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Impacts of biofuel cultivation on mortality and crop yields

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Ground-level ozone is a priority air pollutant, causing ∼22,000 excess deaths per year in Europe[1], significant reductions in crop yields[2] and loss of biodiversity[3]. It is produced in the troposphere through photochemical reactions involving oxides of nitrogen (NO_x) and volatile organic compounds (VOCs). The biosphere is the main source of VOCs, with an estimated 1,150 TgC yr^{-1} (∼90% of total VOC emissions) released from vegetation globally[4]. Isoprene (2-methyl-1,3-butadiene) is the most significant biogenic VOC in terms of mass (around 500 TgC yr^{-1}) and chemical reactivity[4] and plays an important role in the mediation of ground-level ozone concentrations[5]. Concerns about climate change and energy security are driving an aggressive expansion of bioenergy crop production and many of these plant species emit more isoprene than the traditional crops they are replacing. Here we quantify the increases in isoprene emission rates caused by cultivation of 72 Mha of biofuel crops in Europe. We then estimate the resultant changes in ground-level ozone concentrations and the impacts on human mortality and crop yields that these could cause. Our study highlights the need to consider more than simple carbon budgets when considering the cultivation of biofuel feedstock crops for greenhouse-gas mitigation.

The European Union aims to replace 10% of transportation fuel and a proportion (here assumed to also be 10%) of power-generation fuel with biomass-derived fuels by 2020[6]. This may partly be achieved through the use of agricultural waste, but an increase in the cultivation of biofuel feedstock crops on land used for other purposes at present will be necessary[7]. Here we model changes in isoprene emission rates[8] caused by replacing some present agricultural crops and grassland in Europe with short-rotation coppice (SRC). SRC is a biofuel feedstock, used for power generation at present, and may be converted to ligno-cellulosic ethanol for use as a liquid transportation fuel in the future[7]. We then use a global chemistry transport model[9] (CTM) to quantify resultant changes in ground-level ozone concentrations. Finally, high-resolution population[10] and crop distribution[11] data sets are used with dose–response functions to quantify the effects that the simulated changes in ground-level ozone concentrations have on human mortality and crop yields.

At present, there are 215 Mha of land under cultivation, pasture or set-aside in Europe[12]. Over the next 20 years, it is anticipated that food demand in Europe will remain relatively constant, whereas crop yields will continue to increase, freeing present agricultural land for bioenergy production[12]. A total of 72 Mha (16 Mha in western EU countries, 29 Mha in eastern EU countries and 27 Mha in Ukraine) has been identified as being available for cultivation of ligno-cellulosic bioenergy feedstock in Europe[12]. In our study, we turn over these areas from crops, grassland and wasteland within our model vegetation distribution to SRC cultivation. Figure 1a shows the distribution of biofuel feedstock (as a fraction of total vegetation) used in our scenario. These additional SRC crops are projected to provide ∼120 Mt yr^{-1} of gasoline equivalent[13], sufficient to meet present EU targets[6].

Effects on ground-level ozone

Planting 72 Mha of SRC species (poplar, willow or eucalyptus) in place of crops, grass or barren ground results in a substantial increase in isoprene emissions (from 11.5 TgC yr^{-1} to 16.0 TgC yr^{-1}), and hence concentrations, across the model domain, shown in Fig. 1b. The spatial distribution of these increases follows the land-use change in Fig. 1a as isoprene has a short atmospheric lifetime (1–3 h). NO_x emissions resulting from fertilizer use are assumed to remain unchanged when food and fodder crops are replaced with biofuel crops[13,14]. The relatively high background levels of NO_x in Europe mean that the rate of photochemical production of ozone is generally limited by the availability of VOCs, with an increase in isoprene emissions leading to enhanced ozone formation[2]. Following SRC planting in the model, annual mean ground-level ozone concentrations increase by an average of 0.8 ppbv across the region. The greatest monthly change occurs in July (+2.5 ppbv; Fig. 1c). Local increases in monthly mean ground-level ozone concentrations of over 6 ppbv occur in eastern Europe where land-use change is greatest. Figure 1d shows the increase in the number of days on which the European Commission 8-h guideline value for ground-level ozone of 60 ppbv (ref. 15) is exceeded. Such exceedance days should occur no more than 25 times during a year (averaged over three years)[15]. Although the increase is highest over eastern Europe, there are also considerable impacts over central and southern Europe.

To estimate the sensitivity of ground-level ozone to isoprene emission rates we varied the isoprene emission rate from the SRC by ±50%, running the CTM with unchanged meteorology. The resulting effects on ground-level ozone are shown in Table 1. Broadly speaking, the changes in ozone concentrations vary linearly with isoprene emissions. We then reduced NO_x emissions by 10%, to simulate the reductions in European emissions that have occurred since 2000. This had no significant effect on ozone concentrations (Table 1), showing that the model results are relatively insensitive to our assumptions regarding regional NO_x emissions.

Mortality

Epidemiological studies show that every 10 ppbv increase in 8-h ozone[15] above a threshold of 35 ppbv results in a 0.67% increase in human mortality[16]. Figure 2a shows the population of Europe

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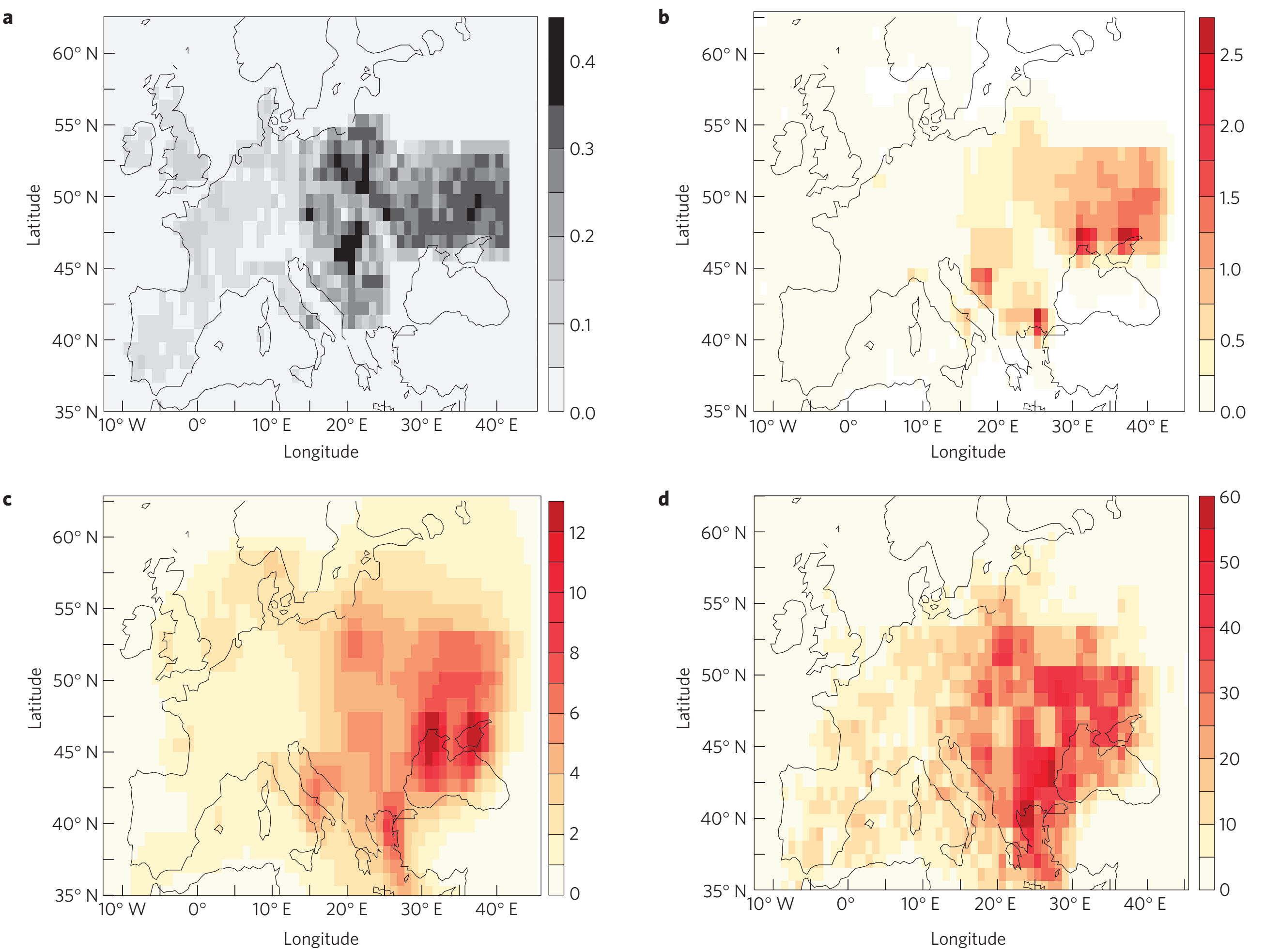

Figure 1 | Effect of replacing crops and grasses with high-emitting SRC species in our biofuel cultivation scenario. **a**, Fraction of vegetation that is SRC biofuel feedstock. **b**, Changes in monthly mean isoprene concentrations (ppbv) in July. **c**, Changes in monthly mean surface ozone concentration (ppbv) in July. **d**, Changes in number of exceedance days (days on which 8-h ozone concentrations exceed 60 ppbv; ref. 15) during the year.

Table 1 | Range of simulated impacts for original CTM simulations (Base case), altered isoprene emission rates sensitivity study (Isoprene), reduced NO_x emissions study (NO_x) and box model simulations (City).

		Ground-level ozone concentration changes (ppbv)		Impacts		Economic losses (2010 US$ billion)	
		Annual mean O_3	Monthly mean O_3	Additional mortality	Crop losses (Mt)	Additional mortality	Crop losses
Base case		0.78	2.61	1,365	7.84	6.4–7.8	1.2–1.9
Isoprene	Min	0.41	1.38	680	3.94	3.3	0.6
	Max	1.12	3.66	1,890	10.80	11.0	2.0
NO_x		0.76	2.56	1,330	7.62	6.3–7.6	1.1–1.8
City	Min	–	–	565	–	2.7–3.2	–
	Max	–	–	1,260	–	5.9–7.2	–

Further details are available in the Supplementary Information.

in 2006[10], with the increases in ground-level ozone concentrations following cultivation of 72 Mha of SRCs, expressed as SOMO35, in Fig. 2b. SOMO35 is the accumulated 8-h ozone above the 35 ppbv threshold over the course of a year. Figure 2c shows the projected annual increase in mortality due to this increase in ozone exposure. Increases in mortality are highest in the regions with the largest increases in ozone, but there are also substantial impacts in the populous northwest. Overall our model study suggests that cultivating 72 Mha of SRC biofuel feedstocks in place of traditional crops in Europe would result in 1,365 (95% confidence interval, CI = ±100) premature deaths annually, an increase of ∼6% in the 22,000 deaths attributed at present to ozone in Europe[1], at an estimated cost of around US$7.1 billion (2010) (ref. 17; see Supplementary Information for details of these calculations).

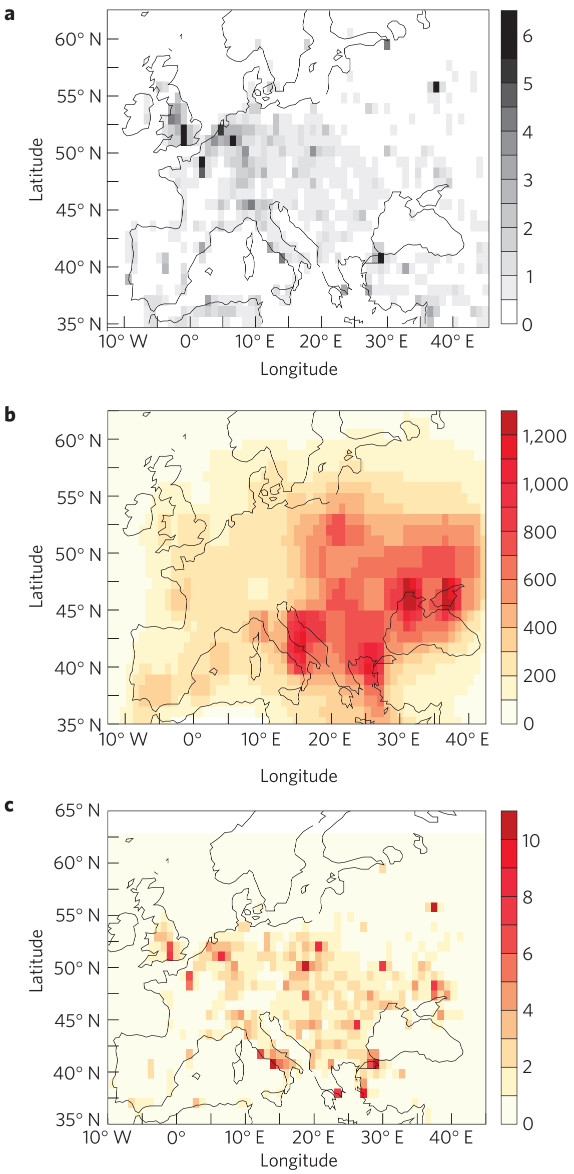

Figure 2 | Impact of increasing ground-level ozone concentrations on mortality. a, Population distribution[10] (millions). **b**, Changes in sum of 8-h ozone[15] above a threshold of 35 ppbv, SOMO35 (ppbv days). **c**, Deaths brought forward as a result of planting SRC.

The 95% confidence interval quoted above was calculated from a Monte Carlo analysis ($n = 10^4$) in which isoprene emission rates, the sensitivity of ground-level ozone to changes in isoprene emission rate, and the ozone-mortality dose–response factor were all assumed to vary, reflecting the sources of uncertainty within our impact assessment.

There are further uncertainties in our projected increases in ground-level ozone concentrations in urban conurbations due to the spatial scale of our global CTM. High levels of NO, such as those in many city centres, lead to reductions in ground-level ozone concentrations[2]. We have assumed that the changes in ground-level ozone simulated in our study are equally distributed across rural, suburban and urban areas within the same grid cell. This is likely to over-estimate ground-level ozone changes (and therefore mortality) in city centres. To study this further, we performed a series of simulations using a chemistry box model[18] to assess the sub-grid cell effects of high urban NO on the ozone changes simulated by the CTM. We find that NO titration does reduce the ozone increases simulated by the global CTM in city centres, but, under all conditions of NO concentration, the increased isoprene from planting SRCs causes increases in ground-level ozone and therefore increases mortality (see Table 1 and Supplementary Information for further details).

Crop yields

The present standard European metric for assessing ozone damage to vegetation is the accumulated exposure of vegetation to ozone above a threshold of 40 ppbv over the growing season (AOT40; ref. 15). We focus here on two key cereal crops: wheat, which is the main commercial crop in Europe (annual production ~190 Mt; ref. 11), and is known to be very ozone-sensitive[19]; and maize, an important food and fodder crop (~70 Mt; ref. 11), which is more ozone-tolerant[19]. Figure 3a shows the annual yield of wheat and maize in 2000[11], with modelled increases in AOT40 in Fig. 3b. Substantial areas of agricultural production experience increases in AOT40 sufficient to damage vegetation and reduce crop yields. Figure 3c shows the wheat and maize crop lost as a result of the simulated increase in ground-level ozone caused by planting 72 Mha of SRC in agricultural areas across Europe. We estimate an annual loss of ~7.1 (CI = ±0.30) Mt of wheat (3.5% of the present crop) and ~0.8 (CI = ±0.02) Mt (1%) of maize. This is a ~50% increase in the wheat and maize yields estimated to be lost to ozone damage in 2000[20] and represents an estimated economic loss of around US$1.5 billion (2010) (ref. 21). The 95% confidence intervals were derived from a Monte Carlo analysis in which isoprene emission rates, the sensitivity of ground-level ozone to changes in isoprene emission rates, and crop yield dose–response factors were assumed to vary. Our box model study shows that the effects of locally high NO emissions on rural ozone concentrations do not affect our projections of crop damage.

Conclusions

Overall, our study suggests that the widespread cultivation of 72 Mha of SRC for biofuel feedstock in Europe would have small but important impacts on ground-level ozone concentrations and hence on human mortality and crop productivity. As ground-level ozone is a priority air pollutant, much work has gone into strategies for reducing emissions of its NO_x and VOCs precursors. A multi-model study projected decreases of up to 0.8 ppbv in annual mean ground-level ozone as a result of a 20% reduction in anthropogenic ozone-precursor emissions in Europe alone[22], resulting in 2,500 fewer ozone-related deaths per year[23]. The Clean Air for Europe Programme calculated that implementation of present pollution control legislation could avoid as many as 5,500 ozone-attributable deaths per year[1]. These simulations were based on emission reductions under present climate conditions. A study of European ground-level ozone under changing climate suggested that summertime mean ground-level ozone could rise by 2 ppbv by 2030, with increased isoprene emissions accounting for as much as 30% of this[24]. The implications of our study are that the widespread replacement of present crop and grassland with SRC cultivation in the near future could negate much of the effects of present ozone-related pollution control policies. Moreover, the overall health impacts of SRC cultivation may be greater than those calculated here because isoprene also leads to the formation of secondary organic aerosol particles, which are known to have detrimental health effects[25]. However, present uncertainties about secondary organic aerosol particle formation, size distribution, atmospheric lifetimes and health effects are too great to allow reliable quantification at this time.

The impacts of biofuel cultivation on air quality could be mitigated through careful selection of feedstock crop[26] or through genetic engineering to reduce isoprene emissions[27] or by growing SRC in areas where an increase in isoprene emissions will not

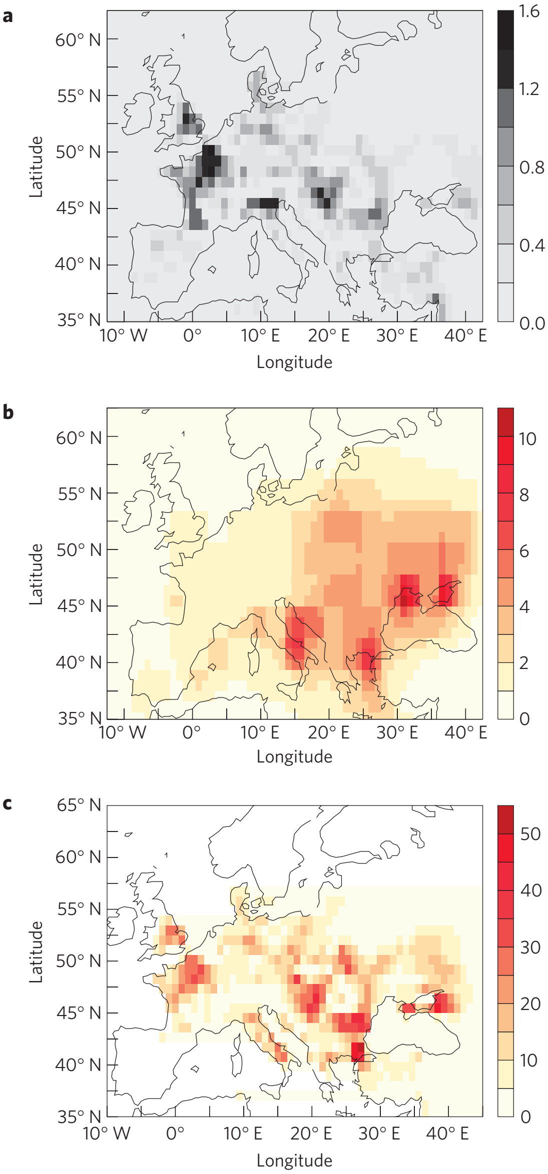

Figure 3 | Impact of increasing ground-level ozone concentrations on crop yield. a, Wheat and maize yield (Mt) in 2000[11]. **b**, Changes to the AOT40 metric (accumulated exposure to ozone over a threshold of 40 ppbv) in units of ppmv h (ref. 15). **c**, Wheat and maize production losses (kt) as a result of planting 72 Mha of SRC.

result in enhanced ozone formation. Shifting production away from populous areas or regions of intense agricultural production would ameliorate the effects of increased ground-level ozone. Our study shows the need for high-resolution site-specific impact assessments of future biofuel cultivation.

Methods

Atmospheric chemistry modelling. We used the Frontier Research System for Global Change/University of California Irvine (ref. 9) global CTM driven by European Centre for Medium-Range Weather Forecasts meteorological data at T42L37 resolution (2.8° by 2.8°) for 2001 to simulate isoprene emissions and atmospheric chemistry. We diagnose sub-gridscale structure using the second-order moment scheme, giving an effective diagnostic resolution of 0.9° by 0.9° (ref. 9). Anthropogenic emissions were taken from the International Institute for Applied Systems Analysis inventory for the year 2000; biogenic isoprene emissions were calculated online using the Model of Emissions of Gases and Particles from Nature v2.04 parameterized canopy emissions environment activity algorithms[8]. Other biogenic VOCs were not included in the simulations as they have a much smaller effect on tropospheric ozone. Emissions associated with the production of ethanol from SRC feedstock and the final combustion of the biofuel have not been considered. The National Center for Atmospheric Research vegetation distribution for 2001[8] was used to generate isoprene emissions. For the SRC scenario, the vegetation distribution was altered to include a broadleaf-tree biofuel crop in place of present crops or grasses. Appropriate isoprene emission rates and dry deposition velocities were assigned to each land-use class (see Supplementary Information for further details).

We used the Cambridge Tropospheric Trajectory Model of Chemistry and Transport tropospheric chemistry box model[18] to assess the effects of large urban areas on our projected changes in ground-level ozone. We followed air masses for a period of 4 days across a domain consisting of rural, suburban and city-centre regions with meteorological conditions and anthropogenic emissions representative of London in July[18]. The differences in simulated ozone concentrations with and without biofuel cultivation were analysed and the number of premature deaths calculated as below.

CTM evaluation. The CTM has been shown to reproduce observed ozone measurements as well as other global chemistry models[22]. Isoprene chemistry remains uncertain, but the impact of this uncertainty on projected ozone concentrations is believed to be small (a maximum of 25%; ref. 28). We compared monthly mean ground-level ozone concentrations from the model simulation against measurements from 131 European Monitoring and Evaluation Programme (EMEP) monitoring sites across Europe[29]. The CTM results were biased high during the summer months, but agreed well with observations in winter. As summer is the main growing season and the time of year with most ozone exceedances, we scaled the modelled ozone concentrations to improve the fit to observations before calculating the impacts on human health and crop yield. Monthly scaling factors were derived by minimizing the root mean square error (r.m.s.e.) between modelled and measured concentrations at each EMEP site, and the same scaling was used for all simulations. The adjusted ozone concentrations were then used to calculate the standard air quality metrics. The r.m.s.e. indicated that these metrics compared well to those generated from the EMEP measurements (see Supplementary Information for details).

Human health impacts. There is considerable uncertainty in the relationship between increased ground-level ozone and human health impacts. We limit our analysis to premature mortality, based on daily exposure to elevated ozone, as the effects of chronic exposure have not been adequately quantified[25]. We use a threshold of 35 ppbv, in line with World Health Organisation air quality guidelines, although the existence of a threshold ozone concentration is uncertain[25]. We applied the following algorithm[23] daily to every grid cell individually, summing the results over the region for a year:

$$\Delta \mathrm{Mort} = y_0(1 - \exp(-\beta \Delta x))\mathrm{Pop}$$

where ΔMort is the number of additional daily mortalities resulting from the SRC scenario, y_0 is the baseline mortality rate in the population, β is the concentration–response factor, Δx is the change in 8-h ozone and Pop is the grid cell population. The concentration–response factor, β, was taken as a 0.67% increase in mortalities for every 10 ppbv increase in ozone, based on the results of a meta-analysis of European epidemiological studies[16]. The baseline mortality rate of 10 per 1,000 deaths was calculated from World Health Organisation mortality data for Europe[30].

Crop impacts. We calculated yield reductions and crop production losses[20] for each grid cell based on algorithms developed from meta-analysis of Europe-wide field trials[19]

$$\text{For wheat RY} = -0.0161 \times \text{AOT40} + 0.99$$
$$\text{For maize RY} = -0.0036 \times \text{AOT40} + 1.02$$
$$\text{CPL} = (1 - \text{RY}) \times \text{CP}$$

where RY is the yield reduction relative to the theoretical yield without ozone damage, CPL is the crop production loss and CP is the actual crop production for 2000. AOT40 is the accumulated exposure to ozone over a threshold value of 40 ppbv. The integration of AOT40 is over time, hence it has units of ppmv h. To convert to AOT40 in units of ppbv h, multiply by 1,000. AOT40 is calculated for daylight hours (08:00–20:00) for the three-month growing season, May to July, for Europe[15]. The relationship between AOT40 and crop damage remains uncertain[19,20], but the approach adopted here represents present policy best-practice. We use actual crop yield for the year 2000[11] without accounting for the effects of present ozone damage, and our projected crop production loss is therefore likely to be an under-estimate.

Economic losses. We used the Organisation for Economic Co-operation and Development analysis of Value of a Statistical Life[17] for Europe for 2005 to calculate the economic impact of the projected additional deaths. We used Eurostat crop prices[21] for the most recent three years (2009–2011) to calculate the cost of the simulated crop production losses.

Monte Carlo analysis. Confidence intervals for premature mortality and crop production losses were calculated from a Monte Carlo analysis with a sample size of 10^4. Isoprene emission factors for SRC tree species, changes in ozone concentration in response to changes in isoprene emissions, and the dose–response factors for both mortality and crop losses were assumed to vary. These variables were taken to follow normal distributions with mean values taken from the original simulation and variances either calculated in this study (see Supplementary Information for details) or taken from previous meta-analyses[16,19].

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Author contributions

All authors devised the research, analysed the results and wrote the paper; K.A. conducted the model simulations.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to C.N.H.

Competing financial interests

The authors declare no competing financial interests.