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ORIGINAL ARTICLE

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Ozone burden in a changing climate – contrasting the costs of emission controls and benefits for health and agriculture in Austria

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Abstract
Climate change alters atmospheric chemistry and meteorological conditions in ways that exacerbate surface ozone pollution, with consequences for human health and agriculture. In Austria, where ambitious emission controls have improved air quality in the past, rising temperatures and elevated methane abundances in the context of climate change may counteract these gains. This paper assesses the societal welfare effects of ozone exposure in Austria under future climate scenarios by comparing a medium (RCP4.5) to a high (RCP8.5) emission scenario for 2030 and 2050. We further introduce a novel scenario (RCP8.5+), in which only Austrian ozone precursor emissions are more stringently controlled under a global high-emissions context, to evaluate the effectiveness of national emission controls. Net effects are quantified by integrating market costs – agricultural yield changes and emission control costs assessed in a computable general equilibrium model – with non-market health costs. Results show that in 2030, emission control costs in RCP4.5 exceed the societal welfare benefits of a reduced ozone burden compared to RCP8.5. By 2050, however, benefits outweigh costs with a benefit-cost ratio (BCR) of seven. This shift reflects higher upfront control costs in 2030, which lead to sustained air quality improvements through mid-century. In RCP8.5+, national emission controls yield strong benefits with a BCR of eight. While both scenarios (RCP4.5 and RCP8.5+) reduce yield losses compared to RCP8.5, health benefits dominate the societal welfare gains. These findings underscore the local benefits of national air quality management, highlighting its effectiveness as an abatement strategy for managing ozone risks in a warming climate.

Keywords Ozone · CGE model · Climate change · Health · Agriculture · Climate penalty

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1 Introduction

Climate and air quality are inextricably linked. On the one hand, many criteria pollutants, such as surface ozone (O_3), contribute to the radiative forcing of climate change; on the other, climate change degrades air quality by increasing the efficiency of chemical formation pathways and changes in ambient meteorological conditions and removal processes (Dewan and Lakhani 2022; Fiore et al. 2015; IPCC 2021; Lyu et al. 2023). This latter effect is commonly referred to as *climate penalty*, describing the compromising role of climate change on air quality (Crooks et al. 2022; Wu et al. 2008). These interactions have direct implications for achieving internationally established air quality guidelines and enforcing air pollution legislation. In Europe, this includes the EU Ambient Air Quality Directive (2008/50/EC)[1] and its revision[2] in 2024 aimed at aligning with updated World Health Organization (WHO 2021) recommendations.

O_3 forms in the presence of nitrogen oxides (NO_x), volatile organic compounds (VOCs) and sunlight. Both NO_x and VOC emissions originate from natural as well as anthropogenic sources. NO_x emissions stem predominantly from human activities, such as commercial and residential combustion processes, energy production and land transportation (Szopa et al. 2021). Climate change, through rising temperatures and longer-lasting stagnation events (*blocking*), enhances O_3 production efficiency at mid-latitudes. Due to the short lifetime of O_3 precursors (hours to days) and the non-linearity in O_3 production, concentrations are highly variable in time and space. In addition, elevated methane concentrations contribute to higher background O_3 levels and influence the O_3 seasonal cycle (Rieder et al. 2015).

As an air pollutant, O_3 is harmful to human health and agricultural yields (von Schneidemesser et al. 2020). O_3 is a respiratory irritant with elevated concentrations contributing to excess mortality (Farzad et al. 2021; Kim et al. 2020; Lim et al. 2019; Zheng et al. 2015). Considering 2021 emissions, climatic conditions and exposure patterns, 24 000 premature deaths are attributable to O_3 in Europe in 2022 (EEA 2022). By impairing plant growth, O_3 exposure also threatens agriculture and global food security (Tai et al. 2021). In the Northern Hemisphere, O_3-related reductions in wheat yields were estimated at 10% on average for the period 2010–2012 (Mills et al. 2018). Such yield losses also carry significant economic costs (Pei et al. 2023). In India, constrained wheat yields due to O_3 exposure are estimated to drive up market prices by up to 40%, relative to a no-pollution scenario (Pandey et al. 2023).

While previous research has explored the chemistry-climate interactions that shape O_3 air quality (Fiore et al. 2015; Im et al. 2022; Rieder et al. 2018), assessments of their broader economic and societal impacts remain limited. Some studies quantify health-related costs of climate-driven changes in O_3 exposure, such as Yang et al. (2019), who estimate a reduction in mortality under RCP4.5 and an increase under RCP8.5 in the US by mid-century. In addition, Selin et al. (2009) emphasize the role not only of climate change but also of precursor emission changes for global future welfare effects of O_3. However, these studies do not consider policy responses that explicitly target O_3 precursor emissions and could reduce exposure.

Studies that analyse policy interventions typically examine air quality improvements as co-benefits of climate change mitigation, under the assumption of static climate condi-

[1] Directive −2008/50 - EN - EUR-Lex, last access: 09. 04.2025.

[2] Directive - EU −2024/2881 - EN - EUR-Lex, last access 09.04.2025.

tions, evaluating the trade-offs between control costs and the benefits of reduced impacts on health. For example, in a global study assessing health co-benefits of the Paris Agreement, Markandya et al. (2018) find that health benefits alone are sufficient to justify stringent mitigation in some regions, including China and India. This finding is reinforced by Reis et al. (2022), whose global modeling framework projects that welfare-maximising climate policies could reduce premature deaths by 1.62 million globally in 2050. Recent work also adds further regional detail. Zhang et al. (2021) show that for the Sichuan Province in China climate change mitigation can yield substantial health co-benefits that far exceed the costs of implementation. Despite their broad coverage of air pollution-related health effects, these studies do not explicitly include O_3-specific effects or impacts on agriculture.

At the EU level, Vrontisi et al. (2016) find that the economy-wide costs of EU air quality policies are offset by positive agricultural yield effects, reduced mortality and morbidity, as well as positive feedback effects from increased demand in the sectors producing abatement technologies. Lanzi et al. (2023) find similar effects for the Arctic Council countries, showing how improvements in air quality can bring net economic gains via positive effects on health and labor productivity, as well as crop yields. Focusing on climate change mitigation, these studies do not assess how policies perform under different warming trajectories.

This paper addresses this gap by linking global emission scenarios, local O_3 precursor controls, and climate-driven changes in O_3 formation to assess the societal welfare effects of O_3 exposure in Austria. Austria provides a relevant case study: as a small and landlocked country, its O_3 levels are shaped by transboundary flows from neighboring countries as well as local NO_x and non-methane volatile organic compound (NMVOC) emissions, while changes in its own precursor and greenhouse gas (GHG) emissions have limited influence on global climate forcing. This allows us to examine the effectiveness of unilateral emission controls as an abatement strategy in a warming, high-emission world. Our results therefore offer insights into how targeted air quality policies can help manage O_3 burdens in a changing climate.

Building on this motivation, the paper explicitly quantifies the societal welfare effects associated with changing O_3 burdens under different climate and emission pathways. We contrast the costs of local O_3 precursor controls with the benefits for health and agriculture across three emission scenarios through 2050. Two scenarios follow global GHG concentration pathways and their corresponding European O_3 precursor emissions: *RCP4.5* for a *medium* and *RCP8.5* for a *high emission scenario* (Moss et al. 2010; van Vuuren et al. 2011). A third scenario applies stricter Austrian O_3 precursor emissions consistent with their RCP2.6 trajectory, while all global and European GHG concentrations, meteorology and chemical boundary conditions remain those of RCP8.5. This design isolates the effect of unilateral, national-scale precursor emission reductions of a single country in a high-emission world.

Societal welfare effects are quantified by combining non-market and market costs. Non-market costs include impacts on mortality and morbidity, while market costs comprise the economy-wide effects of agricultural yield losses and the costs of O_3 precursor emission control, both quantified in a multi-sectoral computable general equilibrium model (CGE). Consistent with standard practice in impact analysis, impacts are evaluated across warming scenarios relative to a fixed socioeconomic baseline (e.g., Cortés Arbués et al. 2024; Dellink et al. 2019), with mitigation-related assumptions remaining constant across all scenarios.

This allows a ceteris paribus assessment, in which O_3-related damages are treated as climate impacts and precursor emission controls represent a local abatement strategy.

2 Methodology and data

This study combines ambient O_3 air quality data from targeted chemistry-transport model experiments with a quantification of the societal and economic impacts of O_3 exposure to contrast the costs and benefits of different emission scenarios. The primary metrics in our analysis are the hourly maxima exceeding 35 ppb and AOT40 (Accumulated Ozone exposure over a Threshold of 40 ppb), as indicators of the O_3 burden on health and agriculture, respectively, with societal welfare effects acting as a comprehensive measure of health impacts and economy-wide effects from agricultural yield changes and precursor emission control costs.

The methodological approach followed in this paper is illustrated in Fig. 1. We distinguish between non-market and market costs of O_3 exposure. Non-market costs quantify and monetize health impacts, while market costs enter the macroeconomic CGE model-based assessment via changes in agricultural productivity and alterations in the production cost structures of sectors implementing emission controls. The integration of non-market and market costs estimates societal welfare effects for both the near (2030) and far (2050) future.

2.1 Future surface ozone concentrations under different emission scenarios

Future O_3 concentrations are derived from an ensemble of high resolution (9 km x 9 km) WRF-Chem model simulations, which is a regional climate model with coupled chemical processes (RADM2 mechanism: Stockwell et al. 1990; Fast et al. 2006; Grell et al. 2005; Peckham et al. 2011; Powers et al. 2017). The model is applied over a continental European domain using regional scenarios for short-lived climate forcers such as NO_x, NMVOCs, SO_2, CO, and PM, consistent with global emission baskets under the corresponding RCPs. As we consider meteorological and chemical boundary conditions from a global model (CESM) the effects of NOx reduction, methane concentration, and radiative forcing are taken into account and fully represented in the regional chemistry-climate model, including

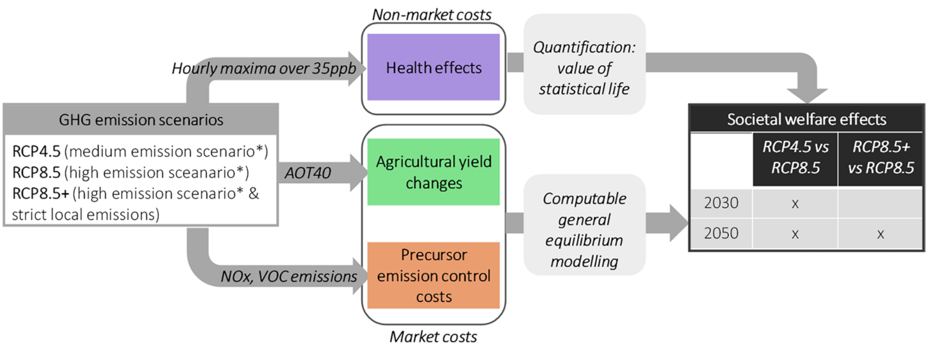


Fig. 1 Methodological approach followed in this study. *Following the global RCP emission trajectory and associated methane abundances and warming levels

the temperature dependence of the chemical reactions and BVOC emissions. This setup ensures that transboundary flows of O_3 and its precursors are modelled properly.

We consider two emission scenarios based on the established Representative Concentration Pathways (RCPs), that provide greenhouse gas (GHG) and short-lived climate forcer emission trajectories and their associated climate forcing levels (Moss et al. 2010; van Vuuren et al. 2011): a *medium emission scenario* (RCP4.5) and a *high emission scenario* (RCP8.5). Simulations for the RCP4.5 (Clarke et al. 2007; Smith and Wigley 2006; Wise et al. 2009) and RCP8.5 (Riahi et al. 2017) scenario for 2030 and 2050 are conducted for 10-year time slices, for 2026–2035 and 2046–2055, respectively.

Although RCP8.5 has recently been argued to represent a low-likelihood pathway over the 21st century (Hausfather and Peters 2020), it remains highly relevant for our assessment for two reasons. First, methane concentrations – which are a key driver of background O_3 – have closely followed RCP8.5 projection in recent years. Second, observed global GHG emissions and policy-based projections and related warming remain consistent with RCP8.5 projections up to mid-century (Schwalm et al. 2020). This makes RCP8.5 a useful upper-bound representation of O-related risks through 2050, while RCP4.5 represents a medium-emission alternative.

In addition to the primary simulations, we conduct a sensitivity experiment for 2050, referred to as RCP8.5+, where Austria applies stricter local O_3 precursor emissions (NO_x and VOC) consistent with the RCP2.6 precursor trajectory, while all global and European GHG concentrations and meteorological boundary conditions remain in line with RCP8.5. This design allows us to isolate the effect of unilateral Austrian precursor reductions on future O_3 burdens under otherwise unchanged high-emission global conditions. Given Austria's small spatial extent and its small contribution to global GHG emissions, changes in Austrian NO_x and VOC emissions have negligible feedback on global climate, making this scenario scientifically appropriate and internally consistent. Detailed information on Austrian emission pathways is provided in Figure A1.1.

Hourly O_3 concentrations were bias-corrected (Staehle et al. 2024) for elevations lower than 1500 m above sea level. For the health assessment, the daily maximum hourly mean over 35 ppb was calculated and aggregated to compute the average annual sum of hourly maxima exceeding 35 ppb. For the impact on crops the AOT40 metric (Accumulated Ozone exposure over a Threshold of 40 ppb) is employed. The AOT40 value is calculated by summing the differences between the hourly O_3 concentrations and the 40ppb threshold between 8:00 AM and 8:00 PM local time during the main growing season (June, July, August), when photosynthesis occurs and plants are most susceptible to O_3 damage.

2.2 Non-market costs: health effects

This study builds on the health impact assessment framework developed by Moshammer et al. (2024), which estimates the deaths attributable to O_3 in Austria under different global emission scenarios. The analysis incorporates demographic changes according to the district-level population forecasts for Austria provided by the Austrian Conference on Spatial Planning (ÖROK 2022). Motivated by a previous study that found the best correlation between daily hourly maxima and O_3-related mortality (Moshammer et al. 2013), we use the daily maximum hourly mean above the 35 ppb threshold from Moshammer et al. (2024) for our health impact monetization.

To contextualize premature mortality attributable to O_3 with the economic costs from emission controls and agricultural losses, we employ the value of statistical life (VSL) to quantify the monetary benefit of mortality risk reduction. The VSL represents the monetary value of marginal reductions in an individual's risk of premature death (Markandya et al. 2018), not the value of a person's life itself, but rather the willingness to pay for such risk reductions (OECD 2012, 2016). The widely established OECD (2012) EU-wide VSL estimate corresponds to USD 3.6 million (2005 USD), with a mean error of ± 50%, spanning a range between USD 1.8–5.4 million. For a detailed description of how the VSL for Austria is calculated, see Equation A1.1 in the appendix. For consistency with the model baseline (described in section 2.5), we use GDP projections from the SSP database (Crespo Cuaresma 2017; Riahi et al. 2017) in line with the SSP2 narrative for estimating future VSL. The resulting VSL estimates for the baseline, 2030 and 2050, are presented in Table A1.1 in the appendix. In terms of total population forecast, we find that overall trends from the regionally specific projections for Austria (ÖROK 2022) slightly exceed most recent SSP2 projections, by approximately 2% and 5%[3,4] in 2030 and 2050, but qualitative trends align.

No standard measure exists for the economic cost of morbidity (OECD 2014). Following the recommendations of the World Bank (Narain and Sall 2016; Hunt et al. 2016), we assume morbidity costs to be a 10% share of overall mortality costs in each scenario. As non-market costs, health effects do not enter the model-based assessment. Instead, they are added ex post to the welfare effects, alongside those resulting from market costs.

2.3 Market costs: agricultural yield changes

To assess the impact of O_3 on crop yields in Austria, we apply crop-specific exposure-response functions (ERFs) developed in Mills et al. (2007). These functions are based on plant response data synthesized from over 700 published studies and conference proceedings, covering a wide range of European agricultural and horticultural crops. Our analysis focuses on Austria's most significant crops in terms of both cultivation area and yield, with data on production volume and share of cropland occupied by each crop type in 2020 sourced from Statistics Austria (2021). The selected crops are categorized based on their sensitivity to O_3 exposure: O_3-sensitive crops (e.g., wheat and soybean), moderately sensitive crops (e.g., sugar beets, potatoes and maize), and O_3-resistant crops (e.g., barley) (Mills et al. 2007).

We derive relative yield changes at the district level using crop-specific cultivation area data, which were made available upon request from the Austrian Paying Agency for Agriculture and Rural Development (AMA). This data provides crop- and location-specific yield per hectare information, available annually at the federal state level for grains (e.g. 2021: AMA 2021b, 2021a) and at a national level for the remaining crops considered (Statistics Austria 2021). To control for annual variation in yield per hectare, we compute five-year averages between 2016 and 2020. This allows us to estimate stable and representative baseline yield estimates at the district level.

[3] SSP Scenario Explorer, total projected population count in 2030: 9.1 million, 2050: 9.3 million, last access: 09.04.2025.

[4] https://www.statistik.at/en/statistics/population-and-society/population/demographische-prognosen/population-projections-for-austria-and-federal-states, total projected population count in 2030: 9.3 million, 2050: 9.8 million, last access: 09.04.2025.

Next, we integrate AOT40 values (as derived in Sect. 2.1) with district-level crop yield data and apply the ERFs from Mills et al. (2007) for the key growing months of June, July, and August, following consultations with representatives of Styria's provincial chamber of agriculture. By implementing this approach, we estimate yield losses for each selected crop at the district level under different O_3 exposure scenarios. These district-level yield changes are then aggregated at the national level for use in the CGE model, ensuring that regional variability in O_3 exposure and crop sensitivity are accurately captured. To isolate the effects of changes in O_3 levels, we assume that crop area and cultivation patterns remain constant through 2050. This assumption excludes any potential structural changes resulting from socioeconomic or climate change dynamics.

2.4 Market costs: precursor emission controls

Precursor emission control costs for NO_x and VOCs are based on the GAINS optimization module (Kleinman 2005), which identifies cost-effective technology portfolios by allocating emission control measures across sectors. This approach ensures the optimal allocation of resources for air quality control (Amann et al. 2011; Vrontisi et al. 2016). The considered measures are *end-of-pipe* technologies, capturing emissions at their source rather than changing the structural composition of production (Vrontisi et al. 2016).

We distinguish between two GAINS emission control scenarios: the (i) *no further controls* (NFC) scenario, where regulations already in force are followed, yet without further controls until 2050 and the (ii) *with existing measures* (WEM) scenario, which presupposes compliance with all clean air policies and climate change mitigation measures passed (but not necessarily yet in force) by January 2018. These scenarios are chosen to ensure consistency with the corresponding RCP4.5 and RCP8.5 projections.

The NFC scenario corresponds to local anthropogenic NO_x and VOC emissions for RCP8.5, whereas the WEM scenario aligns with the emission levels projected for RCP4.5 by 2050 (see appendix Figure A1.1). In this analysis, national emission trajectories for NO_x and VOC for RCP8.5 are approximated by the NFC scenario, while national emissions in RCP4.5 and in RCP8.5+ are approximated by the WEM scenario, as O_3 precursor emissions in RCP2.6 and RCP4.5 closely align for the relevant time horizon.

Although GAINS scenarios cover mitigation measures, these are not included in our economic assessment. We incorporate only the end-of-pipe precursor control costs for NO_x and VOC. Baseline mitigation assumptions are held constant across all scenarios to isolate the effect of O_3 precursor controls by contrasting scenarios that differ only in O_3 burdens and the cost of implementing different levels of O_3 precursor controls (via end-of-pipe technologies).

Absolute precursor control costs increase both in the NFC and the WEM scenario until 2030 compared to 2015. After 2030, costs begin to decrease. Following the principle of optimality, the highest emission control costs are found in the automotive industry, which accounts for approximately 80% of the total costs in both scenarios in 2030. By 2050, when mitigation potentials in the automotive industry become increasingly exhausted, the power sector becomes more prominent in emission abatement, accounting for 31% and 24% of overall emission control costs in the NFC and WEM scenarios, respectively. Significant abatement is also required in the chemical, metal and printing industries, with lesser efforts in other industrial and service sectors. Total emission control costs across scenarios are included in Table A1.2 in the appendix.

2.5 Macroeconomic analysis

Welfare effects of market costs are assessed using WEGDYN-AT, a recursive-dynamic, multi-sectoral computable general equilibrium (CGE) model of the Austrian economy (Mayer et al. 2021). The model captures private consumption through a representative private household, endowed with the factors of production - land, capital, labor. These factors are employed by profit-maximizing producers to generate output via constant elasticity of substitution (CES) production functions. The economic structure is grounded in an input-output table comprising 87 NACE[5]-classified economic sectors, along with a social accounting matrix (SAM) for Austria for the year 2014, both provided by Statistics Austria. For the purpose of this study, the model was refined to allow for greater granularity in the representation of the Austrian economy. This enhanced structure enables the explicit incorporation of sector-specific agricultural yield losses and industry-level emission control costs. See appendix Table A1.3 for a detailed sector overview.

Incomes generated from the factors of production accrue to the representative household, which allocates them between consumption and saving in pursuit of utility maximization. A government agent collects taxes on production factors, value added, output and exports, using the revenues for public consumption and transfers to households. Consistent with the European Stability and Growth Pact, the model assumes that the government pursues a balanced budget, which implies that public revenues equal public expenditures. Austria is modeled as a small open economy, with international trade represented via import and export flows from and to the rest of the world. The socioeconomic trajectory underlying the scenario formulation follows the *SSP2-Middle of the Road* narrative (O'Neill et al. 2014; Riahi et al. 2017), which reflects moderate trends in economic growth.

O_3-induced agricultural yield losses enter the model as a decline in productivity in the crop production sector. As we cover only the most important crops in terms of area and output produced, the impact calculated in Sect. 2.3 is weighted to account for the share of crop production covered. This share amounts to 85%. For the assessment of emission control costs, we adopt the approach proposed in Vrontisi et al. (2016), which treats these costs as compulsory production expenditures. These expenditures increase sectoral production costs in the abating industries but do not contribute to capital accumulation.

Finally, to derive a comprehensive measure of societal welfare, we combine macroeconomic welfare effects – expressed in Hicksian Equivalent Variation (a measure of changes in consumption opportunities between scenarios) – with the monetized non-market costs of health impacts estimated in Sect. 2.2. This integrated welfare metric facilitates the comparative assessment of policy scenarios across both market and non-market dimensions.

[5] Statistical classification of economic activities in the European Union, https://ec.europa.eu/eurostat/statistics-explained/index.php? title=Glossary: Statistical_classification_of_economic_activities_in_the_European_Community_(NACE) , last access: 09.04.2025.

3 Results

The presentation of results follows the schematic structure outlined in Fig. 1, beginning with regionally explicit changes in key O_3 exposure indicators across the three emission scenarios. We then examine associated non-market (health-related) and market (agricultural and emission control) costs at the national level. Finally, we integrate these findings to assess net societal welfare effects.

Our analysis focuses on contrasting the absolute and relative costs and benefits across emission scenarios for the years 2030 and 2050. Rather than evaluating changes relative to present-day conditions, the focus is placed on the differences between alternative future pathways, providing a clearer understanding of the implications of emission choices under a changing climate.

3.1 Relative changes in future ozone exposure

Future differences in relative O_3 burdens are shaped by three key drivers: reductions in local precursor emissions, changing global methane background concentrations, and climate-related meteorological changes (particularly temperature and atmospheric stagnation). As shown in Fig. 2, the medium emission scenario (RCP4.5) results in substantially lower O_3 burdens compared to the high emission scenario (RCP8.5) in 2030 and 2050 for both metrics. While SOMO35 is calculated for the whole year, the AOT40 refers to the summer months June, July, August only, thus reflecting local ambient meteorological conditions in these specific months and resulting in higher regional variability compared to the SOMO35. By 2050, the RCP8.5+ scenario – which assumes unilateral precursor emission reductions in Austria – yields the largest overall improvements, irrespective of the distribution of agricultural areas and crops.

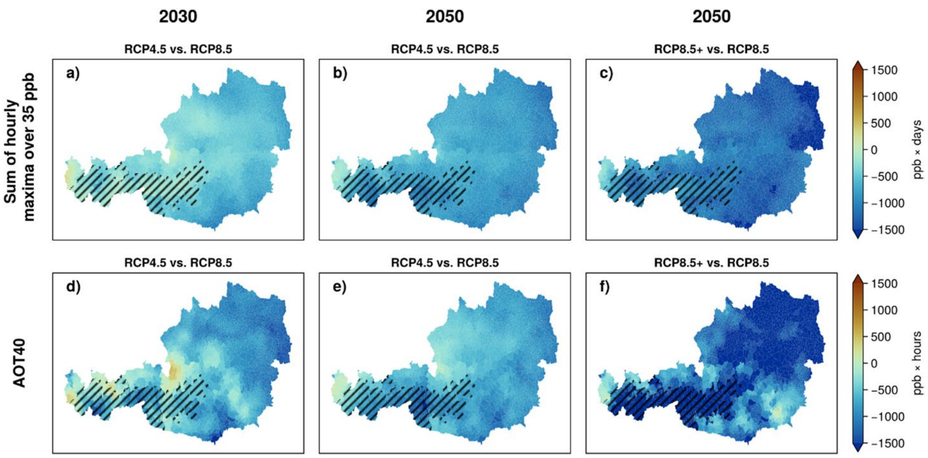


Fig. 2 Differences between various emission scenarios (RCP4.5, RCP8.5 and RCP8.5+), in terms of the 10-year-average sum of hourly maxima over 35 ppb (a-c) and 10-year average AOT40 for June-July-August (d-f) are shown for the near future (2030, ∅ 2026–2035) and mid-century (2050, ∅ 2046–2055). Shaded areas were bias corrected but excluded from the analysis as they lie largely above 1500m of altitude in the model domain. Human and cropland exposure in these areas is very small.

The most pronounced reductions are observed in rural areas, where O_3 formation is NO_x limited, making them particularly responsive to NO_x control measures in RCP4.5 and RCP8.5+. In addition, eastern Austria – a region that holds dense urban areas and key agricultural production zones sees larger improvements than the mountainous western regions. The stark contrast between RCP8.5 and RCP8.5+ highlights the potential effectiveness of domestic precursor emission controls even in the face of adverse global conditions such as rising methane concentrations and higher temperatures, which contribute to the so-called *climate penalty* on O_3 formation.

Gains in terms of the sum of hourly maxima above 35 ppb across scenarios relative to RCP8.5 increase over time, due to significantly lower spring and early summer O_3 burdens in RCP4.5 and RCP8.5+. For AOT40, we do not find a continuous decrease contrasting RCP4.5 and RCP8.5 until 2050 because in summer the impact of methane on O_3 production is less important than local NOx and VOC emissions and ambient temperature. Thus, we find the largest decrease in O_3 burden for RCP8.5+ vs. RCP8.5 due to the biggest difference in precursor emissions but with the same temperature.

These regionally explicit changes in sum of hourly maxima over 35 ppb and AOT40 across scenarios have significant implications for the aggregate population and cropland exposure in Austria. To assess the broader significance of these effects and contrast the outcomes across different scenarios, the subsequent sections transition from this fine regional resolution to the national-level quantification of associated health effects and agricultural yield changes.

3.2 Non-market costs: health effects

We find significant differences in O_3-related health impacts across scenarios (see appendix Table A2.1 for absolute numbers in each scenario). In 2030, the estimated number of O_3-attributable deaths is 399 and 451 in RCP4.5 and RCP8.5 – both exceeding the 394 road fatalities recorded in Austria in 2024[6]. When including morbidity, the O_3-attributable monetized health costs reach EUR 2 739 million and EUR 3 102 million, respectively.

By 2050, reductions in domestic precursor emissions in RCP4.5 and RCP8.5 + decrease O_3-attributable deaths in 2050 to 385 and 372, respectively. In contrast, under RCP8.5, mortality rises significantly to 521 deaths – well above current road mortality, with associated health costs of EUR 4 764 million.

These comparisons are visualized in Panel a of Fig. 3, which represents: (i) avoided O_3-attributable deaths in 2030 in RCP4.5 relative to RCP8.5 and in 2050 in RCP4.5 and RCP8.5 + relative to RCP8.5 (left axis), (ii) corresponding monetized health effects (right axis), (iii) error bars reflecting the ± 50% upper and lower bound thresholds of the VSL.

In 2030, 53 O_3-attributable deaths can be avoided in RCP4.5 compared to RCP8.5. This is due to a lower level of precursor emissions in RCP4.5, especially in densely populated areas, with an immediate improvement in local air quality. This reduction translates into health benefits of EUR 363 million, with a potential range from EUR 181 to 544 million, depending on VSL assumptions.

By 2050, the benefits of reduced emissions are even more pronounced: 136 deaths are avoided in RCP4.5 relative to RCP8.5, generating health benefits of EUR 1 240 million – more than three times the 2030 value. Importantly, even under the global high-emission

[6] Unfallstatistik 2024, last access: 09.04.2025.

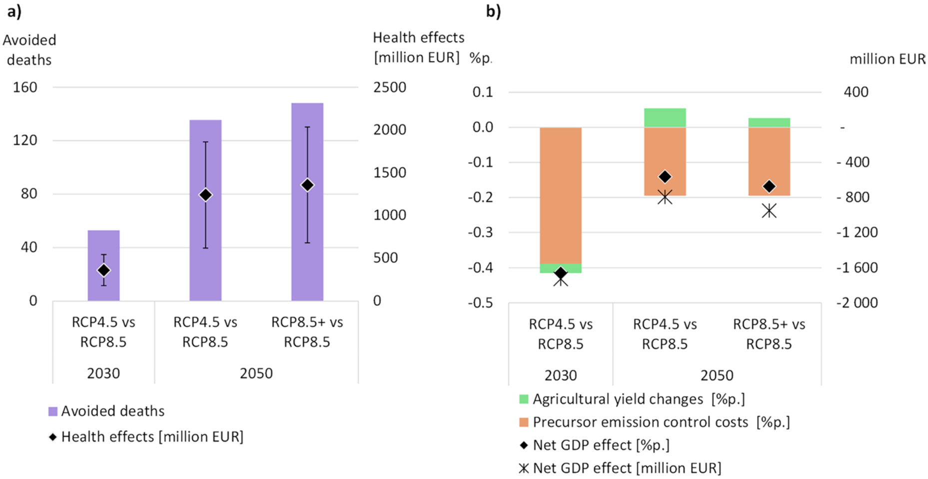


Fig. 3 Panel **a**: Difference in avoided deaths (left vertical axis) and associated health effects in million EUR (right vertical axis) between scenarios in 2030 and 2050. Error bars indicate upper and lower bound values of VSL estimations. Panel **b**: Effects of agricultural yield changes, precursor emission controls and their aggregated net effect on gross domestic product (GDP) in Austria, contrasted for RCP4.5 and RCP8.5 in 2030 and RCP4.5 and RCP8.5 and RCP8.5+ and RCP8.5 in 2050.

trajectory, strict unilateral national controls on precursor emissions in RCP8.5+ are highly effective. These domestic measures reduce population exposure despite elevated global backgrounds and higher O_3-forming efficiency due to warming. Compared to RCP8.5, RCP8.5+ avoids 148 deaths, resulting in EUR 1 356 million in health benefits.

3.3 Market costs: agricultural yield changes and precursor emission controls

O_3-related market costs considered in this study comprise agricultural yield changes and precursor emission control costs, quantified in terms of their effect on gross domestic product (GDP) after considering both direct and indirect macroeconomic dynamics. This is visualized in Panel b of Fig. 3. We find that the joint consideration of market costs in terms of their GDP effect results in negative net effects from stricter emission controls in 2030 and 2050 for all scenario comparisons. Thus, despite positive effects in terms of agricultural yield changes by 2050, these cannot outweigh the costs from stricter emission controls.

3.3.1 Agricultural yield changes

The crop- and location-specific assessment of O_3 exposure impacts on relative yield changes, reveals distinct differences across crop types. As illustrated in Fig. 4, wheat, soybean and potatoes show the greatest reductions in relative yield, whereas barley remains largely unaffected, and sugar beet even exhibits yield gains under higher O_3 conditions.

When aggregating these crop-specific yield changes based on their contribution to total crop production, direct yield losses in 2030 are estimated at 6.8% and 5.4% in RCP4.5 and RCP8.5, respectively. This relatively narrow gap reflects the predominance of meteorologi-

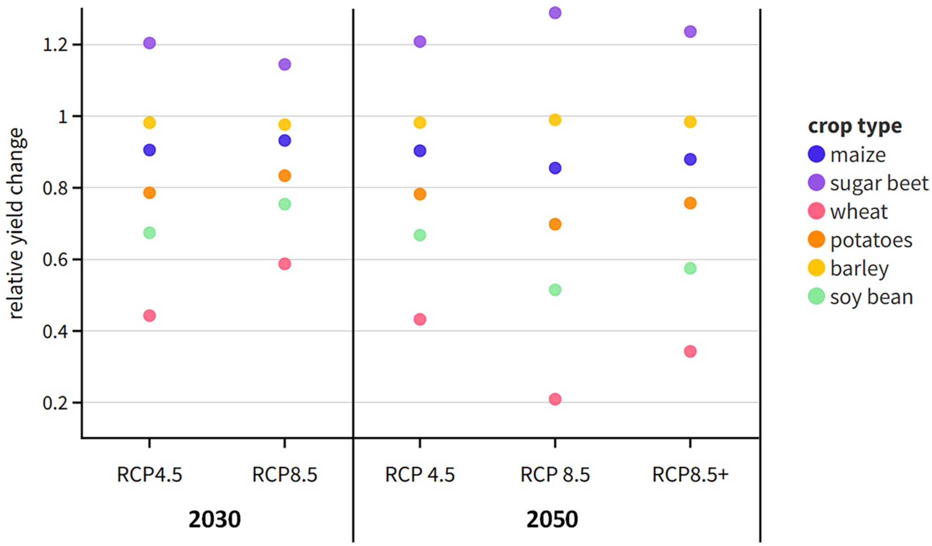


Fig. 4 Relative yield changes for different crop types relevant in the context of Austria across scenarios in terms of district weighted sums. Based on the exposure-response functions by Mills et al. (2007).

cal variability – including temperature and stagnation effects – over the influence of precursor emission changes and climate penalties in the near term.

However, by 2050, differences across scenarios become more pronounced. Under RCP4.5, yield losses remain relatively stable at 6.9%, as precursor emission reductions offset the negative effects of a warming-induced climate penalty. In contrast, aggregate yield losses increase sharply to 9.8% in RCP8.5. Importantly, unilateral domestic emission controls in RCP8.5+ mitigate some of these effects, reducing losses to 8.0% despite higher global emission levels in this scenario. These aggregate effects are driven by two key interactions.

The first interaction is crop sensitivity to O_3 exposure and economic relevance of each specific crop. For instance, among O_3-sensitive crops, wheat yield losses contribute significantly to overall reductions due to its substantial share in the agricultural sector. Conversely, while soybean losses are considerable, they have a minor impact on the overall sector due to their smaller economic contribution. Maize, despite showing moderate losses, has a higher relevance in the sector due to its greater economic importance. Barley, although one of the major crops grown in Austria, experiences minimal impact due to its relative O_3 resistance.

The second interaction combines the spatial overlap of high O_3 values with cultivation areas. Significant changes in relative agricultural output occur where high AOT40 values coincide with large cultivation areas. Conversely, high AOT40 values in regions with little or no cultivation have negligible effects on agricultural output. This is exemplified by Lower Austria, a major agricultural region in the Northeast of Austria that is experiencing high AOT40 values under higher emission scenarios. Similar patterns are observed in Upper Austria (Northwest of Austria) and Burgenland (East of Austria). The combination of these two drivers is most evident in the case of wheat, an important crop with large cultivation areas in the highly exposed region of Lower Austria, leading to substantial impacts on overall agricultural output.

The macroeconomic implications in terms of GDP effects are represented in Panel b of Fig. 3. In 2030, the difference in agricultural sector output between RCP4.5 and RCP8.5 (see appendix Figure A2.1) leads to a GDP reduction of 0.03% points (%p) in 2030. By 2050, the smaller direct yield losses in RCP4.5 translate into reduced GDP losses of 0.05%p, relative to RCP8.5. Similarly, emission controls under RCP8.5+ lower GDP losses by 0.03%p compared to RCP8.5. Overall, we find that spillovers to downstream sectors and GDP effects resulting from O_3-related yield changes are small, despite significant direct effects and associated output effects. This is due to the small value share of agricultural production in overall Austrian economic output.

3.3.2 Precursor emission controls

Complementing the effects on agricultural yield, economy-wide effects arise from the implementation of O_3 precursor emission controls, particularly in sectors such as manufacturing, energy and transport. These sectors not only face direct abatement obligations, but also serve as key upstream and downstream inputs across the Austrian economy. As such, emission control measures lead to indirect spillovers through changes in factor demand, production costs and relative prices, with effects on GDP (illustrated in Panel b of Fig. 3).

With absolute emission control costs peaking in 2030, macroeconomic effects are correspondingly stronger in 2030 than in 2050. GDP losses in RCP4.5 exceed those in RCP8.5 by 0.39%p in 2030, driven by more stringent emission reduction requirements. These losses reflect a combination of sectoral output reductions, primarily in abating sectors, and second-order effects in connected sectors, such as construction, private and public services, affected through relative factor price changes. Within energy sectors, we see a shift from gas and heat to electricity, which retains a comparative advantage from relatively lower emission control costs. Thus, overall effects in the electricity sector are marginal. Absolute changes in sectoral output levels are depicted in appendix Figure A2.1.

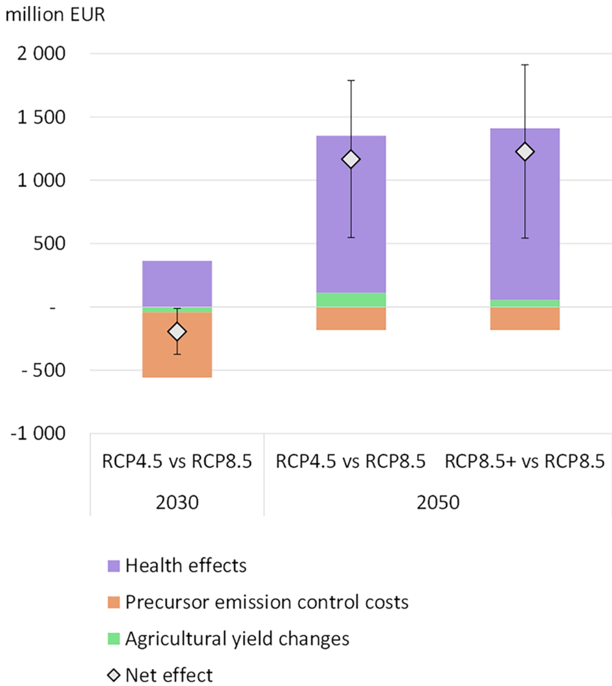
By 2050, the overall GDP effect of stricter emission controls narrows slightly. The difference between RCP4.5 and RCP8.5 (and equivalently between RCP8.5+ and RCP8.5) amounts to −0.19%p. This smaller impact reflects declining emission control costs towards 2050. As indicated in Figure A2.1, qualitative implications in terms of sectoral output effects are similar to 2030. However, we see that as energy sectors bear a larger proportion of abatement costs by 2050 in RCP4.5/RCP8.5+ and RCP8.5, comparative advantages of the electricity sector disappear. Note however, that overall differences in the output effect of energy between RCP4.5/RCP8.5+ and RCP8.5 are small. As in 2030, we find that the most pronounced differences in terms of absolute output effects arise in manufacturing, private and public service sectors.

3.4 Societal welfare effects

For a holistic comparison of costs and benefits across scenarios, we combine monetized non-market costs in terms of health effects and market costs from agricultural yield effects and emission control costs into an integrated measure of societal welfare effects. These aggregated results are illustrated in Fig. 5.

Contrasting societal welfare effects in 2030 between RCP4.5 and RCP8.5, we find that the resulting net effect from combining market and non-market costs is EUR −193 mil-

Fig. 5 Difference in societal welfare effects from combined market and non-market costs between RCP4.5 and RCP8.5 in 2030 and RCP4.5 and RCP8.5 and RCP8.5+ and RCP8.5 in 2050. The net effect shows the combined effect from health effects, agricultural yield changes and precursor emission controls, where error bars indicate upper and lower bounds for the estimated VSL.



lion, corresponding to a benefit-cost ratio (BCR) of 0.6. This negative net effect is a result of societal welfare losses from emission controls that amount to EUR 510, complemented with welfare losses from agricultural yield effects of EUR 42 million. These are only partly offset by benefits from reduced health impacts, which are valued at EUR 363 million. These results suggest that, in the near future, the costs and benefits do not justify stricter controls in line with RCP4.5 compared to RCP8.5.

By 2050, net welfare effects in RCP4.5 are positive, when compared to a high emissions scenario in RCP8.5. Overall, a positive net effect of EUR1167 million in RCP4.5 compared to RCP8.5 is attained, translating into a BCR of 7.4. This results from societal welfare losses from emission controls in RCP4.5 compared to RCP8.5 amounting to EUR 183 million. Also, we find that a reduction of agricultural yield losses creates societal welfare gains of EUR 110 million. Health effects from avoided mortality and morbidity in RCP4.5 compared to RCP8.5 amount to EUR 1 240 million. This combined effect makes RCP4.5 more beneficial than RCP8.5 from a societal welfare perspective.

Benefits also arise when contrasting RCP8.5+ and RCP8.5. with net positive societal welfare effects of EUR 1 227 million and a BCR of 7.7, we find that unilateral emission controls in a high emission scenario pay off in terms of societal welfare benefits. While effects from emission controls are negative, reducing societal welfare by EUR 183 million, these are counterbalanced by benefits from reduced damages on agricultural yields, increasing societal welfare by EUR 54 million in RCP8.5+ compared to RCP8.5. Also, benefits from avoided mortality in RCP8.5 + compared to RCP8.5 are distinct, amounting to EUR 1 356 million. Thus, despite the strong influence of background emissions on local O_3 levels, we find that the unilateral adoption of stricter emission controls in Austria in a high GHG emission scenario (RCP8.5+) creates overall welfare benefits in 2050, compared to a scenario where Austria also remains on a high emission path, according to RCP8.5.

4 Discussion

Our study shows the importance of adopting a holistic perspective on the societal and economic implications in integrated climate-air quality assessments. The findings shed light on the interplay between climate and local emissions in determining future O_3 burdens and the trade-offs between short-term costs and long-term benefits of emission controls in the Austrian context.

4.1 Climate–air quality interactions

Future O_3 burdens are driven by both changes in climate and in the chemical regime of O_3 production. In a high emission scenario (RCP8.5), ambient O_3 burdens are projected to be higher than in a medium emission scenario (RCP4.5), driven by elevated O_3 backgrounds (emerging as a consequence from increasing methane burdens) and a more favorable meteorology propelling higher O_3 production efficiency, particularly during spring. These results highlight the mutual benefits of ambitious climate policy for ambient air quality.

In addition, in a scenario with ambitious local O_3 precursor emission reductions (RCP8.5+) - the climate penalty - which facilitates O_3 formation in a warming climate, can be counteracted. The adoption of stricter precursor emission controls in Austria in a high GHG emission scenario is beneficial in the long term, outweighing negative effects of enhanced regional backgrounds and warming climate in RCP8.5+ compared to RCP8.5. This highlights the importance, effectiveness and scope of local air quality measures in a warming world.

While the decoupling of global GHG emissions and local socioeconomic and precursor trajectories is appropriate for a small country such as Austria, where unilateral action has a limited effect on the global climate, this approach is not transferrable to larger emitting regions as changes in NO_x and VOC emissions of major emitters would affect radiative forcing and create feedbacks that would need to be accounted for.

Moreover, our focus on O_3 impacts and precursors does not capture the interaction with climate mitigation policies and their potential for structural change within the economy and emitting sectors. To explore the link between national mitigation strategies and air quality benefits in a warming world, future work may combine mitigation and abatement responses in a coupled modeling framework, to advance our understanding of these dynamics.

4.2 Economic costs and welfare trade-offs

In line with our findings, the GDP effects of agricultural losses from O_3 exposure are likely to be relatively low in most industrialized countries, but they remain negative and should not be overlooked. With about one third of Austrian land covered by agriculture (Statistics Austria 2018), Austrian agricultural production patterns are considered cultural heritage and allow for a high degree of self-sufficiency, with domestic demand for wheat – an O_3-sensitive crop- met by 94% (BML 2022). This underscores the broader societal and cultural implications of agricultural losses, in addition to economic metrics. While we find small GDP impacts from O_3-related yield changes in Austria, it is important to also recognize that these findings may not be generalizable to countries where agriculture plays a more significant role in the economy. In many developing and emerging economies, agriculture contributes a much larger share to GDP and employment, making these nations more vulnerable to environmental factors affecting crop yields.[7] In such contexts, the economic repercussions of O_3-induced agricultural losses can be more pronounced, potentially leading to significant GDP effects and implications for food security and poverty rates in rural areas (Mbow et al. 2019).

In terms of societal welfare two implications emerge from our results. Firstly, we find that in 2050, the comparison of market costs from emission control costs and agricultural benefits alone in an industrialized economy like Austria would not yet provide sufficient incentives to pursue stricter precursor emission controls. However, benefits increase manifold, when health effects are considered. Secondly, even though we find that benefits from emission controls in 2030 cannot compensate for the costs in terms of societal welfare effects, the benefits from precursor emission controls accrue until 2050, enabling significant welfare gains. This indicates a trade-off between short-term costs and long-term benefits. These results are in line with Jensen et al. (2013), who find that in the context of UK GHG emission reduction strategies, long-term benefits involve initial net societal costs.

A limitation of our analysis concerns the valuation of non-market health effects, which constitute the largest component of the welfare impacts identified. These non-market costs rely on the VSL approach and results are therefore sensitive to the normative assumptions embedded in VSL estimates. Nonetheless, we explicitly report uncertainty ranges and show disaggregated contributions of market- and non-market cost components, which demonstrates that qualitative conclusions are robust to a large range of non-market valuation outcomes.

4.3 Relevance in the context of climate change impacts in Austria

Our results add a novel aspect to the assessment of climate change impacts in Austria. When comparing with the positive direct effect of climate change, i.e. the prolonged growing season and higher temperatures, on agricultural yields (Steininger et al. 2015), we find that the indirect negative consequences of O_3 on agricultural crop production outweigh the positive economy-wide effect. This should also be seen in the context of other potentially relevant climate change impacts like heat and drought, which affect agricultural production and are typically increasing with higher warming scenarios. Similarly, O_3-related premature mortality is a relevant addition to the heat-related deaths (Steininger et al. 2015). In the medium emission scenario (RCP4.5) and the near future (2030), we see a greater contribution from O_3-related premature mortality, while heat-related mortality dominates for strong temperature increases (RCP8.5) in the far future (2050). Nevertheless, we find that O_3-related deaths

[7] For instance, in 2023 agriculture generates 20–40% of the country's GDP in many African countries, while in Austria it accounts only for 1.3% There are also some European countries that have a stronger dependence on agriculture, such as Albania with around 16%, Ukraine and Moldova with around 8% or Hungary with around 5% OECD and World Bank (2025), https://ourworldindata.org/grapher/agriculture-share-gdp, last access: 09.04.2025.

can amount to up to one fifth of heat-related deaths by 2050 in a high emission scenario (RCP8.5).

4.4 Analytical scope

The presented results constitute conservative estimates regarding the costs related to O_3 exposure and associated with precursor emission controls. Given the single country focus, we do not account for the positive demand effects on sectors providing end-of-pipe technologies (Vrontisi et al. 2016), as these technologies are unlikely to be fully supplied domestically. In terms of costs associated with O_3 exposure, additional non-market costs arise from impacts on ecosystems and biodiversity (Fuhrer et al. 2016). While research links the interactions of O_3 and ecological processes (Mills et al. 2013) to date, insufficient quantification in terms of societal welfare effects does not allow us to consider these effects in the underlying paper. Further research may also investigate the societal welfare effects of O_3 on physical performance (Klingen and van Ommeren 2020) and worker productivity (Zivin and Neidell 2012), effects that have been empirically established but remain to be quantified for applicability in the Austrian context.

5 Conclusion

This paper investigates the societal welfare implications of three O_3 concentration levels in a changing climate, two in accordance with the global GHG emission scenarios in line with RCP4.5 and RCP8.5, and one scenario representing unilateral strict emission controls in a high GHG emission scenario (RCP8.5+). We consider market costs via changes in agricultural production as well as emission control costs of O_3 precursors and non-market costs via health implications.

The results show that emission controls pay off in terms of net societal welfare until mid-century, when health impacts are accounted for. In 2030, net societal welfare losses remain. This shows that from a societal perspective, the benefits on agricultural yield and avoided O_3-related mortality and morbidity come into effect only towards 2050, while emission control costs peak already in 2030.

Contrasting scenarios with and without unilateral precursor emission controls in a high global emission environment (RCP8.5), the reduction of O_3 precursors in Austria (RCP8.5+) proves to be beneficial, with benefits exceeding the costs sevenfold. This finding demonstrates that local precursor control measures can meaningfully reduce O_3-related damages even when global GHG emissions remain high and no comparable measures are implemented in neighboring countries. Our results therefore highlight the significant local benefits of unilateral air quality measures in a small industrialized economy, as an effective abatement strategy to reduce increasing O_3 burdens in a high emitting world.

Our results underscore the role of local emissions in shaping future O_3 burdens, even as global background concentrations increase and temperatures rise. This study reinforces the importance of local emission controls not only for mitigation, but also as a means to counteract the O_3-related climate penalty – the warming-induced increase in O_3 formation efficiency - and therefore informs air quality management in a changing climate.

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Data availability Any data that is not included in the SM or model code will be made available on request from the corresponding author.

Declarations

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