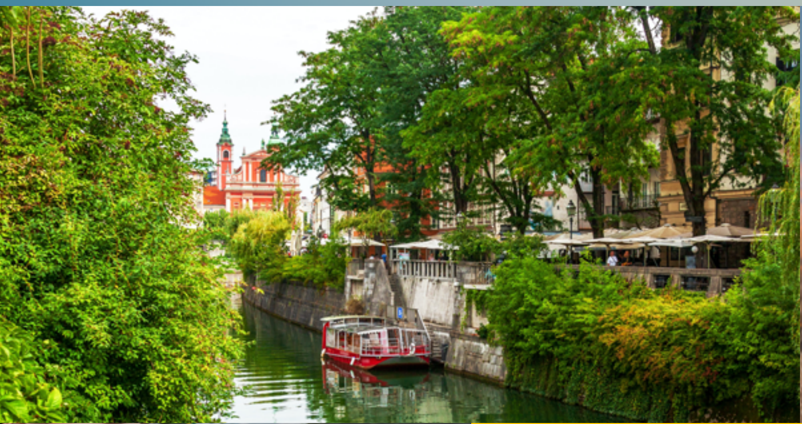
EXHAUSTION

White Paper
January 2024

Exposure to heat and air pollution in Europe

Cardiopulmonary impacts and benefits of mitigation and adaptation



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This White Paper has been developed by the EXHAUSTION consortium and reflects a selection of important findings and results from the project. The Paper includes key research and policy recommendations.

Contents

Summary of key policy recommendations

During the EXHAUSTION policy and stakeholder conference in November 2023 we developed key policy recommendations from the project (revised in January 2024):

1. Due to the interactive effects of air pollution and heat, policies reducing air pollution concentrations in Europe, such as the revised Ambient Air Quality Directive, will not only reduce the health effects of air pollution but also prevent death and disease from heat.

2. Even in the most optimistic emission scenarios, it is anticipated that the contribution from wildfires to air pollution will increase. There needs to be stronger wildfire management and prevention.

3. Policies and measures addressing the health risks from air pollution should be included in heat–health action plans developed across Europe.

4. Health should be a driver for climate change mitigation, as urgent cuts in greenhouse gas emissions will have immediate and long-standing health benefits. Climate change adaptation policies, strategies and measures are needed at the same time.

5. Air pollution and climate change policies should not be two separate policy areas but need to go hand in hand to capitalize on the synergistic effects and to harvest the health co-benefits.

6. The design of health-related climate change adaptation policies should be supported by strong scientific evidence and encourage evaluation studies on specific strategies and measures.

7. There is a diverse and uneven distribution of the socioeconomic impacts connected to the health effects of climate change among and within countries. This underlines the importance of addressing issues regarding climate justice, equity and fairness within Europe, which should be considered by policymakers.

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Bringing air pollution reduction policies and climate change mitigation and adaptation policies together is essential to reduce death and disease from air pollution and heat and protect people from their interactive effects.

Photo: Istockphoto/ Werawad Ruangjaroon

Heat and high levels of air pollution have an interactive effect on health, particularly for vulnerable people

- There is an increased risk of cardiovascular (CVD) and respiratory disease and death associated with heat exposure, with the strongest heat effect on respiratory diseases.
- An elevated risk for heat-related mortality and morbidity was shown for the older age groups, as well as for people living in densely populated or less green areas. In the south of Europe, the health effects of heat were stronger in socioeconomically deprived areas.
- In the warm season, high levels of air pollution ($PM_{2.5}$ and ozone) increase the heat-related risk for heart- and lung diseases in Europe (data from cities in 15 European countries). Again, the effect is strongest for respiratory diseases.
- Significantly higher health effects of heat together with high concentrations of air pollutants were observed, for example, in Portugal, Spain, the UK, Germany, and Switzerland, with effects being most prominent in the south of Europe. In contrast, inconsistent patterns were found for northern European countries, e.g., Norway and Sweden.
- Bringing air pollution and climate mitigation and adaptation policies together will enhance the health co-benefits and reduce heat-related mortality and morbidity.

The research has demonstrated a range of important new insights:

Environmental factors do not affect humans in isolation; instead, populations are exposed to a combination of environmental factors. Therefore, it is essential to investigate the interplay of these factors.

Reducing air pollution leads not only to an immediate improvement in health and prevention but also the heat effects on health will be lower – preventing deaths and diseases related to heat.

Our results not only confirm the health effects of heat but provide additional information on heat-related risks and on vulnerability factors in non-urban areas:

Climate change is interacting with individual-level and area-level characteristics, so that, for example, greater heat vulnerability is observed for the older age groups and in areas with high population density, high degree of urbanization, low green coverage, and high levels of $PM_{2.5}$.

Authors: Franziska Matthies-Wiesler, Alexandra Schneider, Susanne Breitner-Busch (Helmholtz Munich)

Key policy recommendations

The EU's Ambient Air Quality Directive and the updating of guidance for heat-health action plans at the European level, and their adaptation and implementation on a national level are policy instruments for which the research results are relevant. Generally, a comprehensive view on multi-exposures is essential.

- The role of air pollution on days with high temperatures or during heatwaves needs to be considered in the context of climate change adaptation, such as in heat-health action plans, especially addressing vulnerable groups and areas at risk.
- Potential co-exposure to air pollution (including air pollution from wildfires) should be considered in the updating of guidance for developing and implementing national, regional and local heat-health action plans, according to their specific context.
- Climate change mitigation strategies and measures that reduce emissions will, at the same time, address the interactive effects of high air pollution levels and heat as so-called health co-benefits.
- The established interactive effects of heat stress and air quality need to be reflected in the context of the EU Ambient Air Quality Directive. The alignment of new air pollution limit values with the latest WHO Air Quality Guidelines will significantly help mitigate and adapt to climate change.
- New knowledge on the health effects of high temperatures and heatwaves, interactions between temperature and air pollution and implications for specific vulnerable population groups needs to be integrated into the education and training of medical professionals.

Overall, there is a high potential for beneficial effects on health and prevention of diseases by reducing air pollution and in considering air pollution in heat health prevention and protection. Even if the relative risks of air temperature and air pollution for our health might be small compared to other individual or lifestyle risk factors, the entire population is affected; therefore, there is a high number of attributable cases.

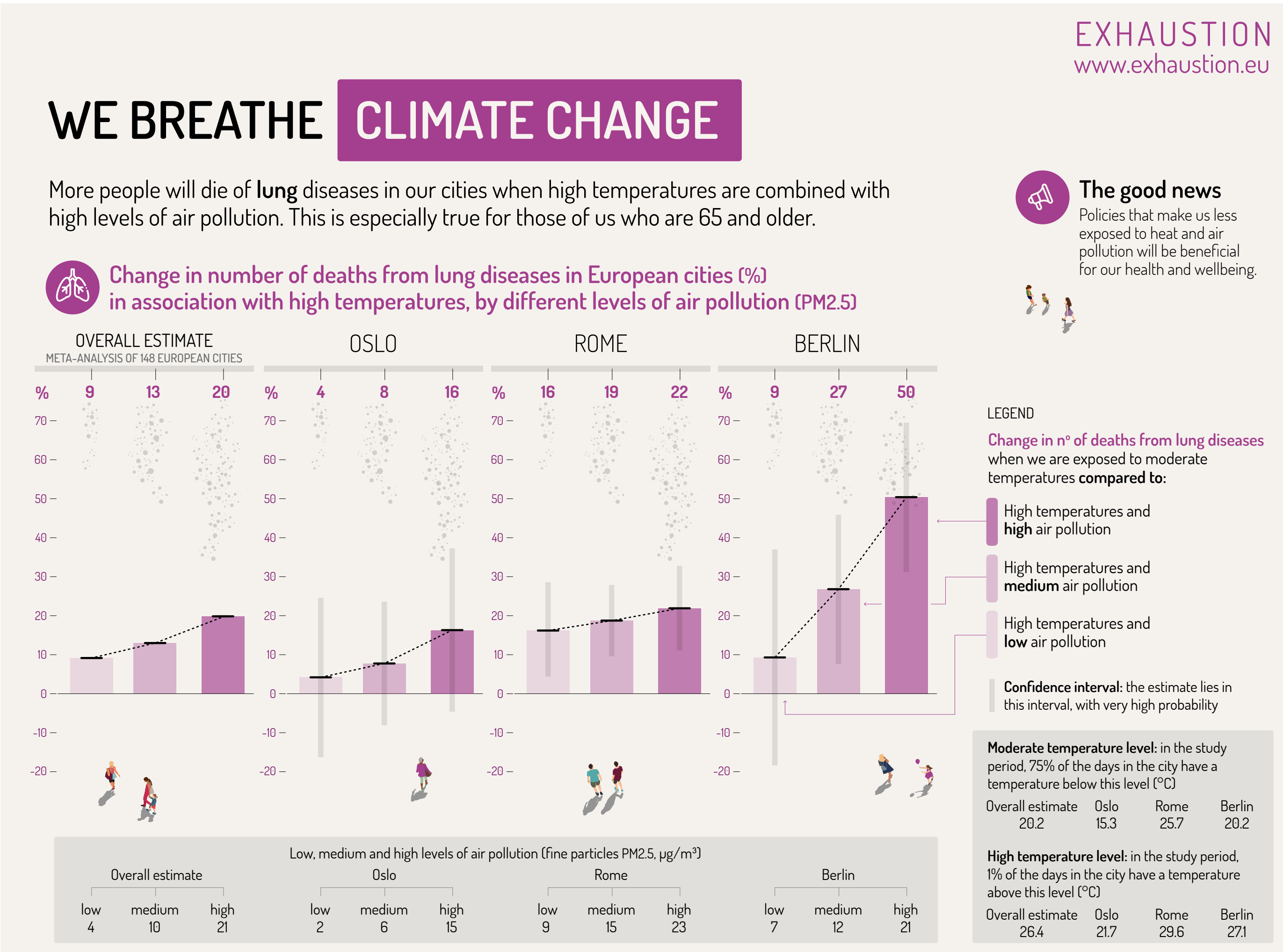

Figure 1: The visualisation shows the health impact of simultaneous exposure to high temperatures and particulate air pollution ($PM_{2.5}$). It explains the percent change in the number of deaths from lung diseases when the temperature increases from medium to high levels, given low, medium or high air pollution levels.

Key research recommendations

Based on the project results, some specific research gaps were identified that need to be addressed to inform further stakeholders and decision-makers as well as climate change mitigation and adaptation processes:

- Investigate the interplay of air temperature exposure with other environmental factors (e.g., green space or biodiversity) as well as with social factors ("environmental justice").
- Deepen insight into adaptation processes (behavioural and physiological).
- Describe the pathophysiological mechanisms for the impact of temperature on health.
- Examine the interplay of outdoor and indoor temperatures.
- Establish exposure-response functions for temperature and more detailed cause-specific cardiopulmonary mortality and hospital admissions.
- Assess changes over time in the exposure-response relationship and the role of adaptation and heat vulnerability factors.
- Investigate long-term health impacts of non-optimal temperatures (and their interplay with air pollution).

Policy makers, decision-makers and stakeholders identified the following opportunities and needs at the EXHAUSTION policy conference on 15 November 2023:

Air pollution reduction measures are a success story. The project research results show the importance of connecting the air and climate agenda. Especially in the European "heat hot-spots" (especially in cities), people suffer from the double climate penalty - heat and air pollution - and the most vulnerable populations suffer the most.

There are additional points for future study designs, projects and policy implications at the heart of adaptation strategies and other measures to reduce adverse environmental exposures, such as:

- Consideration of mental health effects
- Provision and coordination of research data
- Recommendations on monitoring of compliance and evaluation of measures
- Vulnerability is not a choice: equity and justice need to be addressed in policies
- Costs of inaction are higher than costs of action for all scenarios

Ljubljana, Slovenia.

Key takeaways

Overall, understanding the effects of heat, particularly in socioeconomic deprived and less green areas, and the interaction with air pollution is critical to support the development of effective and equitable public health policies at European, national, and local levels. Concrete implications for policy development include:

- Policies reducing air pollution concentrations in Europe, such as the EU's revised Ambient Air Quality Directive, will not only reduce the health effects of air pollution but also prevent death and disease from heat due to the interactive effects of air pollution and heat.
- The joint effects of air pollution and heat need to be considered in heat-health action plans as they are being developed across Europe.
  Combining air pollution and climate change policies is essential to avoid trade-offs and harvest health co-benefits.

Scientific methodology and research findings

The research in EXHAUSTION behind the findings presented above used a geographically very diverse database with spatially varying resolution; specifically, we:

- defined the methods to be applied in a rigorous and standardized way across all investigated urban, suburban, and rural locations to provide exposure--response functions and health effects estimates, including potential effect modifiers,
- established quantitative exposure-response functions for cardiopulmonary diseases in association with short- and long-term impacts of (extreme) air temperatures for European cities, small areas (e.g., municipalities, lower layer super output areas or administrative districts) or cohorts with individual participant data to estimate effects at the national level as well as in urban, suburban, and rural areas,
- assessed the interactive effects of high air temperature and air pollution, thereby providing insights into how the interplay of meteorology and air quality affects healthy living in urban and rural areas in Europe,
- assessed effects by susceptibility/risk factors such as having a pre-existing chronic disease, age and sex,
- identified epidemiological effect modifiers (e.g., urbanicity, population density, green areas, gross domestic product, unemployment rate, population above 65 years of age, type of landscape) that influence heat-related mortality and morbidity in urban and rural areas, respectively.

Publication date	First author	Last author	Title	Journal
10/10/2023	Massimo Stafoggia	Francesca de' Donato	Joint effect of heat and air pollution on mortality in 620 cities of 36 countries	Environment International
10/1/2023	Sofia Zafeiratou	Klea Katsouyanni	Assessing heat effects on respiratory mortality and location characteristics as modifiers of heat effects at a small area scale in Central-Northern Europe	Environmental Epidemiology
9/1/2023	Siqi Zhang	Alexandra Schneider	Assessment of short-term heat effects on cardiovascular mortality and vulnerability factors using small area data in Europe	Environment International
7/15/2023	Masna Rai	Alexandra Schneider	Temporal variation in the association between temperature and cause-specific mortality in 15 German cities	Environmental Research
4/1/2023	Pierre Masselot	Antonio Gasparrini	Excess mortality attributed to heat and cold: a health impact assessment study in 854 cities in Europe	The Lancet Planetary Health
4/1/2023	Masna Rai	Susanne Breitner	Heat-related cardiorespiratory mortality: Effect modification by air pollution across 482 cities from 24 countries	Environment International
12/16/2022	Masna Rai	Alexandra Schneider	Achievements and gaps in projection studies on the temperature-attributable health burden: Where should we be headed?	Frontiers in Epidemiology
7/6/2022	Siqi Zhang	Alexandra Schneider	Climate change and cardiovascular disease – the impact of heat and heat-health action plans	e-Journal of Cardiology Practice
6/10/2021	Sofia Zafeiratou	Klea Katsouyanni	A systematic review on the association between total and cardiopulmonary mortality/morbidity or cardiovascular risk factors with long-term exposure to increased or decreased ambient temperature	Science of the Total Environment
11/9/2020	Annette Peters	Alexandra Schneider	Cardiovascular risks of climate change	Nature Reviews Cardiology
3/26/2020	Siqi Zhang	Alexandra Schneider	Climate change and the projected burden of future health impacts–The Project EXHAUSTION	Public Health Forum

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820655.

The duration and magnitude of heatwaves are projected to increase in Europe under all emission scenarios, while the level of air pollutants will decrease under most emission scenarios.

In a climate with increasingly frequent and extended heatwaves, mitigation of ozone and particulate matter will benefit health

- Heatwaves are projected to increase faster in duration and in magnitude by mid-century than in the past, even under the Sustainability scenario (SSP1). Southern Europe is projected to experience the most intense heatwaves and to encounter the largest increases.
- A decrease in surface ozone concentrations of up to 20% is projected in 2050 compared to the levels in 2015, assuming Middle of the road and Sustainability scenarios. The least ambitious mitigation scenario leads to a slight increase of 3% by mid-century.
- Substantial increases are expected in the emission and pollution hotspots like the Po Valley in Italy, Ruhr industrial belt in Germany, the Benelux region (Belgium and the Netherlands) and over major cities under the Middle of the road and Regional rivalry scenarios.
- Surface $PM_{2.5}$ concentrations are projected to decrease across Europe, in particular over central and eastern Europe, under all the scenarios by up to 55%, however with a slower rate as compared to the near past (1981-2010).

Factory in the Netherlands
Photo: Istockphoto / AlbertPego

Authors: Ulas Im (AU), Mikhail Sofiev (FMI), Zhuyun Ye (AU), Risto Hänninen (FMI), Sourangsu Chowdhury (CICERO), Roxana Bojariu (ANM).

Research findings

The increase in heatwave duration and magnitude until mid-century are projected to be significantly higher compared to that in the past. The projected future trends are very heterogeneous across Europe, with the largest increase in trend over southern Europe and much smaller increases in northern and western Europe.

The majority of southern Europe will experience an increase of 5 to 11 days per decade in heatwave duration, which is 2 to 3 times larger than in the past.

If we take Italy as an example, even under the Sustainability scenario (SSP1), heatwave duration will increase by around 15 days per decade, which is substantially larger than the heatwave duration of 1.2 days per decade during 1981-2010.

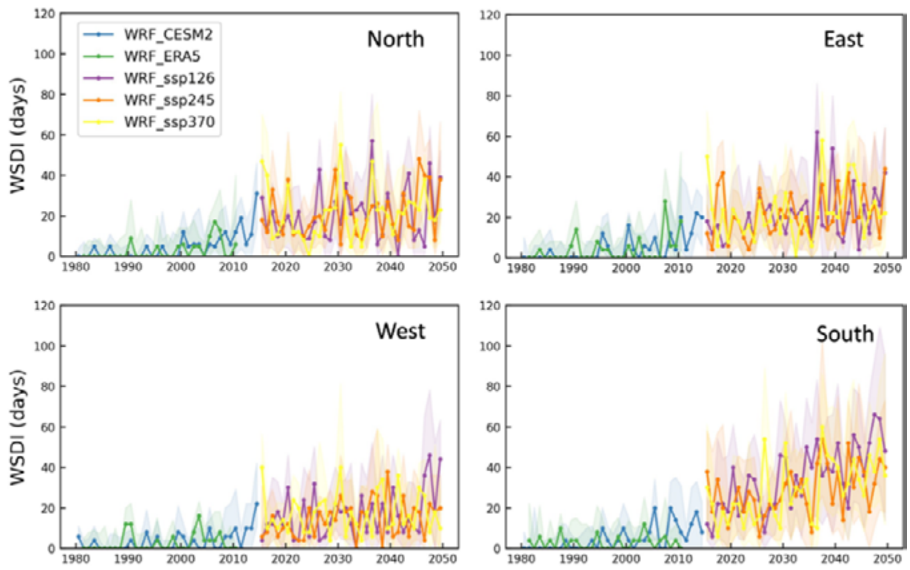

Figure 1: Heatwave duration and magnitude over different regions in Europe in near past (1990-2014) and between 2015 and 2050 under the Sustainability scenario (SSP1-2.6), Middle of the road scenario (SSP2-4.5) and Regional rivalry scenario (SSP3-7.0).

Mitigation scenarios

In EXHAUSTION, we have adopted the Shared Socioeconomic Pathways (SSP) used in the 6th Assessment Report (AR6) from the Intergovernmental Panel on Climate Change (IPCC). We have used SSP1, SSP2, and SSP3 scenarios, where SSP1 and SSP3 define various combinations of high or low socio-economic challenges to climate change adaptation and mitigation, while SSP2 describes medium challenges of both kinds and is intended to represent a future in which development trends are not extreme but rather follow middle-of-the-road pathways.

In this White Paper, we use the following terminology: A Sustainability scenario (SSP1), a Middle of the road scenario (SSP2) and a Regional rivalry scenario (SSP3), the first representing the scenario with the highest emission reductions. These are coupled with Representative Concentration Pathways: RCP 2.6, RCP 4.5, RCP 7.0, and the white paper also refers to SSP1-2.6, SSP2-4.5 and SSP3-7.0

Trends of ozone concentrations depend on a particular scenario and time period

The ten-years mean population-weighted surface ozone (O_3) concentration decreases by almost 14% from 2015-2025 to 2040-2049 in the Sustainability scenario.

It decreases by 2% in the Middle of the road scenario, and increases by 3% in the Regional rivalry scenario.

For air pollution ($PM_{2.5}$) the trends are more homogeneous:

The ten-years-mean population-weighted surface $PM_{2.5}$ concentrations decrease by 48% from 2015-2025 to 2040-2049 in the Sustainability scenario. It decreases by 27% in the Middle of the road scenario and only by 16% in the Regional rivalry scenario.

In the Sustainability scenario, air pollution ($PM_{2.5}$), concentrations decrease by about 10 microgram per cubic meter (10 μg/m³) over central and eastern Europe. Despite the decreases, however, relatively high concentrations remain.

Despite the decreases in air pollution ($PM_{2.5}$), it takes years to meet the WHO Air Quality Guidelines from 2021 (5 μg/m³). Averaged over continental Europe, the guideline is projected to be met after 2025 under the Sustainability scenario, to be met after 2040 under the Middle of the road scenario, and to be still challenging by mid-century under the Regional rivalry scenario.

Milano, Italy

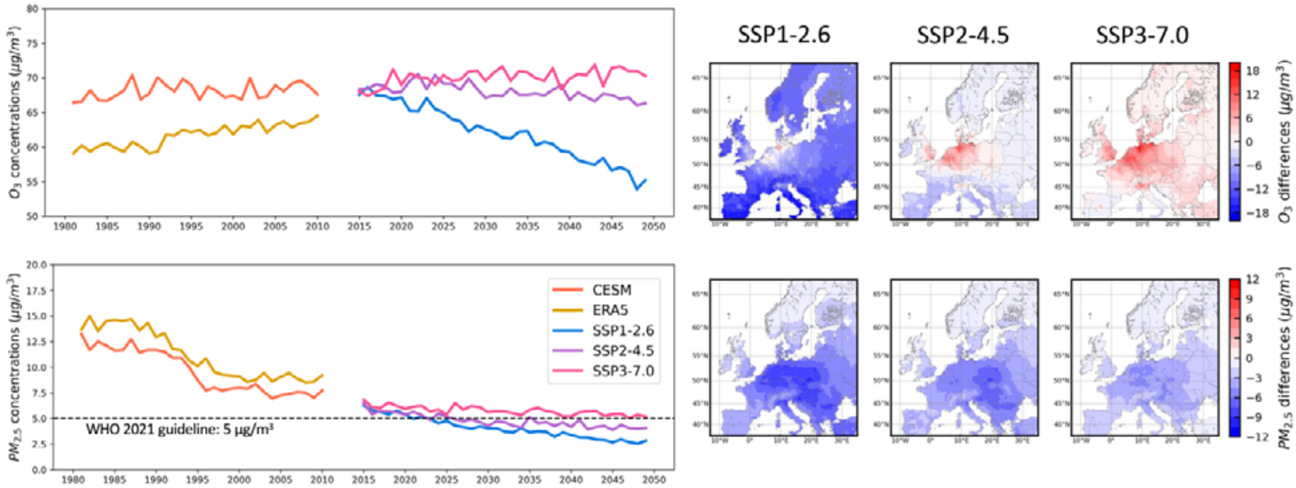

Figure 2: Timeseries of annual mean population-weighted land surface ozone (O_3) (upper panel) and air pollution ($PM_{2.5}$) (lower panel) concentrations over continental Europe (left panel), and the spatial distribution of changes in surface O_3 and $PM_{2.5}$ concentrations under the different emission scenarios.

Key policy recommendations

Due to the interactive effects of air pollution and heat documented by researchers in EXHAUSTION, policies reducing air pollution concentrations in Europe, such as the EU's revised Ambient Air Quality Directive, will not only reduce the health effects of air pollution but also prevent death and disease from heat.

Ambitious legislations to reduce the causes of climate change and promote clean air should be timely adopted to mitigate adverse health impacts.

Air pollution and climate change policies should not be two separate policy areas but need to go hand in hand to harvest the health co-benefits.

Key research recommendations

Further research is needed to improve climate and air pollution models with more accurate representation of physical and chemical governing processes of the Earth system to achieve more accurate predictions.

More research is needed to improve anthropogenic and natural emission estimates that better take into account European energy policies and population dynamics and that account for tailored adaptation to climate change.

Open data should be promoted in order to design strategies and evaluate impacts

Po valley, Italy

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820655.

Without strong adaptation measures the extended heatwaves and increased drought will strongly increase the appearance of fires and air pollution from fires in Europe already by the middle of the century.

Smoke concentrations from fires may double by the middle of the century

- Even under the most ambitious mitigation scenario, SSP1-2.6, the increase in future temperature and drought duration will induce more fires and expose people to larger amounts of harmful fine particulate matter ($PM_{2.5}$) originated from fires.
- In the European region, without strong climate--change mitigation, fires are expected to increase everywhere, with the result that air pollution concentrations from fire ($PM_{2.5}$) would double in most European regions by the mid-century, when compared to mean between 1980-2000.
- The largest absolute increase in air pollution ($PM_{2.5}$) from fires is expected to appear in southern and eastern Europe, special hotspots being for example Western Türkiye, Northern Italy, and Sicily.

Mitigation scenarios

In EXHAUSTION, we have adopted the Shared Socioeconomic Pathways (SSP) used in the 6th Assessment Report (AR6) from the Intergovernmental Panel on Climate Change (IPCC). We have used SSP1, SSP2, and SSP3 scenarios, where SSP1 and SSP3 define various combinations of high or low socio-economic challenges to climate change adaptation and mitigation, while SSP2 describes medium challenges of both kinds and is intended to represent a future in which development trends are not extreme but rather follow middle-of-the-road pathways.

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Ulas Im (AU), Mikhail Sofiev (FMI), Zhuyun Ye (AU), Risto Hänninen (FMI), Sourangsu Chowdhury (CICERO), Roxana Bojariu (ANM)

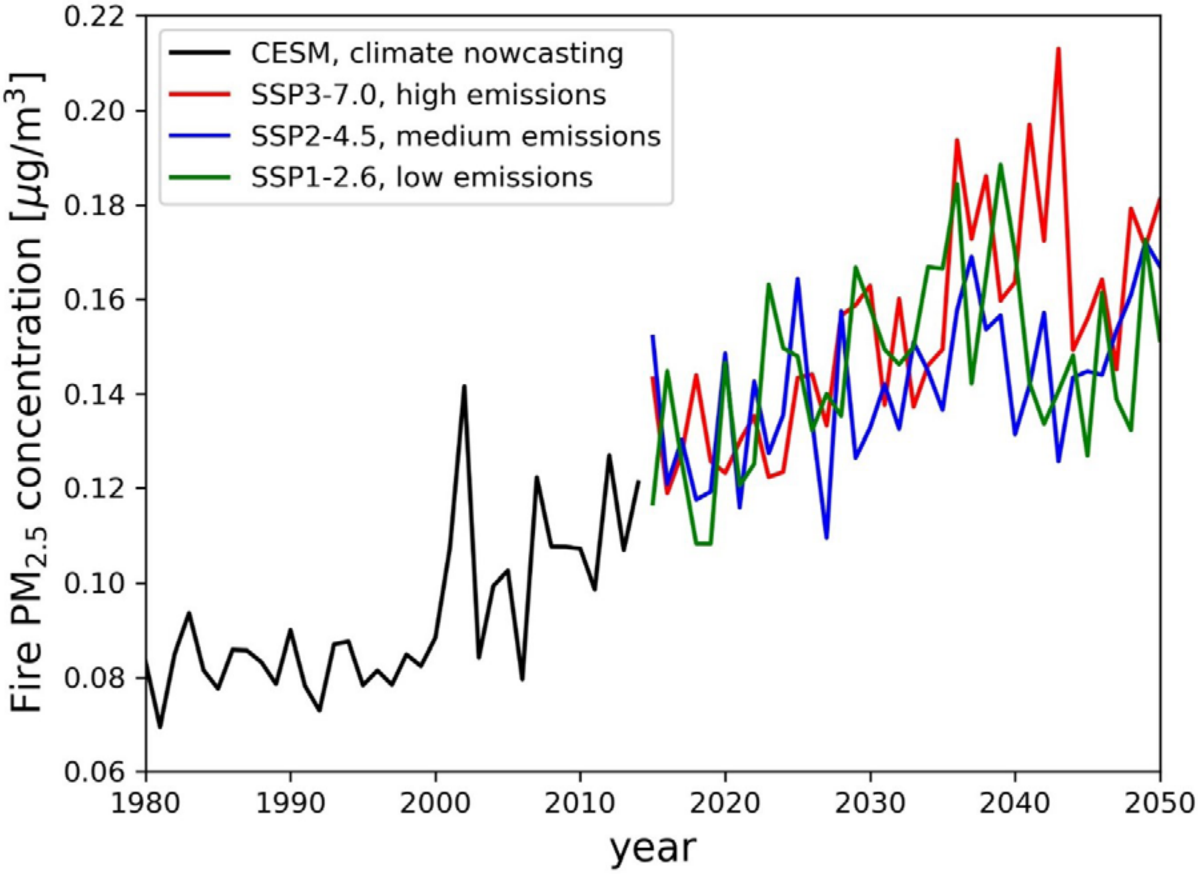

Figure 1: In all three future scenarios considered, the yearly mean concentration of air pollution ($PM_{2.5}$) originating from fires would increase similarly till middle of the century, when the concentrations are expected to be about twice compared to values between 1980 and 2000.

Research findings

Whereas the levels of air pollution from anthropogenic particulate matter are predicted to continue their decreasing trend, the fire smoke concentrations are predicted to rise till the mid-century.

The absolute levels will increase mostly in regions where the concentrations are already higher than average (Figure 2). The largest increases are in southern and eastern Europe. Special hotspots appear in Northern Italy (Po Valley), Sicily, western parts of Türkiye and the Moscow region, where the yearly mean fire originated $PM_{2.5}$ concentration may exceed the level of one microgram per cubic meter (1.0 μg/m³), especially in the Regional rivalry scenario (SSP3-7.0).

If considering the whole European region (Figure 2), the mean fire smoke concentration during 1980-2009 is approximately 0.09 μg/m³. By the mid-century, this value will be increased by 0.06 μg/m³ in the Sustainability and Middle of the road scenario, while the increase will be 0.08 μg/m³ in the Regional rivalry scenario.

While the anthropogenic air pollution ($PM_{2.5}$) levels keep decreasing, the fire smoke will become relatively more important source of particulate matter, causing increasing health risks.

Fires include:

- Agricultural fires
- Wildfires
- Fires on other vegetated lands

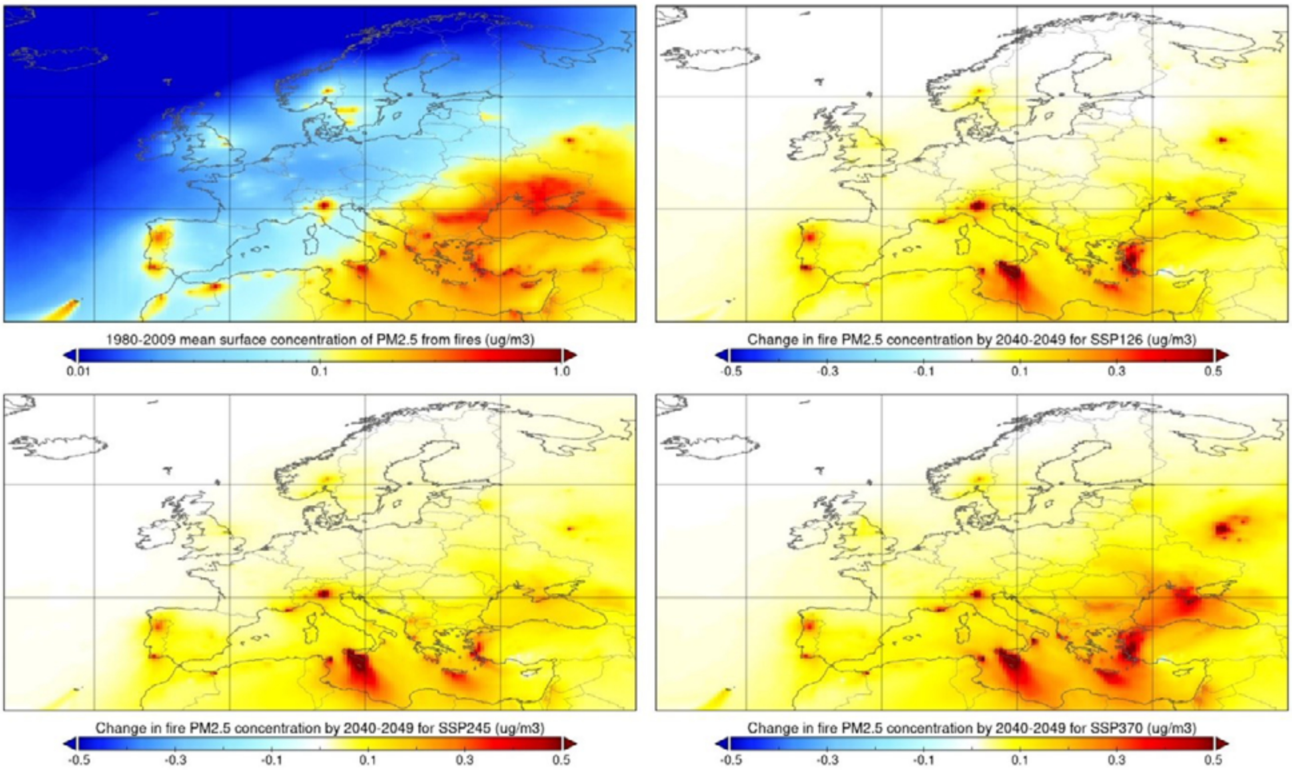

Figure 2: (top-left) Mean fire originated $PM_{2.5}$ during the historical period of 1980-2009 illustrating that especially South-East Europe is suffering from the fire smoke. Predicted changes at the middle of the century for three different scenarios: SSP1-2.6 (top-right), SSP2-4.5 (bottom-left), and SSP3-7.0 (bottom-right) showing that wildfire smoke concentrations are increased essentially everywhere in Europe, but the increases are typically largest at areas where the concentrations are already large.

Key policy recommendations

- Mitigation of fire smoke exposure refers to: (i) adequate forest management, (ii) introduction of appropriate legislation and (iii) ensuring its acceptance by the society, and (iv) introduction of fire-safe procedures in forestry and agriculture, both at legislative and behavioral levels.

- Strong adaptation measures are required to reduce the impact of fire smoke on health, in a context of increasing risk of wildfires, driven by rising temperatures and more severe droughts.

- More attention should be paid to particulate matter from fires since its contribution to health impacts will rise, compared with particulate matter from anthropogenic origin, whose levels are decreasing.

- Since fire smoke episodes are regularly combined with heatwaves, the combined health effects require even stronger healthcare preparedness in the future climate.

Key research recommendations

- Further research and development of fire forecasting models would increase their capacity to predict future fires and increase preparedness for future fire incidents.
- Including the effect of social and political changes in the fire forecasting models, in addition to weather parameters, would allow to increase their reliability.

Wildfire. Photo: Istock/milehightraveler

Publication date	First author	Last author	Title	Journal
20/09/2023	Rongbin Xu	Shanshan Li	Global population exposure to landscape fire air pollution from 2000 to 2019	Nature
28/03/2022	Yuanyu Xie	Roland Séférian	Tripling of western US particulate pollution from wildfires in a warming climate	PNAS
09/2021	Gongbo Chen	Shanshan Li	Mortality risk attributable to wildfire-related PM2.5 pollution: a global time series study in 749 locations	The Lancet Planetary Health
05/03/2021	Rosana Aquilera	Tarik Benmarhnia	Wildfire smoke impacts respiratory health more than fine particles from other sources: observational evidence from Southern California	Nature Communications

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820655.

Mitigation and adaptation policies are urgently needed to avoid hundreds of thousands of deaths due to heat and cold extremes across Europe.

Photo: Istockphoto/solidcolours

Temperature-related mortality will strongly increase in Europe over the 21st century, though most of the deaths can be avoided by mitigating greenhouse gas emissions and adaptation policies

The current climate change trajectory could result in an almost 50% increase in temperature-related mortality linked to climate change across European urban areas by the end of the century. It was estimated that the total burden could reach more than two million deaths over the century under the Regional rivalry scenario (SSP3), while it can be contained under 700,000 deaths under the Sustainability scenario (SSP1).

The increase in deaths is linked to a surge in heat-related deaths that will outnumber a mild decrease in cold-related deaths for all considered scenarios. This net increase is expected to be far higher under more extreme climate change pathways, whereby the death rates associated with heat could rise ninefold by the end of the century.

There are strong geographical differences across Europe, with the net effect of climate change on temperature-related deaths projected to be particularly strong along the Mediterranean and Adriatic coasts, as well as in eastern European countries such as Romania and Bulgaria.

Adaptation measures through urban planning interventions aiming at decreasing urban heat, for instance through the increase in green areas and the reduction of urban heat island effects, can play a role in attenuating the health impacts.

Prague in spring. Photo: Gunnell E. Sandanger

Authors: Pierre Masselot, Malcolm Mistry, Antonio Gasparrini (LSHTM)

Research findings

Researchers in EXHAUSTION estimate that climate change will result in a clear-cut increase in temperature-related deaths in Europe across all climate change and socio-economic scenarios, from the mildest to the strongest. The increase is linked to a shift of the temperature distribution towards hotter values, resulting in a dramatic surge in heat-related deaths, largely offsetting an expected decrease in cold-related deaths. Projections by the researchers indicate that this increase will happen on top of a concurrent increase in vulnerability linked to population ageing.

The impact of climate change on temperature-related deaths will be particularly exacerbated in the Mediterranean region, where cold-related mortality is already low, as well as in the more vulnerable eastern part of Europe. Results indicate that Northern countries such as the British Isles or Norway could be spared by this increase, although the trend reverses under the most extreme warming scenarios.

The potential role of adaptation policies

The comparison performed between various climate change scenarios suggests that mitigation is paramount to avoiding hundreds of thousands of temperature-related deaths. Adaptation policies that focus on reducing urban temperature and the urban heat island effect can play a role in reducing the mortality burden of climate change.

Further analyses show that increasing tree coverage by 30% across European urban areas could reduce summer mortality by almost 2%, while reducing urban heat island effects in cities could avoid several deaths each summer.

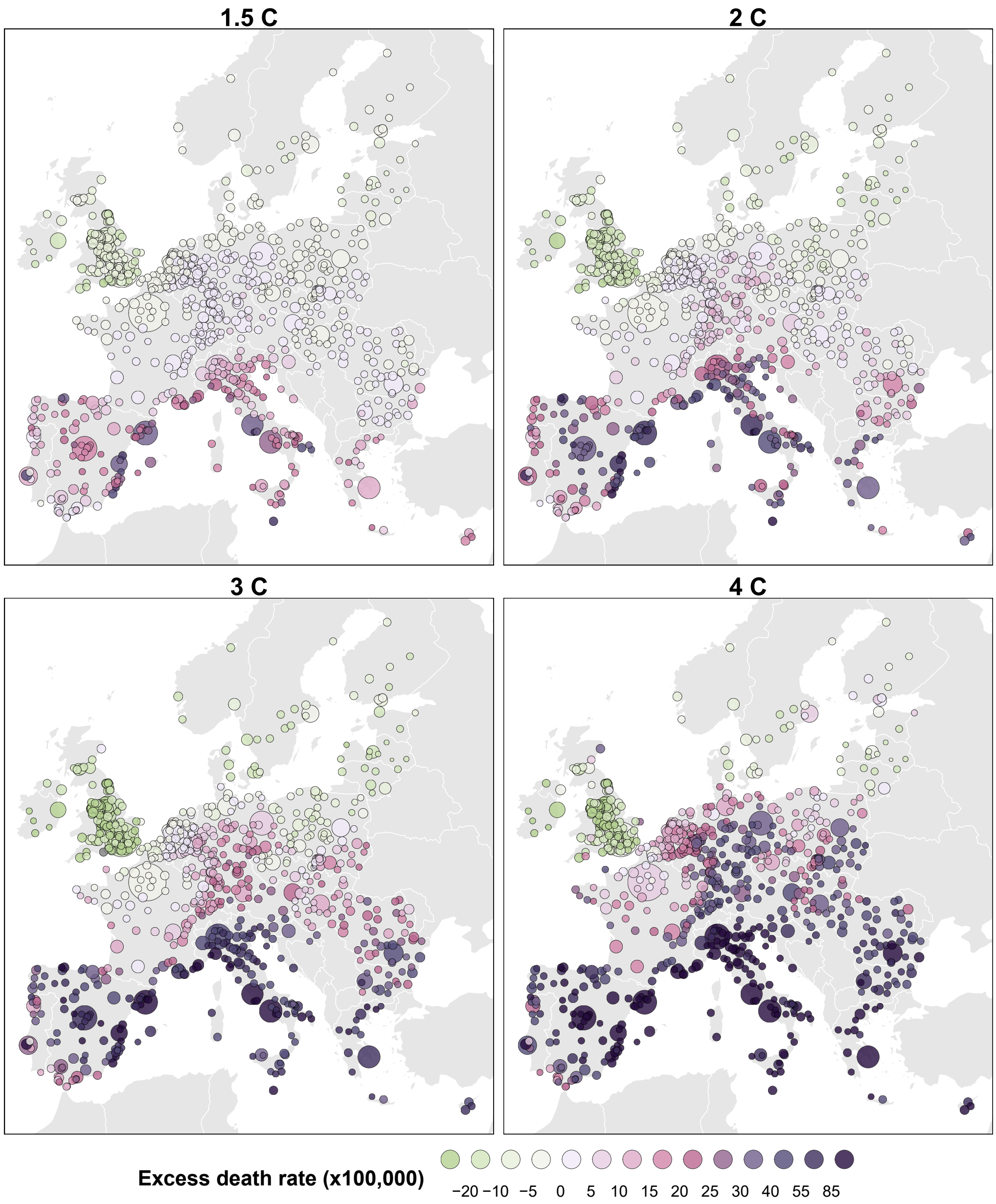

Figure 1: Excess deaths per 100,000 persons in 854 cities in Europe, under scenarios of increase in global mean temperature from 1.5°C to 4°C.

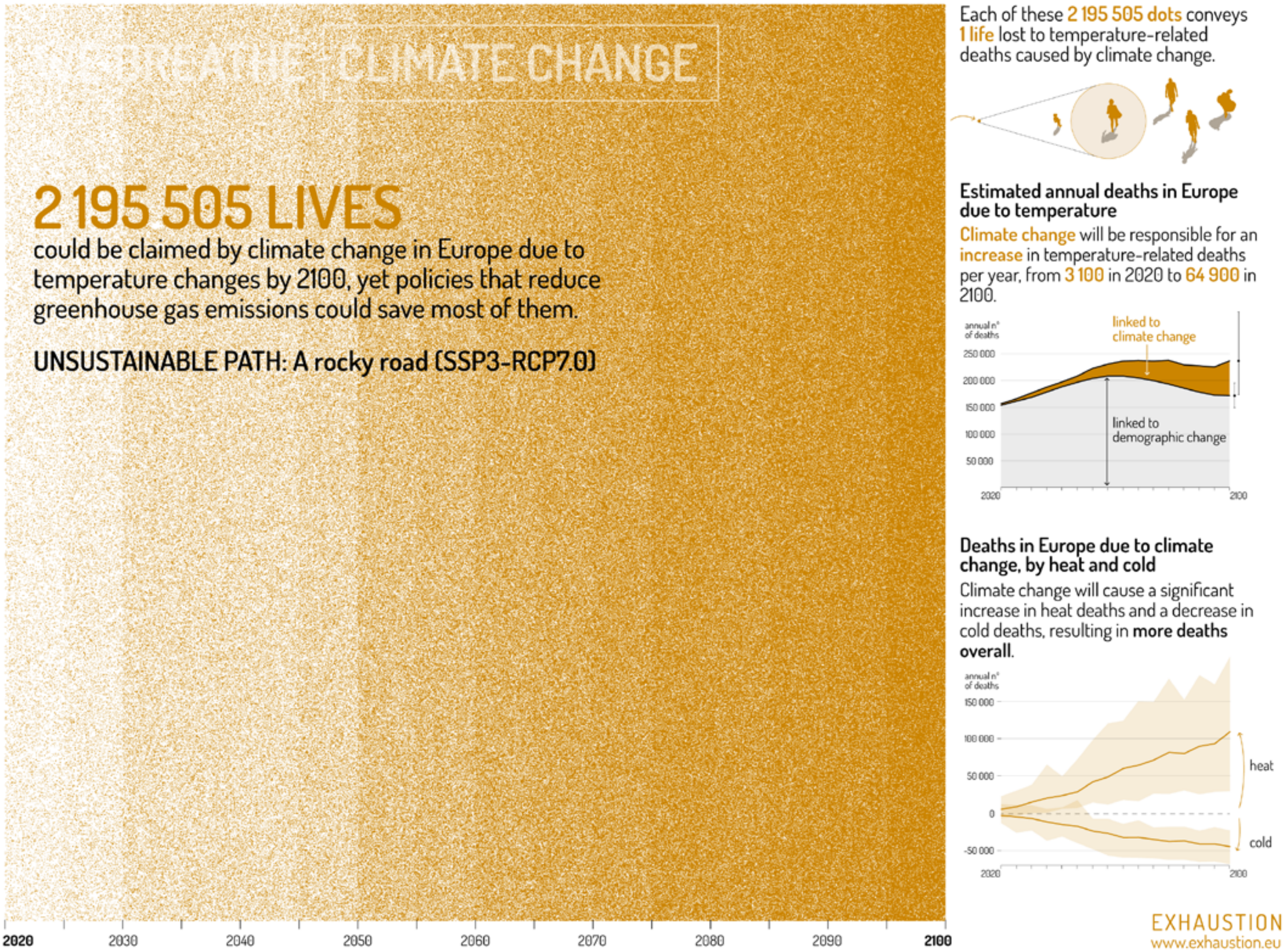

Figure 2: Data vizualisation by the EXHAUSTION project.

Case study:
Net effect of Climate Change in Italy

Among the 30 countries featured in the EXHAUSTION projections, Italy emerges as the country with the most dramatic climate change-related burden.

Mortality due to heat and cold extremes could increase by at least 3,000 annual deaths at a global warming level of 1.5°C above preindustrial levels and potentially up to 17,000 annual deaths if the 4°C mark is reached.

These numbers correspond to 18 additional deaths per 100,000 persons at 1.5°C and more than 120 additional deaths per 100,000 persons each year at 4°C. This increase is more than three times higher than the European average, and double the historical Italian toll of 100 deaths per 100,000 persons.

Key policy recommendations

- Mitigation policies are the key to reduce temperature-related mortality. Policies focusing on rapidly reducing greenhouse gas emissions should be prioritised. Each passing year increases the death toll of climate change.
- Prioritise the most affected areas. Identification of cities with the highest vulnerabilities, and working with local stakeholders to understand how to provide support to the local population.
- Urban planning. There is evidence that planting trees would cool cities, decrease air pollution levels, and provide shade for the local populations. This and other policies should be considered to adapt our cities to a more extreme climate.

Key research recommendations

- More research on the role of adaptation factors and policies. Vulnerability to heat and cold is very variable between locations, but little empirical evidence exists about the specific factors driving these differences in vulnerability.
- Rural population still represents around 40% of the European population and evidence is still limited on the association between temperature and mortality in rural areas.
- Understanding local vulnerabilities necessitates high-definition and standardised datasets on various local environmental, topological and socio-economic characteristics. Creating and facilitating the sharing of such resources is paramount to understanding how to protect the European population.

Publication date	**First author**	**Last author**	**Title**	**Journal**
16/03/2023	Pierre Masselot	Antonio Gasparrini	Excess mortality attributed to heat and cold: a health impact assessment study in 854 cities in Europe	The Lancet Planetary health
31/01/2023	Tamara Iungman	Mark Nieuwenhuijsen	Cooling cities through urban green infrastructure: a health impact assessment of European cities	The Lancet Planetary Health
17/11/2023	Wan Ting Katty Huang	Gabriele Manoli	Economic valuation of temperature-related mortality attributed to urban heat islands in European cities	Nature Communications

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820655.

The costs of climate change are high, and so would be the expected socio-economic benefits of effective adaptation and mitigation of climate change.

Effective adaptation and mitigation can reduce the socio-economic costs of climate change

- Heat stress decreases labour productivity and increases the costs of healthcare, even in countries not normally associated with high temperatures (UK and Norway), as indicated by our empirical analysis.
- In the coming decades, and especially for the most extreme heatwave years, the number of cardio-pulmonary disease (CPD) fatalities during hot summers is predicted to be thousands across the European countries analysed (EU27, EEA, west-Balkan, UK and Türkiye), leading to large welfare costs, when assessed by the OECD methodology for valuing statistical lives. Over the next decade, EU27 heat-related CPD fatalities are projected to increase up to 19,000 per year - a doubling of 1990 levels.
- In a broader, macroeconomic context, our further modelling shows that the associated health effects will lead to an increase in unemployment, which in turn affects international trade and a country's gross domestic product (GDP). These impacts are expected to vary across countries. Out of the three countries studied, Italy is, for example, projected to face the highest rise in unemployment; the UK is likely to encounter the most significant price increase; and Norway may suffer the largest GDP loss.

Research findings

Our research examines the socio-economic costs of climate-driven health effects. We analyze historical data to assess how temperature variations affect labour productivity and healthcare expenditures.

Incorporating these findings, we use microeconomic and macroeconomic models to understand the broader socio-economic impacts, highlighting the urgent need to address these environmental challenges (see Figure 1).

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The EXHAUSTION Project estimates the change in cardiopulmonary mortality and morbidity due to extreme heat and air pollution (including from wildfires) under selected climate scenarios, calculates the associated costs, and identifies effective strategies for minimizing adverse impacts.

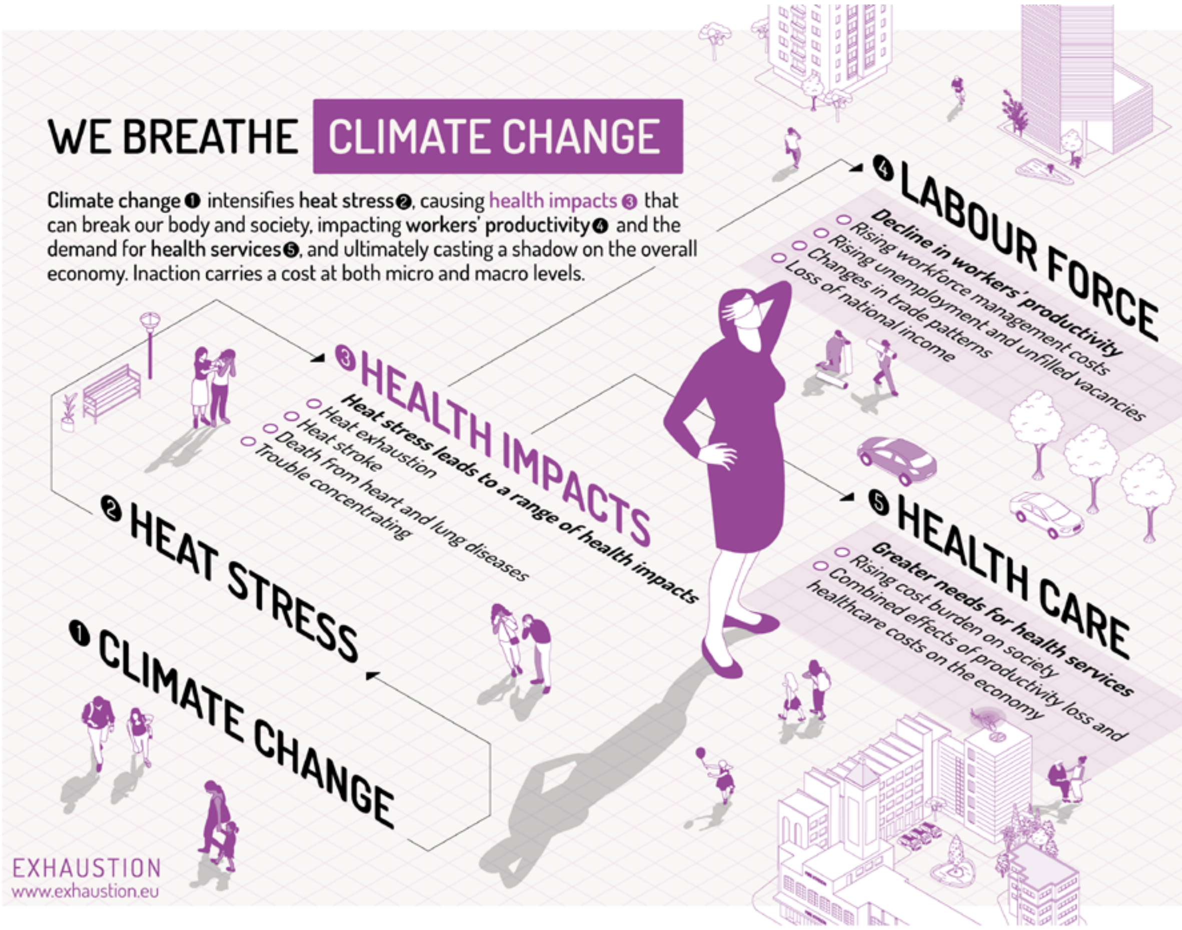

Figure 1: The cost of inaction. Climate change intensifies heat stress, causing health impacts that can break our body and society, impacting workers' productivity and the demand for health services, and ultimately casting a shadow on the overall economy. Inaction carries a cost at both micro and macro levels.

Empirical analysis of the economic consequences of high temperatures

(1) Impact of heat stress on labour productivity in the UK

One part of the empirical analysis uses UK (esp. England & Wales) household panel survey data about individuals' health status and socio-economic characteristics to assess the impact of temperature on labour productivity. In a high-income country with temperate climate, heat-related productivity losses may mostly occur through reduced performance at work, which is hard to measure and may thus get under the radar. We use self-reports of recent under-performance at work related to physical health ('presenteeism' – working while sick).

Our findings show that, in England and Wales between 2010 and 2019, exposure to heat is associated with a greater probability of reporting presenteeism. Each additional day of heat exposure, variously adjusted for its severity, was associated with up to 1.5- and 2.5-times higher incidence of presenteeism in a 4-weeks retrospective period. However, this effect varied across groups. It is more precisely estimated for women, and entirely concentrated in jobs with low physical demands.

(2) Health care costs attributable to heart- and lung diseases in Norway

We also conducted an empirical study in Norway to estimate the direct health care costs from heart- and lung disease (also called cardiopulmonary disease - CPD) using data from the Norwegian Patient Registry (37 000 participants) and assess how ambient air temperature exposure impacts these costs. The association of sociodemographic factors, such as sex, age, education, and income were also assessed.

Our findings indicate that as temperature changes, health care costs attributable to heart and lung diseases also change, but not in a simple, straight-line pattern. We also find that cold temperatures contribute to healthcare costs in Norway. Moreover, we see that there are increased costs for heart and lung diseases associated with the elderly and female participants, thus indicating that healthcare policies need to take these critical vulnerability factors into account.

Modelling heat-related deaths and associated welfare costs

Our modelling shows the highest numbers of heat-related heart- and lung fatalities will occur in Italy, followed by Türkiye, Spain, Romania, Greece and Hungary. We expect annual incidence within the next 25 years to exceed 25 per 100,000 persons in about 25 regions of the Balkans and Hungary (see Figure 2). The EU27 annual average total will more than double from 8,700 heat-related premature CPD fatalities in 1990 to 19,000 by mid-century – peaking up to about 25,000 when considering the hottest decadal heat-wave years across regions.

For the hottest years, EU27 costs are found to triple relative to present annual averages (2015-22), while they will quadruple for west-Balkan and Türkiye (see Table 1). This relies on the OECD methodology for valuing statistical lives. Average annual costs during 2015-22 to EU27 at €25.6-27 billion from heat-related Cardio Pulmonary Disease fatalities are well above the European Environment Agency's estimate of about €16 billion covering all extreme weather damage costs for the same period. Measured against GDP there will be large variations, with average annual costs to EU27 at 0,6%, while most west-Balkan countries will exceed 1%.

However, due to the interactive effects of heat and air pollution (see White paper chapter 1), fatalities due to heart and lung diseases and associated costs can be reduced by aiming for adaptation measures that reduce particulate air pollution ($PM_{2.5}$) to levels recommended by the WHO Air Quality Guidelines. The largest reductions, up to 50%, would occur in west-Balkan countries, while the average annual reduction in Balkan and Mediterranean countries, including Türkiye, could be 30%. With today's levels of air pollution maintained, the number of CPD fatalities over the next 25 years would be about 45% higher (about 150,000 cases) than with an abatement strategy for adaptation via air pollution abatement.

Modelling macroeconomic effects

The microeconomic approach used to assess the direct and immediate costs of health effects due to climate change in all European countries is based on the more immediate, effects, meaning that possible further repercussions on the economy ('market effects') are disregarded. To address consequences of these market effects, we estimate the impacts of health effects on the supply of labour and the demand for health services in UK, Italy, and Norway.

These have been integrated in a global macroeconomic model, which describes how economic agents adapt to these changes, resulting in ripple effects across the markets throughout the entire economy, shedding light on a more comprehensive perspective of health-related costs. The socioeconomic impacts of health effects due to climate change are complicated and differ by country (see Figure 3):

- The declined labour productivity will lead to a substantial increase in unemployment and a reduction in job vacancies across all three represented countries. Out of the three countries studies, the UK appears to be the most affected in this regard. Additionally, Italy's significant heat -related productivity loss will greatly increase the labour costs and reduce total production in the country.

- Climate change is expected to reduce GDP for all countries, with Italy experiencing a more modest GDP decline due to increased trade and consumption goods prices. By contrast, Norway and the UK will face more significant declines in GDP, primarily driven by the lowered consumption and augmented savings.

- The trade effects play important roles on the heterogeneous effects on GDP. The trade balance is expected to increase sharply in Italy, primarily attributed to the reduction in the price of imported foreign goods and a rise in the prices of domestic goods. Conversely, in Norway and the UK, the trade balance is projected to decline, owing to higher domestic prices and a comparative disadvantage in domestic products competing with foreign products.

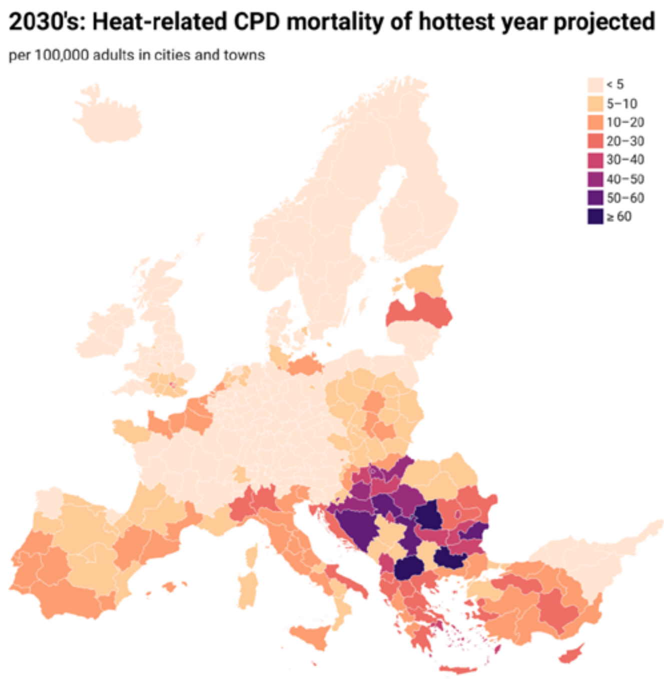

Figure 2: Heatwave scenario 2030s (specific year varies by region): Heat-related CPD deaths per 100,000 adults in cities and towns of single hottest year during a 10-year period projected in the 'Middle of the road'-scenario (SSP2)

Table 1: Annual welfare economic costs of heat-related CPD fatalities at country level (M€)

Year	2015-22	2030-34	2045-49	Max 2030s*	Max 2040s*
Country					
Cyprus (EU)	315	409	483	484	667
Greece (EU)	1,788	2,825	3,723	4,145	4,887
Italy (EU)	10,126	14,243	14,725	17,888	21,563
Malta (EU)	115	156	197	208	265
Portugal (EU)	253	299	435	1,072	1,277
Spain (EU)	2,736	3,413	3,978	5,936	5,782
Türkiye	3,870	7,422	10,980	11,145	16,206
Albania	244	442	492	527	683
Bosnia#	248	488	518	804	1,165
Bulgaria (EU)	912	1,276	1,626	2.004	2,527
Croatia (EU)	565	874	932	1,145	1,577
Kosovo#	16	30	33	50	63
Montenegro	20	46	50	63	79
N Macedonia	120	281	390	501	499
Romania (EU)	2,148	3,715	4,304	5,683	7,150
Serbia	742	1,566	1,608	2,396	3,097
Austria (EU)	401	662	712	922	1,162
Czechia (EU)	191	384	464	703	819
Hungary (EU)	930	1,831	2,077	3,246	3,843
Lithuania (EU)	29	42	86	112	145
Poland (EU)	1,032	2,320	3,259	4,968	5,710
Slovakia (EU)	117	229	275	421	452
Slovenia (EU)	41	74	75	124	145
Belgium (EU)	217	425	420	845	746
France (EU)	1,259	2,160	1,882	4,739	4,563
Germany (EU)	1,671	3,084	3,942	5,678	7,334
Liechtenstein	0	<1	<1	<1	<1
Luxembourg (EU)	2	4	4	7	8
Netherlands (EU)	906	1,832	2,505	3,490	4,524
Switzerland	350	499	534	812	998
Denmark (EU)	61	158	450	664	1,211
Estonia (EU)	52	63	115	184	248
Finland (EU)	76	49	192	163	426
Iceland	0	0	0	0	0
Ireland (EU)	0	10	0	99	4
Latvia (EU)	163	231	402	740	793
Norway	2	13	110	77	314
Sweden (EU)	96	184	484	745	1,187
UK	1,717	3,494	2,391	14,419	9,635
EU27 sum	25,639	40,078	46,813	65,269	77,439
EU27 same VSL	27,152	37,268	40,979	60,643	67,373
All countries, sum	**33,533**	**55,235**	**64,852**	**97,209**	**111,757**

#Imputed CDD

*Sum of the maximum decadal heat spell costs of all individual NUTS2 regions, notwithstanding specific year

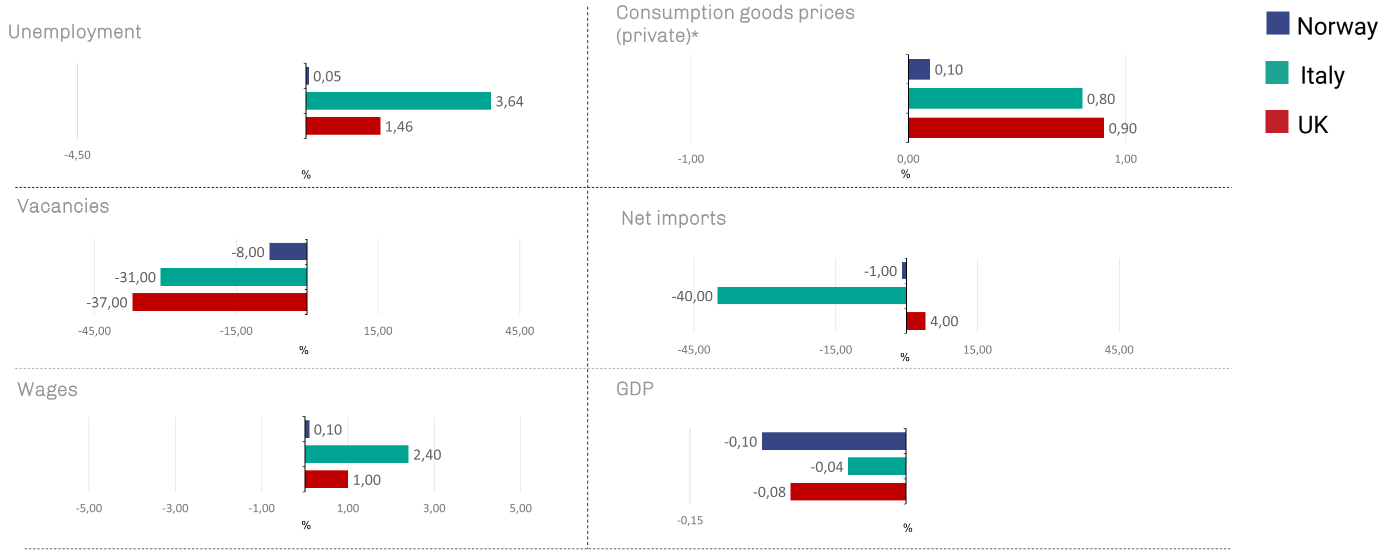

Figure 3: Projected economic impacts (%) by the year 2050 under the Regional Rivalry scenario, SSP3.

Key policy recommendations

- Due to the interactive effects of heat and air pollution ($PM_{2.5}$) as estimated for major cities in the above countries, a suitable measure for adaptation is to target reductions in such air pollution, and the analysis estimates the socio-economic cost savings resulting from the associated reductions in summer mortality for heart- and lung diseases, which amount to 30% for Mediterranean and Balkan countries.

- Emphasizing a macroeconomic approach: A systematic macroeconomic approach is highly recommended when evaluating the broad socio-economic impacts of climate change, with particular attention to the health effects.

- Highlighting differences in impact across countries: The study shows diverse and uneven socio-economic impacts of health effects due to climate change among targeted countries. This highlights potential distributional effects within Europe and the necessity of tailored policy measures that recognize the unique challenges faced by each country to achieve efficiency and equity.

Worker in construction site a hot day in central Athens, Greece. Photo: Istockphoto/Alexandros Michailidis

Key research recommendations

More tailored surveys are needed to better estimate the effects of heat stress on the labour force/workforce.

- Heatwaves are sparse in time and space: thus, population studies require a larger sample of affected individuals, combined with strategies for fast-rollout of data collection.
- Short-term individual output is hard to measure in high-income labour markets. Self-reports are useful but must provide simple quantifiable information to estimate losses. These can be complemented with statistics on daily and hourly absenteeism.
- Research should consider more fully the role of potential physiological factors affecting thermoregulation; individual habits and investments; buildings and the natural environment in the community (green spaces).
- Ideally, there should be linkable data on local climate, infrastructure and policies.

Long-term solutions include occupational heat stress surveillance, which would require, e.g.:

- Routine surveys of firms and workers during/immediately after a heat spell.
- Ad hoc surveys in vulnerable occupations (for example food delivery services and construction workplaces)
- The inclusion of evidence-based legislation and guidelines on compensation, days off, breaks, cooling, in cooperation with relevant actors (trade unions, occupational health workers etc.).

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Partners

ASL ROMA 1 (D EP Lazio), Aarhus University (AU), CICERO Center for International Climate Research, DRAXIS, Finnish Meteorological Institute (FMI), Helmholtz Munich (HMGU), InfoDesignLab (IDL), London School of Hygiene & Tropical Medicine (LSHTM), Luxembourg Institute of Socio-Economic Research (LISER), Meteo Romania (ANM), Norwegian Institute of Public Health (NIPH), Karolinska Institutet (KI), University of Athens (NKUA), University of Oslo (UiO), University of Porto (UPORTO)