Supplementary Information for:

High resolution assessment of air quality and health in Europe under different climate mitigation scenarios

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Supplementary Item List

Supplementary Note 1: Definition of SSP (Shared Socioeconomic Pathway) scenarios used in this manuscript

SSP1: Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation). The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.

SSP2: Middle of the Road (Medium challenges to mitigation and adaptation) The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.

SSP3: Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation) A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions

SSP5: Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation) This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.

Supplementary Note 2: Description of air quality controls for SSP scenarios

As shown in Supplementary Note 1, each SSP scenarios is linked to specific air quality controls. This linkage has been developed in [1]. Here we detail the main features of these air quality controls, as taken from [1].

The strong pollution control scenarios (SSP1 and SSP5) assume that growing interest about health and the environment will drive achievement of pollutant reduction targets that are significantly lower than current levels in the long term. This scenario involves strong development of pollution control technologies. To meet ambitious air quality goals, regions will adopt the best available technologies, or even exceed them, together with enforcement of environmental laws supported by efficient institutions.

The medium pollution control scenarios (SSP2) describes a world where current trends continue. Countries will experience some "catch-up," reaching levels of emission control and policy effectiveness beyond historical ones. Pollution control targets become progressively more ambitious as income rises, and commitment to setting and enforcing these targets strengthens, with greater importance placed on health and environmental protection.

The weak pollution control scenarios (SSP3 and SSP4) suggest that pollution control efforts will be delayed and less ambitious. This will cause high emission levels in large cities of developing countries, inadequate air quality monitoring systems, and weaker institutions that lead to poor enforcement of regulations. Additionally, there will be slow development of international laws and regulations, with slows technological advancements. Trans-boundary pollution will further exacerbate high background pollution levels in many areas.

Supplementary Note 3: Uncertainty and sensitivity analysis

We performed the uncertainty and sensitivity analysis of the applied modelling framework, considering different combinations of parameter values and modelling assumptions. We take into account in particular the air quality model uncertainty, and the health impact assessment uncertainty (climate uncertainties are already taken into account in the data we use, coming from the CMIP6 - Coupled Model Intercomparison Project Phase 6) [1].

Air quality modelling

Air quality modelling results are mainly affected by input data (emissions and boundary conditions) and by the model coefficients related uncertainties. A full sensitivity analysis of how these parameters can affect the results is quite demanding, and out of the scope of this paper. However, the testing of the impact of various model's parameters on the output has been proposed in recent publications. I.e. FASST (FAst Scenario Screening Tool) has been extensively tested to see how its results are impacted by input uncertainty [2, 3], and similarly has been done for SHERPA (Screening for High Emission Reduction Potential on Air) [4]. As in this paper SHERPA is mainly used to convert emissions to concentrations, we can refer to [3] to see a detailed analysis of how input and model coefficients can affect the model results. From the aforementioned study [3], it is clear how the model coefficient has a very limited impact on the air quality model results, while the main uncertainty comes from the emission inventory. Emission uncertainty is partly tackled thanks to emission projections as performed in the CMIP6 project (Coupled Model Intercomparison Project Phase 6, [5]), that intrinsically consider uncertainty in its studies. Also, in terms of initial emission inventory (baseline) we use CAMS (Copernicus Atmospheric Monitoring Service) emissions, that are the state-of-the-art emissions for Europe. Finally, [6] shows how the uncertainty due to the air quality model input (as emissions) is much lower then the one coming from the "Health Impact Assessment" part. This is why in this paper we mainly assess (in a quantitative way, see next Setion) the uncertainty coming from the "health impact assessment" evaluation part of the applied modelling.

Health impact assessment

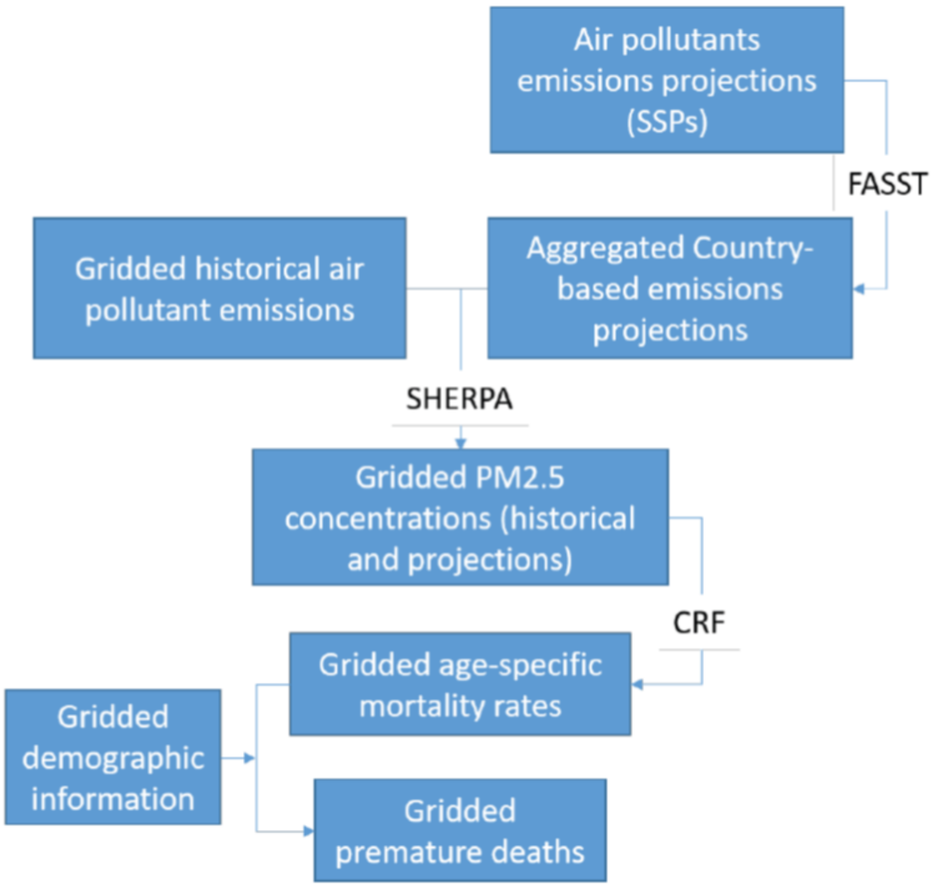
For the health impact assessment part, we performed a full sensitivity analysis, considering how the results are impacted by the main sources of uncertainty in Health Impact Assessment: baseline mortality rate, relative risk, and cut-off value. We considered that, on average, for EU countries, the error in the baseline mortality rate is around 2% [7], and then we created perturbed baseline mortality rate using a uniform distribution around the reference value. For relative risk we used a normal distribution for sampling, using a reference value at 1.062, with confidence interval at 1.040 - 1.083 [8]. Two possible values were considered for the cut-off values, at 0 and 5 micrograms per cubic meters.

The results in terms of uncertainty analysis are presented in the main part of the manuscript, where confidence interval on all results are provided (considering a central estimate, and 5th / 95th percentiles).
Here on the contrary we focus on the sensitivity analysis part, that is to say we try to analyze how the output variability (in this case, the total variance of premature deaths) can be explained by the uncertainty due to the baseline mortality rate, the relative risk and the cut-off.
In Supplementary Fig. 10, in particular, we show (through Global Sensitivity Analysis Indicators as defined in [9]) how baseline mortality uncertainty doesn't play a role in explaining the output variability, both in 2050 and 2100. On the contrary, relative risks and cut-off do play a role. And it's interesting to show how, for climate ambitious scenarios (SSP1), the main variability is linked to the cut-off uncertainty (as PM2.5 concentrations are lower for this scenario, and the cut-off creates a strong discontinuity on the results). The picture changes for less ambitious climate scenarios (SSP3 and SSP5), as the relative risk becomes the main driver for the output variability (being the cut-off impact less important when looking at higher concentrations). Finally, an intermediate situation can be seen for the SSP2 intermediate scenario.

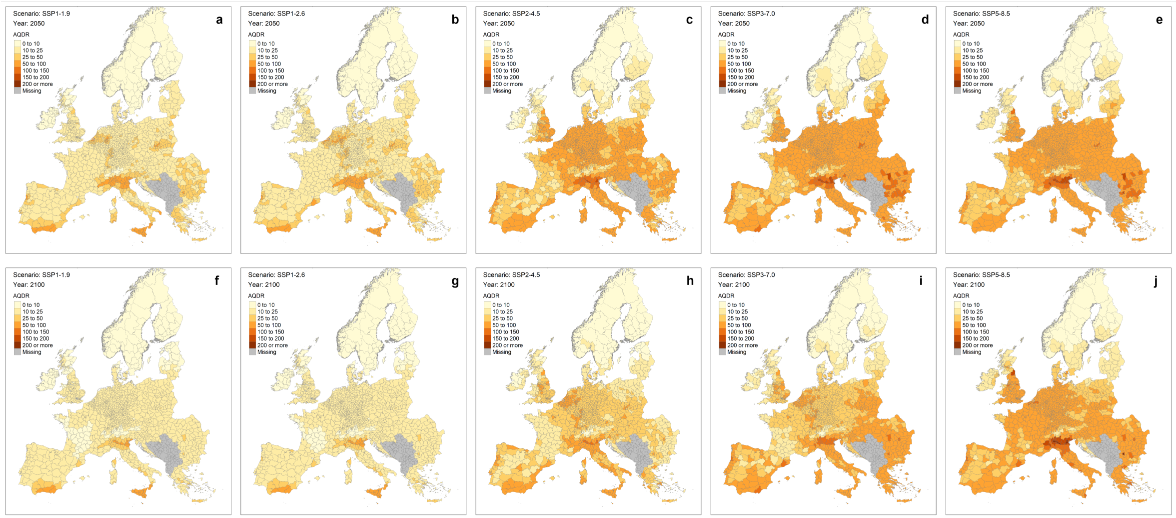
Supplementary Table 1

Table 1: **SSP definition.** Greenhouse gas emissions, air pollution control and global warming for SSP scenarios.

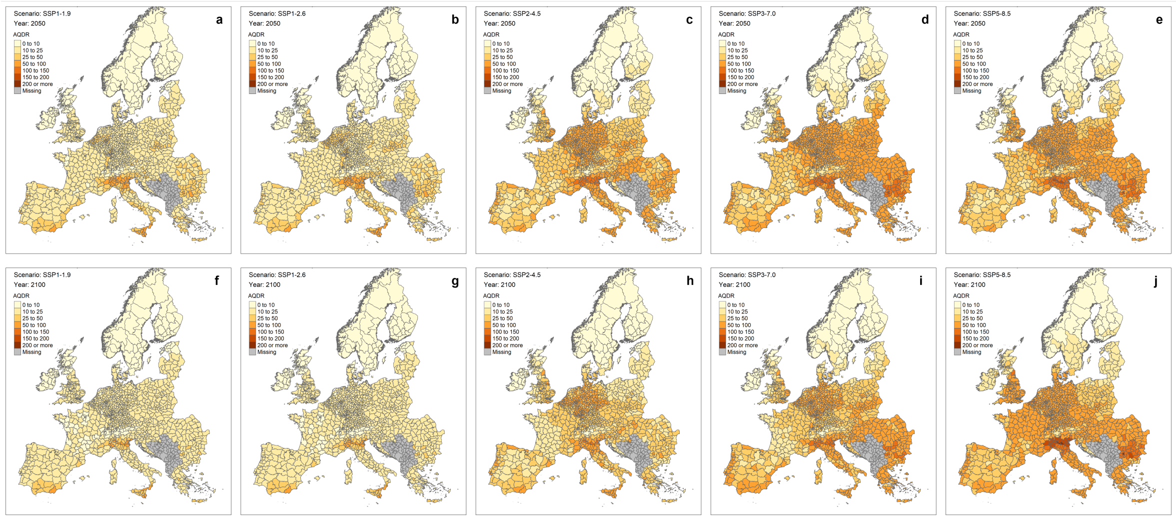
SSP_RCP	Greenhouse Gases	Air Pollution Control	Warming (2081-2100)
SSP1-1.9	very low GHG emissions, CO_2 emissions cut to net zero around 2050	strong	1.4 °C
SSP1-2.6	low GHG emissions, CO_2 emissions cut to net zero around 2075	strong	1.8 °C
SSP2-4.5	intermediate GHG emissions, CO_2 emissions around current levels until 2050, then falling but not reaching net zero by 2100	medium	2.7 °C
SSP3-7.0	high GHG emissions, CO_2 emissions double by 2100	low	3.6 °C
SSP5-8.5	very high GHG emissions, CO_2 emissions triple by 2075	strong	4.4 °C



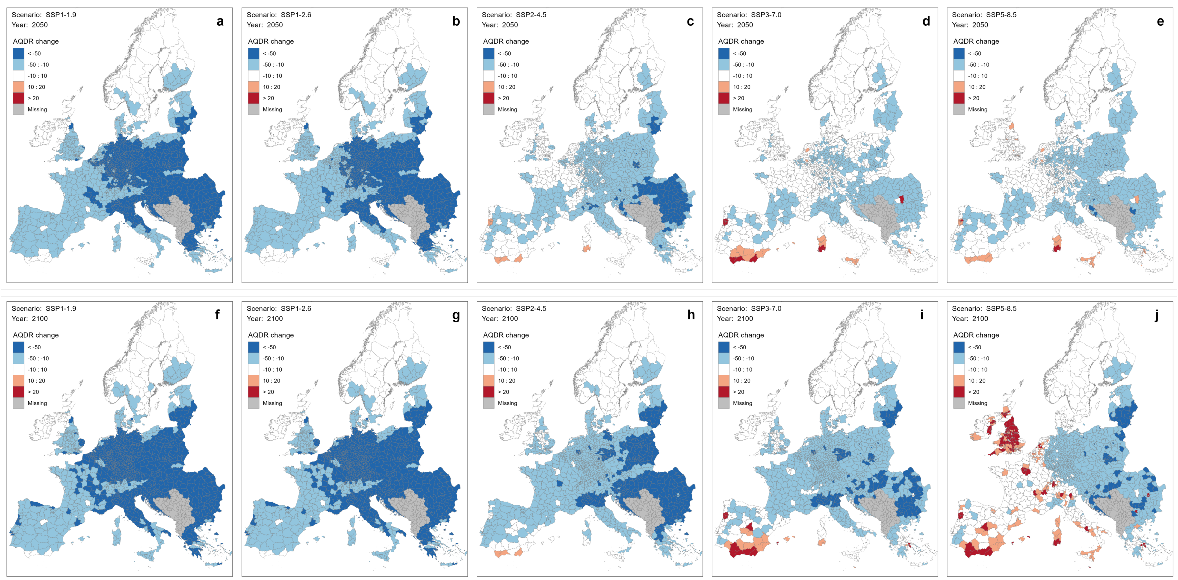
Supplementary Figure 1: **Modelling framework.** Modelling framework used in this study to compute premature deaths of climate scenarios, detailing the steps from emission projections to premature deaths evaluation.



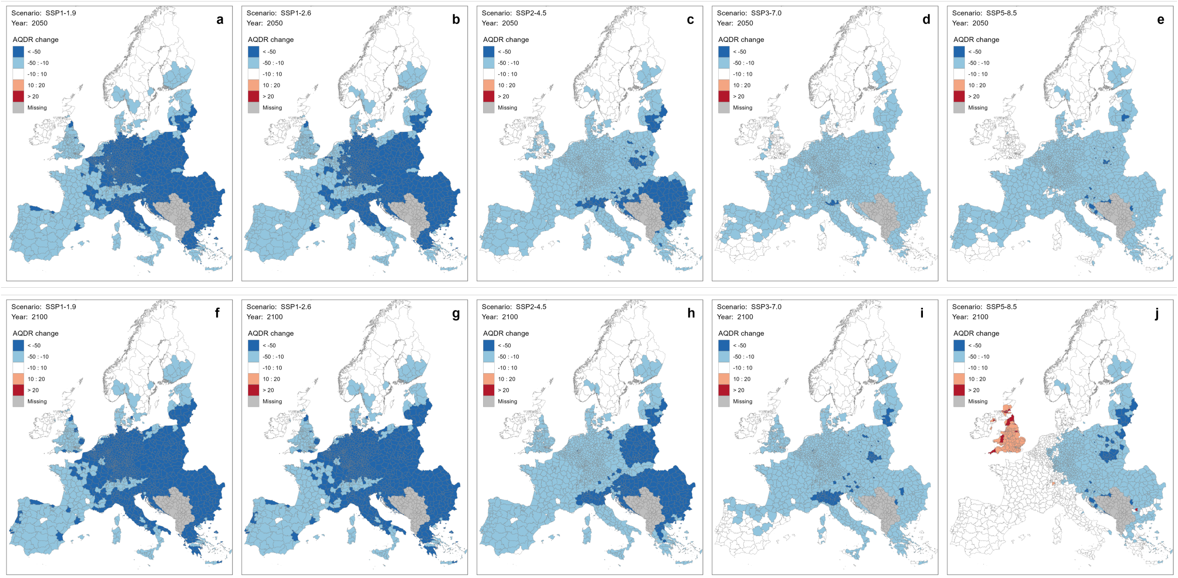
Supplementary Figure 2: **Premature death rates, dynamic approach.** Premature death rates attributable to air quality (AQDR) at NUTS3 level per 100,000 inhabitants - Dynamic demographic approach. (a, b, c, d, e) represent results for 2050, respectively for SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5, while (f, g, h, i, j) the correspondent results for 2100. Countries and NUTS3 boundaries come from Eurostat/GISCO.



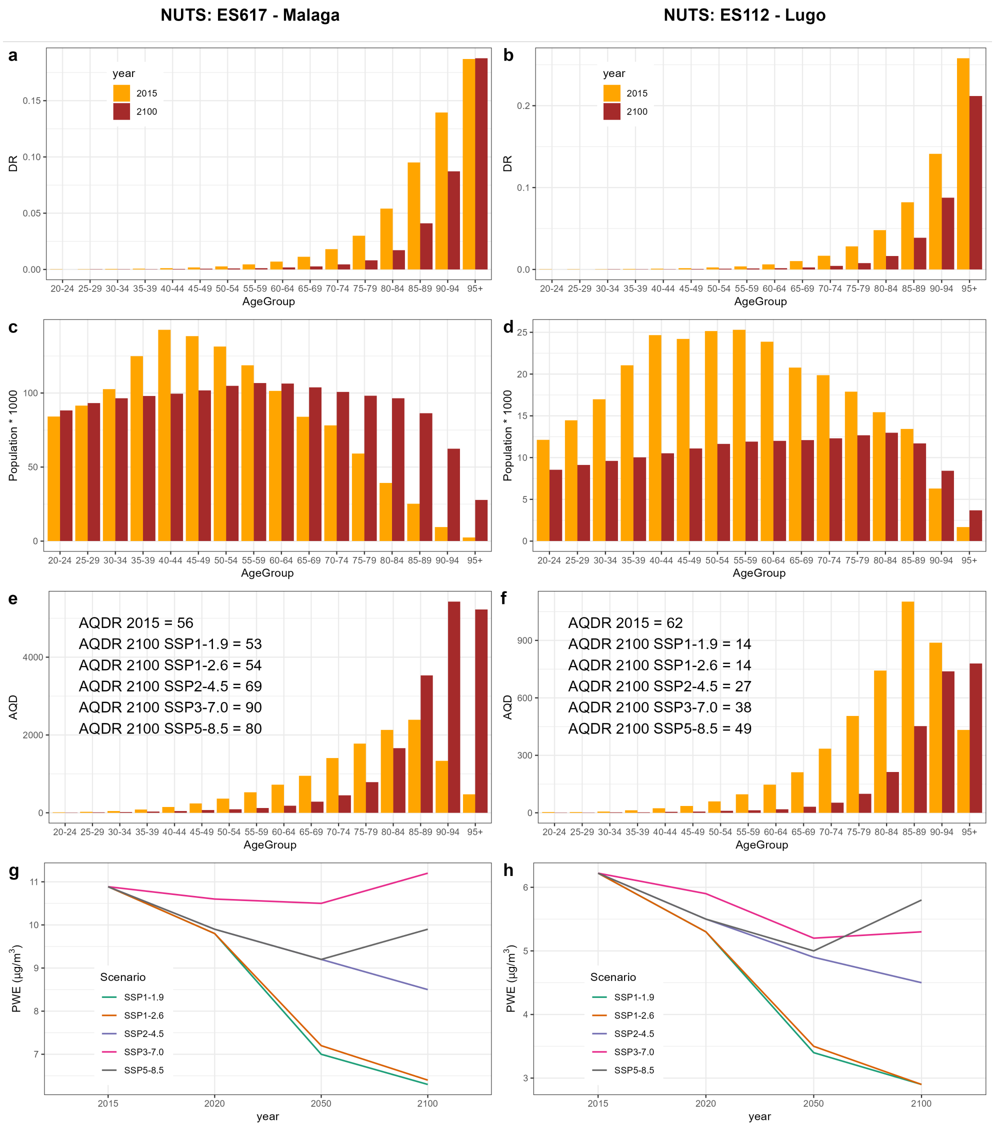
Supplementary Figure 3: **Premature death rates, static approach.** Premature death rates attributable to air quality (AQDR) at NUTS3 level per 100,000 inhabitants - Static demographic approach. (a, b, c, d, e) represent results for 2050, respectively for SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5, while (f, g, h, i, j) the correspondent results for 2100. Countries and NUTS3 boundaries come from Eurostat/GISCO.



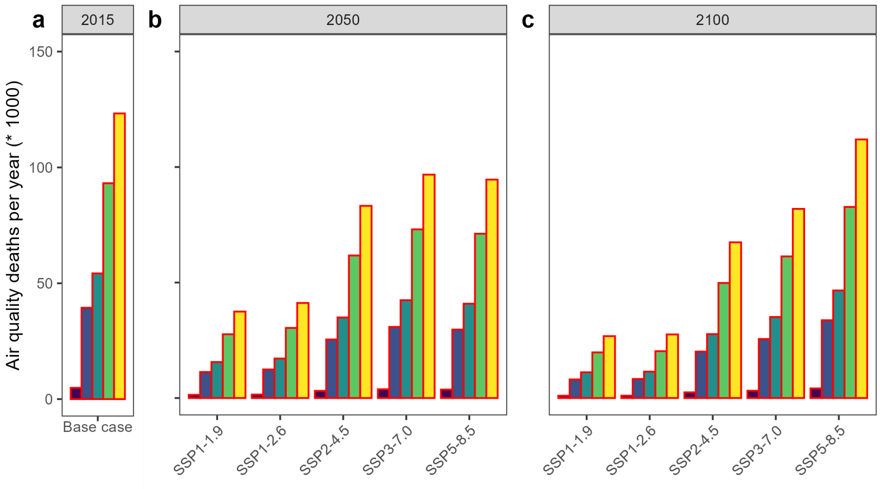
Supplementary Figure 4: **Change in death rates, dynamic approach.** Change in death rates attributable to air quality in 2050 and 2100 compared to baseline - Dynamic demographic approach. (a, b, c, d, e) represent results for 2050, respectively for SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5, while (f, g, h, i, j) the correspondent results for 2100. Countries and NUTS3 boundaries come from Eurostat/GISCO.



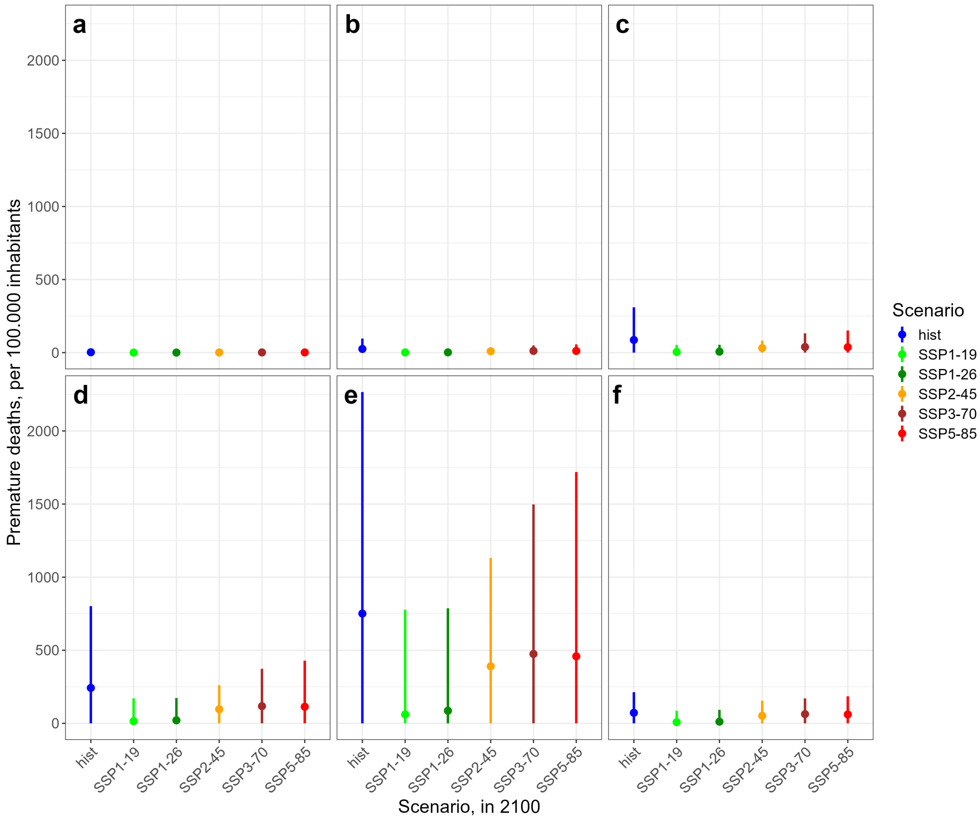
Supplementary Figure 5: **Change in death rates, static approach.** Change in death rates attributable to air quality in 2050 and 2100 compared to baseline - Static demographic approach. (a, b, c, d, e) represent results for 2050, respectively for SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP5-8.5, while (f, g, h, i, j) the correspondent results for 2100. Countries and NUTS3 boundaries come from Eurostat/GISCO.



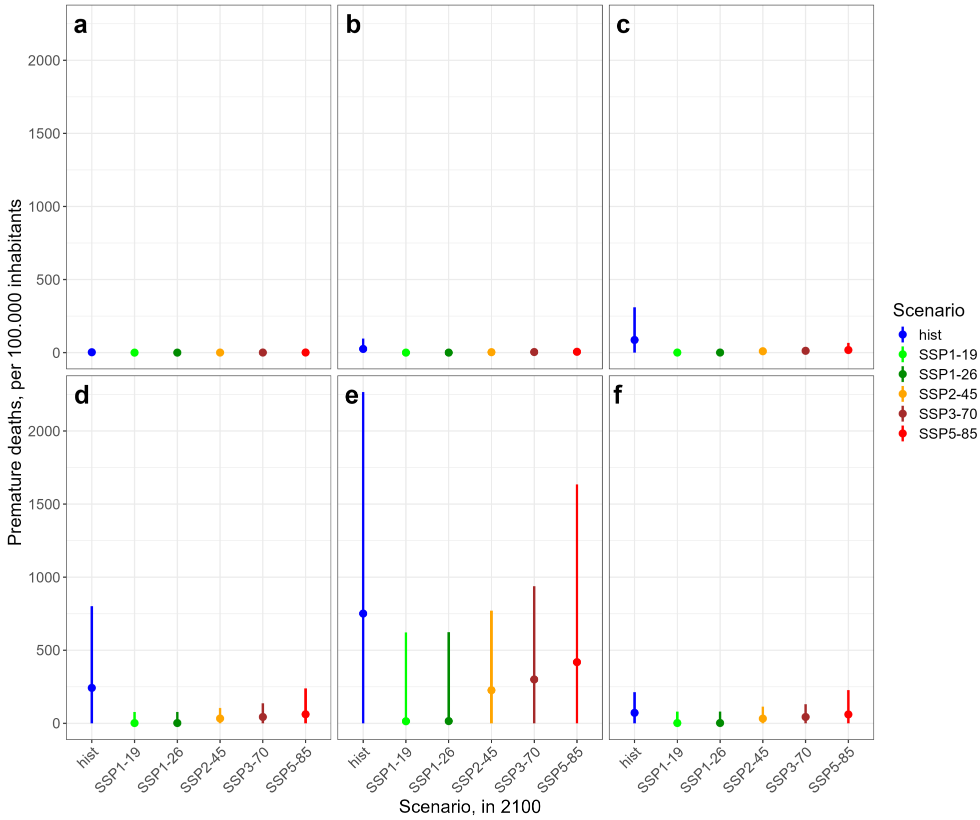
Supplementary Figure 6: **Detailed overview for two specific NUTS3** (a, b) Overview of death rate (DR), (c, d) population by 5-year age-group, (e, f) deaths attributable to air quality (AQD) by 5-year age-group, and (g, h) Population Weigthed Exposure by scenario for two NUTS3 having different AQDR time trend. Dynamic demographic approach.



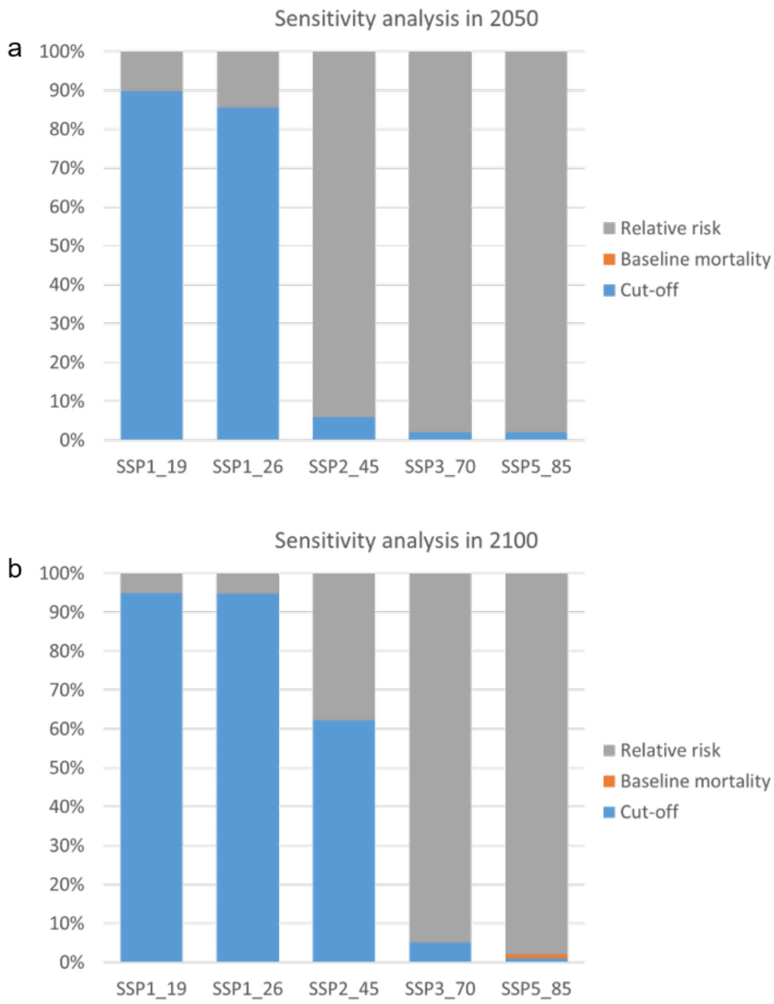
Supplementary Figure 7: **Premature deaths by age group, static approach.** Premature deaths attributable to PM2.5 for different age groups for (a) 2015 and in (b) 2050 and (c) 2100 for the different SSP scenarios. Results for the static demographic scenario.



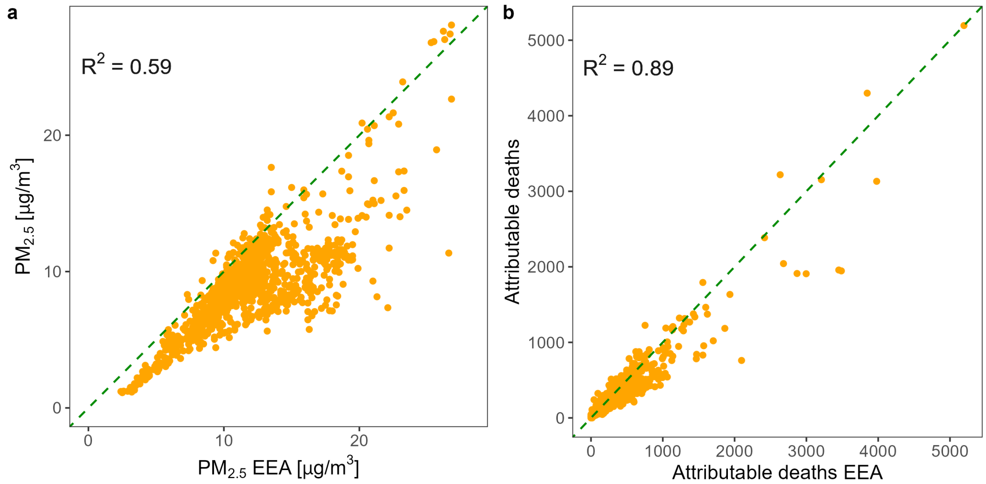
Supplementary Figure 8: **Mortality rate average and variability by NUT3, in 2050.** Mortality rate average and variability for the whole Europe, by age group, computed starting from NUTS3 values, for 2015 and for different SSP scenarios in 2050, considering the dynamic demographic approach. (a) represents age class '20-44' years, (b) age class '45-64', (c) age class '65-74', (d) age class '75-84', (e) age class '85+', (f) 'all age classes' together.



Supplementary Figure 9: **Mortality rate average and variability by NUT3, in 2100.** Mortality rate average and variability for the whole Europe, by age group, computed starting from NUTS3 values, for 2015 and for different SSP scenarios in 2100, considering the dynamic demographic approach. (a) represents age class '20-44' years, (b) age class '45-64', (c) age class '65-74', (d) age class '75-84', (e) age class '85+', (f) 'all age classes' together.



Supplementary Figure 10: **Sensitivity analysis of model output.** Sensitivity analysis of model output, looking at the "Sensitivity Indicator" as defined in [9]. The indicator shows how much each input uncertainty (baseline mortality, relative risk, cut-off) can explain the output variability (in this case premature deaths), in percentage. Results are shown for (a) 2050 and (b) 2100, for the 5 considered SSP scenarios.



Supplementary Figure 11: **Model Validation.** Validation for the year 2015 of the Air Quality Model results and of the premature deaths. Both scatters compare at NUTS3 level our estimate (x-axis) and the EEA estimates (y-axis) considering (a) air quality and (b) premature deaths.

Supplementary References

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