RICARDO
Member of WSP

ECONOMIC IMPACTS OF O3 EXPOSURE

Final Report

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1. INTRODUCTION

1.1 STUDY OVERVIEW

Air quality is an important social, economic and environmental driver within the EU and globally. Exposure to poor air quality is attributed to detrimental human health conditions, environmental degradation and associated economic costs for individuals and public services. This study assesses the health and environmental impacts specific to exposure to O_3 across the EU and selected Member States using best available data from 2022. The study further qualitatively explores the role of methane (CH_4) in the formation of O_3, drawing on existing academic literature to understand the extent to which methane mitigation could lead to a reduction in O_3 concentrations.

Exposure to air pollutants lead to varying types and magnitude of health and environmental impact due to their distinct chemical properties, sources, and modes of interaction with biological and environmental systems. As understanding of these impacts and interactions improves, international, EU, and national legislation have targeted reductions of air pollutant emissions and air quality concentrations through a series of legislative measures. Notable EU legislation has included the National Emission reduction Commitments Directive[1] focused on reducing air emissions below levels deemed harmful to human health and ecosystems through setting reduction commitments for key pollutants (nitrogen oxides - NO_x, non-methane volatile organic compound - NMVOC, fine particulate matter - $PM_{2.5}$, sulphur dioxide - SO_2, ammonia - NH_3). The Ambient Air Quality Directive (revised in 2024)[2] has established concentration limit values and a harmonised EU air quality management system. Policies focused on CH_4 emissions have typically been included within broader frameworks to address greenhouse gases (GHG), but the 2024 'Methane Regulation[3]' sets requirements for operators to measure, report, and verify methane emissions for fuels.

This study analyses the formation of O_3 across the EU in 2022, reviewing geographic locations where concentrations are most (and least) significant. O_3 concentration target values are included within the AAQD, and more stringent guidelines are set by the World Health Organisation (WHO)[4]. However, O_3 concentrations targets have not been met in many areas within the EU. O_3 is not directly emitted, but is a secondary pollutant formed by complex photochemical reactions. As such, reducing O_3 concentrations to meet these targets requires nuanced policies and measures, including targeting multiple pollutants contributing to its formation, rather than a solitary source. Pollutants which contribute, to varying degrees, to the formation of O_3 include NOx, VOCs, and carbon monoxide (CO). Another key pollutant is methane (CH_4), which is emitted primarily through the agricultural sector and livestock production in the EU.

The relationship between health and environment and exposure to O_3 concentrations is well documented across academic literature and policy assessments, and policymakers have increasingly focused on mitigating these impacts. There is a growing body of evidence detailing the relationship between O_3 and respiratory morbidity and mortality[5] and damage to plants and trees leading to substantial losses in agricultural crop yield[6][7][8]. The European Environment Agency (EEA)[9] has also explored the impacts to both health and the environment resulting from exposure to O_3, finding, most notably, that 94% of the EU's urban population exposed to harmful levels and that remaining within WHO's Air Quality Guideline values could potentially

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1 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2016.344.01.0001.01.ENG&toc=OJ:L:2016:344:TOC

2 https://eur-lex.europa.eu/eli/dir/2024/2881/oj/eng

3 https://eur-lex.europa.eu/eli/reg/2024/1787/oj/eng

4 https://www.who.int/publications/i/item/9789240034228

5 https://environment.ec.europa.eu/topics/air/clean-air-outlook_en

6 Mills, G., Hayes, F., Simpson, D., Emberson, L., Norris, D., Harmens, H., Büker, P., Evidence of widespread effects of ozone on crops and (semi-)natural vegetation in Europe (1990-2006) in relation to AOT40- and flux-based risk maps. Glob. Change Biol. 17, 592–613, 2011.

7 Tai, Sadiq, Pang, Yung, Feng, 2021, Impacts of Surface Ozone Pollution on Global Crop Yields: Comparing Different Ozone Exposure Metrics and Incorporating Co-effects of CO2 https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2021.534616/full

8 Emberson et al, 2018, Ozone effects on crops and consideration in crop models, https://www.sciencedirect.com/science/article/pii/S1161030118301606

9 EEA, 2025, Methane, climate change and air quality in Europe: exploring the connections, Methane, climate change and air quality in Europe: exploring the connections | Publications | European Environment Agency (EEA)

prevent 70,000 premature deaths annually in the EU. Based on 2022 O_3 concentrations levels, a health and environmental assessment has determined the associated impacts.

1.2 SCOPE

The study has evaluated the impact of O_3 concentrations modelled by the Chemical Transport Model (CTM) within the European Monitoring and Evaluation Programme (EMEP) in 2022. The most recent CH_4 emission data were download from the European Environment Agency (EEA)[10] and are those reported by Member States in 2025 for the years 1990 to 2023. Air quality emission and concentration data has been collected for the EU-27 and selected Member States (Denmark; France; Germany; Hungary; Italy; Spain).

The assessment of the economic impacts resulting from exposure to O_3 concentrations within the EU27 and the selected Member States has focused on:

- **Health** impacts in terms of mortality and morbidity (respiratory).
- **Environmental** impacts including crop (wheat) production and forest biomass.
- Monetised **economic valuations** (EUR) of the impact upon health and the environment.

[10] https://www.eea.europa.eu/en/analysis/maps-and-charts/greenhouse-gases-viewer-data-viewers?activeTab=8a280073-bf94-4717-b3e2-1374b57ca99d

2. THE ROLE OF METHANE IN O_3 FORMATION

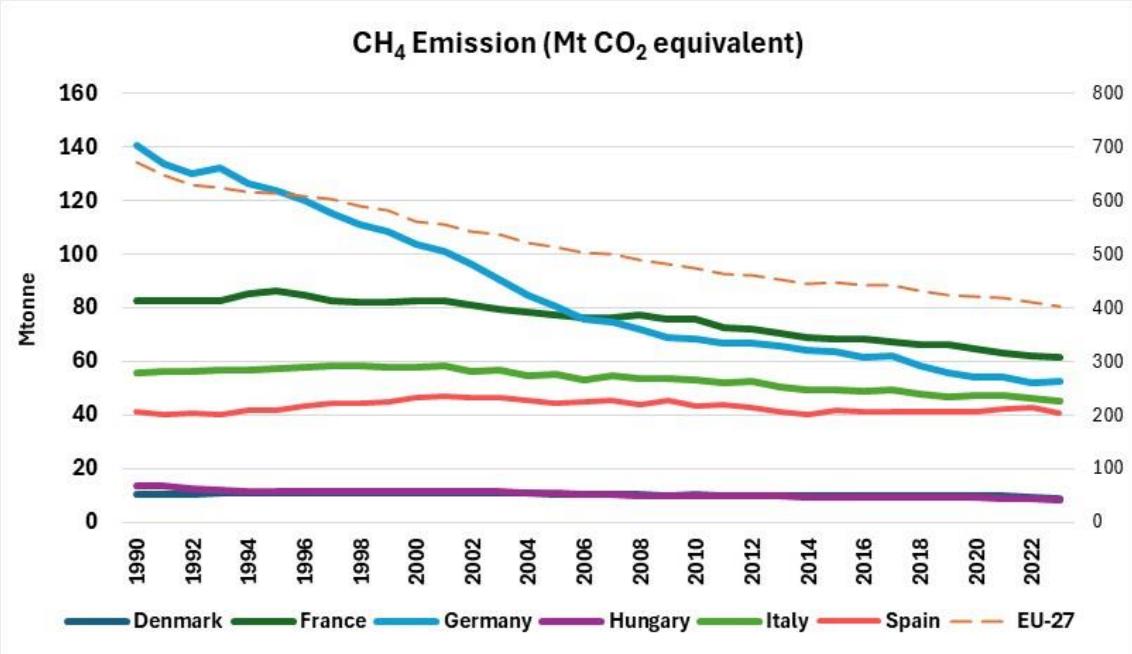
CH_4 is a short-lived greenhouse gas (GHG) with an atmospheric lifetime of about 12 years. Owing to its significant contribution to global warming and climate change, it is classified as a short-lived climate forcer. However, its role extends beyond climate forcing to include significant contributions to ozone (O_3) formation.

Whilst not currently classified as an air pollutant, previous studies have demonstrated and estimated the air quality improvements that could result from reducing CH_4 emissions (e.g. UNEP [2022][11], Acquah et al [2025][12], Butler [2024][13], Bessagnet [2024][14]).

2.1 METHANE EMISSIONS IN THE EU

Current EU policies have helped to reduce CH_4 emissions, as reported by EU27 Member State[15], by approximately 39% since 1990. However, agriculture remains the dominant source (57%), followed by waste (23%) and energy supply (11%).

Figure 2-1 Total net emissions of CH4 (in Mtonnes of CO2 equivalent)



Note: Member State's emissions are shown on the primary axis on the left. CH_4 emissions for the EU-27 as a whole are shown as a secondary axis on the right.

[11] Global Methane Assessment 2030: Baseline Report | UNEP - UN Environment Programme
[12] 10.5194/acp-25-13665-2025
[13] UNECE PDF
[14] 10.2760/376659
[15] https://www.eea.europa.eu/en/analysis/maps-and-charts/greenhouse-gases-viewer-data-viewers?activeTab=8a280073-bf94-4717-b3e2-1374b57ca99d

Figure 2-2 Total net emissions of CH_4 per capita (in tonne of CO_2 equivalent)[16]

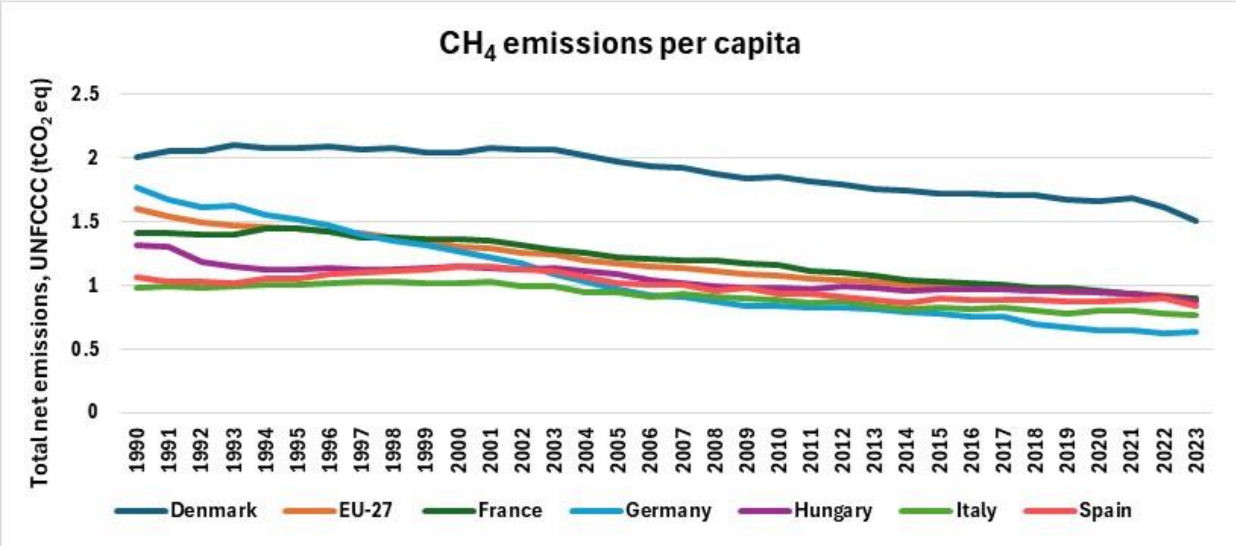
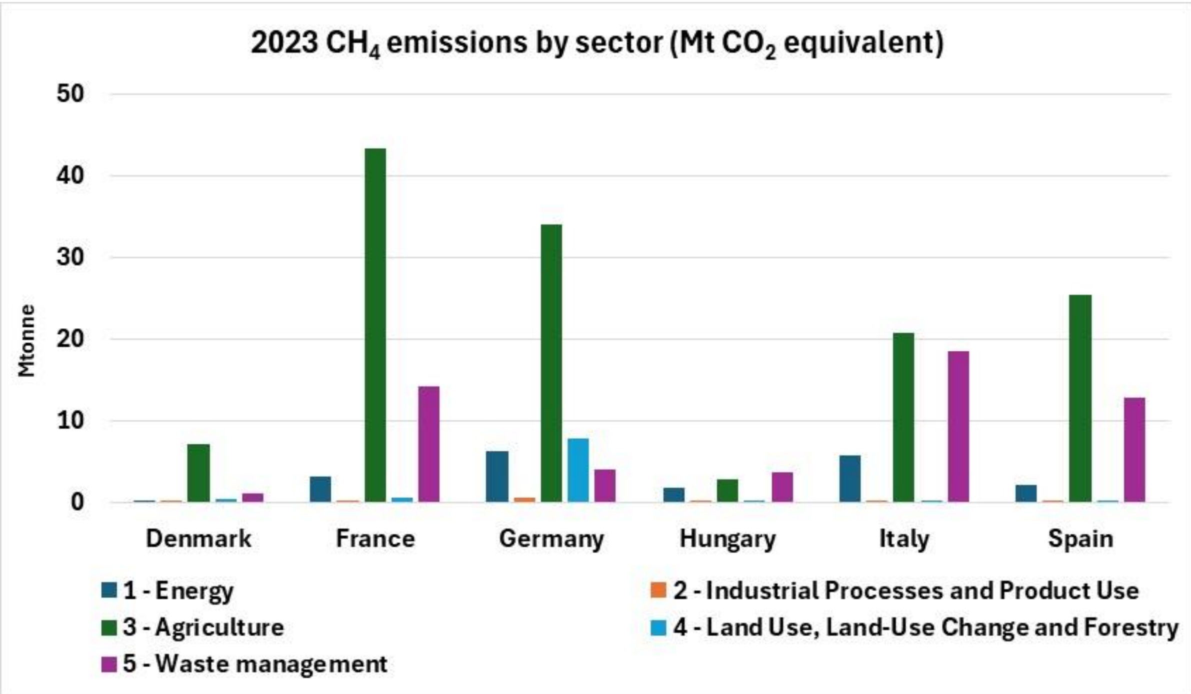


Figure 2-3 Sectoral CH_4 Emissions for 2023 (in Mtonne CO_2 equivalent)[17]



2.2 CURRENT LEGISLATIVE LANDSCAPE

The trend in reduction in CH_4 has been driven by international, EU and national policies targeting GHG emissions, including the implementation of international frameworks such as the *Kyoto Protocol*[18], *Paris Agreement*[19], and EU legislation (for example *Regulation (EU) 2018/1999 on the Governance of the Energy*

[16] https://www.eea.europa.eu/en/analysis/maps-and-charts/greenhouse-gases-viewer-data-viewers?activeTab=8a280073-bf94-4717-b3e2-1374b57ca99d

[17] https://www.eea.europa.eu/en/analysis/maps-and-charts/greenhouse-gases-viewer-data-viewers?activeTab=8a280073-bf94-4717-b3e2-1374b57ca99d

[18] https://unfccc.int/process-and-meetings/the-kyoto-protocol

[19] The Paris Agreement | UNFCCC

Union and Climate Action[20], *Regulation (EU) 2024/1787*[21]) which helped establish monitoring, reporting and verification of national inventories for CH_4 (and other GHG gases). The *2003 EU Emissions Trading System (ETS)* further helped refine monitoring and reporting systems of GHG emission in some sectors including for CH_4[22]. More recent ambitions include the *Global Methane Pledge*[23], THE*2020 EU Methane Strategy*[24] which sets out actions to reduce CH_4 emissions across sectors, and the EU Methane Regulation[25] which has a focus on reducing emissions in the energy sector. Continued and renewed ambition is important if the EU is to meet its 2030 and 2050 climate targets as reductions need to continue to grow, particularly in sectors which are stalling such as agriculture.[26]

Unlike NO_x and NMVOCs, CH_4 has a relatively uniform distribution throughout the atmosphere, meaning emissions from one region affect ozone levels globally. CH_4 emissions are therefore critical target for inclusive international air quality and climate change strategies, requiring international agreements and inclusion of CH_4 in air quality frameworks like the Gothenburg Protocol and National Emissions Ceilings Directive 2016/2284/EU (NECD). To date, little to no progress has been made to integrate CH_4 and wider GHG emissions within air emissions or air quality regulation and or policies. While CO, NOx, NMVOC, and SOx are reported under Kyoto Protocol and Regulation (EU) 2018/1999 as secondary pollutants, attempts to include CH_4 within the NEC Directive failed.

The recently published evaluation of the NECD[27] concluded that there will not be a review of the Directive in the immediate future, but the option for future revisions and amendments remains. As such the initial proposal to include Emission Reduction Commitments for CH_4 in the NECD has been removed despite the evaluation report acknowledging the direct impact of CH_4 emissions on ozone formation.

SWP section 2.1.4

The air pollutant with the biggest impacts on human health in Europe is $PM_{2.5}$, followed by ozone (O_3) and NOx. The NECD sets emission reduction commitments for direct emissions $PM_{2.5}$ and NOx. While it does not regulate ozone emissions directly (as ozone is a secondary air pollutant that forms in the atmosphere by reactions of ozone precursors in the presence of sunlight and heat) it does set reduction commitments for the emissions of ozone precursors NOx and NMVOC (but not for methane, which is an important ozone precursor also).

Thus an ambitious revision of the NECD - including methane, particularly from agriculture - is necessary to deliver the revised AAQD, protect health, and align air and climate policy.

2.3 OZONE FORMATION (AND HOW CH4 PLAYS A PART IN IT)

Ground-level ozone (O_3) is not emitted directly; it forms through photochemical reactions involving methane (CH_4), nitrogen oxides (NO_x), and sunlight, see below.

[20] Regulation - 2018/1999 - EN - EUR-Lex
[21] Regulation - EU - 2024/1787 - EN - EUR-Lex
[22] https://eur-lex.europa.eu/eli/dir/2003/87/oj/eng
[23] Homepage | Global Methane Pledge
[24] https://ec.europa.eu/commission/presscorner/detail/en/ip_20_1833
[25] https://eur-lex.europa.eu/eli/reg/2024/1787/oj/eng
26https://www.eea.europa.eu/en/analysis/publications/methane-emissions-in-the-eu-the-key-to-immediate-action-on-climate-change#:~:text=CH4%20emissions%20from%20the,heat%20in%20the%20energy%20sector.

[27] Evaluation of the National Emission Reduction Commitments Directive - Environment , National Emission Reduction Commitments Directive Evaluation - Environment

Figure 2-4 Methane role in O_3 formation

Step 1: Methane Oxidation Initiation
CH_4 reacts with hydroxyl radicals (OH) in the troposphere:

$CH_4 + OH \rightarrow CH_3 + H_2O$

This step is crucial because OH radicals control methane's atmospheric lifetime.

→

Step 2: Formation of Formaldehyde and Peroxy Radicals
The methyl radical (CH_3) reacts with O_2 to form CH_3O_2 (methyl peroxy radical):

$CH_3 + O_2 \rightarrow CH_3O_2$

CH_3O_2 reacts with NO, producing NO_2 and CH_3O:

$CH_3O_2 + NO \rightarrow CH_3O + NO_2$

CH_3O further oxidizes to formaldehyde (HCHO), which is another ozone precursor.

→

Step 3: Ozone Formation
NO_2 photolyzes under sunlight (hv)**:**

$NO_2 + hv \rightarrow NO + O$

The free oxygen atom combines with O_2 to form ozone:
$O + O_2 \rightarrow O_3$

This cycle repeats, sustaining ozone production as long as methane and NO_x are present.

To understand historical trends in O_3 concentrations, the EEA[28] has analysed long-term trends of air pollutants at European and national level for consistency and comparability. Within the EEA report, different typologies of O_3 were monitored at air quality monitoring stations (rural, suburban, and urban background sites, as well as traffic and industrial sites) over the 2005 – 2021 period. The findings indicated that at background sites the annual mean O_3 concentration has slightly increased over this period, although there was a reduction in high peak concentrations (by an average of 6%). Wider literature has more broadly suggested that the most extreme peaks in O_3 have subsidised over recent decades, but the trend in average mean O_3 concentrations is less clear and have not shown the same visible reductions as CH_4 within the EU, with no clear correlation yet observed.

It is important to note O_3 formation in the troposphere depends on a nonlinear relationship between CH_4, NO_x, VOCs, and sunlight. While CH_4 is a precursor to O_3, its impact on O_3 formation depends on the availability of other precursors (NO_x and VOCs). Moreover, CH_4 persists in the atmosphere for about 12 years, whereas O_3 is shorter-lived, lasting only days to weeks. Consequently, changes in CH_4 emissions take years to fully appear, and the associated O_3 response may be gradual or delayed. Moreover, O_3 levels are strongly affected by local weather conditions—such as temperature, humidity, and wind—which can obscure or override the influence of CH_4 changes over short timescales (e.g. over a year). This helps to indicate the importance of continued CH_4 reductions in the EU and global co-ordinated action to reduce methane emissions to ensure the full benefit (including upon ozone background concentrations) is achieved.

2.4 KEY FINDINGS ON CH_4 AND ITS ROLE IN O_3 FORMATION

As noted, CH_4 is a precursor to O_3 formation. The 2024 JRC report (Bessagnet [2024][29]) evaluates CH_4 emission trends and their impact on ozone concentrations globally and in Europe. CH_4 is identified as being responsible for 35–37% of harmful ground-level ozone, making it a critical target for air quality improvement. The report projects that ozone-related mortality linked to CH_4 will rise by 7% by 2050 under current policies, even with stringent reduction measures.

[28] https://www.eionet.europa.eu/etcs/etc-he/products/etc-he-products/etc-he-reports/etc-he-report-2023-8-long-term-trends-of-air-pollutants-at-european-and-national-level-2005-2021
[29] 10.2760/376659

Other studies (e.g. UNEP [2022][30], Acquah et al [2025][31], Butler [2024][32]), exploring the relationship between CH_4 emissions and O_3 concentrations, have illustrated the need for global CH4 emission reductions alongside reductions in the EU to influence local O3 concentrations. Reducing CH4 emissions in the EU alone will not be sufficient to reduce the impacts of Ozone in the region.[33] A further study has linked CH_4 reduction with avoidance of losses in wheat production, specifically noting its role as an ozone precursor in the EU[34] and globally[35].

The analysis also quantifies agricultural and crop yield losses due to CH_4-driven O_3 formation, estimating global losses of 13–16% by 2030 under high-emission scenarios. Conversely, ambitious CH_4 mitigation could reduce crop losses by up to 37%, highlighting strong co-benefits for food security. The report advocates for international cooperation and integrated strategies to further reduce CH_4 emissions. It emphasises that CH_4 reduction is not only a climate imperative but also a public health and agricultural priority, reinforcing its inclusion in EU and global air quality frameworks.

2.5 LIMITATIONS AND PERSPECTIVE

CH_4 emissions have not been used as part of the O_3 modelling (or subsequent economic assessment) within this study, but are provided for illustrative purposes only. To fully assess and understand the O_3 chemistry and more particularly the link with CH_4 emissions, a sensitivity modelling exercise should be undertaken to further research how the change in background CH_4 emissions leads to a change in O_3 concentrations, similar to what has been done in the 2024 JRC study. This study, amongst others, assessed how simulation models can help us understand the correlation between increases in CH_4 emissions and corresponding changes in O_3 concentrations.

Alternatively, the use of a climate model could be proposed as such models using greenhouse gas and air pollutants emissions and also calculate air quality concentrations. However, these models are typically of a coarser spatial resolution (e.g. 50 km × 50 km) which makes their use to support a health impact assessment unsuitable. Coarse resolution averages pollutant concentrations over large areas, smoothing out local peaks and dips in air quality concentration. This masks high-exposure hotspots, leading to underestimated health impacts because real population exposure is diluted.

O_3 chemistry is also driven by other precursors (NO_x and VOC) and a detailed analysis based on diverse emission reduction scenarios, including these precursors should be considered. A detailed modelling exercise by sectors can also be undertaken to estimate the role and impact of sectoral emissions to O_3 concentrations. This approach can help to identify the relative importance of each sector, assess their spatial and temporal impacts, and evaluate the effectiveness of targeted mitigation strategies.

As also explained in Hayes et al. (2025)[36], it may be valuable to assess the comparative benefits of reducing CH_4 emissions within the UNECE region (compared to outside) as CH_4 is a globally mixed species in the atmosphere. CH_4 is a greenhouse gas with long atmospheric lifetime relative to some other pollutants such as black carbon, NOx or NH_3[37]. Unlike other O_3 precursors, such as VOC and NO_x whose impacts are largely local or regional to where they are emitted, CH_4 influences global O_3 formation irrespective of the location of its emissions. Comparing reductions inside and outside the UNECE will further strengthen the argument that regional mitigation needs to be carefully coordinated and more importantly supported by global cooperation to reach a meaningful impact.

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[30] Global Methane Assessment 2030: Baseline Report | UNEP - UN Environment Programme
[31] 10.5194/acp-25-13665-2025
[32] UNECE PDF
[33] Belis, C. A. and Van Dingenen, R., 2023, *Air quality and related health impact in the UNECE region: source attribution and scenario analysis* (https://acp.copernicus.org/articles/23/8225/2023/acp-23-8225-2023-supplement.pdf).
[34] Global efforts addressing methane emissions is a key factor to further reducing ozone-induced yield losses of crops in Europe, 2025, https://www.sciencedirect.com/science/article/pii/S0269749125010279?ref=pdf_download&fr=RR-2&rr=996d3d1f697b5b0b
[35] Marginal Damage of Methane Emissions: Ozone Impacts on Agriculture, 2023, https://link.springer.com/article/10.1007/s10640-022-00750-6
[36] Hayes, F., Sharps, K., van Caspel, W. E., Klimont, Z.. Heyes, C., Fagerli, H., Global efforts addressing methane emissions is a key factor to further reducing ozone-induced yield losses of crops in Europe, Environmental Pollution, 382, 126654, https://doi.org/10.1016/j.envpol.2025.126654, 2025.
[37] Methane is a short-term GHG owing to it's 12 year atmospheric life which is far shorter than CO_2. But relative to other Ozone precursors, it is long lived atmospheric species. Nonetheless, once broken, its oxidation products act as short-lived climate forcers

Key limitations based on our current understanding:

- *Underlying uncertainty of input date used*: Studies such as Acquah et al.[38] highlight that differences in emission inventories significantly affect ozone and CH_4 lifetime estimates, introducing uncertainty in model outputs.
- *Model Variability*: Reports such as Butler's UNECE[39] summary note high inter-model variability in O_3 response to CH_4 changes, indicating that results depend on model assumptions and chemistry schemes.
  - *Limited Observational Data*: Most studies rely heavily on simulations rather than long-term observational datasets, which constrains validation of modelled CH_4 to O_3 relationships.

Further Work Needed

- *Expand Observational Networks*: More ground-based and satellite observations are needed to validate model predictions and track CH_4-driven O_3 formation.
- *Integrated Mitigation Strategies*: Future work should explore co-control of CH_4 and traditional ozone precursors (NO_x, NMVOCs) for synergistic benefits.
- *Global Coordination*: CH_4 global influence requires international agreements and inclusion in air quality frameworks like the Gothenburg Protocol.
- *Sector-Specific Analysis*: Research should refine attribution of CH_4-driven O_3 to specific sectors (agriculture, energy, transport) to guide targeted interventions.

3. EU OZONE CONCENTRATIONS

This section of the study assesses the current air quality status in 2022 in Europe in terms of O_3 concentrations through the use of data reported under European Monitoring and Evaluation Programme (EMEP)[40].

3.1 METHODOLOGY

3.1.1 Modelled O_3 concentration

The O_3 data collected within the study has been based on the most recent available year (2022) at the start of the project as modelled by the chemical transport model (CTM) within the European Monitoring and Evaluation Programme (EMEP). This programme is a scientifically based and policy driven programme under the Convention on Long-range Transboundary Air Pollution (CLRTAP). The model has been described in greater detail in Appendix A.

The selection of the EMEP/MSC-W model has been driven by the availability of the O_3 metrics needed for the health and environmental assessment, the availability of the model results and the robustness (evaluation process) of these results. Appendix A summarises the different criteria used for the selection of which AQ modelling tool would be most suitable for the type of assessment and scope of this study.

Among four possible modelling options, two are based on existing modelled datasets (EMEP and Copernicus Atmosphere Monitoring Service - CAMS) and one on emission modelling (FAST - FAst Scenario Screening Tool[41]). While EMEP and CAMS correspond to air quality models results, i.e. accessing to air pollutants concentrations such as O_3, FAST is developed to directly provide the impact of preexisting emission scenarios on these air pollutants concentrations and provides the resulting health, economic and climate impacts.

In comparison, Ricardo's modelling capability with the Community Multiscale Air Quality (CMAQ) model has also been considered as part of the selection process. However, the scope of this study has necessitated the use of readily available datasets. By leveraging our modelling capability instead of relying on existing post-

[38] 10.5194/acp-25-13665-2025
[39] UNECE PDF
[40] https://www.emep.int/mscw/index.html
[41] https://tm5-fasst.jrc.ec.europa.eu/

processed model outputs, we gain greater flexibility in calculating metrics, selecting spatial resolution, choosing the analysis year, and conducting emission scenario assessments. However, such modelling leads to an increase in computing time and requires large data storage. Such demanding information technology is not required by using the existing postprocessed model results such as those from EMEP/MSC-W in this report.

A full description and detail of the EMEP/MSC-W model is provided in Appendix A.

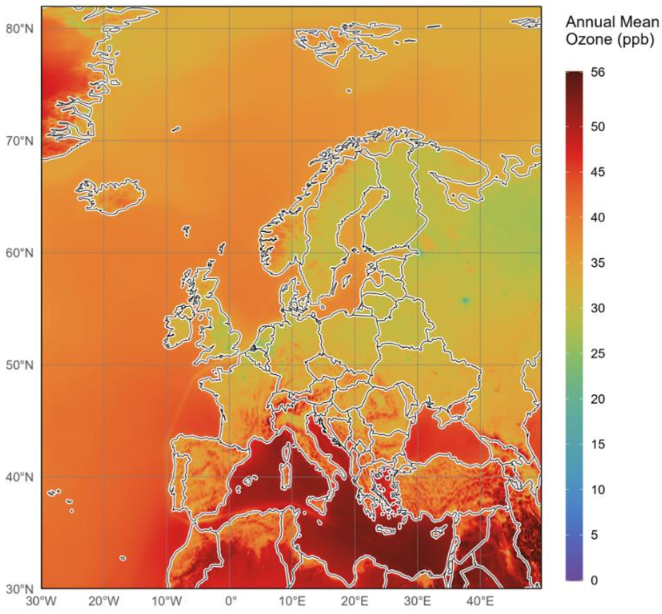
3.2 FINDINGS

3.2.1 Modelled O_3 metrics

Annual mean O_3 concentrations, see Figure 3-1, show a clear South-North gradient with higher concentrations in the Southern countries (e.g. Italy) compared to the Northern countries (e.g. Germany, Norway). This gradient is likely related to the different meteorological conditions as O_3 is formed through photochemical reactions involving sunlight. Southern Europe receives more intense sunlight and higher temperatures, which accelerates O_3 formation. It is also possible that more stable weather conditions (such as reduced wind) are present in the South, trapping pollutants such as O_3 precursors. Higher concentrations are modelled over sea and ocean, related to a lower sink of O_3. Indeed, the main sink of O_3 is the dry deposition (on vegetation) which does not occur over seas.

Denmark and Germany have the lowest mean O_3 concentration in 2022 (33 ppb), while Italy has the highest value (41 ppb). Hungary records 35 ppb, France 36 ppb and Spain 39 ppb. Lower O_3 concentrations are also calculated over densely populated areas such as cities (Madrid, Paris, Berlin), conurbations (Benelux) and areas with intense agricultural and industrial activities present such as the Po Valley. These areas are exposed to high concentrations of NO_2 which significantly contributes to deplete ground level O_3. High concentrations of NO emitted locally scavenge O_3, a process leading to formation of NO_2. Close to sources of NO_x (= NO + NO_2), this titration process can act as an O_3 sink (noting of course the significant negative environmental impacts of NO_2 as a pollutant). Because of these reactions, a decrease in NO_x can lead to an increase in O_3 and vice-versa. O_3 levels are typically highest in the areas downwind of air emissions sources such as major cities and industrial areas. While local emissions of NO_x can mitigate some of the production of O_3 at source, the transboundary movement of CH_4 means that it goes on to contribute to O_3 production in other areas where NO_x is not as present.

Figure 3-1 Annual mean O_3 concentration (ppb) in 2022.



Similarly, the SOMO35 metric (Figure 3-2), which is an indicator used to measure the health impact and corresponds to the sum of O_3 means over 35 ppb, and the maximum of O_3 concentrations (Figure 3-3) indicate marked gradients from North to South. SOMO35 is an indicator typically applied within health impact assessments (greater detail provided in the Glossary). The metric maximum of O_3 shows the maximum O_3 concentration occurrences.

Figure 3-2 SOMO35 (ppb.day) in 2022.

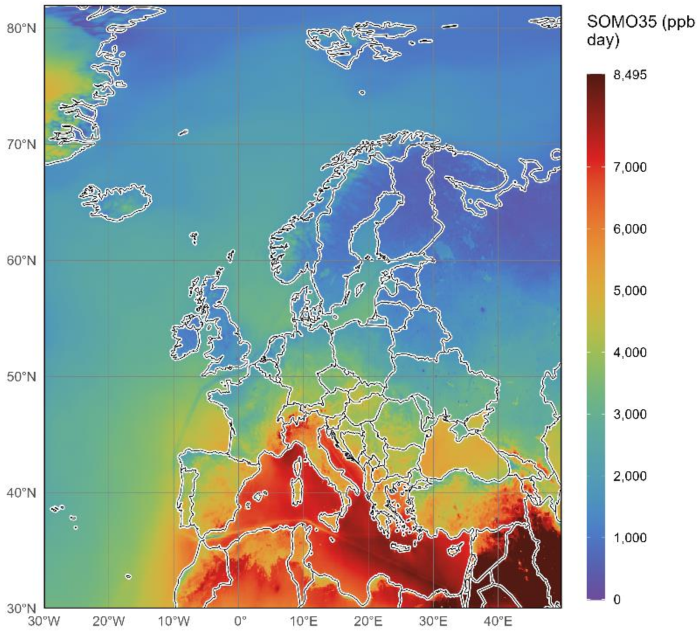


Figure 3-3 Surface maximum O_3 concentration (ppb) in 2022

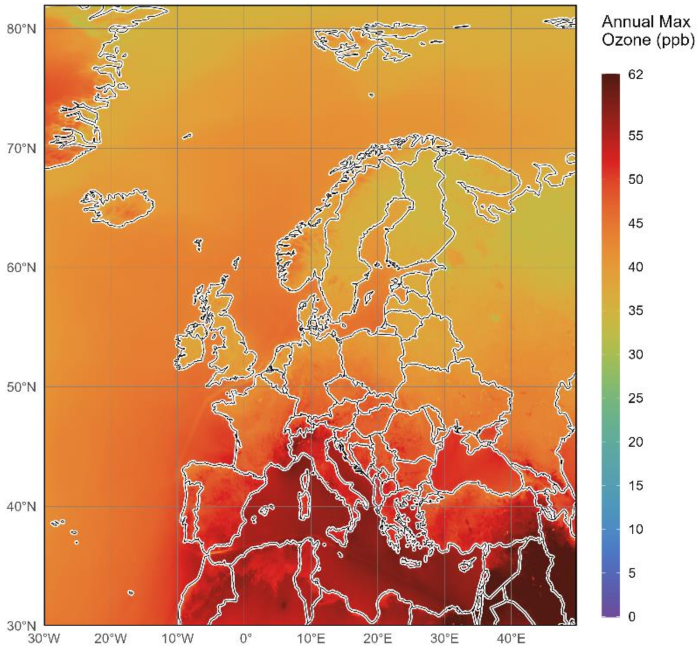


Figure 3-4 shows EU-AOT40 metrics, typically related to forests and crops and commonly used in environmental assessments. The AOT40 values correspond to the accumulated amount of O_3 over the threshold value of 40 ppb and are calculated using EU definitions[42]. AOT40 based limit values have been set by the EU AAQD and by UNECE. In the EU directive the long-term objective for crops (AOT40c) is set to 3000 parts per billion by hour (ppb.h) and UNECE's critical level for forests (AOT40f) is 5000 ppb.h.

A further definition of AOT-40 is calculated with the EMEP/MSC-W, named MM-AOT40 (Figure 3-5). MM-AOT40 is calculated for growing season between May-July and 1m altitude (EU-AOT40 is calculated for the April-September growing season and at 3m altitude).

The O_3 annual mean concentration, AOT40 forest and AOT40 crop show an increasing gradient from North to South. The figures also show the critical level for forests (5000ppb.h) and the long-term objective for crops (3000 ppb.h) are exceeded over large parts of Europe.

The EMEP report[43] explains AOT40 has been used as an indicator of O_3 damage to vegetation in the past. A clear advantage of this metric is that modelled levels can be compared to real-world measurements. However, AOT40 does not necessarily reflect the actual damage to crops and forests as AOT40 does not fully capture the complexity of how plants respond to O_3. AOT40 assumes damage is proportional to exposure above 40 ppb, but actual damage depends on uptake through the plant stomata, which varies with humidity, temperature, and plant health. As a result, the preferred metric in recent years has been the phyto-toxic O_3 dose (POD) since POD consider stomatal flux. POD calculates the actual flux of O_3 into the plants, based on soil moisture deficit and other environmental factors. Plants regulate their stomata opening depending on the soil moisture to control their water balance. In dry conditions the plants tend to close the stomata opening, effectively also limiting the uptake of O_3. This POD metric is used in Environmental assessment (Section 4.2).

[42] The term "EU definitions" refers to the official methodology and standards set by the European Union for calculating and interpreting environmental metrics like AOT40 (Accumulated Ozone exposure over a Threshold of 40 ppb)
[43] emep.int/publ/reports/2024/EMEP_Status_Report_1_2024.pdf

Figure 3-4 EU-AOT40 for Forests and Crops (ppb.h) in 2022

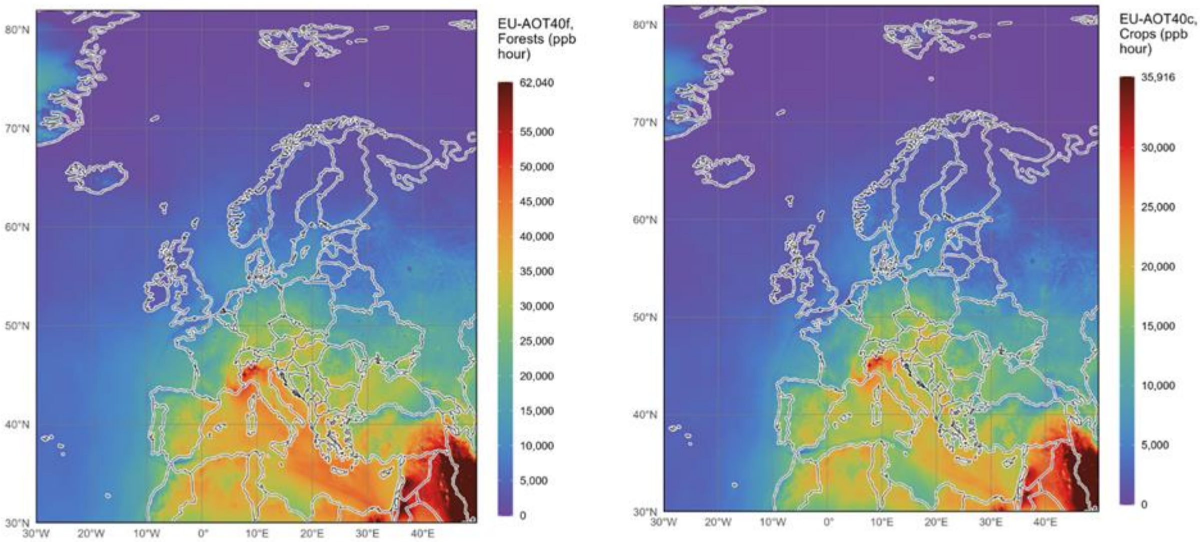
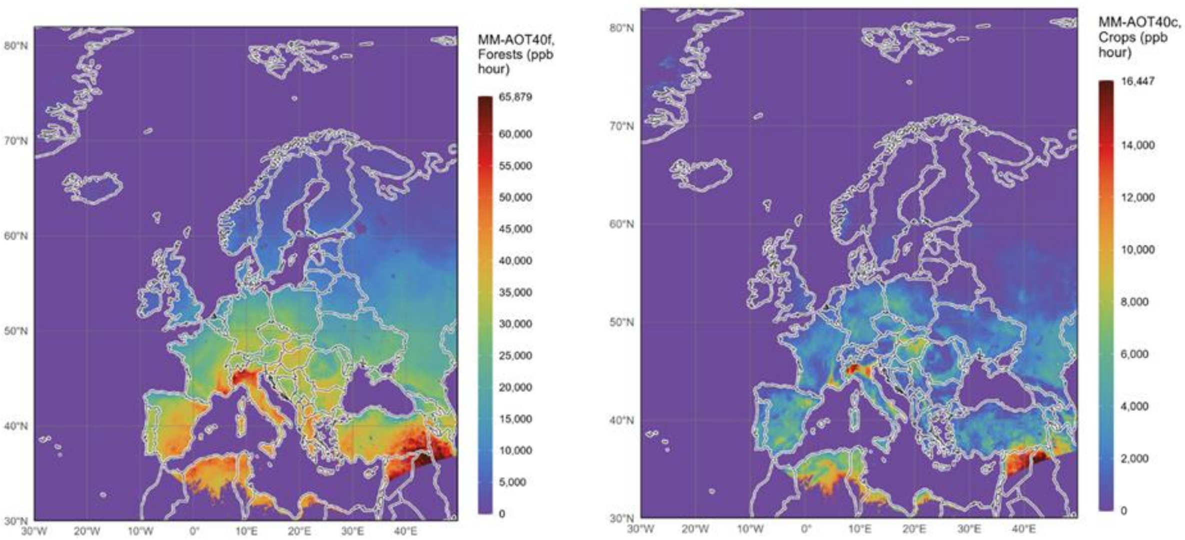


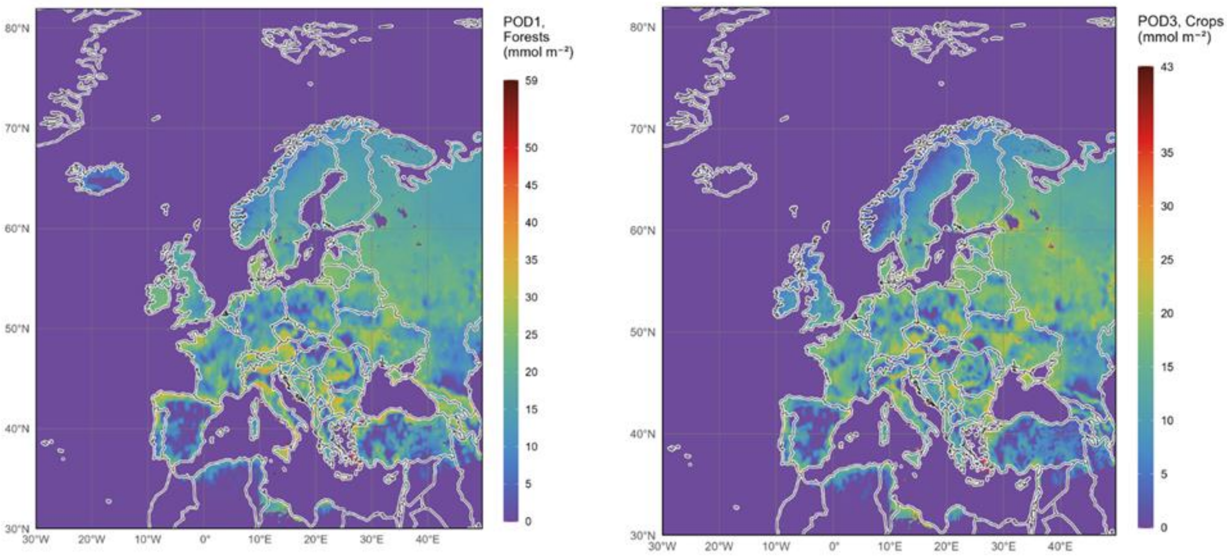
Figure 3-5 MM-AOT40 for Forests and Crops (ppb.h) in 2022



The phyto-toxic O_3 dose (POD1) and (POD3) are shown in Figure 3-6. It corresponds to the accumulate O_3 flux of 1 mmol/m^2 and 3 mmol/m^2, respectively. These POD values are calculated with generic vegetation categories, the so-called IAM (integrated assessment modelling) categories. Therefore, these POD metrics are calculated in the EMEP/MSC-W model with a common definition of the growing seasons in all countries. However, the growing season likely differs depending on the locations and Member State.

In contrast to other metrics (O_3 concentration, maximum O_3, SOMO35, AOT40), POD presents a mixed figure (no clear South-North gradient is seen). This difference can be explained by the fact that POD depends not only on O_3 levels but also on the additional parameters described above. It reflects that plants in more humid climates are generally more susceptible to high ozone levels than those in arid regions.

Figure 3-6 10 POD1 for decidous forest (mmole/m2) and POD3 for wheat (mmole/m^2) in 2022.



3.2.2 Comparison of reported O_3 concentrations with modelled annual mean O_3 concentrations

Reported O_3 data, as measured by monitoring stations, captures the seasonality and short-term O_3 concentrations, which are not as clearly observed through annual mean concentrations as seen in section 3.2.1**.** Annual average O_3 concentration statistics smooth out seasonal jumps (i.e exceedances) in O_3 concentration caused by particular weather conditions, such as heat waves for example, because periods of exceedance are averaged out across the year and compensated by periods of low O_3 concentration. In this section we illustrate that Member States are still exceeding the maximum daily eight hour running mean in 2022 (and 2023, 2024) despite the annual average mean concentrations in Section 3.2.1 appearing to present a picture of low annual mean concentrations.

Under the AAQD EU 27 Member States have to report metrics for O_3 long term objectives and target values for Health and Vegetation Table 3-1. Since 2022 alert threshold and information threshold have been included and are also shown in the table.

The health metrics are exceedances of the maximum daily eight hour running mean. A Member State can therefore exceed these metrics during periods of high O_3 for example in the summer without longer periods of lower concentrations diluting these results. Multiyear metrics help to distinguish areas with persistent high O_3 concentrations from those affected by a single year meteorological conditions.

The AOT40 vegetation metric, as previously mentioned, is a seasonal metric covering the growing period and, like the health metric, provides a more focused results on when concentrations are likely to be at their highest. As with the health metrics, the 5-year AOT 40 target value allows for assessment reducing some of the effects of meteorological conditions in individual growing seasons.

Table 3-1 Air Quality Directive Reporting Metrics for Ozone

Reporting Metric	Protection Target	Reporting Metric Value
Long term objective (LTO)	Health	Maximum daily eight hour running mean exceeding 120 µg.m^{-3}
Target Value (TV) – 3 year average	Health	Maximum daily eight hour running mean exceeding 120 µg.m^{-3} – not to be exceeded

Reporting Metric	Protection Target	Reporting Metric Value
		more than 25 times per calendar year averaged over 3 years.
Long term objective (LTO)	Vegetation	AOT40 6000 $\mu g.m^{-3}.h$
Target Value (TV) – 5 year average	Vegetation	AOT40 18000 $\mu g.m^{-3}.h$
Information Threshold (INT)	Health	Hours exceeding 180 $\mu g.m^{-3}$
Alert threshold (ALT)	Health	Hours exceeding 240 $\mu g.m^{-3}$

The *Alert Threshold* and *Information Threshold* are triggered when pollution episodes result in high peaks in concentration. Reporting these annually since 2022 provides further evidence to locations particularly susceptible to high O_3 concentrations.

Member States split their geographies up into zones (typically a mixture of urban areas and more rural areas). Reporting is carried out on a zonal basis and a maximum concentration or number of exceedance is provided per zone. While this does not capture the complete picture it does provide an indication as to the extent of elevated levels of O_3 across the Member State.

Table 3-2 shows the Ozone reporting results for Member States; Denmark, France, Germany, Hungary, Italy and Spain, for 2022 (to 2024). Blank cells indicates no exceedance in any of the zones. The total number of zones exceeding in a Member State are shown with the percentage of the total shown in brackets. The number of Air Quality Zones per Member State depends on the population and area of the country. It should be noted that there are a varying number of zones reported between the Health and Vegetation metrics.

In 2022 (and 2023-2024) exceedances occurred in the majority of the zones in the Member States reviewed for the Long-Term Objective for Health. When looking at the Target Value (over 3 years) a reduction can be seen in most of the Member States.

The compliance metrics and alert and information thresholds all require time scales that reflect short term concentrations or seasonal features. **The Health metrics allow for high concentration episodes to be captured which are missed in an annual average, these high occurrences can be only once or twice a year which are lost when averaging of a year.**

While France, Italy, Germany and Spain all showed consistently high exceedances of the Long Term Objectives for health, demonstrating systematic failures for the countries, Italy was the stand out for exceedances of the Target Value, Alert and Alarm Thresholds for health, which suggest the role of other factors such as heat, sunlight, wind conditions and other non-MVOCs can play in the creation of ozone. Exceedances for vegetation are consistently high across all countries analysed even where health exceedances are less, which reflects the relative sensitivity of vegetation to ozone exposure. The reported metrics mirror the annual mean concentrations showing that in the southern Member States of Italy and Spain *the Alert Threshold* and *Information Threshold* were exceeded in at least one zone showing that these Member States experience higher concentrations compared to those countries further north.

Table 3-2 Proportion of Air Quality Zones exceeding Ozone metrics

Objective Type	Protection Target	Country	Number of zones exceeding per year (exceeding zones as a percentage of the total)		
			2022	2023	2024
Long term objective (LTO)	Health	Denmark	-	2 (67%)	2 (67%)
		France	61 (87%)	61 (87%)	56 (80%)
		Germany	68 (100%)	65 (100%)	65 (100%)
		Hungary	9 (90%)	9 (90%)	9 (90%)
		Italy	65 (97%)	64 (96%)	61 (91%)
		Spain	117 (91%)	117 (89%)	103 (78%)
Target Value (TV)	Health	Denmark	-	-	-
		France	12 (17%)	13 (19%)	12 (17%)
		Germany	11 (16%)	9 (14%)	10 (15%)
		Hungary	2 (20%)	2 (20%)	2 (20%)
		Italy	47 (70%)	49 (73%)	45 (67%)
		Spain	10 (8%)	14 (11%)	20 (15%)
Alert threshold (ALT)	Health	Denmark	-	-	-
		France	-	-	-
		Germany	-	-	-
		Hungary	-	-	-
		Italy	2 (3%)	2 (3%)	1 (2%)
		Spain	-	1 (1%)	1 (1%)
Information Threshold (INT)	Health	Denmark	-	-	-
		France	29 (41%)	15 (21%)	7 (10%)
		Germany	34 (52%)	9 (14%)	13 (20%)
		Hungary	2 (20%)	1 (10%)	3 (30%)
		Italy	36 (62%)	30 (51%)	26 (44%)
		Spain	29 (22%)	15 (11%)	12 (9%)
Long term objective (LTO)	Vegetation	Denmark	-	1 (100%)	1 (100%)

Objective Type	Protection Target	Country	Number of zones exceeding per year (exceeding zones as a percentage of the total)		
		France	57 (81%)	55 (79%)	38 (54%)
		Germany	49 (100%)	49 (100%)	44 (96%)
		Hungary	1 (100%)	1 (100%)	1 (100%)
		Italy	16 (73%)	18 (82%)	16 (76%)
		Spain	96 (93%)	89 (86%)	72 (75%)
Target Value (TV)	Vegetation	Denmark	-	-	-
		France	19 (27%)	16 (23%)	6 (9%)
		Germany	14 (29%)	8 (16%)	1 (2%)
		Hungary	1 (100%)	1 (100%)	1 (100%)
		Italy	12 (55%)	15 (68%)	10 (48%)
		Spain	33 (32%)	24 (23%)	22 (23%)

4. ECONOMIC IMPACTS

The assessment of the economic impacts of exposure to O_3 concentrations has focused on capturing the impacts upon human health (mortality and morbidity) and the environment (wheat production and forest biomass). The approach has initially explored the direct impact of exposure to O_3 concentration upon each indicator, i.e. in terms of attributed incidences of disease or a change in tonnes of wheat produced. Each impact has been subsequently monetised to determine the associated economic cost.

The economic assessment has been undertaken independently for each of the six Member States and for the EU-wide assessment. The results represent the annual economic impact for the year 2022 only, as based on the air quality data reported in Section 3.

The approach, scope, and findings of the health and environmental assessments have been included within Sections 4.1 and 4.2 respectively.

4.1 HEALTH ASSESSMENT

There is a strong body of evidence linking human exposure to air pollutants and adverse effects on human health, including respiratory and cardiovascular diseases, and premature mortality.[44,45,46] This health impact assessment focuses on quantifying the potential impacts of exposure to O_3 on the health of the population of the EU and selected Member States in 2022 from modelled O_3 concentrations in the air. The assessment has focussed on the following health endpoints: premature statistical (all-cause) mortality, and morbidity represented by respiratory hospital admissions.

To further contextualise the results, the health impacts are monetised by assigning a monetary value to the outcomes, capturing the societal implications of air pollution. This process highlights both the public health impact and the broader societal costs of polluted air. The results of the health impact assessment are used to estimate the monetised economic impacts in terms of non-market health costs (based on willingness to pay estimates), and costs associated with the respiratory hospital admissions.

4.1.1 Methodology

This section details the methods used for the health impact assessment of O_3 concentrations. The method relies on established scientific evidence, including the WHO 2021 Air Quality Guidelines (AQG)[47], which assume a linear relationship between pollutant concentrations and health risks. The Figure below provides an overview of the health impact assessment methodology.

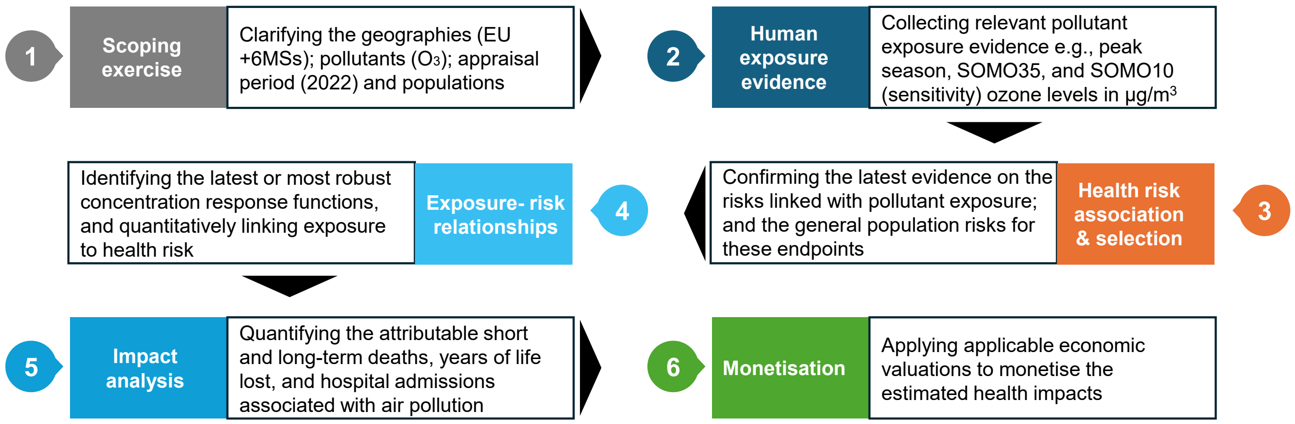
[44] European Commission: Directorate-General for Environment, IIASA, , EMRC, , MET Norway, , TNO, , e-misia, , RIVM, , & Logika Group, (2025). Support to the development of the fourth clean air outlook : final report, Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2779/8768689

[45] WHO (2021). WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Available at: https://iris.who.int/server/api/core/bitstreams/551b515e-2a32-4e1a-a58c-cdaecd395b19/content

[46] WHO (2013). Health risks of air pollution in Europe: HRAPIE project: new emerging risks to health from air pollution: results from the survey of experts. Available at: https://iris.who.int/server/api/core/bitstreams/6d99ab82-8320-40b1-b080-eee217591c72/content

[47] WHO (2021). WHO global air quality guidelines. Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Available at:https://iris.who.int/bitstream/handle/10665/345329/9789240034228-eng.pdf

Figure 4-1 Overview of health assessment methodology



4.1.2 Findings and sensitivity analysis

This section summarises the results of the health impact assessment, described in terms of the average mortality (statistical deaths), Life Years lost (YLL), and respiratory hospital admissions caused by both short-term (SOMO35 metric) and long-term (peak season metric) O_3 exposure in 2022. The estimates presented in this section include sensitivity ranges that explore the uncertainties associated with the concentration response functions (CRFs), which characterise the relationship between exposure to pollutant concentrations and health outcomes. These uncertainties are represented by the associated 95% confidence intervals (CI)[48]. The impacts include a 'central' estimate estimated using the central value of the CRF, and 'low' and 'high' sensitivity estimates using the lower and upper bounds of the 95% CI associated with the CRFs. The results of the additional sensitivity analysis using the SOMO10 metric are presented in Section 4.1.3.

The findings suggest that **short-term exposure** to O_3 (represented by SOMO35 concentrations) **potentially resulted in over 43,000** [95% CI: 34,000-52,000] **attributable premature deaths, and over 8,000** [95% CI: 1,000-14,300] **hospital admissions due to respiratory illness in the EU-27**. The Table below presents a summary of the short-term health impacts assessed for the EU-27 and the six Member States.

Table 4-1 Health impacts from short-term O_3 exposure (SOMO35 concentrations) in 2022 (central [low-high] estimates)

Geography	Mortality (Statistical deaths) due to short-term exposure	Life Years lost (YLL) from deaths due to short-term exposure*	Respiratory hospital admissions due to short-term exposure
Germany	**7,000** [6,000-9,000]	**7,000** [6,000-9,000]	**1,000** [200-2,000]
Denmark	**200** [180-300]	**200** [180-300]	**50** [10-90]
Spain	**5,000** [4,000-6,000]	**5,000** [4,000-6,000]	**500** [100-1,000]
France	**5,000** [4,000-6,000]	**5,000** [4,000-6,000]	**600** [100-1,000]
Hungary	**1,500** [1,000-2,000]	**1,500** [1,000-2,000]	**80** [10-100]
Italy	**9,000** [7,000-11,000]	**9,000** [7,000-11,000]	**1,000** [100-2,000]
EU-27	**43,000** [34,000-52,000]	**43,000** [34,000-52,000]	**8,000** [1,000-14,300]

** Please note: The YLL are equal to the number of premature deaths based on the Clean Air Outlook's assumption of 1 year of life expectancy lost per premature death due to short-term* O_3 *exposure.*

Considering long-term exposure to O_3 (based on peak season concentrations), **the total mortality burden is estimated at over 73,000** [95% CI: 0-146,000] **statistical deaths and 775,000** [95% CI: 0-1,558,000] **years of life lost in the EU-27 in 2022**. Additionally, it is estimated that long-term exposure could result in 12,000

[48] A confidence interval (CI) is a range of values derived from sample data that is likely to contain the true value of an unknown population parameter (in this case, population risk from exposure). It quantifies the uncertainty associated with a sample statistic based on the associated confidence level. A 95% confidence level means that if we were to take multiple samples and create confidence intervals, approximately 95% of those intervals would contain the true population parameter.

[95% CI: 2,000-23,000] respiratory hospital admissions in the EU-27. The Table below presents a summary of the long-term health impacts assessed for the EU-27 and the six Member States.

Table 4-2 Health impacts from long-term O_3 exposure (peak season concentrations) in 2022 (central [low-high] estimates)

Geography	Mortality (Statistical deaths) due to long-term exposure	Life Years lost (YLL) from deaths due to long-term exposure	Respiratory hospital admissions due to long-term exposure
Germany	**14,000** [0-29,000]	**155,000** [0-311,000]	**2,000** [400-4,000]
Denmark	**500** [0-1,000]	**5,000** [0-11,000]	**100** [20-200]
Spain	**6,000** [0-13,000]	**66,000** [0-134,000]	**700** [100-1,000]
France	**9,000** [0-18,000]	**96,000** [0-194,000]	**1,000** [200-2,000]
Hungary	**2,000** [0-5,000]	**26,000** [0-52,000]	**100** [20-200]
Italy	**13,000** [0-26,000]	**140,000** [0-282,000]	**1,000** [200-2,000]
EU-27	**73,000** [0-146,000]	**775,000** [0-1,558,000]	**12,000** [2,000-23,000]

Using the same CRFs, the EEA[49] estimated over 27,000 [95% CI: 21,000-33,000] attributable deaths and 279,000 [95% CI: 221,000-338,000] years of life lost due to short-term O_3 exposure, and around 70,000 [95% CI: 0-137,000] attributable deaths and 689,000 [95% CI: 0-1,348,000] years of life lost due to long-term O_3 exposure in the EU-27 in 2022[50]. The long-term estimates are comparable to this Study, but the short-term estimates are lower than those in this Study, explained by differences in the SOMO35 concentrations from the EMEP and EEA datasets. The EEA also estimated around 12,000 [95% CI 2,000-23,000] attributable hospital admissions for respiratory disease in Europe in 2019[51] which is aligned with the estimates presented in this Study.

The Tables below present the monetised health impacts of short-term and long-term O_3 exposure respectively, in constant 2024 euros. It is estimated that the costs associated with hospital admissions due to respiratory conditions resulting from exposure to the modelled O_3 concentrations could range between €45 million [95% CI: 5-85 million] (for short-term impacts) to €70 million [95% CI: 10-135 million] (for long-term impacts) in 2022. The **non-market impacts – the costs associated with the loss of life years – are significantly larger and could range between €5 billion** [95% CI: 4-6 billion] (for short-term impacts) **to €88 billion** [95% CI: 0-178 billion] (for long-term impacts) **for the EU-27 in 2022**.

It is important to note that the non-market valuations represent the estimated monetary value of the welfare loss to individuals and society from illness or premature death that is not reflected in direct market costs, i.e. it is not captured through healthcare expenditures. So, the value is not a direct cost to the economy but a monetised reflection of the aggregated **burden upon individuals**. It is typically measured via willingness-to-pay approaches to reflect the loss of life years, quality of life, and wellbeing.

[49] Soares et al. (2024). Health Risk Assessment of Air Pollution: assessing the environmental burden of disease in Europe in 2022. (Eionet Report – ETC HE 2024/6). European Topic Centre on Human Health and the Environment. Available at: https://www.eionet.europa.eu/etcs/etc-he/products/etc-he-products/etc-he-reports/etc-he-report-2024-6-assessing-the-environmental-burden-of-disease-related-to-air-pollution-in-europe-in-2022/view

[50] Soares et al. (2024). Health Risk Assessment of Air Pollution: assessing the environmental burden of disease in Europe in 2022. (Eionet Report – ETC HE 2024/6). European Topic Centre on Human Health and the Environment. Available at: https://www.eionet.europa.eu/etcs/etc-he/products/etc-he-products/etc-he-reports/etc-he-report-2024-6-assessing-the-environmental-burden-of-disease-related-to-air-pollution-in-europe-in-2022/view

[51] Kienzler et al. (2022). Estimating the morbidity related environmental burden of disease due to exposure to PM2.5, NO2 and O3 in outdoor ambient air. (Eionet Report – ETC HE 2022/11). European Topic Centre on Human Health and the Environment. Available at: https://www.eionet.europa.eu/etcs/etc-he/products/etc-he-products/etc-he-reports/etc-he-report-2022-11-estimating-the-morbidity-related-environmental-burden-of-disease-due-to-exposure-to-pm2-5-no2-and-o3-in-outdoor-ambient-air

Table 3-5 Monetised health impacts from short-term O_3 exposure in 2022 (million €, 2024 prices) (central [low-high] estimates)

Geography	Non-market disease burden from short-term exposure (million €)	Costs associated with respiratory hospital admissions from short-term exposure (million €)
Germany	**820** [640-990]	**6.0** [1.0-12.0]
Denmark	**26** [20-32]	**0.5** [0.1-1.0]
Spain	**530** [410-640]	**3.0** [0.5-6.0]
France	**580** [460-710]	**3.0** [0.5-6.0]
Hungary	**160** [130-200]	**0.5** [0.1-1.0]
Italy	**1,000** [790-1,200]	**6.0** [0.5-12.0]
EU-27	**4,900** [3,900-6,000]	**45.0** [5.0-85.0]

Note: The costs should not be aggregated as there may be potential for overlap across the categories.

Table 4-4 Monetised health impacts from long-term O_3 exposure in 2022 (million €, 2024 prices) (central [low-high] estimates)

Geography	Non-market disease burden from long-term exposure (million €)	Costs associated with respiratory hospital admissions from long-term exposure (million €)
Germany	**17,700** [0-35,500]	**12.0** [2.0-23.0]
Denmark	**590** [0-1,200]	**0.5** [0.1-1.0]
Spain	**7,600** [0-15,000]	**4.0** [0.5-6.0]
France	**11,000** [0-22,000]	**6.0** [1.0-12.0]
Hungary	**2,900** [0-6,000]	**0.5** [0.1-1.0]
Italy	**16,000** [0-32,000]	**6.0** [1.0-12.0]
EU-27	**88,500** [0-178,000]	**70.0** [10.0-135.0]

Note: The costs should not be aggregated as there may be potential for overlap across the categories.

Across the Member States, **the largest health impacts were estimated for Germany and Italy, whereas the smallest impacts were estimated for Denmark**. These results are driven by a combination of O_3 concentrations, size of the affected population groups and the baseline risk rates.

4.1.3 Additional sensitivity analysis: metrics and counterfactuals

This Section discusses three key drivers of the estimated health impacts of ozone exposure.

Firstly, outputs of the health impact assessment are directly dependent on the modelling and analysis of potential O_3 concentrations. For example, this Study highlights differences in the short-term impacts of ozone exposure due to differences in the SOMO35 concentrations modelled from the EMEP and EEA datasets.

Secondly, the estimated health impacts are directly dependent upon the concentration response functions (or CRFs) which quantify the relationship between exposure and attributable impacts (in terms of mortality or respiratory hospital admissions). There are inherent uncertainties in these CRFs, represented by the associated 95% confidence intervals. The central value, lower bound and upper bounds of the CRFs have already been taken into account in central, low and medium estimates presented in the main findings of this Study (see Section 4.1.2 above).

Thirdly, the health impacts are also sensitive to the choice of counterfactual values. The values chosen in this Study are aligned with the WHO Air Quality Guideline (AQG) levels, which represent the lowest levels of exposure for which there is evidence of adverse health effects. While it is widely acknowledged that there are no "safe" levels of exposure to air pollution, the relationships between exposure and observed health impacts (i.e., the CRFs) are underpinned by scientific evidence regarding the lowest level of observed exposure at which a non-zero increase in risk occurs – referred to as the AQG levels by the WHO. In its latest publication, the WHO has recommended a peak season ozone AQG level of 60 µg/m³, with an interim target 2 of 70 µg/m³, which is the threshold in the SOMO35 metric. These levels are widely used as counterfactual concentrations in studies estimating the health impacts of O_3 exposure in Europe. The Table below summarises published estimates of the impacts of ozone exposure in the Europe, for ease of comparison of methodology, counterfactual concentrations and estimates.

Table 4-5 Summary of impacts of O_3 exposure in Europe, estimated by published studies

Study	Approach	Data source	Ozone metric	Counterfactual concentration	Estimated impacts
Clean Air Outlook 4 (2025)[52]	Health impact assessment for the EU-27 in 2025 using the peak season CRF from this Study	EMEP; Eurostat	SOMO35	35 ppb (70 µg/m³)	• 69,000 attributable deaths, monetised to €6.5 billion • 16,000 respiratory hospital admissions, monetised to €78 million
Soares et al. (2024)[53]	Burden of disease assessment for the EU-27 in 2022 using the same CRFs as this Study	ETC air quality maps for 2022[54]; Eurostat	Peak season	60 µg/m³	• 70,000 [95% CI: 0-137,000] attributable deaths • 689,000 [95% CI: 0-1,348,000] years of life lost
			SOMO35	35 ppb (70 µg/m³)	• 27,000 [95% CI: 21,000-33,000] attributable deaths • 279,000 [95% CI: 221,000-338,000] years of life lost
Kienzler et al. (2022)[55]	Burden of disease assessment for Europe in 2019 using the same CRF as this Study	ETC air quality maps for 2019[56]; Eurostat	SOMO35	35 ppb (70 µg/m³)	• 12,000 [95% CI: 2,000-23,000] attributable hospital admissions for respiratory disease

As an additional test of the sensitivity of the impacts to the choice of counterfactual, we also estimated the impacts of ozone exposure using the SOMO10 metric. The SOMO10 is based on a lower threshold of 10 ppb

[52] European Commission: Directorate-General for Environment, IIASA, , EMRC, , MET Norway, , TNO, , e-misia, , RIVM, , & Logika Group, (2025). Support to the development of the fourth clean air outlook : final report, Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2779/8768689

[53] Soares et al. (2024). Health Risk Assessment of Air Pollution: assessing the environmental burden of disease in Europe in 2022. (Eionet Report – ETC HE 2024/6). European Topic Centre on Human Health and the Environment. Available at: https://www.eionet.europa.eu/etcs/etc-he/products/etc-he-products/etc-he-reports/etc-he-report-2024-6-assessing-the-environmental-burden-of-disease-related-to-air-pollution-in-europe-in-2022/view

[54] Horálek et al. (2024), Air quality maps of EEA member and cooperating countries for 2022: PM10, PM2.5, ozone, NO2, NOx and benzo(a)pyrene spatial estimates and their uncertainties, ETC HE Report 2024/4X, European Topic Centre on Human Health and the Environment (ETC HE), Kjeller.

[55] Kienzler et al. (2022). Estimating the morbidity related environmental burden of disease due to exposure to PM2.5, NO2 and O3 in outdoor ambient air. (Eionet Report – ETC HE 2022/11). European Topic Centre on Human Health and the Environment. Available at: https://www.eionet.europa.eu/etcs/etc-he/products/etc-he-products/etc-he-reports/etc-he-report-2022-11-estimating-the-morbidity-related-environmental-burden-of-disease-due-to-exposure-to-pm2-5-no2-and-o3-in-outdoor-ambient-air

[56] Horálek et. al. (2022), European air quality maps for 2019, PM10, PM2.5, Ozone, NO2 and NOx Spatial estimates and their uncertainties, ETC/ATNI Report 1/2021. Available at: https://www.eionet.europa.eu/etcs/etc-atni/products/etc-atni-reports/etc-atni-report-1-2021-european-air-quality-maps-for-2019-pm10-pm2-5-ozone-no2-and-nox-spatial-estimates-and-their-uncertainties

(compared to 35 ppb for SOMO35) and therefore provides a lower counterfactual concentration for sensitivity testing of attributable health impacts.

The findings of this additional sensitivity analysis suggest that exposure to O_3, represented by SOMO10 concentrations, potentially resulted in around 116,000 [95% CI: 91,000-141,000] attributable premature deaths, and around 21,000 [95% CI: 3,000-38,500] hospital admissions due to respiratory illness in the EU-27. The Table below presents a summary of the SOMO10-based health impacts assessed for the EU-27 and the six Member States.

Table 4-6 Additional sensitivity analysis of health impacts from SOMO10 exposure in 2022 (central [low-high] estimates)

Geography	Mortality (Statistical deaths) due to SOMO10 exposure	Life Years lost (YLL) from deaths due to SOMO10 exposure*	Respiratory hospital admissions due to SOMO10 exposure
Germany	**22,000** [17,000-26,000]	**22,000** [17,000-26,000]	**4,000** [1,000-6,600]
Denmark	**1,000** [900-1,400]	**1,000** [900-1,400]	**200** [40-500]
Spain	**11,000** [8,000-13,000]	**11,000** [8,000-13,000]	**1,000** [200-2,200]
France	**15,000** [11,000-18,000]	**15,000** [11,000-18,000]	**2,000** [300-3,300]
Hungary	**3,000** [2,600-4,000]	**3,000** [2,600-4,000]	**200** [30-300]
Italy	**17,000** [14,000-21,000]	**17,000** [14,000-21,000]	**1,600** [260-3,100]
EU-27	**116,000** [91,000-141,000]	**116,000** [91,000-141,000]	**21,000** [3,000-38,500]

** Please note: The YLL are equal to the number of premature deaths based on the Clean Air Outlook's assumption of 1 year of life expectancy lost per premature death due to short-term* O_3 *exposure.*

Comparing with the main estimates in the Study, the lowest impacts are estimated for the SOMO35 metric whereas the highest impacts are estimated for the SOMO10 metric, confirming that metrics with lower counterfactual values lead to higher attributable impacts. The Table below presents the estimated mortality impacts from ozone exposure using different metrics and counterfactual values, for ease of comparison.

Table 4-7 Comparison of mortality (statistical deaths) from O_3 exposure in 2022, by metric (central [low-high] sensitivities)

Metric	SOMO35	Peak season	SOMO10 (additional sensitivity analysis)
Counterfactual	***70 µg/m³***	***60 µg/m³***	***20 µg/m³***
Germany	**7,000** [6,000-9,000]	**14,000** [0-29,000]	**22,000** [17,000-26,000]
Denmark	**200** [180-300]	**500** [0-1,000]	**1,000** [900-1,400]
Spain	**5,000** [4,000-6,000]	**6,000** [0-13,000]	**11,000** [8,000-13,000]
France	**5,000** [4,000-6,000]	**9,000** [0-18,000]	**15,000** [11,000-18,000]
Hungary	**1,500** [1,000-2,000]	**2,000** [0-5,000]	**3,000** [2,600-4,000]
Italy	**9,000** [7,000-11,000]	**13,000** [0-26,000]	**17,000** [14,000-21,000]
EU-27	**43,000** [34,000-52,000]	**73,000** [0-146,000]	**116,000** [91,000-141,000]

A review of the literature highlights a lack of consensus regarding the use of thresholds or counterfactuals in health impact assessment. While counterfactuals aligned with the WHO 2021 AQG levels are commonly used in Europe and several global studies[57,58], the UK's Committee on the Medical Effects of Air Pollutants

[57] Malashock et al. (2022). Global trends in ozone concentration and attributable mortality for urban, peri-urban, and rural areas between 2000 and 2019: a modelling study. The Lancet Planetary Health, Volume 6, Issue 12, Pages e958-e967, ISSN 2542-5196. Available at: https://doi.org/10.1016/S2542-5196(22)00260-1.

[58] Vicedo-Cabrera et al. (2020). Short term association between ozone and mortality: global two stage time series study in 406 locations in 20 countries. BMJ (Clinical research ed.), 368, m108. Available at: https://doi.org/10.1136/bmj.m108

(COMEAP)'s latest guidance from 2015[59] does not recommend the use of a threshold for quantification for short-term effects in the UK and identifies thresholds for long-term effects as an area for further review. Overall, a counterfactual level defined at 0 μg/m^3 would not be consistent with the scientific evidence for Europe detailed above. Moreover, such a counterfactual would also not offer an achievable or realistic alternative for comparison as it does not account for the levels of non-anthropogenic ozone derived from natural sources that cannot be eliminated from the air by controlling man-made pollution.

More broadly, associations between ozone exposure (measured using different metrics) and health impacts remain highly uncertain and subject to change as newer evidence becomes available. For example, the high-confidence association between mortality and peak season exposure to ozone from Huangfu and Atkinson (2020)[60], used as a basis for the AQG levels recommended by the WHO in 2021, has been found to be inconsistent by a recent meta-analysis by Kasdagli et al. (2024)[61], which in turn finds that ozone is only confidently associated with respiratory mortality measured using annual mean exposure[62]. The findings for attributable respiratory mortality using annual mean O_3 concentrations suggest that such exposure resulted in around 17,000 [95% CI: 7,000-27,000] attributable premature deaths, and around 178,000 [95% CI: 71,000-285,000] years of life lost due to respiratory mortality in the EU-27. The Table below presents a summary of the annual mean-based health impacts assessed for the EU-27 and the six Member States. To note, this estimates have been calculated to illustrate the range of results (within the sensitivity analysis) depending on the ozone metric which informs the assessment.

Table 4-6 Additional sensitivity analysis of respiratory mortality impacts from annual mean exposure in 2022 (central [low-high] estimates)

Geography	Respiratory mortality (Statistical deaths) due to long-term exposure (annual mean)	Years of life lost (YLL) from respiratory mortality due to long-term exposure (annual mean)
Germany	**1,000** [500-2,000]	**13,000** [5,000-20,000]
Denmark	**200** [100-250]	**2,000** [700-3,000]
Spain	**4,000** [1,000-6,000]	**40,000** [16,000-64,000]
France	**2,000** [800-3,000]	**22,000** [9,000-35,000]
Hungary	**300** [100-500]	**3,000** [1,000-5,000]
Italy	**5,000** [2,000-8,000]	**51,000** [20,000-81,000]
EU-27	**17,000** [7,000-27,000]	**178,000** [71,000-285,000]

Nevertheless, this Study showcases that ozone exposure, measured using metrics (i.e., peak season and SOMO35) and non-zero counterfactual levels aligned with the latest WHO guidance[63] may result in thousands of premature deaths and billions of euros in human health costs. Further, the additional sensitivity analysis has highlighted that the estimated health impacts of ozone exposure are highly sensitive to the choice of endpoint, ozone metric and counterfactual concentration, with lower counterfactuals necessarily resulting in larger attributable impacts. The high degree of heterogeneity in the current epidemiological evidence regarding the health impacts of ozone exposure suggests that this remains an important area for future research.

[59] COMEAP (2015). Quantification of Mortality and Hospital Admissions Associated with Ground-level Ozone. Available at: https://assets.publishing.service.gov.uk/media/5a80ea7fe5274a2e87dbc8ab/COMEAP_Ozone_Report_2015__rev1_.pdf

[60] Huangfu and Atkinson (2020). Long-term exposure to NO2 and O3 and all-cause and respiratory mortality: A systematic review and meta-analysis. Environ Int 144:105998. Available at: https://doi.org/10.1016/j.envint.2020.105998

[61] Kasdagli et al. (2024). Long-Term Exposure to Nitrogen Dioxide and Ozone and Mortality: Update of the WHO Air Quality Guidelines Systematic Review and Meta-Analysis. International journal of public health, 69, 1607676. Available at: https://doi.org/10.3389/ijph.2024.1607676

[62] Annual mean has been defined as the average concentration of hourly surface O3 over the course of a full year as described in the EMEP dataset

[63] As of the completion of this Study, this refers to WHO (2021). WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Available at: https://iris.who.int/server/api/core/bitstreams/551b515e-2a32-4e1a-a58c-cdaecd395b19/content

4.2 ENVIRONMENTAL ASSESSMENT

4.2.1 Introduction

In addition to detrimental impacts upon human health, increased levels of atmospheric pollutants are harmful to the natural environment. Excessive exposure to air pollution can affect a wide range of vegetation, with the most significant effects including reduced growth, yield losses and lower seed production. Mitigating air pollution is therefore essential to protect ecosystems and maintain biodiversity.

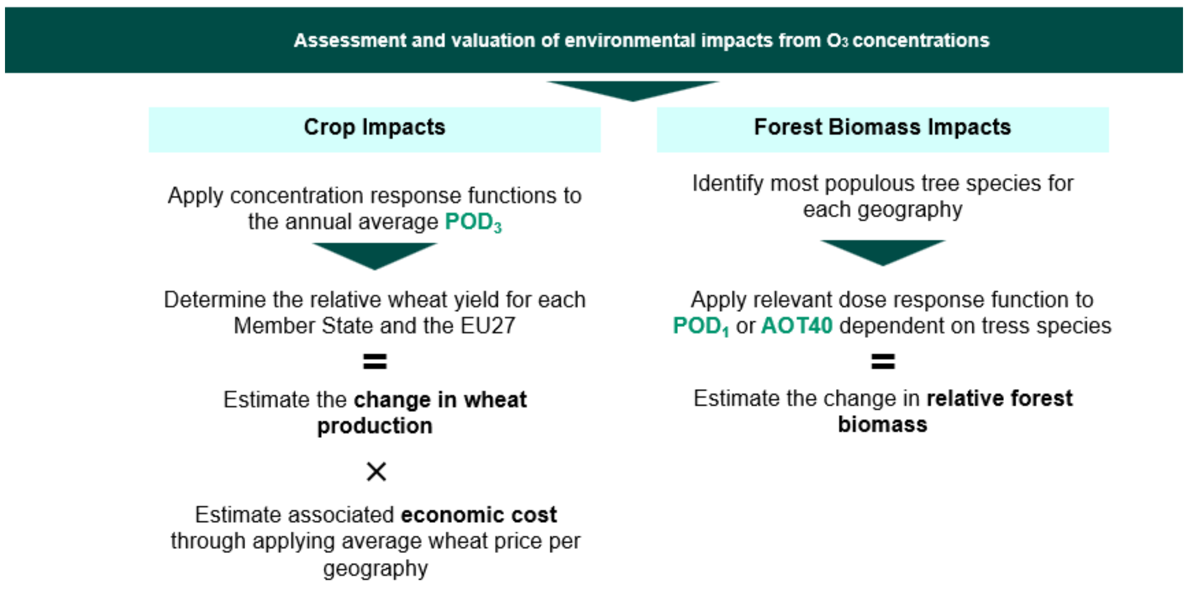
The focus of this study is the impact of O_3 concentration exposure upon wheat and forests. Elevated levels of O_3 can lead to chlorotic and necrotic lesions on the leaf surface of sensitive species, reduced growth from reduced photosynthesis[64] and also reductions in the quantity and quality of crop yield[65]. These effects are commonly observed, to varying degrees, across Europe. The assessment has quantified the impacts of exposure to O_3 upon wheat and forests by calculating the change in wheat production and total forest biomass attributed to O_3 exposure. The change in wheat production has been subsequently monetised to provide an estimate of the associated economic impact.

4.2.2 Methodology

The overarching approach to assessing the impact upon crop (wheat) yield and relative forest biomass has been illustrated in the figure below.

The full detailed methodology has been provided in Appendix C.

Figure 4-2 Approach to environmental assessment



4.2.3 Findings

A summary of the cost of the findings of the environmental assessment has been provided in Table 4-8. This includes the following for each of the six Member States and the EU27 resulting from exposure to O_3 concentrations. Notably, the EU is estimated to have lost 3.45 - 4.22 billion euros in wheat production alone with an average biomass loss for forest of 5.8%.

- Change in wheat production
- Change in forest biomass

[64] https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2023.1244515/full
[65] https://www.sciencedirect.com/science/article/abs/pii/S0048969724039676

- Economic valuation of a change in wheat production (based on absolute 2022 wheat prices)[66].

Table 4-8: Overview of findings of the environmental assessment

Geography	Decrease in wheat production (kt)	Cost of decrease in wheat production (M EUR)		Decrease in total forest biomass (%)
		Minimum	***Maximum***	
Germany	1,910	€570	€700	3.5%
Denmark	460	€120	€140	5.3%
Spain	380	€120	€150	1.9%
France	2,880	€620	€760	2.7%
Hungary	210	€60	€80	1.1%
Italy	630	€210	€260	3.9%
EU27	11,460	€3,450	€4,220	5.8%

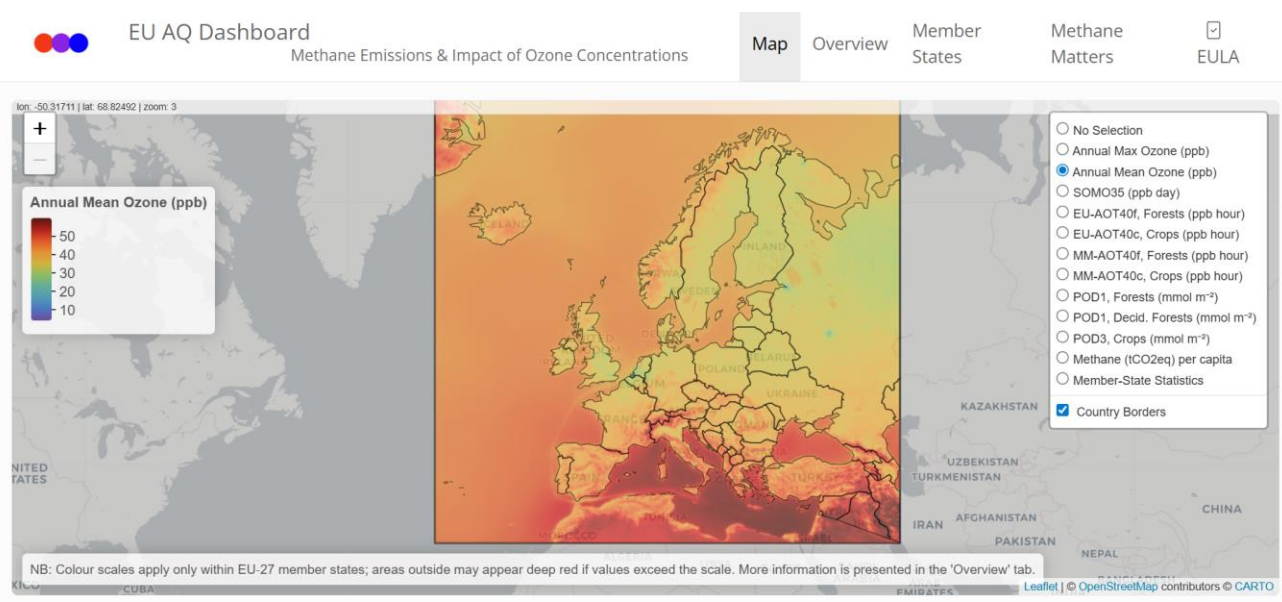
[66] Wheat prices were based on Eurostat data. For France the most recent data was for 2017 prices.

5. INTERACTIVE MAP

As part of the study an interactive dashboard was developed to more effectively communicate spatial data analysis to stakeholders. The main component of the dashboard is an interactive map which shows 1km × 1km gridded O_3 statistics, including AOT40 and POD_y. Specific features include:

- A "layer control" menu allowing for different statistics to be toggled between easily while retaining the existing extent of the map.
- A distinct legend per layer. If a user hovers over a grid-cell, the exact value it represents will be shown above the legend.
- A 'member-state' level statistics options, which allows users to click on a selection of EU member states to get higher-level statistics such as population weighted means. These values are also tabulated in a separate tab of the dashboard.
- "Utility layers" which can optionally be appended to the map, which include clear country borders and a satellite image basemap to help users get an appreciation for, e.g., topography.

Figure 5-1 A screenshot of the interactive map. The user is hovering over a grid cell, and the exact value is being shown at the top-right.



This dashboard was constructed using the Quarto[67] scientific publication system using the R statistical programming language and a collection of open-source R packages.[68] While R was involved in its initial construction, the dashboard itself is a "static"/serverless HTML file which has no R or other server requirements. As a result, the dashboard can be treated like any local file, such as an image or PDF document; it can be zipped, emailed, shared, stored on physical drives, and opened (in its case, using any modern web browser). Being a HTML file, it can also be hosted on any given web domain, or embedded in another website using an <iframe>.

[67] https://quarto.org/

[68] https://www.r-project.org/. Spatial data manipulation and visualisation packages include **sf**, **terra**, **leaflet**, **leafem** and **leaflegend**. Country boundaries were obtained using **rnaturalearth**. Data manipulation was achieved with the **tidyverse** collection of R packages. The "turbo" colour palette was accessed via **viridisLite**.

6. CONCLUSIONS

Despite decades of air quality legislation and emission reduction efforts, ground-level ozone (O_3) concentrations across Europe continue to exceed both EU target values. The persistence of these exceedances is evident in widespread breaches of health and vegetation metrics, including AOT40 and SOMO35, particularly in southern Member States. This ongoing challenge has profound implications: short- and long-term exposure to O_3 is associated with thousands of premature deaths annually, increased respiratory morbidity, and significant economic costs. In parallel, elevated O_3 levels contribute to reduced crop yields and forest biomass, threatening food security and ecosystem resilience.

Methane (CH_4) plays a critical role in sustaining O_3 formation through complex photochemical reactions. Although CH_4 is not classified as an air pollutant under current EU air quality legislation, it significantly contributes to harmful ground-level ozone globally. Its long atmospheric lifetime and uniform distribution mean that emissions from any region contribute to O_3 formation worldwide. This global influence explains in part why, despite reductions in CH_4 emissions within the EU, O_3 concentrations remain persistently high. Integrating CH_4 mitigation into air quality strategies would not only support the EU meet its 2030 and 2050 climate targets, but could deliver significant co-benefits for health and ecosystems, complementing traditional controls on NO_x and VOCs.

Key findings from this assessment underline the scale of the problem. In 2022, short-term exposure to O_3 was linked to approximately 43,000 premature deaths and 8,000 respiratory hospital admissions across the EU-27, while long-term exposure may have contributed to over 73,000 deaths and 775,000 years of life lost. The associated non-market health costs are estimated at up to €88 billion annually. The study has also acknowledged the uncertainty within the health impact analysis. This discussion has attempted to illustrate the ongoing debate and evolving research on the most suitable approach and metrics to accurately model the health impacts of ozone exposure. For example, the use of alternative ozone metrics within the sensitivity analysis has highlighted the potential for far greater impacts than estimated using current guidance. Environmental impacts are similarly severe: O_3 exposure resulted in an estimated 11.5 million tonnes reduction in wheat production and a 5.8% decline in forest biomass EU-wide, equating to economic losses of up to €4 billion. These figures highlight the dual burden of O_3 pollution on public health and ecosystems.

Looking ahead, the opportunity to revise the National Emission Ceilings Directive (NECD) offers a critical opportunity to integrate methane into air quality legislation and strengthen alignment between air pollutant and greenhouse gas reduction strategies. Embedding CH_4 within the NECD, alongside traditional ozone precursors, would enable a more holistic approach to tackling O_3 exceedances. Coupled with international cooperation under frameworks such as the Gothenburg Protocol and the Global Methane Pledge, this integration could deliver significant health and environmental benefits while advancing climate objectives.

Addressing this issue requires urgent, coordinated, and collaborative policy development across sectors and governance levels. Future frameworks must align air pollutant and GHG reduction targets, strengthen international cooperation, and prioritise measures that deliver synergistic benefits. Without such integrated action, Europe risks continued exceedances, escalating health burdens, and irreversible environmental damage.

Appendix A: Overview of ozone modelling options

Table 6-1. Overview of the advantages and drawbacks of the ozone modelling options which can be considered for this report. A colour code is used to show the good (green), medium (orange) and less favoured (red) options.

Model	International reporting	Evaluation	Availability	File size	More recent air quality year	Spatial resolution of the air quality simulation	Emissions preparation	Representativeness of the emission	O_3 metrics	POD variable	Representativeness of the air quality simulation	Emission scenario analysis	Health Impact assessment
EMEP/MSC-W	Official report under CLRTAP	Annually validated	Processed data available online (direct download)	Mb	2022	0.1°×0.1°	Not needed	Official reporting emission (EMEP)	Annual averaged data, so limited to the existing list provided in the dataset	Already calculated	Rely on one model	Not possible (using already processed data)	Required calculation based on the air pollutants metrics
CAMS	Published online within CAMS programme	Quarterly evaluated[69]	Processed data available online (direct download)	Mb	2022 (reanalysis)	0.1°×0.1°	Not needed	CAMS emissions are based on various existing data sets	Hourly O_3 concentrations, so flexibility on calculating metrics (e.g. SOMO10, AOT40)	Not available	Can use an ensemble of 11 models: ensemble products yield on average better performance than the individual model products.	Not possible (using already processed data)	Required calculation based on the air pollutants metrics

[69] https://atmosphere.copernicus.eu/regional-services

Ricardo modelling using CMAQ	Official reporting by the US Environment Protection Agency – While it is used as an official reporting in Europe, it is commonly used for air quality studies in Europe.	Validation can be performed (additional task). A former version is constantly validated internally	Need to perform the simulation: Running time of ~few weeks	Tb	Flexible: Different years can be modelled	Flexible: 50km×50km Or 10km×10km Or 2km×2km (finer spatial resolution requires larger disk space and computing time)	Processing of the emissions is required to undertake the air quality simulation	Flexible: Can used the official reporting emission (EMEP) or other inventories	Hourly O_3 concentrations, so flexibility on calculating metrics (e.g. SOMO10, AOT40)	Can be calculated using Ricardo's Surface Ozone Flux Model (additional task).	Rely on one model	Flexibility in using different emission scenarios	Required calculation based on the air pollutants metrics
FAST	Devlopped by the European Commission (JRC) and not used for European reporting	Air quality concentrations are based on EMEP/MSC-W	online	Online tool	Used to assess impact of future emissions (e.g. 2030)	0.1°×0.1°	Prescribed emissions (HTAP)	Prescribed emissions (HTAP)	Provided SOMO35, Max O3,	Not available but not necessary since the health impact assessment is calculated	Rely on one model	Already calculated	Already calculated

A.1 EMEP/MSC-W Air quality model

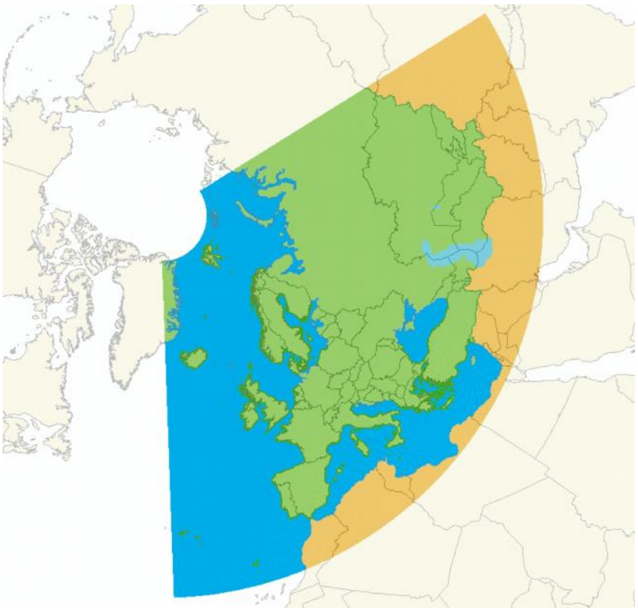
This study focuses on compiling and assessing 2022 O_3 concentrations in Europe based on findings provided in the 2024 EMEP report[70]. The modelled O_3 concentrations presented within this report are calculated by the EMEP/MSC-W[71], an atmospheric CTM. This type of CTM is commonly used to simulate the atmospheric chemistry processes required to simulate how gases and particles move and react in the atmosphere. It simulates how pollutants are transported by winds, turbulence, and convection; and chemical reactions between atmospheric species (e.g., O_3 formation, aerosol chemistry). These models also allow users to estimate the potential outcomes of different emission control strategies. The EMEP/MSC-W model provides a comprehensive representation of the emission, formation, destruction, transport, and deposition of numerous primary and secondary air pollutants. It is specifically designed to calculate air concentrations and deposition fields for major acidifying and eutrophying pollutants, photo-oxidants and particulate matter.

EMEP/MSC-W is a three-dimensional Eulerian model, described in detail in Simpson et al. (2012)[72], calculating the concentrations and depositions at a 0.1° latitude x 0.1° longitude spatial resolution. The results from the EMEP/MSC-W simulations are publicly accessible through the annual reports (EMEP, 2024), and the associated datasets can be freely downloaded[73].

The objective of these annual EMEP status reports is to provide an overview of the status of transboundary air pollution in Europe, tracing progress towards existing emission control protocols and supporting the design of new protocols, when necessary (EMEP, 2024). These results are revised every year[74].

The modelling domain covers the geographic area between 30°N-82°N latitude and 30°W-90°E longitude as presented in Figure 6-1.

Figure 6-1 EMEP modelling domain. Figure taken from (EMEP, 2024)



[70] emep.int/publ/reports/2024/EMEP_Status_Report_1_2024.pdf

[71] European Monitoring and Evaluation Programme / Meteorological Synthesizing Centre - West

[72] Simpson, D., Benedictow, A., Berge, H., Bergström, R., Emberson, L. D., Fagerli, H., Flechard, C. R., Hayman, G. D., Gauss, M., Jonson, J. E., Jenkin, M. E., Nyíri, A., Richter, C., Semeena, V. S., Tsyro, S., Tuovinen, J.-P., Valdebenito, Á., and Wind, P.: The EMEP MSC-W chemical transport model– technical description, Atmos. Chem. Phys., 12, 7825–7865, https://doi.org/10.5194/acp-12-7825-2012, 2012.

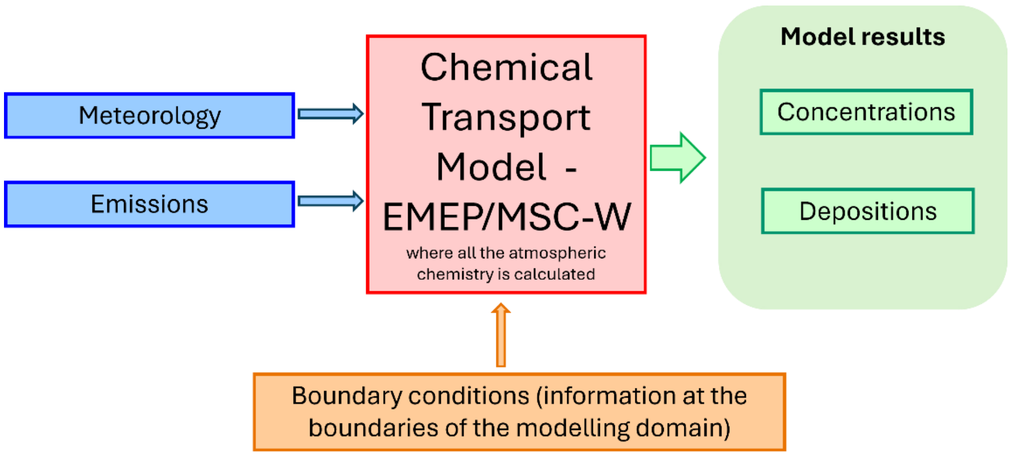
[73] https://www.emep.int/mscw/mscw_moddata.html

[74] https://www.emep.int/mscw/mscw_publications.html

CTMs such as EMEP/MSC-W consider the influence of the meteorology, emission inventories and transboundary pollution (also named as “boundary conditions”) on the calculation of the pollutants’ concentrations and depositions as summarised in Figure 6-2. This enables modelling the regional atmosphere and interactions in three dimensions; with the simulation happening simultaneously for all locations (gridded cells of the modelling domain) and parameters (e.g. pollutants) moving through all cell faces.

In the EMEP/MSC-W model CH_4 is treated as part of the general chemical background of the atmosphere, independent of local air pollution sources. Along with CH_4, the background chemistry also includes compounds such as O_3, and others that are present over large areas and vary only slowly over time. Unlike nitrogen oxides (NO_x) or volatile organic compounds (VOCs), which are released from local sources, such as traffic or industry and react quickly in the nearby air, CH_4 has sufficient lifetime to mix throughout the global atmosphere. Nevertheless, CH_4 is included in the model because it plays an important role in the wider atmospheric chemistry. It affects the number of reactive substances (or oxidants), such as O_3 and certain radicals (e.g. hydroxyl radical), which help break down other pollutants. By including CH_4 as a constant background level, the model can better simulate how air pollution behaves and changes over time across Europe.
The use of this model is time-consuming and requires an important disk space to usually handling Tb of data. However, the data used in this report is postprocessed and made available by the Norwegian Meteorological Institute. This enables access to the model results without undertaking the air quality simulation with this EMEP/MSC-W model.

Figure 6-2 Schematic diagram of the EMEP/MWC-W model functioning



The model calculates surface concentrations of gases and aerosols, along with various ground-level O_3 metrics. These O_3 metrics encompass annual mean and maximum O_3 levels, as well as cumulative exposure indicators such as:

- SOMO35 (Sum of O_3 Means Over 35 parts per billion [ppb]),
- AOT40 for forests and agricultural crops (Accumulated O_3 Over 40 ppb),
- MMAOT40 (AOT40 for forest upper canopy),
- AOT40 during the growing season for wheat (used as a proxy for temperate crops),
- POD1 (O_3 Flux for deciduous forests),
- POD3 (O_3 Flux during the growing season).

Full definitions for all metrics are provided in Appendix : Glossary.

It is important to note that the available dataset only provides averaged values, such as the annual mean surface O_3 concentration, without access to finer temporal resolution. In contrast, the WHO guideline and the EU Ambient Air Quality Directive (AAQD) limits are based on more detailed

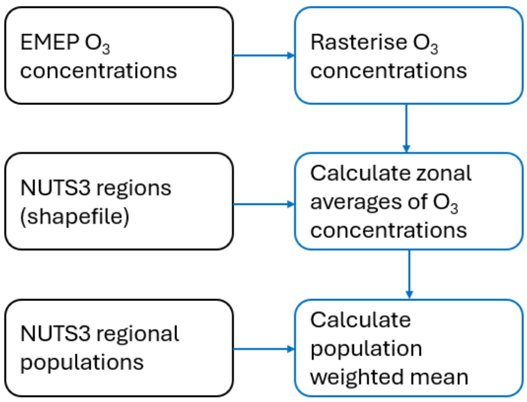
timeframes—using either seasonal data (WHO peak season limit[75]: 60 µg/m³) or 8-hourly mean limits (WHO[76]: 100 µg/m³; AAQD[77]: 120 µg/m³), requiring hourly concentrations to estimate these metrics.

A.1.1 Population data

To assess the impact of O_3 concentration on human health, population data was used as a proxy to calculate population weighted mean concentrations for the selected Member States. Population data[78] for 2022 has been chosen to be consistent with the selected year of the air quality model simulation. NUTS3 is the most disaggregated level of statistical population data available for regions in the European Union (EU). The advantage of using detailed NUTS3 regions is to use localised air quality concentrations and a granular population weighting in the health assessment.

O_3 annual mean concentrations across the EU were rasterised using GIS and Python scripts, and zonal averages by NUTS3 region were calculated. Thus, the O_3 annual mean concentrations from the EMEP results have been postprocessed to calculate the annual population weighted mean concentration using the NUTS3 zonal averages and populations (see Figure 6-3).

Figure 6-3 Input data and processing flow for calculating population weighted mean



[75] https://www.who.int/news-room/feature-stories/detail/what-are-the-who-air-quality-guidelines
[76] https://www.who.int/news-room/feature-stories/detail/what-are-the-who-air-quality-guidelines
[77] https://eur-lex.europa.eu/eli/dir/2024/2881/oj/eng
[78] Nomenclature of Territorial Units for Statistics (NUTS3) https://ec.europa.eu/eurostat/web/regions/database

Appendix B: Health assessment methodology

The health impact assessment was conducted in seven steps, as follows:

Step 1: Defining the pollutant concentrations. Human exposure was characterised by estimating the short-term and long-term population-weighted mean concentrations (in μg/m^3) of O_3 in 2022 (see Section 4.1). It was assumed that population exposure did not differ by age group. A counterfactual concentration[79] was also defined for short-term and long-term exposure metrics, aligned to the 2021 WHO AQG levels which represent the lowest levels of exposure for which there is evidence of adverse health effects.

Short-term exposure: Short-term exposure has historically[80] been assessed based on the SOMO35 metric (i.e., the $SOMO35_{annual\ sum}$), which is defined as the accumulated daily maximum 8-hour mean O_3 concentration in excess of 35 parts per billion (equivalent to 70 μg/m^3). Thus, 70 μg/m^3 is used as an implicit counterfactual concentration for short-term exposure in this Study. SOMO35 concentrations were sourced from the EMEP (see Section 3). To get the average daily mean maximum 8-hour mean concentration (i.e., the $SOMO35_{dm}$), the SOMO35 concentration was transformed as follows:

$$SOMO35_{dm}\ (\mu g/m^3) = \frac{SOMO35_{annual\ sum}\ (\mu g/m^3.days)}{365\ (days)}$$

Long-term exposure: According to the WHO Global AQG (2021)[81], long-term exposure is linked to the peak season metric, which is defined as the average of the daily maximum 8-hour mean O_3 concentrations in the six consecutive months with the highest six-month running-average O_3 concentration. The WHO recommends a peak season O_3 AQG level of 60 μg/m^3, which is used as a counterfactual concentration for long-term exposure in this Study. Since peak season concentrations for 2022 were not available from the O_3 modelling, these were sourced from the 'Burden of disease of air pollution' dataset published by the European Environment Agency (EEA)[82] which can be approximated to the $MDA8_{AS}$ metric[83] published by the EMEP.

Step 2: Affected population. The populations that could be affected by these pollutant concentrations were identified, based on the latest available evidence from Eurostat[84] and an understanding of the literature (see Steps 3 and 4).

Step 3: Health risks, association and selection. The latest evidence[85] of health risks associated with air pollutant exposure for O_3 was reviewed, and the relevant health pathways or endpoints were selected for the analysis – i) premature (all-cause) mortality; and ii) respiratory hospital admissions. In addition, baseline risks

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[79] The counterfactual concentration is a threshold level of exposure which represents the concentration of an air pollutant above which health impacts are expected to begin to occur.

[80] Studies using the SOMO35 as a short-term exposure indicator include: Fourth Clean Air Outlook (2025). Available at: https://data.europa.eu/doi/10.2779/8768689; and Soares et al. (2024). Health Risk Assessment of Air Pollution: assessing the environmental burden of disease in Europe in 2022. (Eionet Report – ETC HE 2024/6). European Topic Centre on Human Health and the Environment. Available at: https://www.eionet.europa.eu/etcs/etc-he/products/etc-he-products/etc-he-reports/etc-he-report-2024-6-assessing-the-environmental-burden-of-disease-related-to-air-pollution-in-europe-in-2022/view

[81] WHO (2021). WHO global air quality guidelines. Particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Available at:https://iris.who.int/bitstream/handle/10665/345329/9789240034228-eng.pdf

[82] EEA (2024). Burden of disease of air pollution (Countries, NUTS regions and cities), tabular data (2005-2022). Available at: https://sdi.eea.europa.eu/catalogue/srv/api/records/258fa83c-dec6-4d88-b1fb-959f2d90008f?language=all

[83] The EMEP Status Report (2025) describes the $MDA8_{AS}$ as the April to September average of the maximum daily 8-hour running average ozone concentrations, which correspond to the peak season level specified by WHO. EMEP Status Report 1/2025. Transboundary particulate matter, photo-oxidants, acidifying and eutrophying components. Joint MSC-W & CCC & CEIP & CIAM Report. Available at: https://emep.int/publ/reports/2025/EMEP_Status_Report_1_2025.pdf

[84] Eurostat (2023). Population on 1st January by age, sex and type of projection. Available at: https://ec.europa.eu/eurostat/databrowser/view/proj_23np/default/table?lang=en [accessed on 04.09.2025]

[85] European Commission: Directorate-General for Environment, IIASA, , EMRC, , MET Norway, , TNO, , e-misia, , RIVM, , & Logika Group, (2025). Support to the development of the fourth clean air outlook : final report, Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2779/8768689

were also documented from a range of sources, including Eurostat[86], WHO[87] and the IHME Global Burden of Disease studies[88].

Step 4: Concentration Response Functions. For the selected pathways, the latest and/or most robust concentration response functions (CRFs) were identified from the Fourth Clean Air Outlook (2025) and the WHO Global AQG (2021), which provide the effect measure per unit increase in exposure. These CRFs capture the relationships between pollutant exposure and health outcomes such as all-cause mortality from short-term exposure[89], all-cause mortality from peak season exposure[90] and morbidity represented by respiratory hospital admissions[91].

Table 6-2 Overview of CRFs used in the health impact assessment

Health outcome	Exposure metric	CRF per 10 µg/m³ [95% CI]	Age group
All-cause mortality	Peak season	1.01 [1.00-1.02]	25+ years
All-cause mortality	SOMO35	1.0043 [1.0034- 1.0052]	All ages
Hospital admissions for respiratory diseases	SOMO35 and peak season	1.0044 [1.0007-1.0083]	65+ years

Step 5: Impact analysis. Three health impact metrics have been covered by the study, described in. These include the potential: i) number of statistical deaths; ii) number of respiratory hospital admissions; and iii) iii) Life Years lost due to premature mortality. The impacts were assessed across the central and 95% confidence interval associated with the CRFs, to account for the uncertainties across the underpinning studies.

The $Impact$ (in terms of either $Premature\ deaths$ or $Respiratory\ hospital\ admissions$) is estimated using the CRF per µg/m³ increase in O_3 exposure, baseline mortality or incidence rates ($Baseline\ rate$) and size of the affected population group ($Affected\ population$) as follows:

- <u>For short-term impacts</u>: $Impact = SOMO35_{dm} * CRF * Baseline\ rate * Affected\ population$ where $SOMO35_{dm}$ refers to the daily mean values derived from the SOMO35 concentrations.
- <u>For long-term impacts</u>: $Impact = (C_A - C_0) * CRF * Baseline\ rate * Affected\ population$ where C_A refers to the modelled peak season O_3 concentration and C_0 refers to the counterfactual peak season concentration (equal to 60 µg/m³).

The number of statistical deaths is further used to estimate the potential Life Years lost (YLL) due to premature mortality: $YLL = Premature\ deaths * life\ expectancy\ lost\ per\ premature\ death$

<u>For short-term impacts:</u> The Fourth Clean Air Outlook (2025)[92] proposes a conservative approach of assuming that deaths from short-term O_3 exposure are equivalent to the loss of 1 year of life expectancy per death. This is due to the high variability in the conclusions of work on chronic impacts of O_3, although it is acknowledged that this could potentially undervalue O_3 health impacts.

[86] Eurostat (2023). Hospital discharges by diagnosis, in-patients, total number. Available at: https://ec.europa.eu/eurostat/databrowser/view/hlth_co_disch1/default/table?lang=en [accessed on 10.10.2025]

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[88] IHME (2025). Global Burden of Disease (GBD). Available at: https://www.healthdata.org/research-analysis/gbd [accessed on 10.10.2025]

[89] The CRF for all-cause mortality linked to short-term ozone exposure, referenced in the WHO Global AQG (2021), is originally from Orellano et al. (2020). Short-term exposure to particulate matter (PM10 and PM2.5), nitrogen dioxide (NO2), and ozone (O3) and all-cause and cause-specific mortality: systematic review and meta-analysis. Environ Int. 142:105876. Available at: https://doi.org/10.1016/j.envint.2020.105876

[90] The CRF for all-cause mortality linked to peak season ozone exposure, referenced in the Fourth Clean Air Outlook (2025), is originally from Huangfu and Atkinson (2020). Long-term exposure to NO2 and O3 and all-cause and respiratory mortality: A systematic review and meta-analysis. Environ Int 144:105998. Available at: https://doi.org/10.1016/j.envint.2020.105998

[91] The CRF for respiratory hospital admissions linked to short-term ozone exposure, referenced in the Fourth Clean Air Outlook (2025), is originally from WHO (2013). Health risks of air pollution in Europe: HRAPIE project: new emerging risks to health from air pollution: results from the survey of experts. Available at: https://iris.who.int/server/api/core/bitstreams/6d99ab82-8320-40b1-b080-eee217591c72/content

[92] European Commission: Directorate-General for Environment, IIASA, , EMRC, , MET Norway, , TNO, , e-misia, , RIVM, , & Logika Group, (2025). Support to the development of the fourth clean air outlook : final report, Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2779/8768689

For long-term impacts: The deaths from long-term O_3 exposure have been assumed to be equivalent to a loss of 11 years of life expectancy, on average, in line with evidence from the IHME Global Burden of Disease studies[93].

Therefore, the true impacts of O_3 exposure potentially lie within the range between the estimated short-term and long-term impacts.

The Table below provides an overview of the health impact metrics included in this Study.

Table 6-3 Overview of health impact metrics included in the health impact assessment

Impact	Metric	Description
Mortality	Statistical deaths	This represents the number of deaths that could be attributed to air pollution at a point in time based on scientific studies exploring the relationship between air pollution and mortality risk. It is a statistical or risk-based estimate, which means that air pollution is a risk factor that can contribute to higher rate of deaths at a moment in time, rather than air pollution being the only responsible cause. This calculation is not an estimate of the number of people whose untimely death is caused entirely by air pollution but a way of representing the effect across the whole population of air pollution when considered as a contributory factor to many more individual deaths.
Life Years lost (YLL)	LYs lost from deaths	This measures the years of life lost due to premature deaths, i.e., deaths occurring prematurely when compared to baseline or average life expectancy in each geography. Air pollution is a risk factor that is associated with higher mortality rates also at younger ages, directly linked to a higher rate of premature deaths, and thus, years of life lost. An average of around 1 life year lost due to premature deaths from short-term exposure, and 11 life years lost due to premature deaths from long-term exposure has been assumed, based on the available evidence.
Healthcare activity	Respiratory hospital admissions	This metric represents the number of cases and hospital admissions across different health endpoints attributable to exposure to air pollution. These estimates are based on scientific studies exploring the relationship between air pollution, ill-health risk and healthcare demand. These are statistical or risk-based estimates, which means that air pollution is a risk factor that can contribute to higher rates of illness and/or hospital care demand at a moment in time, rather than air pollution being the only responsible cause.

Step 6: Monetisation of impacts. The estimated health impacts (see Step 6) were monetised using unit values published by the Fourth Clean Air Outlook (2025)[94], as follows:

Non-market disease burden, which represent the non-market health and wellbeing costs associated with the Life Year losses from premature deaths due to O_3 exposure. These mortality impacts are monetised using the Value of a Life Year (VOLY), which reflects the amount that individuals are willing to pay for an additional

[93] Based on evidence from the IHME (2025). Global Burden of Disease (GBD). Available at: https://www.healthdata.org/research-analysis/gbd [accessed on 10.10.2025].

[94] European Commission: Directorate-General for Environment, IIASA, , EMRC, , MET Norway, , TNO, , e-misia, , RIVM, , & Logika Group, (2025). Support to the development of the fourth clean air outlook : final report, Publications Office of the European Union. Available at: https://data.europa.eu/doi/10.2779/8768689

year of life lived[95]. Non-market valuations represent the estimated monetary value of the welfare loss to individuals and society from illness or premature death that is not reflected in direct market costs, i.e. it is not captured through healthcare expenditures. So, the value is not so much a direct cost to the economy but a monetised reflection of the aggregated **burden upon individuals**. It is typically measured via willingness-to-pay approaches to reflect the loss of life years, quality of life, and wellbeing.

$$Non - market\ disease\ burden = YLL * VOLY$$

- Hospital admission costs, which represent the costs associated with the respiratory hospital admissions linked to O_3 exposure. These were monetised using the unit values per respiratory hospital admission (referred to as $Unit\ value$ below).

$$Hospital\ admission\ costs = Hospital\ admissions * Unit\ value$$

The estimated impacts were expressed in 2024 prices by adjusting for inflation using suitable GDP deflators[96].

Step 7: Additional sensitivity analysis. The main analysis conducted as part of this Study (see Steps 5-6 above) already includes sensitivity analysis based on the uncertainties in the scientific evidence and strength of association between exposure and impacts (quantified by the 95% Cis associated with the CRFs). As an additional exploration, the sensitivity of the impacts to the choice of metric and counterfactual values was tested using SOMO10, which is defined as the accumulated daily maximum 8-hour mean O_3 concentration in excess of 10 parts per billion (equivalent to 20 μg/m^3), and also the annual mean, which is defined as the annual average of the hourly surface O_3 concentrations.

Since SOMO10 concentrations for 2022 were not available from the O_3 modelling, these were sourced from the 'Burden of disease of air pollution' dataset published by the European Environment Agency (EEA)[97]. The methodology for estimating the impact using SOMO10 is as that outlined for SOMO35 above. The annual mean concentrations were sourced from the O_3 modelling based on the EMEP (see Section 3). The methodology for estimating the impact on respiratory mortality using the annual mean is similar to that outlined for peak season, using a CRF per 10 μg/m^3 of 1.05 [95% CI 1.02,1.08][98] applied to adults (30+ years). Please refer to Section 4.1.3 for the uncertainties and sensitivities analysis.

Appendix C: Environmental assessment methodology

Crop damage

To determine the impact of O_3 exposure on wheat production a literature review was undertaken to determine the most applicable concentration response function (CRF). The selected CRF was obtained from an academic study[99] which compiled exposure-yield relationships for various O_3 metrics and types of crop. The CRF determines the relative yield as a result of exposure to POD_3 (Phytotoxic O_3 Dose above a threshold flux of 3 nmol O_3 m^{-2} s^{-1}). It is a flux-based metric used to assess the amount of O_3 that actually enters plant leaves through stomata, rather than just the ambient concentration in the air. The CRF for wheat is as below, where RY = relative yield.

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[95] The value of a life year (VOLY) is a concept used to assess the economic value of an additional year of life by estimating that individuals are willing to pay for a reduction in their risk of dying. It is typically estimated through surveys that elicit respondents' preferences regarding the value of life years. This value is typically used in government policy evaluations to assess the benefits of interventions like air pollution mitigation.

[96] Eurostat (2025). Gross domestic product (GDP) and main components (output, expenditure and income). Available at : https://ec.europa.eu/eurostat/databrowser/view/namq_10_gdp$defaultview/default/table?lang=en [accessed on 10.10.2025]

[97] EEA (2024). Burden of disease of air pollution (Countries, NUTS regions and cities), tabular data (2005-2022). Available at : https://sdi.eea.europa.eu/catalogue/srv/api/records/258fa83c-dec6-4d88-b1fb-959f2d90008f?language=all

[98] Kasdagli et al. (2024). Long-Term Exposure to Nitrogen Dioxide and Ozone and Mortality: Update of the WHO Air Quality Guidelines Systematic Review and Meta-Analysis. International journal of public health, 69, 1607676. Available at: https://doi.org/10.3389/ijph.2024.1607676

[99] https://www.frontiersin.org/journals/sustainable-food-systems/articles/10.3389/fsufs.2021.534616/full

$$RY = 1 - 0.0064POD3$$

The steps followed to apply the response function to determine the impact upon wheat are as follows:

Step 1: Apply concentration response functions to the annual average POD_3

The first step applied the average POD_3 for each geographic focus of the study (six Member States and the EU27) to the wheat CRF. This calculation provided the relative wheat yield for each Member State and the EU27. The average POD_3 was taken from the modelled concentrations within EMEP, as detailed in Section 1.1

Step 2: Estimate decrease in wheat production

The decrease in wheat production was determined through applying the relative wheat yield to the wheat production in each Member State and EU27. Member State and EU wheat production levels were obtained from Eurostat[100].

Step 3: Estimate the economic cost associated with the decrease in wheat production

The economic cost of the decrease in wheat production was estimated through applying the price of wheat per Member State, as obtained from Eurostat[101] and representative of 2022. Due to the uncertain nature of wheat price, ± 10% was applied to the value to provide a range of economic impacts to account for fluctuations from the 2022 price year.

Forest damage

Step 1: Identify impacted metrics

The impact of air pollution on forests is dependent on the tree species. The first step in determining the impact upon forest biomass is therefore to understand the composition of tree species within the forested regions. Within the scope of this study the environmental impact assessment has focussed on the most common tree species within geographic area.

Step 2: Identify concentration response function (CRF)

The relevant CRF was obtained from a study[102] which derived O_3 dose-response relationships for five European forest tree species. The CRF determines the relative total biomass (RTB) as a result of either POD_1 (POD above a threshold flux of 1 nmol O_3 m^{-2} s^{-1}) or AOT40 (Accumulated O_3 concentration) over 40 ppb. POD_1 has been applied within the response functions for the two most common tree species in the selected Member States, namely Norway spruce and Oak.

POD is also the preferred metric for determining the impact of O_3 upon Scots pine, which is the most common tree species in EU27. However, to application of the CRF for Scots pine required the use of POD_2 **Error! Bookmark not defined.** . However, as the data collected through the EMEP model (detailed in Section 2) does not include POD_2 concentrations the CRF based on the AOT40 metric was applied[103].

The table below details the CRF obtained for each of the most common tree species for each Member State and the EU27.

Table 6-4: Most common tree species for each country and the associated CRF

Geography	Most common tree species	CRF
Germany	Norway spruce[104]	RTB = 1 – (0.0022*POD_1)

[100] https://ec.europa.eu/eurostat/databrowser/view/tag00047/default/table?lang=en&category=t_agr.t_apri

[101] https://ec.europa.eu/eurostat/databrowser/view/tag00059/default/table?lang=en&category=t_agr.t_apri

[102] https://www.sciencedirect.com/science/article/abs/pii/S0269749115003267

[103] Although it is not possible to state the exact difference in results for this assessment as a result of substituting AOT40 tor POD_2, the use of POD_2 is considered more robust as it accounts for variance in stomatal uptake (e.g. closure) and other environmental constraints. AOT40 therefore may over-estimate the impact in environments where plants typically close their stomata, but under-estimate in environments with high stomatal activity (humid and cool climates).

[104] https://www.forstwirtschaft-in-deutschland.de/german-forestry/forest-facts/?L=1

Geography	Most common tree species	CRF
Denmark	Norway spruce[105]	
Spain	Oak[106]	RTB = 1.01 – (0.0024*POD_1)
France	Oak[107]	
Hungary	Oak[108]	
Italy	Oak[109]	
EU27	Scots pine[110]	RTB = 1 – (0.0021*AOT40)

Step 3: Application of relevant concentration response function to air quality data (POD1 or AOT40)

The assessment applied the annual average POD_1 for each of the six Member States and the annual average AOT40 for the EU27 to the relevant CRF (Table 3-1). This provided the % reduction in total forest biomass as a result of O_3 exposure. The average POD_1 and AOT40 were taken from the modelled concentrations within EMEP, as detailed in Section 3.

The economic impact of O_3 exposure to forests was not calculated as there is not a sufficient evidence base to determine the monetised value of a change in forest biomass.

Appendix D: Glossary

AAQD	Ambient Air Quality Directive
AOT40	AOT40 is the accumulated amount of O_3 over the threshold value of 40 ppb. The corresponding unit are ppb.hours (abbreviated to ppb.h). The usage and definitions of AOT40 have changed over the years though, and also differ between UNECE and the EU. For UNECE work, AOT40 values are best estimated for local conditions (using information on real growing seasons for example), and specific types of vegetation. In the EU approaches, O_3 concentrations are taken directly from observations (at typically ca. 3 m height), or grid-average 3 m modelled values.

[105] https://eng.naturstyrelsen.dk/nature-protection-projects/forestry
[106] https://www.miteco.gob.es/content/dam/miteco/es/biodiversidad/estadisticas/aef2019_completo_estandar_tcm30-534526.pdf
[107] https://inventaire-forestier.ign.fr/IMG/pdf/memento_2024.pdf
[108] https://nfi.nfk.gov.hu/
[109] https://link.springer.com/book/10.1007/978-3-030-98678-0
[110] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021SC0652

In the Mapping Manual (LRTAP 2009) approaches, there is a strong emphasis on estimating AOT40 using O_3 levels at the top of the vegetation canopy.

Since O_3 concentrations can have strong vertical gradients, this approach leads to lower AOT40 estimates than with the EU approach.

4 metrics are presented:

- EU-AOT40c - AOT40 calculated using EU criteria, from modelled (grid-average, 3 m) or observed O_3, for the assumed crop growing season of May-July. Here they use the EU definitions of day hours as 08:00-20:00.
- EU-AOT40f - AOT40 calculated using EU criteria from modelled (grid-average, 3 m) O_3, or observed O_3, for the assumed forest growing season of April-September. Here they use the EU definitions of day hours as 08:00-20:00.
- MM-AOT40f - AOT40 calculated for forests using estimates of O_3 at forest-top. This AOT40 is that defined for forests by LRTAP (2017), but using a default growing season of April-September. These calculations are made to the generic deciduous land-cover category denoted IAM_DF (Simpson et al. 2012).
- MM-AOT40c - AOT40 calculated for agricultural crops using estimates of O_3 at the top of the crop. This AOT40 is close to that defined for agricultural crops by LRTAP (2017), but using a default growing season of May-July, and a default crop-height of 1 m. These calculations are made to the generic land-cover.

CH_4 — Methane

CLRTAP — Convention on Long-range Transboundary Air Pollution

CMAQ — Community Multiscale Air Quality

EEA — European Environment Agency

EMEP — European Monitoring and Evaluation Programme

EMEP/MSC-W — European Monitoring and Evaluation Programme / Meteorological Synthesizing Centre - West

EU — European Union

Eurostat — Eurostat is the statistical office of the European Union

IAM — Integrated Assessment Modelling

NUTS — Nomenclature of Territorial Units for Statistics:
Statistical dataset provided by Eurostat

O_3 — O_3

POD — Phyto-toxic O_3 dose, is the accumulated stomatal O_3 flux over a threshold (1 or 3 mmol.m^{-2} in our case). It corresponds to the accumulated plant uptake of O_3 above this threshold during a specified time or growth period.
POD1 is used for forests and POD3 for the crops' growing seasons assessment.

SOMO35 — The Sum of O_3 Means Over 35 ppb is the indicator for health impact assessment recommended by WHO. It is defined as the yearly sum of the daily maximum of 8-hour running average over 35 ppb. For each day the maximum of the running 8-hours average for O_3 is selected and the values over 35 ppb are summed over the whole year.

UNECE — United Nations Economic Commission for Europe

WHO — World Health Organisation

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