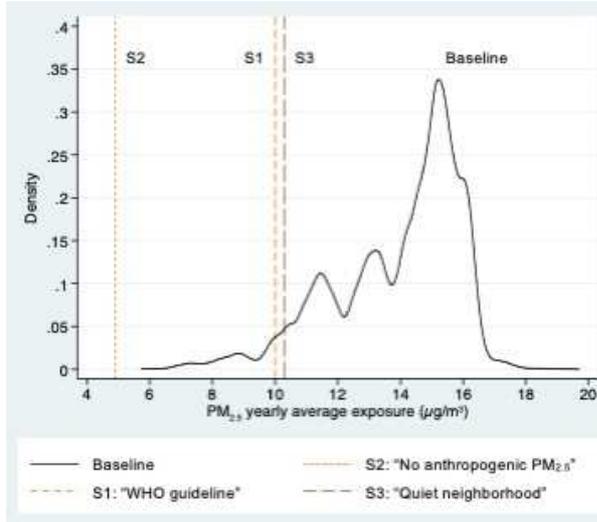
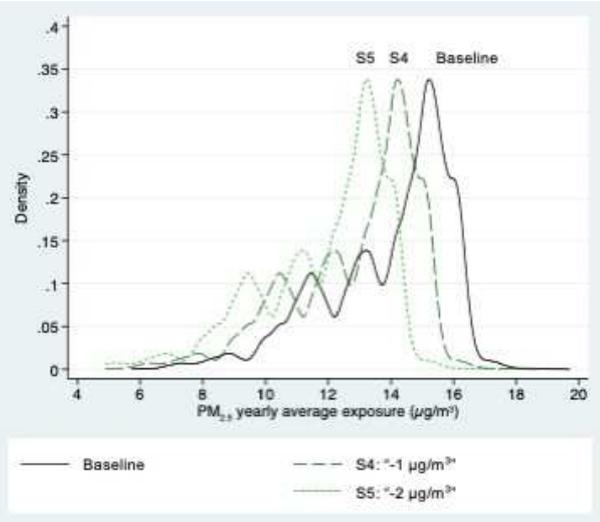


Figure 2. Fine particulate matter (PM_{2.5}) exposure distribution in the populations of (i) Grenoble and (ii) Lyon conurbations (yearly average exposure during the period 2015-2017, in $\mu\text{g}/\text{m}^3$). (1.5-column fitting image)

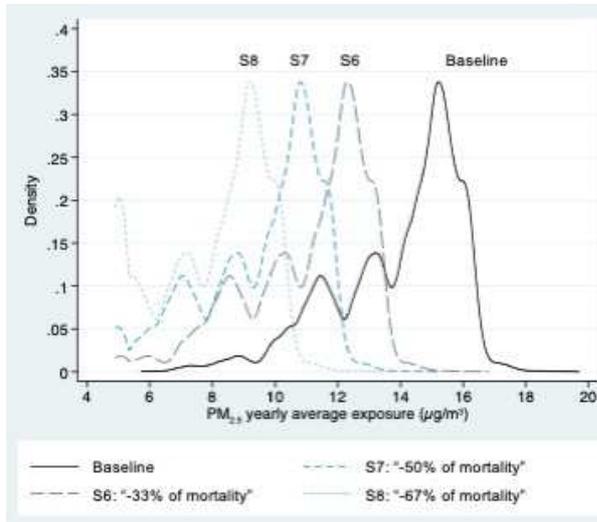
(i) Scenarios S1 to S3



(ii) Scenarios S4 to S5



(iii) Scenarios S6 to S8



(iv) Scenarios S9 to S10

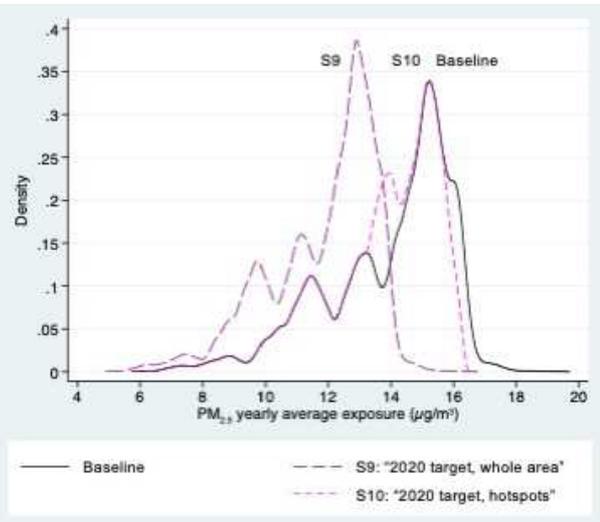
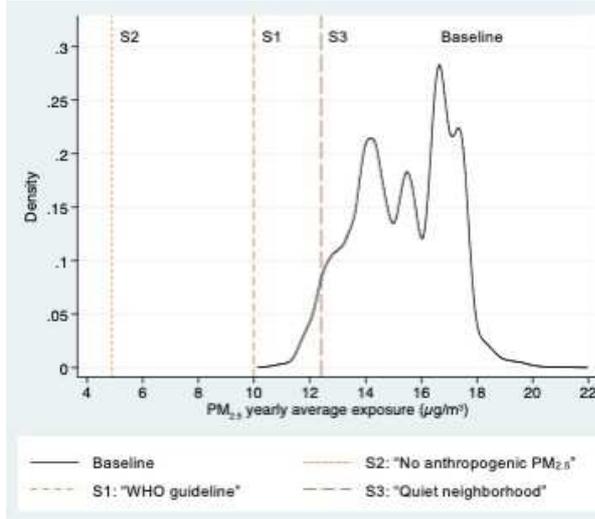


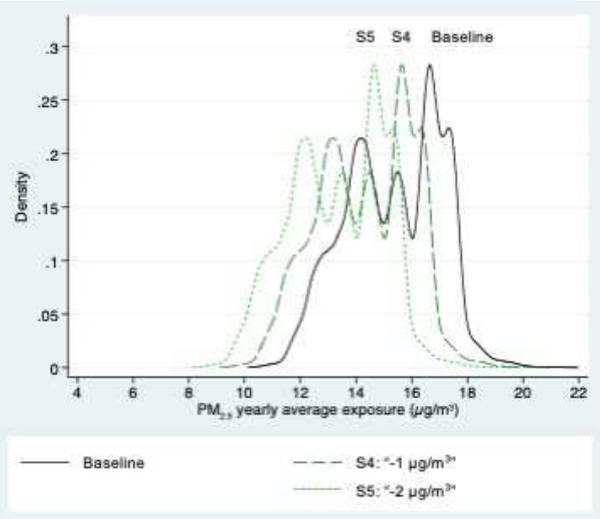
Figure 3a. Expected fine particulate matter (PM_{2.5}) exposure levels for the Grenoble conurbation population (yearly average exposure, in μg/m³) under each PM_{2.5} level reduction scenario: (i) scenarios targeting a spatially homogeneous value in the whole area (S1 to S3), (ii) scenarios decreasing homogeneously PM_{2.5} in the whole study area (S4 and S5), (iii) scenarios targeting a specific reduction in PM_{2.5}-related mortality in the whole study area (S6 to S8), and (iv) scenarios inspired by the 2008/50/EU Directive (S9 and S10). The black solid line shows the distribution of PM_{2.5} exposure during the 2015-2017 (baseline) period.

(2-column fitting image)

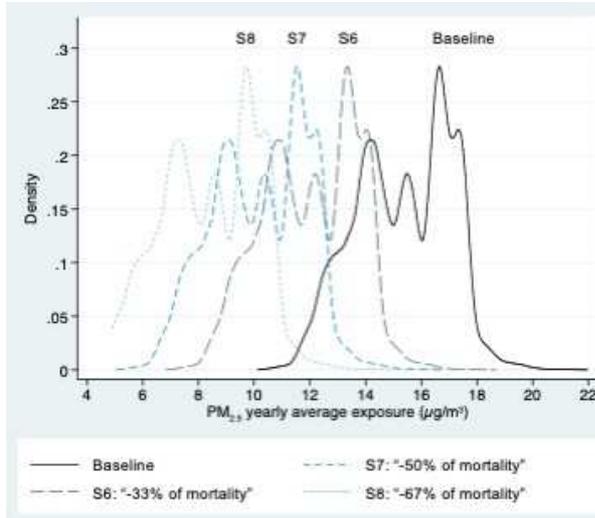
(i) Scenarios S1 to S3



(ii) Scenarios S4 to S5



(iii) Scenarios S6 to S8



(iv) Scenarios S9 to S10

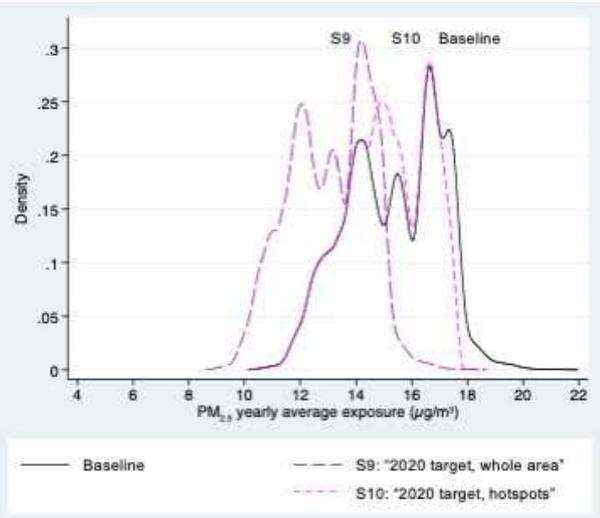
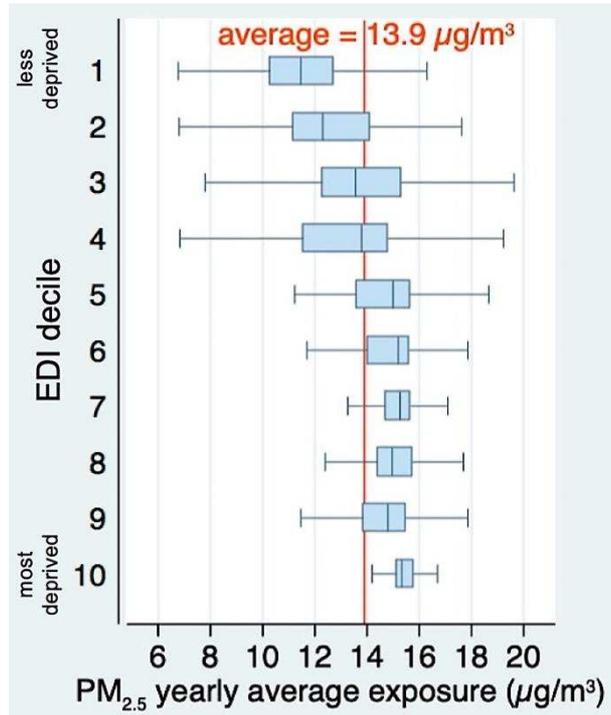


Figure 3b. Expected fine particulate matter (PM_{2.5}) exposure levels for the Lyon conurbation population (yearly average exposure, in $\mu\text{g}/\text{m}^3$) under each PM_{2.5} level reduction scenario: (i) scenarios targeting a spatially homogeneous value in the whole area (S1 to S3), (ii) scenarios decreasing homogeneously PM_{2.5} in the whole study area (S4 and S5), (iii) scenarios targeting a specific reduction in PM_{2.5}-related mortality in the whole study area (S6 to S8), and (iv) scenarios inspired by the 2008/50/EU Directive (S9 and S10). The black solid line shows the distribution of PM_{2.5} exposure during the 2015-2017 (baseline) period.

(2-column fitting image)

(i) Grenoble conurbation



(ii) Lyon conurbation

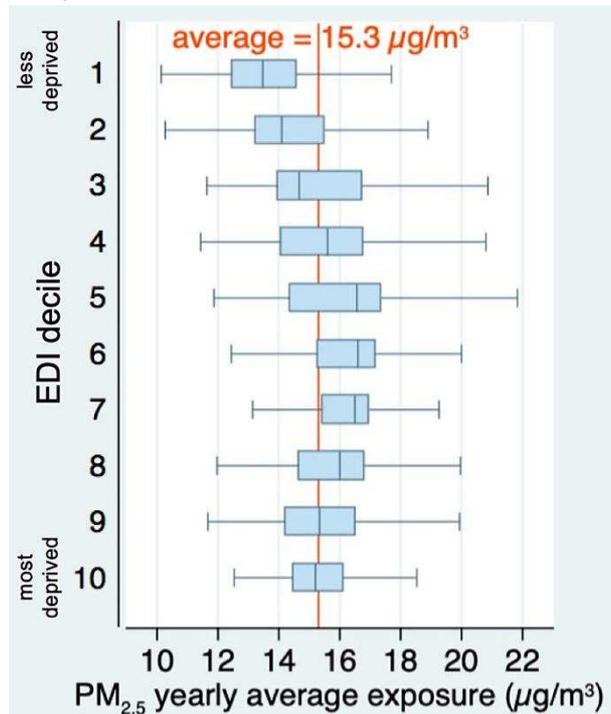
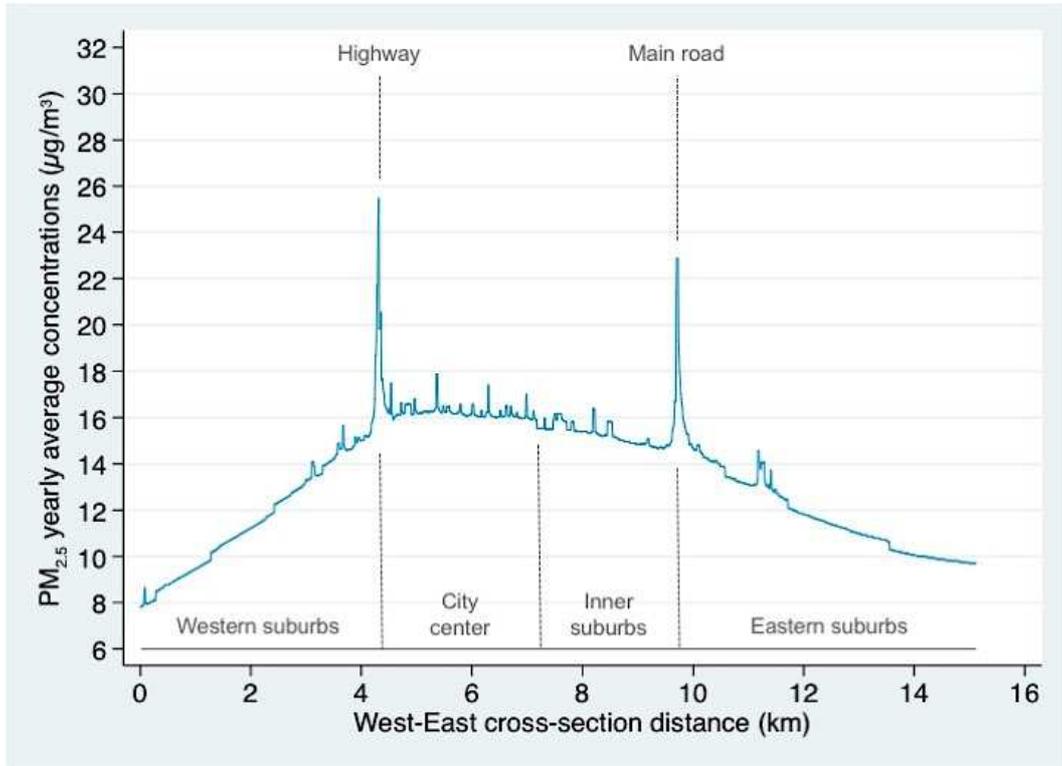


Figure 4. Fine particulate matter (PM_{2.5}) exposure levels in (i) Grenoble and (ii) Lyon conurbation populations split into ten equally sized groups according to the social deprivation status (yearly average PM_{2.5} exposure during the period 2015-2017, in $\mu\text{g}/\text{m}^3$; European Deprivation Index, EDI, the 10th decile corresponding to the most deprived population).

(1-column fitting image)

(i) Grenoble conurbation



(ii) Lyon conurbation

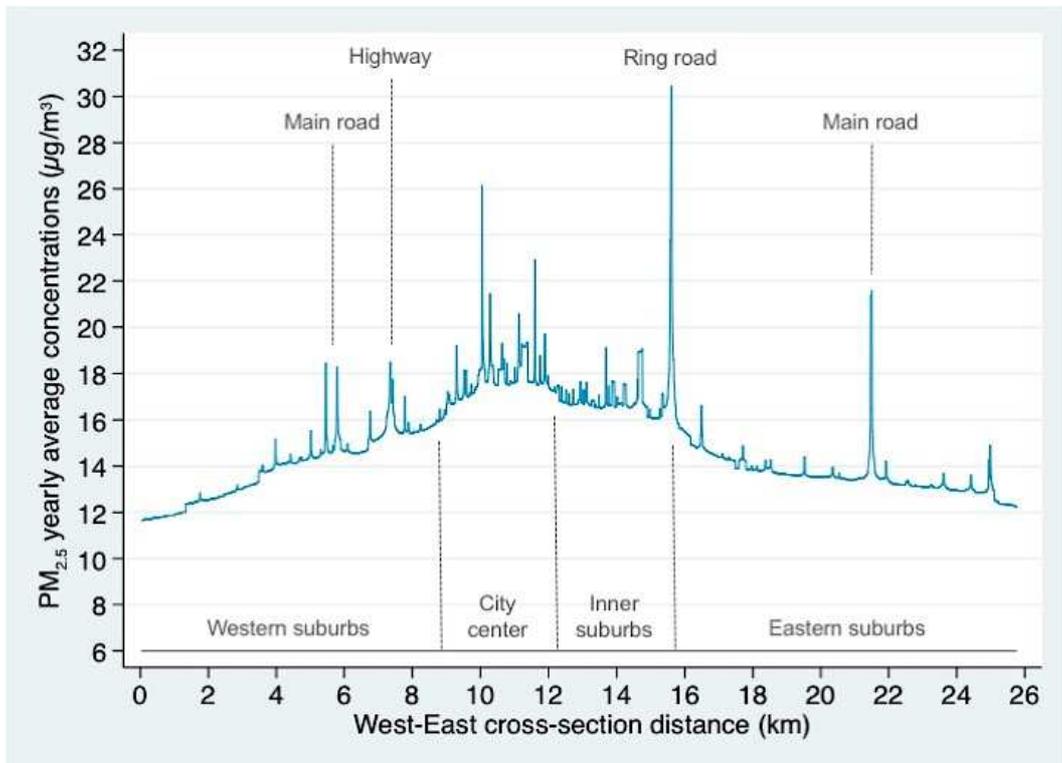


Figure S1. PM_{2.5} levels in a West-East cross section passing through the city center and going through the suburban cities of (i) Grenoble and (ii) Lyon conurbations (yearly average concentrations during the period 2015-2017, in µg/m³).

(1.5-column fitting image)