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Global efforts addressing methane emissions is a key factor to further reducing ozone-induced yield losses of crops in Europe☆

Felicity Hayes [a,*], Katrina Sharps [a], Willem E. van Caspel [b], Zbigniew Klimont [c], Chris Heyes [c], Hilde Fagerli [b]

[a] UK Centre for Ecology & Hydrology, Deiniol Road, Gwynedd, Bangor, UK
[b] EMEP MSC-W, Norwegian Meteorological Institute, Oslo, Norway
[c] Pollution Management Research Group, Energy, Climate, and Environment (ECE) Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

ABSTRACT

This study has shown that there is a large potential to avoid wheat production losses through global efforts to reduce emissions of non-methane ozone precursors. In addition, global efforts to reduce methane concentrations could avoid additional wheat production losses due to the role of methane as an ozone precursor. Ex-post analysis on scenarios used within the European Monitoring and Evaluation Programme Meteorological Synthesizing Centre – West (EMEP-MSC-West) model revealed that within the United Nations Economic Commission for Europe (UNECE) region (excluding North America and Israel) in 2050 using the LOW future emission scenario, the reduction in ozone as a consequence of reducing global non-methane precursor emissions showed avoided wheat production losses of 6.4 million tonnes compared to that with current legislation. For the EU27 countries this was 3.1 million tonnes of wheat, equating to a value of approximately €675 million. Reducing both non-methane and methane ozone precursors globally have avoided wheat production losses in the UNECE region in 2050 totalling 9.0 million tonnes, compared to that calculated from emissions in current legislation. Within EU27 this was 4.4 million tonnes of wheat, equating to a value of approximately €976 million.

Within the UNECE region (excluding North America and Israel) the relative benefits of additional reductions in non-methane emissions within the region, non-methane emissions in the rest of the world, and global efforts to reduce methane emissions, were approximately equal. This demonstrates the benefits from reducing regional non-methane emissions, global non-methane emissions and global methane as contributing factors to avoiding crop yield losses due to their role in ozone formation.

1. Introduction

1.1. Ozone

Ground-level ozone is not emitted directly, but is a secondary pollutant formed by photochemical reactions involving precursor molecules that can include oxides of nitrogen (NOx), carbon monoxide (CO) and volatile organic compounds (VOCs). The photochemistry of ozone is complex and non-linear, and with simultaneous production and destruction of ozone (Monks, 2005; Monks et al., 2015). Ozone and ozone precursors can travel downwind at regional and hemispheric scales (HTAP et al., 2010). Although ozone concentrations are measured around the world, measurement sites remain rather sparse, particularly in rural areas. Due to the complexity of the chemistry of ozone precursor reactions, chemical transport models can be used to quantify the impact of local and regional pollution sources on the ozone formation within a particular area. These chemical transport models can be verified using measured data and have the advantage that the potential impact of changes in emissions of individual precursor species can be evaluated.

Ozone mixing ratios as a function of VOC and NO_x emissions reveal that ozone formation can be limited by either VOCs or NO_x (O'Connor et al., 2014). Additional aspects of the photochemistry include the different reactions of the wide range of chemicals that comprise the VOC group, that includes methanol and isoprene (Monks et al., 2009). Since the 1990's there have been large reductions in emissions of key ozone precursors (NO_x, non-methane volatile organic compounds - NMVOC, and CO) over Europe and North America following the introduction of policies addressing air quality (Archibald et al., 2020; Zhang et al., 2016; Monks et al., 2009; Kuenen et al., 2014). This reduction in ozone precursors has resulted in decreased ozone concentrations in Europe, particularly the highest ozone concentrations (Proietti et al., 2021; Ronan et al., 2020), for example, ozone accumulated over a threshold of 40 ppb declined by 26.5 % between 2000 and 2014. However, the potential impact to vegetation based on ozone uptake to vegetation in

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* Corresponding author.
E-mail address: fhay@ceh.ac.uk (F. Hayes).

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Europe has remained stable over the same period (Proietti et al., 2021). A similar pattern to that seen in Europe was observed in the USA, with a decline in concentration-based ozone metrics over the period 2005–2014, but no change or an increase for ozone uptake to plants (Ronan et al., 2020). Additionally, even though ozone concentrations have decreased in recent years, current concentrations are still a long way in excess of pre-industrial conditions. Even the most stringent scenarios applied in the UNECE region that assume use of additional technology are not projected to reduce ozone concentrations close to this level (Anenberg et al., 2012; Denby et al., 2024).

In contrast to the patterns in Europe and North America, anthropogenic emissions of ozone precursors have continued to rise in many other regions, particularly south-east Asia, where there are increasing emissions of ozone precursors due to a combination of population growth, urbanisation and increased large-scale agro-industry (Shao et al., 2024; Hewitt et al., 2009). Ozone concentrations are continuing to rise in these regions and projections show that concentrations will continue to rise until at least 2060 based on both baseline conditions and current goals scenarios (Nelson et al., 2024). Ozone concentrations are also anticipated to rise in future climate conditions due to increased ozone formation from accelerated chemical reactions (Chen et al., 2024), as well as increasing the emissions of biogenic VOCs (Li et al., 2019).

1.2. Methane

Methane is an ozone precursor, in addition to being a short-lived climate forcer. Short-lived climate forcers have a shorter atmospheric lifetime than carbon dioxide but can still contribute significantly to global warming. Methane is thought to have an atmospheric lifetime of approximately 12 years. Reducing emissions of short-lived climate forcers has been identified as a positive action to slow the pace of global warming (Shindell et al., 2012; Shoemaker and Schrag, 2013; IPCC, 2018; Szopa et al., 2021). However, in current legislation short-lived climate forcers are considered together, rather than as individual chemical species, which allows emissions of methane to be treated as interchangeable with emissions of carbon dioxide based on climate impacts (Mar et al., 2022). The Kyoto Protocol commitments, within the United National Framework Convention on Climate Change, include an overall emissions reduction target expressed as CO_2 equivalent. Similarly, the Paris Agreement allows countries to make mitigation pledges based on CO_2 equivalents. Methane concentrations are continuing to rise, due to increasing emissions (Jackson et al., 2020), with emissions in 2050 anticipated to increase by 30 % compared to those of 2015 (Höglund-Isaksson et al., 2020). Methane is not considered as an air pollutant, as is it is not considered to be directly harmful to health. However, the potential benefits of methane reductions for air quality have been previously shown and estimated (e.g., Anenberg et al., 2012; Amann et al., 2013; Mar et al., 2022; UNEP, 2022; Tatsumi, 2023). Approximately one-third to one-half of total annual emissions of methane are thought to be from anthropogenic sources (Guo et al., 2023), and with models showing that reduced methane emissions could reduce ozone concentrations (West and Fiore, 2005; Staniaszek et al., 2022; van Caspel et al., 2024). These concentration-based assessments have suggested that the consequent reduction in ozone concentration could benefit health by reducing premature mortality due to ozone (e.g., West et al., 2012; UNEP, 2022).

1.3. Impacts of ozone on crops

Impacts of ozone on plants include reduced photosynthesis, premature leaf senescence and reduced growth. Ozone enters the stomata, after which reactions quickly occur in the apoplast, with the formation of reactive oxygen species that act as signalling molecules (Jaspers and Kangasjärvi et al., 2010) in addition to causing damage to membranes (Nowroz et al., 2024). Negative effects of ozone have been demonstrated on a wide range of vegetation including trees, herbaceous plants, and crops (Mills et al., 2011a). Many crop species have been shown to be sensitive to ozone, with reductions in yield including for staple crops such as wheat (Pleijel et al., 2018), rice (Frei et al., 2012) and maize (Peng et al., 2018), as well as protein rich crops such as soybean (Li et al., 2024). More recently additional crops have been identified as ozone sensitive, including those of tropical crops (Hayes et al., 2020; Cheesman et al., 2023; Farha et al., 2023). As the main mechanism of impact of ozone on vegetation is via uptake of ozone through the stomata, the impacts on vegetation have been shown to be better related to ozone uptake rather than concentrations in the air (Mills et al., 2011a; Harmens et al., 2018). Dose-response relationships based on stomatal ozone uptake have been developed for several crops (Mills et al., 2011b), and the ozone yield gap in current conditions has been calculated (based on ozone uptake) to be 12.4 %, 7.1 %, 4.4 % and 6.1 % for soybean, wheat, rice, and maize, respectively (Mills et al., 2018).

1.4. Aims

In this study we aim to quantify the reduction in wheat yield loss that could potentially occur by reducing emissions of methane in addition to reductions in emissions of non-methane ozone precursors. We use the scenarios developed by the EMEP Centre for Integrated Assessment Modelling (CIAM), that separately illustrate the methane and non-methane emissions projections of a very ambitious but feasible scenario to indicate benefits that could be gained by addressing methane pollution as a contributor to ozone pollution, in addition to those of other ozone precursors. These scenarios were developed to contribute to the discussions associated with the ongoing revision of the Gothenburg Protocol (https://unece.org/environment/documents/2024/05/reports/report-executive-body-its-forty-third-session). We compare these to wheat yield losses from ozone concentrations that are projected based on current legislation.

2. Methods

This study comprised ex-post analysis of scenarios that were developed by the EMEP Centre for Integrated Assessment Modelling (CIAM) (Klimont et al., 2023) and processed within the EMEP MSC-West atmospheric chemistry-transport model (van Caspel et al., 2024). Outputs from the EMEP MSC-West atmospheric chemistry-transport model (Simpson et al., 2012) were used as a basis to evaluate the impact on crop yield. The workflow is shown in Supplementary Fig. S1.

2.1. Overview of scenarios used

The emissions scenarios used were developed by the EMEP Centre for Integrated Assessment Modelling (CIAM) to contribute to the discussions around the review of the Gothenburg Protocol and are fully described in Klimont et al. (2023) and van Caspel et al. (2024). These scenarios were developed using the global version of the GAINS model (Amann et al., 2011, 2020; Klimont et al., 2017; Höglund-Isaksson et al., 2020; Winiwarter et al., 2018) and include a current legislation scenario (CLE), a maximum technical feasible (MFR) scenario (not analysed as part of the current study), and a LOW scenario. Background methane concentrations were calculated using global anthropogenic emissions scenarios from CIAM, together with emissions of key compounds affecting the lifetime of methane via oxidation processes, using a box-model (Olivié et al., 2021), with the resulting methane projections used in the EMEP model alongside the full scenario emissions to simulate the impact on ozone concentrations.

The current legislation scenario (CLE) assumes effective implementation of current national and international air pollution and climate policies, e.g., for the EU consistent with the European Green Deal and the Fit for 55 package. Globally, the CO_2 emissions develop along a trajectory similar to the SSP2-4.5 scenarios while for methane the increasing trend continues.

The LOW scenario assumes a very ambitious air quality policy and climate policies compatible with the Paris Agreement goals. Air pollutant emissions are reduced through the full implementation of the proven technical mitigation potential, as defined in the GAINS model (the maximum technically feasible reduction – MTFR). For CO_2, global emissions are consistent with the SSP1-2.6 scenarios and methane is reduced by 50 % by 2050, relative to 2015.

The overall methane background concentrations resulting from the two emissions scenarios in 2050 are 2215 ppb in CLE and 1431 ppb in LOW (against a baseline concentration of 1834 ppb in 2015).

The scenarios used in the current study are for 2050, while van Caspel et al. (2024) used estimates for the whole 2015 to 2050 period. To reduce the effects of meteorological variability on the outcome, each scenario is simulated using meteorological conditions of 2013–2017 and the average was used.

2.2. Overview of the EMEP MSC-W atmospheric chemistry-transport model

The EMEP MSC-W atmospheric chemistry-transport model is described in detail in EMEP MSC-W (2023) and version 5.1 was used to calculate ozone fluxes to wheat using the emissions data for the scenarios above provided from CEIP and the GAINS model. The domain used is for the UNECE region, excluding North America and Israel (referred to as the 'region' in subsequent text, and with everywhere else referred to as the 'rest of the world'). The domain covers the geographic area between 30°N and 82°N latitude and 30°W-90°E longitude and includes the countries of Europe, together with Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan. Some parts of north Africa and Asia are included in the domain, but the methodology for inclusion of emissions from these countries matches that used for the 'rest of the world' rather than that used for the UNECE region. Within the regional domain, 0.1° × 0.1° gridded emissions were used, whereas for the rest of the world, global 0.5° × 0.5° gridded emissions were used. The regional and global grids use 3h meteorological data and ozone data. For both the lateral boundary conditions in the regional simulations and for initial conditions for the regional runs, the 6h output fields from the global simulations were used. Comparison of modelled vs measured values of peak season maximum daily 8-h mean of ozone was carried out as part of model quality checks and showed good agreement (van Caspel et al., 2024). Direct emissions of methane were not included within the EMEP model, concentrations were instead specified on an annual mean basis.

The permutations of the scenarios used in this study are shown in Table 1. Scenarios A, B and C were used to investigate the impact of non-methane compared to methane emissions on ozone-induced wheat production losses. Scenarios A - D are used to compare the influence of regional non-methane emissions to rest of the world non-methane emissions and global methane emissions. Each of the configurations was simulated for each of the five meteorological years between 2013 and 2017 (and then an average used). Global emissions totals for these scenarios for NOx, NMVOCs, CO and CH_4 are given in van Caspel et al. (2024). While the EMEP model and its chemistry are fully time dependent, background methane concentrations are specified at the start of each run and kept fixed throughout the simulation period. This is why methane is expressed in the table as a concentration rather than in terms of emissions.

Table 1
Scenario combinations used in the analysis, based on regional non-methane emissions, rest of the world non-methane emissions, and global background methane concentrations for the year 2050. Note that methane and non-methane emissions (in both CLE: Current Legislation and LOW scenarios) are considered separately.

	Regional Emissions	Rest of World Emissions	Global Methane
A	CLE	CLE	2215 ppb
B	LOW	LOW	2215 ppb
C	LOW	LOW	1431 ppb
D	CLE	LOW	2215 ppb

2.3. Calculation of ozone flux and additional analysis steps

Within the EMEP MSC-W atmospheric chemistry-transport model and using the EMEP 0.1° grid, the ozone flux metric POD_3IAM was calculated using the embedded DO_3SE (Deposition of O_3 for Stomatal Exchange) model. POD_Y (Phytotoxic Ozone Dose) is the accumulated plant uptake of ozone above a threshold of Y during a specified time or growth period. POD_YIAM is a vegetation-type specific POD_Y that is recommended for large-scale modelling, including integrated assessment modelling. For crops this is based on the parameterisation for wheat and full details are given in CLRTAP (2017), and the parameterisation used is given in (Table S1 supplementary material). The Atlantic parameterisations for wheat were used for all grid cells in this study, however, Mediterranean parameterisations are also available with some slight differences, e.g. in g_{max}, VPD and temperature. The key differences compared to the parameterisation used specifically for wheat are the accumulation period and the threshold above which ozone is accumulated. The accumulation period for ozone uptake used in this study was 90 days, centred on the timing of mid-anthesis as this is the most ozone-sensitive growth stage (in this case Days 123–213, start of May to end of July). This 90-day window is recommended to be used for large scale modelling, rather than the shorter windows used for crop-specific modelling, as this is to reduce the influence of interannual variability in timing of ozone episodes and timing of the dates of key physiological parameters. The threshold used to accumulate ozone flux in the current study was 3 nmol m^{-2} s^{-1} as this provides less uncertainty in modelled POD than the higher threshold of 6 nmol m^{-2} s^{-1} that is used in smaller scale studies. The parameterisation for POD_3IAM, unlike the crop-specific parameterisations, also does not include the modifying effect of soil moisture and phenology. The EMEP MSC-West model calculates values for irrigated and non-irrigated crops, and for this study, grid cells were first designated as irrigated or non-irrigated, with cells with >75 % irrigated production classed as irrigated, and all other cells classed as non-irrigated. The final POD_3IAM value for the cell was then given, based on the irrigated or non-irrigated EMEP data. If using the simplified flux models as a stand-alone application, this would indicate the risk of ozone damage under the worst-case scenario where soil moisture is not limiting stomatal ozone flux. However, when used within the EMEP model (Simpson et al., 2012), as in this case, a simplified soil moisture index is included within the EMEP model and thus soil moisture is already accounted for in the output.

Data on the wheat production (irrigated and non-irrigated) per grid cell was taken from the Spatial Production Allocation Model (SPAM) (You et al., 2014) (0.083° resolution) for the year 2010. This was then converted to values for 2015 using national crop production data from the Food and Agriculture Organisation (FAO). Using ArcGIS (ArcMap, version 10.8.2), wheat production per 0.1° grid cell was calculated, based on the production value of the SPAM cell with its pixel centre in the 0.1 cell. If there were more than one SPAM cell centres inside the 0.1° cells, then the mean production value was used. Grid cells were also each given a country ID, based on the area of the country within the cell. If a cell contained areas of more than one country, then the country taking up the majority of the cell was used. Production per grid cell for 2015 is shown in Supplementary Fig. S2.

Calculations of yield loss were made using the equation for POD_3IAM (CLRTAP, 2017) (Equation (1)). The dose-response relationship for wheat used within the LRTAP Convention is based on data from experiments in four countries (Belgium, Finland, Italy and Sweden) over a period of 14 years (CLRTAP, 2017). Yield loss is in comparison to wheat production in pre-industrial ozone concentrations, which was assumed to be 10 ppb. Production loss was then calculated following Mills et al.

(2018) (Equation (2)).

$$\% \text{ yield loss} = (\text{POD}_3\text{IAM} - 0.1)^{*}\ 0.64 \qquad \text{Equation 1}$$

$$\text{Total prod} / (1 - (\text{yield loss} / 100))) - \text{Total Prod}) \qquad \text{Equation 2}$$

Final maps of production loss were created using R (R Core Team (2024)), bringing together EMEP modelled ozone flux data and wheat production data to produce maps showing avoided wheat production losses by comparing outputs of different scenario runs.

Prices of wheat used a flat rate of €219.50 per tonne, which was the value for Paris (Euronext) Milling Wheat in December 2024. The prices give are for guidance only and do not reflect future price predictions and adjustments based on wheat grain availability and demand.

3. Results

3.1. Global emissions reductions scenarios

Overall, the results show that there is a large potential to avoid wheat production losses through additional global efforts to reduce emissions of non-methane ozone precursors. Within the region the potential benefits of reducing global non-methane emissions to those of the LOW scenario compared to those from current legislation in 2050 is avoided wheat production losses of 6.4 million tonnes. Benefits were shown in many countries, with large reductions in avoided wheat losses in many of the countries with the highest wheat production (Fig. 1). The total avoided wheat production losses for the top ten wheat producing countries in the region with reduced non-methane emissions globally compared to current legislation was 5.8 million tonnes (Fig. 2), and within the countries of EU27 this was 3.1 million tonnes, equating to a value of approximately €675 million. Values per country for these scenarios are shown in Supplementary Table 2, and the production losses in 2050 in current legislation, both with and without the predicted increase in global methane concentration, are shown in Supplementary Table 3.

When both non-methane and methane ozone precursors were reduced globally there were avoided wheat production losses in the region totalling 9.0 million tonnes, compared to that calculated from emissions in current legislation, with the benefit apparent across the region (Fig. 1b). The total avoided wheat production loss for the top ten wheat producing countries in the region was 7.2 million tonnes compared to the losses that would occur with current legislation, and within EU27 this was 4.4 million tonnes, equating to a value of approximately €976 million. Overall, the additional benefit of reducing methane emissions compared to reducing non-methane emissions alone was additional avoided production loss of 40 % in the region (44 % in the EU27 countries), with this totalling 2.6 million tonnes and 1.4 million tonnes in the region and in the EU27 countries respectively (equating to €534 million and €301 million, respectively). Additional avoided production loss was shown for all countries within the region, with the range being 22.1 %–71.6 % across the comprising 43 countries when global methane emissions were reduced in addition to non-methane emissions.

The largest benefits in avoided wheat production losses were in countries where the wheat production was highest (Fig. S3 Supplementary information). A comparison between scenarios at the country scale shows a significant increase in avoided wheat production loss as a result of reductions in all emissions, compared to non-methane emissions alone (Paired Student t-test, $t = -3.6454$, $p = 0.0007$), and

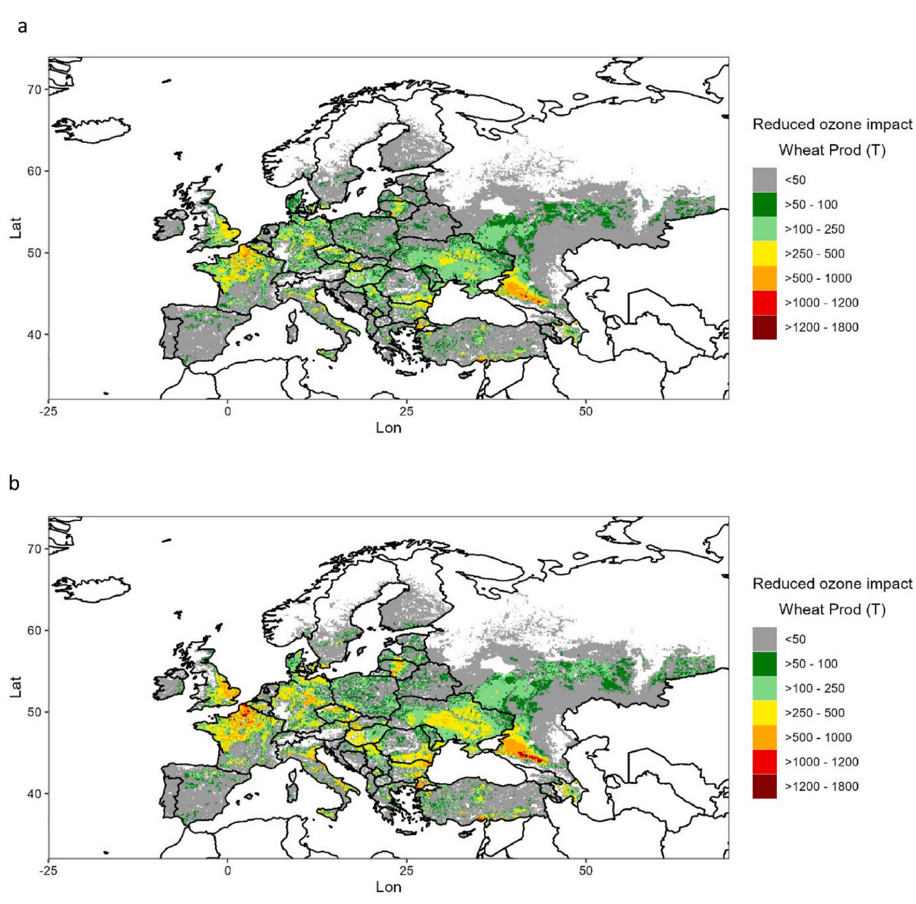

Fig. 1. Additional avoided wheat production losses due to ozone uptake per 0.1° grid cell using the LOW emissions scenario compared to that for current legislation in 2050 for a) non-methane emissions and b) methane and non-methane emissions. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

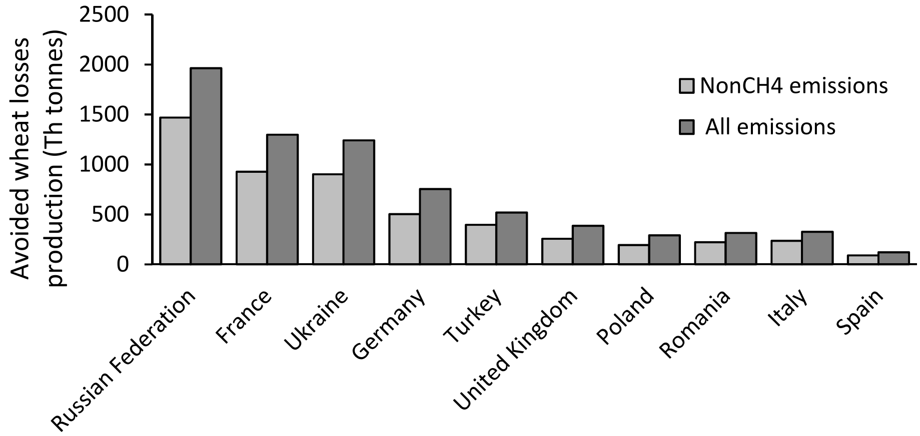

Fig. 2. Additional avoided wheat production losses for year 2050 for the top ten wheat producing countries in the region based on reductions in global non-methane emissions (NonCH4 emissions) and global methane and non-methane emissions (All emissions) – both under the LOW scenario, compared to the losses from the scenario using current legislation.

although the median benefit was slightly higher as a result of reductions in all emissions, compared to non-methane emissions alone, the largest benefits are shown for those in the upper quartile (Fig. 3a). There was a large additional benefit of reducing methane emissions for countries of the EU27, Eastern Europe, Caucasus and Central Asia (EECCA) region and the rest of Europe (Fig. 3b). The difference was only statistically significant for the EU27 countries ($t = -3.2181$, $p = 0.0034$), and not for the EECCA countries ($t = -1.6692$, $p = 0.1461$) or the rest of Europe ($t = -1.8673$, $p = 0.09881$), although the number of countries in these groups was comparatively small.

3.2. Regional non-methane emissions vs rest of world non-methane emissions vs global methane scenarios

Comparison of the impact of reducing non-methane emissions in the UNECE region (excluding North America and Israel), reducing rest of world non-methane emissions, and global efforts (i.e. regional + rest of world) to reduce methane in isolation on avoided wheat losses in the UNECE region shows that reducing future methane concentrations will have an important role in reducing ozone impact on crop production.

Overall, there is an approximately equal benefit in terms of avoided wheat losses when reducing non-methane emissions in the UNECE region, non-methane emissions in the rest of the world (only), and from global efforts to reduce methane emissions compared to those projected to occur with emissions using current legislation (for the year 2050) (Fig. 4). This overall pattern broadly matches that which is seen in individual countries. For many of the largest wheat producing countries, including France, Germany, Poland, and UK, avoided wheat production losses are similar when comparing the impact of reducing non-methane regional emissions, non-methane emissions from the rest of the world, and methane emissions to the stringent LOW scenario compared to current legislation (Fig. 5). There are a few of the countries with greatest wheat production where reducing regional (non-methane) emissions provides the greatest benefits in terms of avoided wheat production losses, for example, Russia, Turkey, and Ukraine (Fig. 5). In these countries, the benefits of reducing rest of the world (non-methane) emissions and methane emissions from those in current legislation conditions to the stringent LOW scenario are broadly similar to each other.

Based on values per country, the median values of avoided wheat production losses in the region also showed similar benefits from reducing non-methane regional emissions, non-methane emissions from

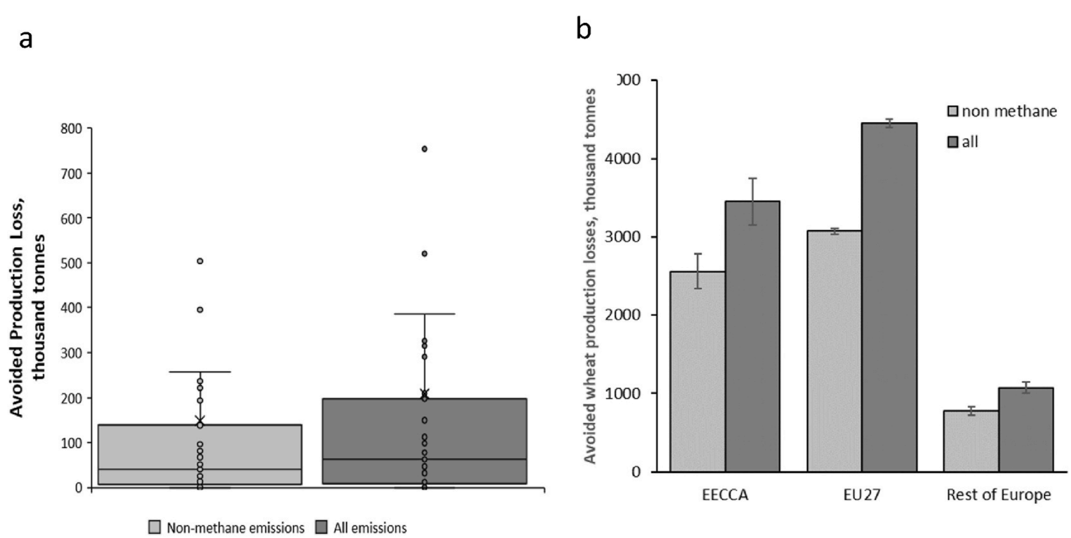

Fig. 3. A) Box-plot of avoided wheat production losses per country in the domain from global non-methane emissions compared with global reductions in all emissions using the LOW scenario, compared to current legislation in 2050. Paired Student t-test $p = 0.0007$. Note the y-axis scale has been constrained for clarity, with the highest outlier points not shown. B) Total avoided wheat production loss for EECCA vs EU27 vs rest of Europe, bars are standard errors. Differences are statistically significant for EU27 only ($t = -3.2181$, $p = 0.0034$).

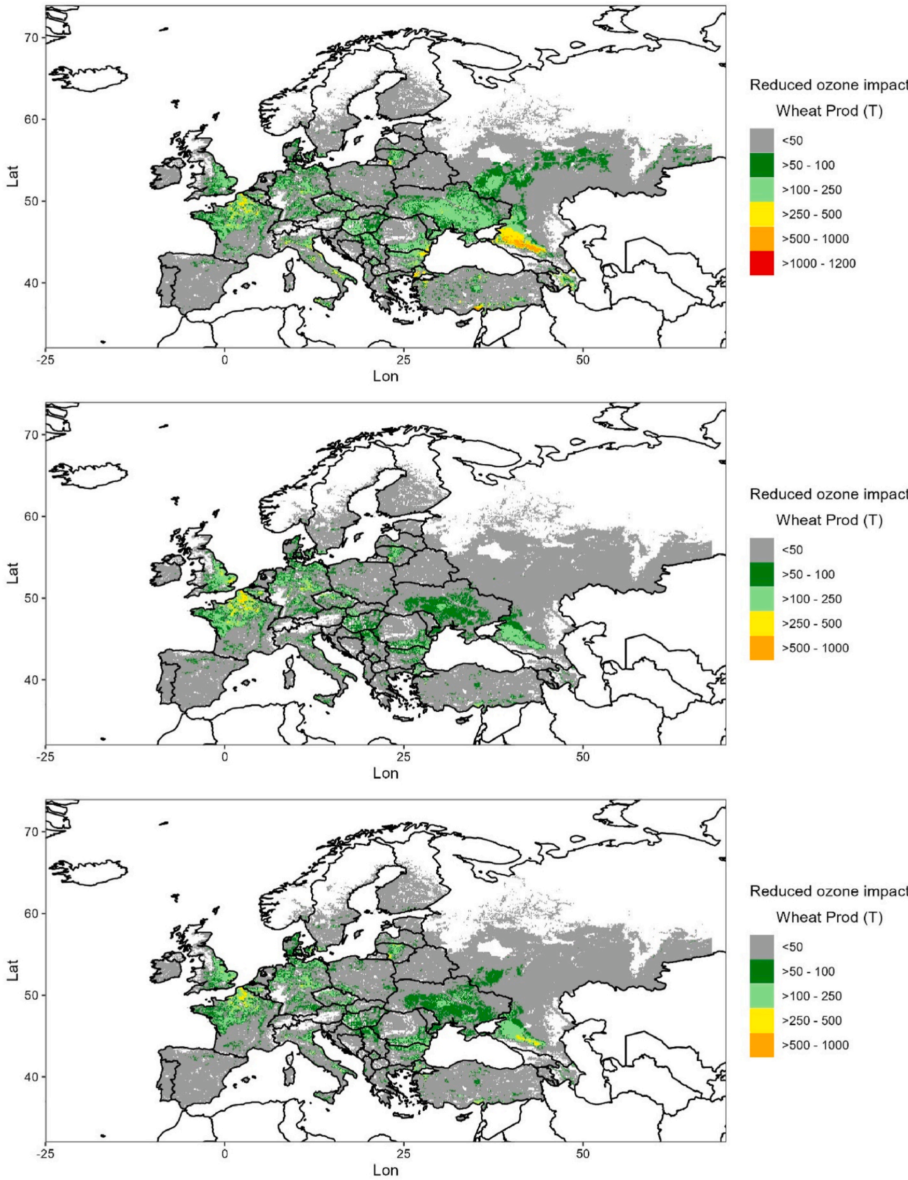

Fig. 4. Additional avoided wheat production losses due to ozone uptake per 0.1° grid cell using the LOW emissions scenario compared to that for current legislation for a) non-methane emissions within the region and b) non-methane emissions from the rest of the world only and c) global methane emissions in 2050. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

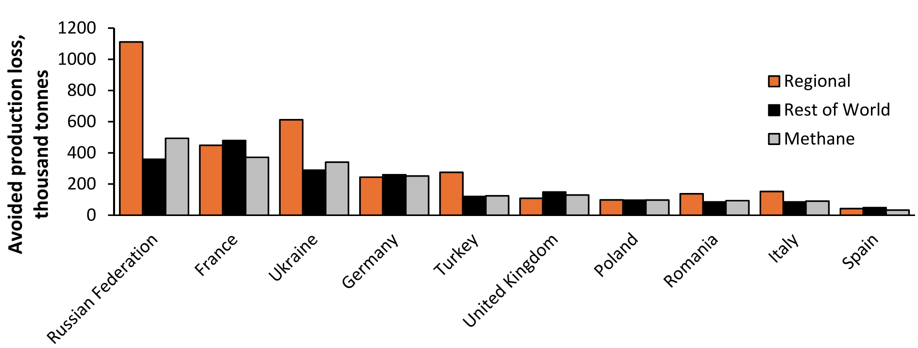

Fig. 5. Additional avoided wheat production losses for the top ten wheat producing countries in the region based on reductions in regional non-methane emissions, rest of the world (only) non-methane emissions, and emissions of methane (using the LOW emissions scenario) compared to the losses from current legislation in the year 2050.

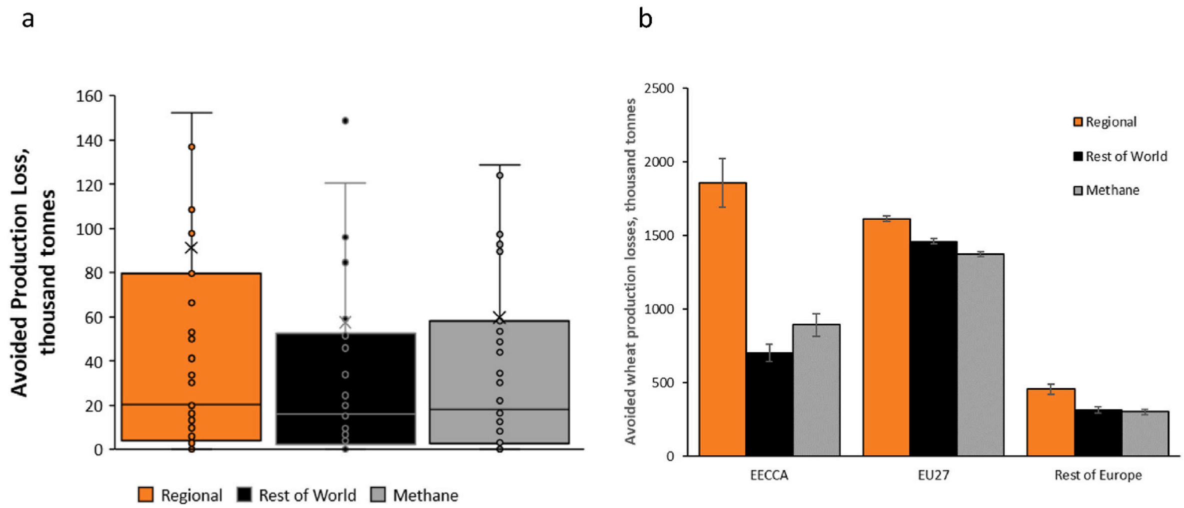

Fig. 6. A) Box plot of avoided wheat production losses per country in the domain from reductions in non-methane emissions within the region, reductions in non-methane emissions in the rest of the world (only) and global reductions in methane emissions (using the LOW scenario), compared to current legislation in 2050. Note the y-axis scale has been constrained for clarity, with the highest outlier points not shown. Differences were not statistically significant. B) Sum of avoided wheat losses for EECCA, EU27 countries and the rest of Europe, bars are standard errors. Differences were not significantly different except for within-region non-methane emissions vs global reductions in methane emissions for the EU27 countries ($p = 0.0418$).

the rest of the world, and global emissions of methane (Fig. 6a). Overall, there was a slightly larger benefit from reductions in within region non-methane emissions, particularly for those countries of the upper quartile, but the differences were not statistically significant.

The benefit of reducing non-methane emissions within the region only had the largest impact on avoided wheat production losses in the EECCA region, with the benefits of reducing methane emissions compared to reducing non-methane emissions from the rest of the world being similar to each other (Fig. 6b), and these differences within the EECCA region not being statistically significant. For the EU27 countries and the rest of Europe the impact of reducing within-region non-methane emissions, reducing rest of the world emissions, and reducing methane globally, were all similar to each other, with slightly larger avoided production losses from reductions in 'within region non-methane emissions' that were statistically different for the EU27 countries ($t = -2.1407$, $p = 0.0418$).

3.3. Comparison of low emissions scenario to pre-industrial conditions

The main focus of the current study is ozone formation based on emissions of ozone precursors with current legislation, compared to that of a stringent emissions reduction scenario. However, even the stringent LOW scenario is calculated to cause substantial yield reductions compared to those of pre-industrial emissions (Fig. 7). Compared to pre-industrial emissions this LOW scenario shows an average yield loss of 6.0 % for the region, and a total production loss for the region of 15.1 million tonnes.

4. Discussion

This analysis shows that global efforts addressing methane emissions could further reduce ozone-induced yield losses of crops compared to addressing non-methane emissions alone. As the stringent LOW scenario still causes substantial yield reductions compared to those of pre-industrial emissions this indicates that ozone-induced crop losses will remain a problem into the future even with stricter control on emissions of ozone precursors than are currently in place.

4.1. Comparison between impacts using crop and health relevant metrics

Some previous studies demonstrating the benefits of reduced ozone concentrations by addressing methane emissions have focussed on health. Ozone is known to be detrimental to health, most frequently causing respiratory symptoms and is also associated with increased mortality (Bell et al., 2005; Huangfu and Atkinson, 2020). A 20 % reduction in anthropogenic global methane emissions has been shown to

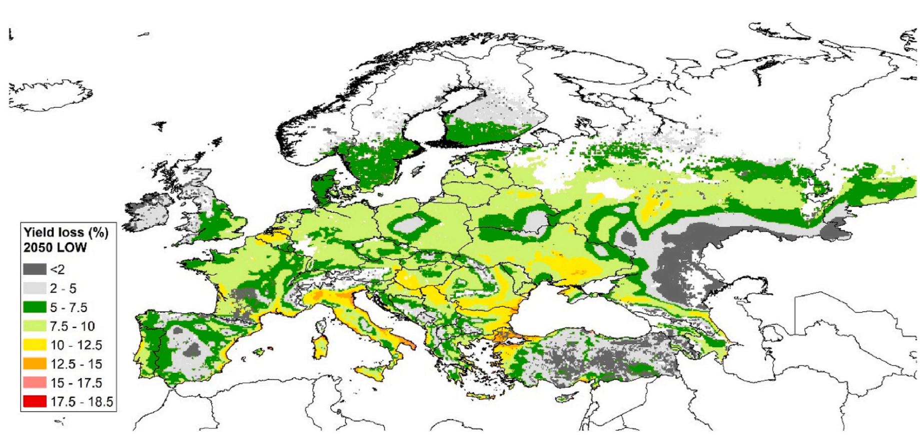

Fig. 7. Percentage yield losses of wheat per grid cell in the LOW scenario compared to those projected based on ozone concentrations in pre-industrial conditions.

reduce potential health impacts due to ozone, with a predicted 30,000 annual reduction in premature deaths (West et al., 2006). Although low to moderate concentrations can be harmful to health, the impacts are most severe when ozone concentrations are high (Bae et al., 2015), and some health impacts studies focus on the number of days of the year on which 75 ppb ozone is exceeded (Akimoto et al., 2015), showing that there were comparatively small benefits of addressing methane emissions to reduce ozone-induced impacts on health. In contrast, in the current study potential benefits of addressing global methane emissions were found even in regions where ozone concentrations are comparatively low, and with some of the largest benefits seen in northern Europe and the Baltic region. This is because ozone impacts on vegetation are linearly related to ozone uptake and these impacts can also be high when moderate ozone concentrations coincide with meteorological conditions that favour ozone uptake. Previous studies have shown that in favourable conditions ozone uptake above thresholds potentially damaging vegetation can occur at ozone concentrations of as little as 10–15 ppb (Cheesman et al., 2023). In addition, in the northern and Baltic regions ozone concentrations tend to be lower due to lower local emissions, so that the relative contribution of methane to the total ozone formation is comparatively high as methane is a more uniformly distributed pollutant due to its relatively long atmospheric lifetime compared to some of the other ozone precursor molecules such as nitrogen oxides, carbon monoxide and non-methane VOCs, which have atmospheric lifetimes of weeks to months (IPCC et al., 2013).

Some previous studies have calculated impacts on crop production based on ozone concentration in the air. A 2–8 % increase in global crop yield, and a 4–19 % increase in global wheat yield, was predicted based on reducing methane in a policy implementation scenario compared to that which would occur due to a 35 % increase in methane as a consequence of emissions due to current legislation (Avnery et al., 2013). However, the study of Avnery et al. (2013) used the ozone concentration metrics AOT40 and W126, which are particularly weighted towards the highest ozone concentrations. The current study, based on ozone uptake, has indicated a potential 40 % increase in yield of wheat in the UNECE region (minus USA and Canada) based on reducing methane emissions by 35 % compared to what could be achieved by reducing non-methane emissions alone. It should be noted that in addition to the different ozone metric used for crop loss calculations, the reference scenario is also different as in the Avnery et al. (2013) study the benefits of reducing methane concentration are in the absence of concurrent additional reductions in non-methane emissions, which is a scenario not included in the current study.

4.2. Regional vs global emissions and uncertainties

There are some countries where the greatest benefit is still to be gained by reducing regional emissions. These are likely the countries where local emissions remain high as implementation measures have been slower to be introduced. However, in these countries there is still additional benefit from reductions in global methane. Both methane and non-methane emissions from some parts of the world can be difficult to predict. The methane scenario projections used within this study fall within the range of the optimistic (SSP1-2.6) and pessimistic (SSP5-8.5) scenarios.

Over recent decades there has been a shift in emissions of both methane and non-methane VOCs from developed countries to developing countries nearer to the equator (Zhang et al., 2016), where there is increased convection resulting in lifting ozone to higher altitudes, where it has a longer lifetime. Currently biogenic emissions of precursors from biomass burning are the largest contributor to ozone concentrations in Africa (Aghedo et al., 2007), and the increasing frequency of large wildfires in regions including Asia and North America due to climate change can have a large influence on global emissions (Chen et al., 2024).

4.3. Uncertainties relating to sensitivity of crops to ozone

For wheat, the areas of maximum benefit in terms of avoided production losses due to ozone for both methane and non-methane emissions are seen where crop yield is highest. This is important when considering the implications for future food security. The wheat cultivars that form the basis of the dose-response relationship in this study were from studies across four countries of Europe. Some studies have shown that the sensitivity of these was similar to cultivars of other regions e.g. Pleijel et al. (2019) showed similarity of sensitivity between European and Asian wheat varieties based on the metric AOT40, with American cultivars being slightly less sensitive to ozone. Another study has shown that European and American cultivars may be slightly less sensitive to ozone than those of India and China based on AOT40, although this may have been confounded slightly by cultivar age (Xu et al., 2024). African cultivars of wheat have been shown to be similar or less sensitive to ozone than European varieties based on ozone uptake (Hayes et al., 2020). It was assumed that the cultivars that will be commercially grown in 2050 will have the same sensitivity to ozone as those of the dose-response relationship. It is possible that this could under-estimate sensitivity to ozone, particularly for what could be possible in 2050, because it has been shown that modern cultivars of wheat are more sensitive to ozone than older varieties (Pleijel et al., 2006; Yadav et al., 2020). This has also been shown for some other crops e.g. soybean (Osborne et al., 2016), suggesting that breeding efforts to improve crop yield may have inadvertently been selecting for traits that are associated with sensitivity to ozone (Feng et al., 2022; Biswas et al., 2008).

The analysis in the current study uses only the time of year when there is active crop growth (for wheat) rather than analysis based on the whole year. By 2050 there could be changes in the timing of crop growth due to climate change, and it has been predicted using models that in Europe wheat sowing could occur 1–3 weeks earlier for spring cereals by 2040 if this were to change to match optimum temperature thresholds for sowing (Olesen et al., 2012). The timing of sowing and harvest for wheat has remained fairly stable in the UK for wheat over previous years, as the sowing and harvest dates tend to be determined by broad climatic factors and to also align with the overall farm management practices (Sheehan and Bentley, 2021). However, there is some evidence of changes to timings of sowing in some regions of India, where sowing occurred 1 week earlier by 2010 than at the beginning of the decade in Haryana and Uttar Pradesh (Lobell et al., 2013), although this was possible due to adoption of reduced-till management practices following the previous crop, which gave a co-benefit to avoid excessive heat at the end of the growing season, rather than as a response to climate changes. This analysis has assumed that meteorology is the same in 2050 as in 2013–2017, which was to allow the consequences of emissions scenarios to be compared without introducing a confounding factor of altered ozone uptake due to changes in climate. It is anticipated that there would be changes in the meteorology during the crop growing season by 2050, but these are difficult to predict precisely at the regional scale. However, note that increased ozone concentration, due to changes in climate increasing ozone formation, is included in the EMEP model.

Uncertainties are also introduced in the growing season used to calculate 90-day POD_3IAM. A set period was used (May to July), for all grid cells in the domain. In reality, the key period for anthesis may vary depending on location. Sensitivity analyses could be carried out by changing the 90-day period for different areas of the EMEP domain, e.g. Mediterranean, Scandinavia to investigate the impact on the final ozone flux values, however this was outside the scope of the current study.

Further uncertainty is introduced by using grid cells of differing resolution (for the different datasets) however, these were the only suitable datasets at this scale currently available and efforts were made to ensure that the wheat production value per cell was representative of production in the area. Also, both the wheat production data and ozone flux data are modelled values. For the SPAM model, outputs are evaluated and validated using different methods, for example by experts at CGIAR centres and by holding crop validation workshops (You et al., 2014). Ozone outputs from the EMEP model have also been validated in various studies, for example, Mills et al. (2018) compared the daily maximum hourly mean ozone concentration (Dmax) data with EMEP modelled data for sites from the global GAW network to investigate model performance during the times of peak ozone each day. Over the course of a year, the EMEP model captured the spatial and temporal variations across the regions well. Van Caspel et al. (2024) also test how well the EMEP model can simulate peak season MDA8 for 56 EBAS stations within the European part of the EMEP region, finding a clear relationship between the 5-year averaged modelled and observed values (Pearson correlation coefficient (r) of 0.87).

4.4. Future work

It is possible that if there are any agreements to address methane specifically, either as a short-lived climate forcer or as an air pollutant, that these would be adopted in countries from around the globe. However, it could be interesting to compare the relative benefits of reducing methane emissions inside the UNECE regions compared to reductions from outside the region, particularly if it is possible that methane emissions could be included in the air quality legislative framework, as this might have a more regional adoption.

The LOW scenario of this study is very stringent, assuming policies and actions that transform agriculture and diet in addition to application of technologies to reduce emissions. From a policy perspective, it could be useful to know if benefits of reducing methane reductions could still be realised with a less stringent scenario. Due to non-linearities linked to the atmospheric chemistry, this would require the development of additional scenarios and with additional analysis of these.

5. Conclusions

This analysis has shown that there are co-benefits between reductions in methane to address global climate change and air quality. Global efforts that address methane emissions could further reduce ozone-induced yield losses of crops compared to addressing non-methane emissions alone. At a regional level, reductions in local non-methane emissions, rest of the world non-methane emissions, and global methane emissions all have an important role to play in reducing the impact of ozone pollution on crop yield loss. Addressing these emissions from stringent, but feasible, future scenarios would significantly reduce crop yield losses due to ozone pollution.

CRediT authorship contribution statement

Felicity Hayes: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Katrina Sharps:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis. **Willem E. van Caspel:** Writing – review & editing, Methodology. **Zbigniew Klimont:** Writing – review & editing, Methodology. **Chris Heyes:** Writing – review & editing, Methodology. **Hilde Fagerli:** Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2025.126654.

Data availability

Data will be made available on request.

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