The impact of biofuel poplar cultivation on ground-level ozone and premature human mortality depends on cultivar selection and planting location

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Abstract

Isoprene and other volatile organic compounds emitted from vegetation play a key role in governing the formation of ground-level ozone. Emission rates of such compounds depend critically on the plant species. The cultivation of biofuel feedstocks will contribute to future land use change, altering the distribution of plant species and hence the magnitude and distribution of emissions. Here we use relationships between biomass yield and isoprene emissions derived from experimental data for 29 commercially available poplar hybrids to assess the impact that the large-scale cultivation of poplar for use as a biofuel feedstock will have on air quality, specifically ground-level ozone concentrations, in Europe. We show that the increases in ground-level ozone across Europe will increase the number of premature deaths attributable to ozone pollution each year by up to 6%. Substantial crop losses (up to ~9 Mt y^{-1} of wheat and maize) are also projected. We further demonstrate that these impacts are strongly dependent on the location of the poplar plantations, due to the prevailing meteorology, the population density and the dominant crop type of the region. Our findings indicate the need for a concerted and centralized decision-making process that considers all aspects of future land use change in Europe, and not just the effect on greenhouse gas emissions.

Introduction

Volatile organic compounds (VOCs) are produced and released to the atmosphere from both anthropogenic and natural sources. Biogenic VOCs (bVOCs) account for over 90% of the non-methane hydrocarbons emitted annually (*1*). Of these, the reactive compound isoprene (2-methyl-1,3-butadiene) is the most significant in terms of both magnitude of emissions (estimated at 500 TgC y^{-1} (*1*)) and subsequent impact on atmospheric composition (*2*). The photochemical oxidation of isoprene in the presence of the nitrogen oxides (NO_x: NO and NO_2) governs the production rate of ground-level ozone (*3*), and leads to the formation of low volatility reaction products that can condense into the aerosol phase (*4*). Both ozone and aerosol are predominantly secondary pollutants with well-documented effects on climate and air quality. Their contribution to radiative forcing since Pre-Industrial times has been quantified as +0.40 (+0.20 to +0.60) W m^{-2} and -0.03 (-0.27 to +0.20) W m^{-2} respectively (*5*). The World Health Organization attributes over 3.7 million deaths worldwide to their combined health effects annually, of which around 0.25 million occur in Europe (*6*). While it is believed that exposure to particulate matter (PM) is responsible for the majority of these premature deaths, ozone pollution has been identified as one of the biggest causes for concern in Europe (*7*). Owing to the high level of uncertainty involved in modelling the formation of biogenic secondary organic aerosol (SOA) and in attributing health impacts of PM to specific sources given the lack of knowledge of the size distribution and toxicity of aerosols of different origins, this study focuses on changes in ground-level ozone in response to projected land use change associated with biofuel feedstock cultivation. Our estimates of air quality impacts associated with biofuel cultivation therefore represent a lower bound.

The synthesis and emission rates of bVOCs are strongly dependent on plant species as well as environmental factors such as light and temperature, and hence are regulated by species distribution (*8*). Land use and land cover change (LULCC) therefore has the potential to substantially alter emissions of bVOCs by changing the occurrence and distribution of plant species at the regional scale (*9,10*). Hurtt et al. identify the large-scale cultivation of biofuel feedstock crops together with afforestation initiatives in the mid-latitudes as key drivers of LULCC in the near future in the moderate Intergovernmental Panel on Climate Change Representative Concentration Pathways (RCPs) scenarios (*11*).

Increasing areas of land are already being converted to the production of bioenergy crops (*11*) in order to meet the growing demand for energy supplies perceived as "carbon-neutral". In particular, the European Union has set a target of 10% replacement of transportation fuels with biofuels and a 10% replacement of its combined heat and power plant feedstock by 2020 (*12*). One of the most important short rotation coppice crops currently used for this purpose is hybrid poplar (produced by crossing various *Populus* species) (*13*), and although the European Union has not mandated that feedstocks are locally grown, environmental and energy security considerations mean that cultivation of poplar is projected to increase.

The replacement of land currently given over to grasses and conventional food crops, few of which emit detectable amounts of isoprene (*8*), with a high isoprene-emitting species such as poplar, will cause the amount of isoprene entering the atmosphere to increase. In the presence of the moderately high concentrations of NO_x found in Europe, emissions of isoprene lead to higher concentrations of ozone and under these conditions isoprene emissions may be one of the most important determinants of ground level ozone concentrations[3]. Different cultivars of poplar have differing isoprene emission rates (*8,13,14*) but also produce different biomass yields (*13,14*).

We have previously shown that the large-scale conversion of agricultural and grass lands in Europe to biofuel crops such as poplar increases ground level ozone concentrations sufficiently to have significant impacts on human mortality (more than 1000 additional deaths annually) and crop yields (a 4% reduction) (*15*). Here, we determine the feasibility of mitigating these impacts through policy intervention, based on either the careful selection of poplar cultivar or well-informed choice of geographic location for future large-scale poplar plantations.

We use experimental data on the relationship between biomass yields and isoprene emission rates from 29 different commercially available cultivars of poplar (*14*) in a model of atmospheric transport and chemistry (*15,16*) to calculate the effects of the large-scale cultivation of these cultivars on ground level ozone concentrations in Europe. We calculate the impacts of this additional ozone on human mortality and crop yields across Europe, for each of a range of cultivar type (low-, mid-, or high-yielding) and defined planting region within the continent.

Methods and materials

LULCC scenarios

Eller et al. (*14*) showed a statistically significant relationship between biomass yield and isoprene emission rate for 29 commercially available poplar hybrids. We categorize these poplar hybrid clones into three groups based on biomass yield; the median yield of each of the low-, medium-, and high-yielding groups is taken as the 10^{th}, 50^{th} and 90^{th} percentiles of the yields of the full set respectively. We determine the median isoprene emission rate for each group (see Table 1 and SI). Meeting the 2020 EU targets for biofuel usage will require the production of 260 Mt (dry weight) of biomass per year (*12,17*). We calculate the land area required to meet this biomass yield target, using the average yield for each of the three groups. We also use emissions and yield data for a fourth poplar clone, genetically manipulated so that it does not emit isoprene. Such a genetically modified organism (GMO) has already been engineered and has been shown to have a biomass yield close to the median of conventional cultivars, with negligible isoprene emission (*13*).

The observed range of biomass yields for the cultivar groups is 4.3-11.5 t(dry weight) ha^{-1} y^{-1}, resulting in land requirements between 23 and 61 Mha for these types. Fischer et al. (2010) (*18*) demonstrated that up to 72Mha of land in Europe currently used for food crop or livestock production could be converted to biofuel feedstock cultivation without jeopardising food security. We distribute this land area required for the additional cultivation of poplar across Europe according to previously identified land availability (*15,18*), under three broad LULCC scenarios, shown in Table 1.

In the first planting scenario, a “fixed area” approach, we assume that 33 Mha of land is converted to poplar cultivation across the EU. This is the land area required to reach the biofuel production target using the medium-yield group of poplar cultivars. The total biomass yield produced from this 33 Mha then depends on the cultivar type used.

In the second LULCC scenario, taking a “fixed yield” approach, we assume that sufficient land is turned over for each cultivar group to ensure that the EU’s biomass requirement is harvested from the poplar plantations annually. In this experiment, the area required differs, depending on the assumed yield of the cultivar used. We also estimate upper and lower bounds for the air quality impacts of the different poplar types for the fixed yield cultivation scenarios.

In a final “regional” approach we assume that a medium-yield cultivar is grown, but that the required 33 Mha of land used are confined to one of four distinct regions within Europe: NW Europe, NWEu; the Mediterranean region, Med; Eastern Europe, EEu; Ukraine, Ukr. The differing environmental conditions in these regions lead to differences in the ozone production resulting from the increase in isoprene emissions, and differences in population density and crop production then also determine the air quality impacts of the modelled land use change. Differences in environmental conditions other than temperature and light within the regions of cultivation (e.g. differences in soil moisture availability) may result in different total biomass yields, but these second-order effects are not accounted for here.

Table 1 shows isoprene emission rates and total emissions for Europe under each of our biofuel cultivation scenarios. Figures in parentheses for the "fixed yield" scenarios indicate the upper and lower bounds used in the sensitivity tests performed to constrain the uncertainties in our estimates (see text above and SI for further details).

		Isoprene emission rate (μg m^{-2} h^{-1})	Biomass yield (Mt odw)	Land area required (Mha)	Total isoprene emissions (Tg y^{-1})
Base case		35	-	-	11.4
Fixed area (33.3 Mha)	Hi	82.8	340	33.3	15.4
	Mid	55.3	260	33.3	14.1
	Lo	28.9	190	33.3	12.8
	GMO	2.0	240	33.3	11.4
Fixed yield (260 Mt)	Hi	82.8 (80.3, 85.2)	260	22.6 (22.0, 23.3)	14.1
	Mid	55.3 (52.9, 57.8)	260	33.3 (32.0, 34.8)	14.1
	Lo	28.9 (27.5, 31.3)	260	61.2 (56.8, 66.3)	13.9
	GMO	2.0	260	35.6	11.4
Regional (33.3 Mha)	Ukr	55.3	260	33.3	14.4
	EEu	55.3	260	33.3	14.1
	NW	55.3	260	33.3	14.0
	Med	55.3	260	33.3	15.1

Under each of the three approaches taken here we account for the impacts of land use change on isoprene emission rates, surface roughness, leaf area indices and deposition processes, factors which have been previously shown to substantially affect ozone concentrations (*19,20*).

Experimental data

Leaf-level isoprene emission rates and total first growth year biomass increases for 29 commercially available hybrid poplar clones (*14*) were used to determine emission factors (basal emission rates at standard conditions

(*1*)) and estimated total biomass yields (per hectare) for a four year growing cycle (*13,14,21*). The following Reduced Major Axis regression relationship (*22*) between the two was determined:

$$y=0.13449\varepsilon+0.35812$$

where y is the yield (t ha^{-1}) and ε is the isoprene emission factor (mg m^{-2} h^{-1}). "Average" emission factors (shown in Table 1) and yields for three groups: low- (taken as the 10^{th} percentile), mid- (median) and high- (90^{th} percentile) yielding, were quantified. The Standard Error of the Mean were also derived and used for a series of sensitivity simulations to provide an upper and lower bound estimate of the air quality impacts of the fixed yield cultivation scenarios. See SI for further details of the data analysis performed. The isoprene emission factor for the GMO poplar clone was derived by assuming a 5% isoprene "leakage" rate based on emissions from a conventional poplar cultivar (*13*).

Atmospheric chemistry modelling

We used the Frontier Research System for Global Change/University of California Irvine (FRSGC/UCI) global chemistry transport model (CTM) to simulate isoprene emissions and atmospheric chemistry (*16*). The CTM calculates biogenic emissions on-line using the Parameterized Canopy Environment Emission Activity algorithms of the Model of Emissions of Gases and Aerosols from Nature (MEGAN) model v2.04 (*9*), here with isoprene emission factors at standard conditions taken from the experimental data outlined above. For the poplar scenarios, the baseline vegetation distribution (*9*) was altered to include a broadleaf tree biofuel crop in place of current crops or grasses. Dry deposition velocities were altered to reflect the changes in land cover (*15*) (see SI for further details). Other biogenic VOCs were not included in the simulations as they have a substantially smaller effect on tropospheric ozone (*2*). Anthropogenic emissions were taken from the International Institute for Applied Systems Analysis inventory for the year 2003 (*23*). Emissions associated with the production of ligno-cellulosic ethanol from woody biomass and the final combustion of the biofuel have not been considered.

The CTM was driven by meteorological data from the European Centre for Medium-Range Weather Forecasts at T42L37 resolution (2.8° by 2.8°) for 2001, with sub-gridscale structure captured using the second-order moment scheme resulting in an effective diagnostic resolution of 0.9° by 0.9° (*16*). The capability of the CTM to capture observed ozone concentrations in Europe has been assessed previously (*15,24*) against measurements taken from EMEP (European Monitoring and Evaluation Program) monitoring stations. The small high bias of the CTM output during the summer months was corrected using monthly scaling factors as outlined in our earlier study (*15*). Given the non-linear response of ground-level ozone concentrations to increased isoprene emissions, the use of a large-scale model is likely to introduce a high bias in projections of the number of premature deaths while under-estimating crop production losses. However, these errors, associated with spatial averaging of ozone concentrations across disparate chemical regimes (urban vs. rural), have been shown to be small (*15*), as have the effects of changes in anthropogenic NO_x emissions since 2003 (*15*).

Impacts analysis

Human mortality

We applied the following dose-response relationship to each gridcell and summed the results over the domain for a year:

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

where ΔMort is the number of additional daily mortalities resulting from the LULCC scenario, y_0 is the baseline mortality rate in the population, β is the concentration-response factor, Δx is the change in 8-hour ozone above a threshold value of 35 ppbv, and Pop is the grid cell population (*25*).

Although there is considerable uncertainty in the quantification of human health impacts arising from increased exposure to ground-level ozone, the above relationship has been developed from meta-analyses of epidemiological studies (*26*). The use of a threshold concentration, while not physiologically realistic, is in accordance with WHO guidelines (*6*) and increases the robustness of disentangling the effects of ozone from confounders such as temperature (*26*). The values of both the concentration-response factor β (set at a 0.67% increase in mortalities for every 10 ppbv increase in ozone (*26*)), and the baseline mortality y_0 (10 per 1000 deaths (*27*)) are Europe-specific values.

The chronic (morbidity) effects of increasing ground-level ozone concentrations are not well established (*6*) and we restrict our analysis to the impacts on mortality.

Crop production losses

We estimate crop production losses for wheat and maize, two of the most commercially important food crops in Europe, based on relative yield reductions in response to increasing ground-level ozone concentrations based on the following expressions:

For wheat $\quad RY = -0.0161*AOT40+0.99$

For maize $\quad RY = -0.0036*AOT40+1.02$

$$CPL=(1-RY)*CP$$

where RY is the yield reduction relative to the theoretical yield without ozone damage, CPL is the crop production loss, CP is the actual crop production for 2000 and AOT40 is the accumulated exposure to ozone concentrations above a threshold of 40 ppbv (*28*). AOT40 is accumulated during daylight hours (08:00 to 20:00) for the three-month growing season, May to July, for Europe (*29*). These parameterizations are based on extensive field studies and use Europe-specific values for the intercepts and gradients (*28,29*). While the response of vegetation to increasing atmospheric concentrations of ozone is highly uncertain and expected to depend on the actual flux of ozone through plant stomata (*30*), the use of the AOT40 metric represents current policy best practice (*31*).

We do not consider the impact of ozone damage on the biomass yield of the poplar cultivated for biofuel production in our scenarios. While some studies have previously suggested that carbon assimilation and hence productivity are reduced in poplar clones exposed to high levels of atmospheric ozone (*32*), we assume that such a reduction in yield would necessarily lead to the expansion of the poplar plantations in order to meet the target yield of 260 Mt y^{-1}. We further assume that this would have a negligible effect on the magnitude or spatial distribution of the increased isoprene emissions.

Economic losses

The economic losses associated with the projected number of premature deaths for each scenario was based on OECD analysis of Value of a Statistical life for Europe for 2005 (*33*). Crop prices for the most recent 3-year period (2009-2011) were taken from Eurostat (*34*) and averaged to estimate the cost of the simulated yield reductions. Costs were converted to 2010 USD values using average exchange rates (*35*) and estimates of deflation (*36*) from the US Government.

Food security

The calories lost for each 1 Mt loss of wheat harvest were estimated from FAO statistics for the nutritional content of wheat flour and assume 5% post-harvesting losses and a 73% flour recovery during the milling process (*37*).

Results and discussion

Effects on isoprene When large areas of very low-isoprene emitting grasses and traditional agricultural crops are replaced by high-isoprene emitting poplar, total European annual isoprene emissions increase, as shown in Table 1. Planting 33 Mha of commercially available poplar cultivar as biofuel crops (i.e. the land area required to meet EU biomass targets for the medium-yielding group of cultivars – the "fixed area" scenario) results in increases of isoprene emissions across the model domain of between 12 and 36% relative to the base case in which no additional poplar is cultivated for biofuel use. It should be noted that, by contrast, planting poplar that has been genetically-modified not to emit isoprene, instead of commercial cultivars, does not affect annual isoprene emissions, as the assumed isoprene "leakage rate" (5%) (*13*) from such cultivars is roughly equal to the emissions from the replaced vegetation (crops and pasture) (*9*).

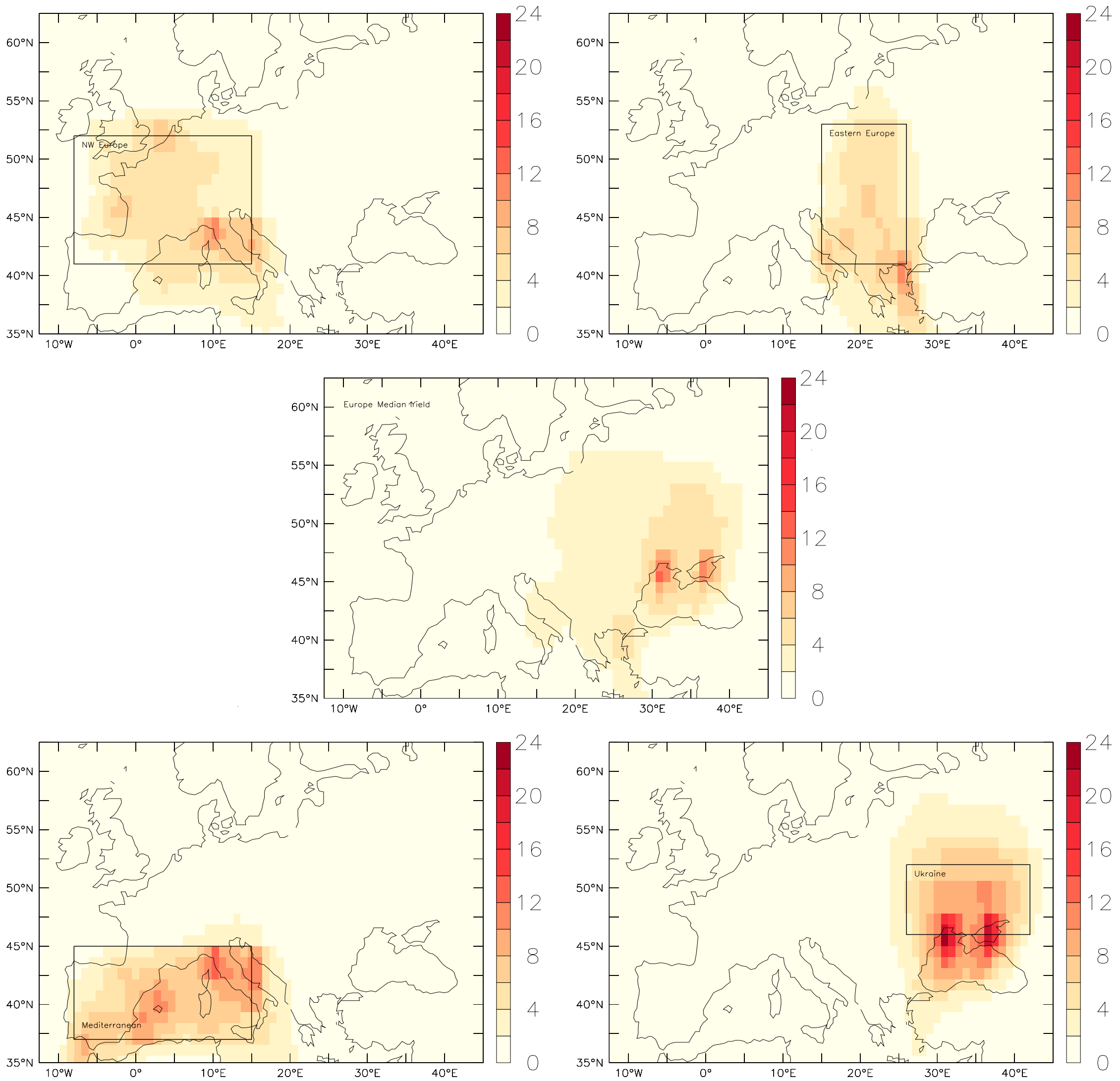
The effect of planting only sufficient areas of poplar to yield the woody biomass required to meet the EU yield target of 260 Mt y^{-1} (the "fixed yield" scenario) is much less variable, with increases of between 22 and 24% in total isoprene emissions, due to the compensating effects of planting density and isoprene emission rate for the cultivar groups – using high-yielding cultivars requires less land to be converted to plantations.

If all of the 33 Mha of land replanted with poplar is concentrated in specific geographical regions instead of being distributed across the continent as a whole (the "regional" scenarios), total annual isoprene emissions are increased by between 23 and 33% compared with baseline emissions (see Table 1). The differences between the emission increases in different regions are due to regional differences in temperature and light intensity, the key environmental drivers of isoprene emissions (*6*). Under these planting scenarios, the maximum increase in emissions occurs when the plantations are located in the hot, sunny Mediterranean region, while biofuel cultivation in cooler, cloudier north-west Europe results in the smallest increase.

The spatial distribution of the absolute changes in isoprene emissions is strongly dependent on the distribution of cultivation. As isoprene is relatively reactive with respect to atmospheric oxidizing species (atmospheric lifetime of around 90 minutes (*38*)), increases in its atmospheric concentration are confined to the vicinity of the location of the emissions.

Effects on ozone Boundary-layer concentrations of NO_x are moderately high across Europe, while emissions of VOCs are generally relatively low (*39*). Hence the boundary-layer atmospheric chemistry of the region is sensitive to increased emissions of volatile organic compounds, with the cycle of radical reactions resulting in enhanced production of ozone in the lower troposphere as emissions rise (*3,39*). While increases in annual mean concentrations of ground-level ozone are modest when considered over the entire domain in all scenarios (reaching around 2% for the commercially available poplar cultivars), increases in monthly mean concentrations for July (when isoprene emissions peak in Europe) can be over 2 ppbv when averaged across the domain as a whole and as high as 18 ppbv for some source locations.

Figure 1. Increases in July monthly mean ground-level ozone concentrations across all of Europe for each of the regional planting scenarios. The centre panel shows the same for the median yielding fixed-land planting scenario for comparison. The boxes drawn on each panel show the extent of the area in which the biofuel poplar plantations were located in each scenario.



Under the regional planting scenarios, where substantial increases in isoprene emissions and concentrations are confined to small areas, the effects on ground-level ozone are more pronounced although localized to the region of cultivation. Although domain-wide changes are of similar magnitude to those simulated under the fixed area and fixed yield scenarios, increases of up to 9 ppbv occur in the July monthly mean ozone concentration in Ukraine, as shown in Figure 1, where high background levels of NO_x are exacerbated by ideal photochemical conditions for ozone production. When cultivation is limited to the Mediterranean ground level annual and July monthly mean concentrations reach 44 and 51 ppbv respectively, compared with 40 and 45.5 ppbv in the base case with no LUC. The smallest increases (of 2.5 and just under 4 ppbv, up from 36 and 41 ppbv) are seen in the cooler, cloudier north-west of Europe.

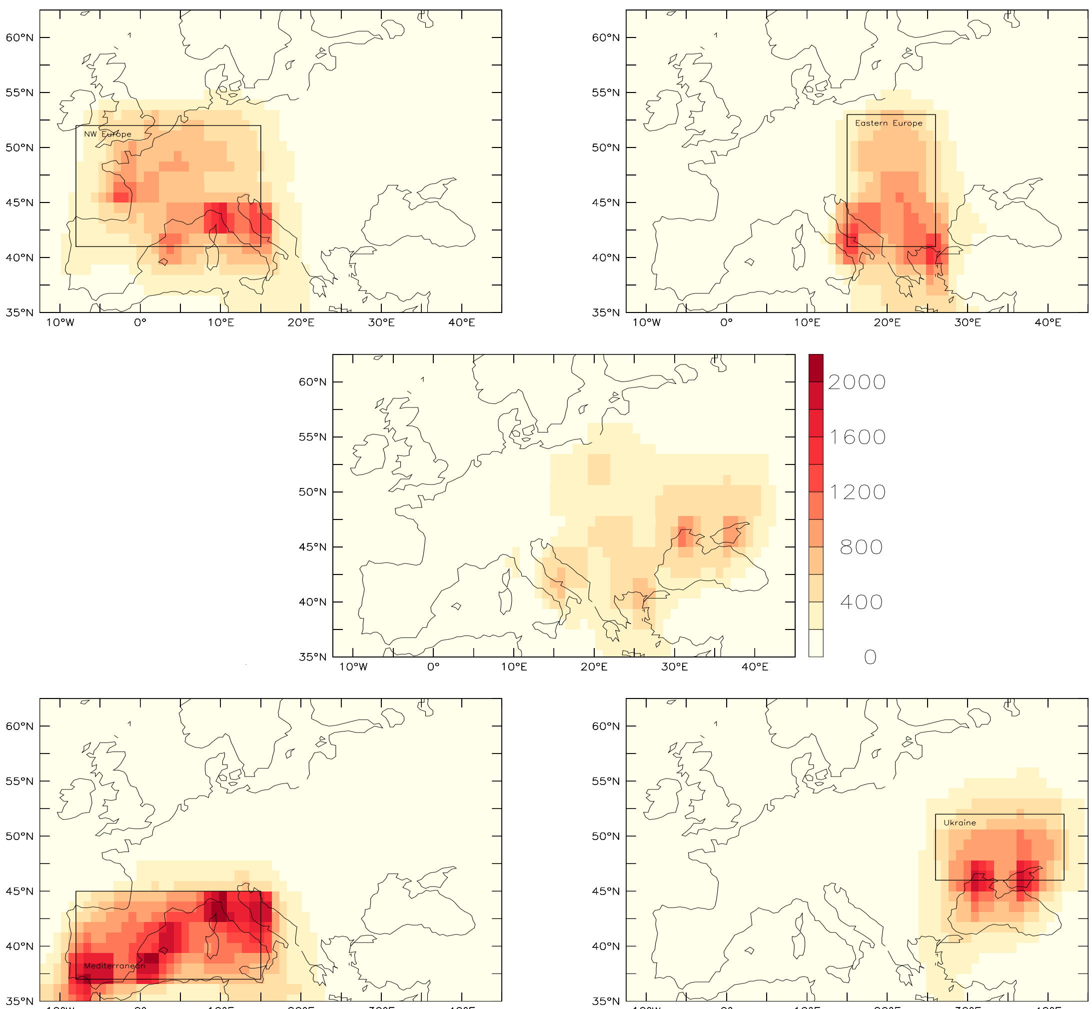
Because background levels of ground-level ozone across Europe are rising (*39*), even the small increases resulting from the realistic planting scenarios developed in this study are sufficient to raise ozone mixing ratios above 40 ppbv in many locations. This is the concentration of ground-level ozone above which adverse effects on both human health and crop yields are thought to be observable (*26,29*).

To put the increases simulated in this study into context, recent modeling studies show that projections of ground-level ozone concentrations in Europe are strongly dependent on changes in both climate and precursor emissions. Most agree that meteorological changes will enhance ozone production over most of the region, although decreases may be observed in the Mediterranean. In particular, changes in climate associated with RCP8.5 are projected to increase summertime domain-averaged mean ozone concentrations by around 1.5 ppb per decade (*40*). However, taken in combination with assumed future decreases in NO_x emissions in the region, some regions may experience decreases in ozone concentrations as the chemistry becomes NO_x rather than VOC limited (*40*).

The increases in ground-level ozone concentrations affect daily maximum 8-hour ozone, the metric used to assess potential health and ecosystem impacts. Figure 2 shows the increase in the accumulated exposure to 8-hour ozone above a threshold of 35 ppbv for each of the regional cultivation scenarios. As in Figure 1, the changes are mostly limited to the region of LUC, although some downwind transport is observable. By contrast, however, the changes are highest in the Mediterranean, where background levels of ozone are already high. Although the absolute changes are higher in the Ukraine, these are not always sufficient to raise ozone above 35 ppbv as background concentrations are lower. While increases in 8-hour ozone in NW Europe are lower still, the magnitude of the changes in accumulated exposure is similar, particularly in areas where ozone levels are already high.

In addition, the EU sets a limit of 60ppbv in 8-hour ozone, as recommended by WHO (5). Days on which this is exceeded (known as "exceedance days" are reportable, with a limit on the number of exceedance days at any monitoring location set at 3 per year. Table 2 shows the increase in total number of reportable days across Europe for each cultivation scenario. Panels (c) and (f) in Figure 2 show the spatial distribution of these changes for the Ukraine and NW Europe cultivation scenarios respectively. While the total number of exceedance days reflect the changes in mean concentrations for the fixed land and fixed yield scenarios in which cultivation occurs throughout Europe, when confined to a small region there are considerable differences, as the current background level of ozone varies markedly between the regions. In line with the increases in 8-hour ozone outlined above, the biggest increase in number of exceedance days occurs in the Mediterranean. By contrast, however, the relatively low concentrations in the Ukraine under current land cover mean that in spite of the large increases in ground-level ozone in this region, 8-hour ozone concentrations still exceed 60 ppbv less often. However, many locations would exceed the 3 day per year reporting threshold.

Figure 2. Increases in annual accumulated ozone exposure across all of Europe for each of the regional planting scenarios. As Figure 1, but showing the increases in the annual accumulated exposure to daily maximum 8-hour ozone concentrations over a threshold of 35 ppv (in ppm days).



The atmospheric lifetime of ozone in the lower troposphere is sufficiently long (of the order of a few days) to allow transport from source locations over 100s of km. Transport from rural areas (i.e. the areas of cultivation) to urban areas is significant in terms of human health impacts as the additional ozone generated as a result of biofuel cultivation penetrates into areas with high population densities. Transport over these distances allows sufficient time for the air mass to become well-mixed and ozone concentrations to become relatively uniform.

Impacts of changes in ground-level ozone concentrations

Table 2 shows the changes in ground-level ozone concentrations and resulting impacts for Europe under each biofuel planting scenario. Figures in parentheses for the "fixed yield" scenarios indicate the upper and lower bounds used in the sensitivity tests performed to constrain the uncertainties in our estimates (see text above and SI for further details).

		Changes in ground-level ozone concentrations (ppbv)		Changes in number of exceedance days	Impacts (annual)		Economic losses (annual) (2010 US$ billion)	
		Annual mean	Monthly mean	Additional days/year	Additional mortality/year	Crop losses (Mt/year)	Additional mortality/year	Crop losses (Mt/year)
Base case		(35.2)	(38.8)	(24680)	(22,000)	(14.3)	-	-
Fixed area (33.3 Mha)	Hi	0.59	2.04	13921	1040	7.87	5.4	1.5
	Mid	0.40	1.42	9146	710	5.42	3.7	1.1
	Lo	0.21	0.77	4495	380	2.90	2.0	0.6
	GMO	0.007	0.026	163	15	0.14	0.08	0.03
Fixed yield (260 Mt)	Hi	0.41	1.44	9324	720 (700, 820)	5.49 (5.31, 5.66)	3.7	1.1
	Mid	0.40	1.42	9146	710 (700, 825)	5.42 (5.39, 6.33)	3.7	1.1
	Lo	0.39	1.36	8754	680 (650, 850)	5.20 (4.99, 6.53)	3.5	1.0
	GMO	0.007	0.027	173	15	0.15	0.10	0.03
Regional (33.3 Mha)	Ukr	0.33	1.45	7985	490	3.96	2.6	0. 8
	EEu	0.39	1.06	10075	725	5.42	3.8	1. 1
	NW	0.54	1.43	10011	1210	8.65	6.3	1.7
	Med	0.64	1.50	11283	990	4.25	5.2	0.8

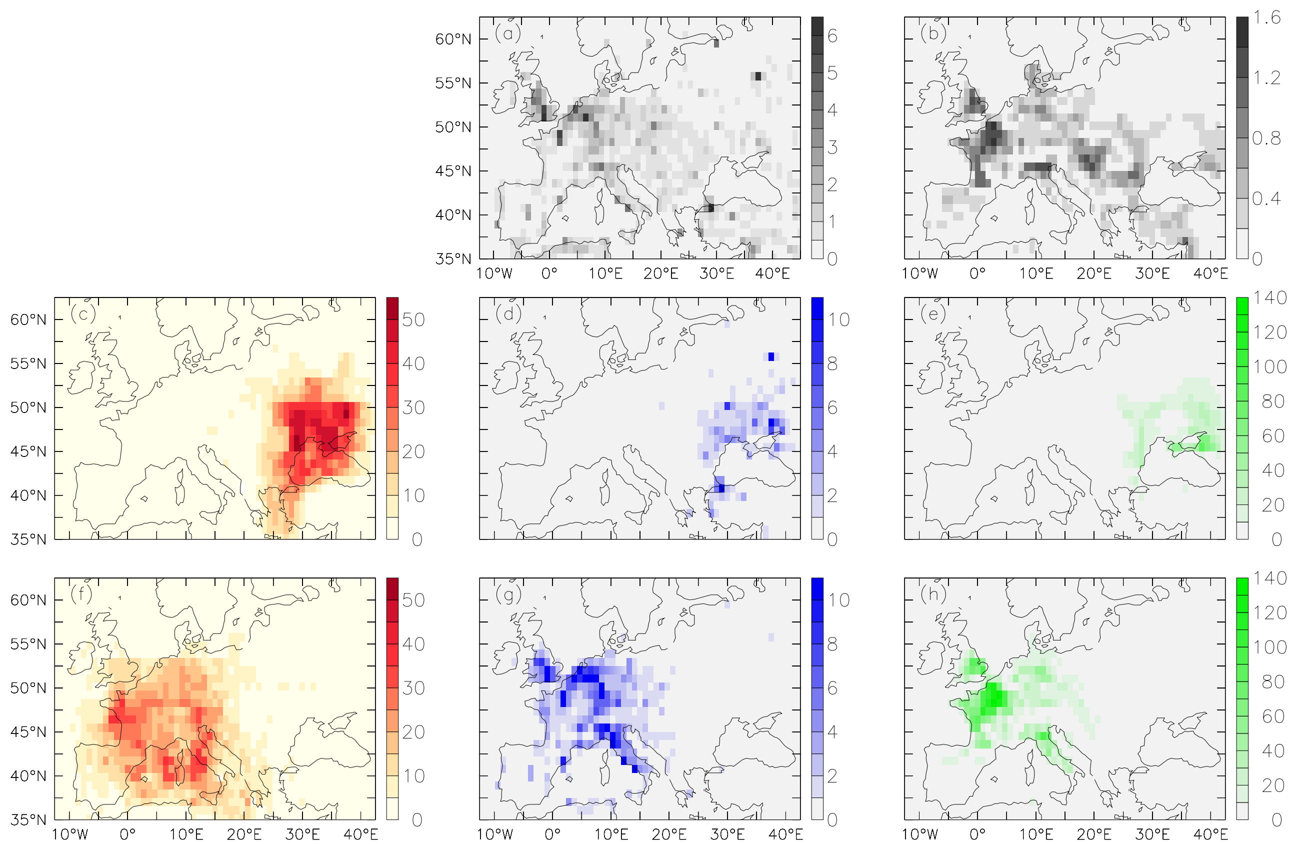
Impacts on human mortality

Ozone is a powerful oxidant known to cause cellular damage with consequential effects on both chronic and acute cardio-respiratory diseases (*39,6*). Such diseases result in increased ill-health, hospital admissions, morbidity and mortality. Epidemiological studies have shown clear and statistically significant links between high-ozone events and health impacts (*25,26*). Meta-analyses of such studies have led to the quantification of increased mortality arising from measured increases in ground-level ozone concentrations (*6,26*). Here we use a numerical relationship developed specifically for Europe (*26*), further details of which are given in the Methods section.

When a fixed area of land (33 Mha) is identified and used for biofuel cultivation, the projected increases in ground-level ozone concentrations are substantial enough under all our scenarios to increase ozone-associated mortality. If high-yielding commercially available cultivars are planted at locations throughout Europe our simulations suggest around 1040 additional deaths per year may result, an increase of ~5% in the 22000 annual premature deaths currently attributed to ground-level ozone in Europe (*31*). Increases in mortality of around 3% are projected for the medium- and low-yielding cultivars.

Again, the impact of the biofuel cultivation is strongly dependent on the region in which the poplar plantations are located, as shown in the central column of Figure 3. If the 33 Mha of medium-yielding cultivars is planted only in the populous NW of the continent (a scenario which yields sufficient biomass to meet the EU's 2020 targets), the impact on mortality is more substantial (~6%). Under our regional planting scenarios, the minimum increase in the number of premature deaths (~2%) occurs when the plantations are located in the more sparsely populated Ukraine. Although small in number, an increase of this magnitude may be sufficient to offset the number of deaths avoided through implementation of emissions control policies in Europe (*7*). By contrast, the use of a genetically modified poplar that does not emit isoprene produces no additional ozone and hence causes no additional mortality across the domain.

Comparison of the different cultivars on a fixed yield (260 Mt) basis with the planting area distributed across



Europe shows that the number of additional deaths due to high levels of ground-level ozone is around 3% relative to the base case for all commercial cultivar types. Based on upper and lower bounds for the isoprene emission factors and biomass yields for the three cultivar types, we estimate the total number of premature deaths to lie between 650 and 850 per annum.

Figure 3 Human health and crop impacts of the regional cultivation of poplar for biofuels. Panel (a) shows the population distribution for Europe for 2006 (taken from the LandScan database (45)) and (b) the yield of wheat and maize (in Mt) for 2000 (46). Panel (c) shows the increases in the number of days on which the daily maximum 8-hour ozone concentration exceeded the EU reporting threshold of 60ppbv ("exceedance days") for the Ukraine scenario; (d) the number of deaths brought forward annually as a result of the changes in ozone for the Ukraine scenario; (e) the loss of wheat and maize production (in kt) as a result of the changes in ozone during the growing season for the Ukraine scenario. Panels (f) to (h) show the same as (c) to (e) for the NW Europe scenario.

Economically, these additional deaths represent a cost to Europe of 2 - 6 billion USD (based on the 2010 dollar value). Increases in morbidity and the associated workdays lost and hospital admissions are not accounted for in this analysis. Furthermore, we have not assessed the impacts on human health of changes in the formation of SOA arising from the increased bVOC emissions. SOA formation is critically dependent on precursor emissions, and observations suggest that condensable products of biogenic origin mainly partition to the aerosol phase in areas of high anthropogenic influence (*41*). The increases in isoprene emissions projected here are expected to result in elevated concentrations of fine particulate matter in urban areas. As no threshold has been observed for health impacts of fine particles any increase in concentration would result in increased mortality (*6*). Thus, our assessment of the number of premature deaths resulting from the cultivation of poplar for biofuel feedstocks should be seen as a lower bound.

Impacts on crop yields

High concentrations of ground-level ozone result in damage to plant cells, impairing photosynthesis and leading to reduced carbon assimilation and ultimately lower biomass yields (*29*). Field studies have demonstrated quantifiable reductions in yields from agricultural crops in Europe resulting from exposure to high concentrations of ground-level ozone during the growing season, leading to the development of numerical relationships used by regulators and policy-makers in the EU to estimate crop damage resulting from ozone pollution (*28,29*). Details are given in the Methods section.

Wheat and maize are two of the most important crops in Europe, with annual yield losses due to ozone damage currently estimated to be around 14 Mt y^{-1} (*28*). Under the biofuel cultivation scenarios used in this study we estimate that further losses ranging from just under 3 to 9 Mt y^{-1} of wheat and maize could occur due to the increases in ground-level ozone concentrations arising from enhanced isoprene emissions associated with poplar cultivation. For the fixed yield scenarios, we estimate that crop production losses lie between 5.0 and 6.5 Mt y^{-1}. This represents additional losses of as much as 60% of those currently attributed to elevated ground-level ozone in Europe.

Again the impacts are highly dependent on the planting region, as can be seen in the right-hand column of Figure 3. Locating poplar plantations in NW Europe, where the dominant crop is wheat which is highly sensitive to ozone damage, results in higher crop losses (~ 8.7 Mt y^{-1}) than locating the same plantations in the Ukraine, where the primary crop of maize is less sensitive (~ 4 Mt y^{-1}).

The economic costs of these additional reductions in crop yield are between 600 and 1700 million USD (at 2010 values). While this may be partially offset by the net value of the biofuel produced, the further reduction in crop yields also jeopardises food security. The loss of 1 Mt y^{-1} of wheat is equivalent to the loss of total calorific intake for ~ 2.9 million people for a year (*37*).

Our model results show that the large scale planting of poplar as a biofuel feedstock in Europe will increase ground-level ozone concentrations across the region. This deterioration in air quality will lead to small but quantifiable impacts on human health and mortality and crop yields, the magnitudes of which will vary with the type of poplar cultivars used and the chosen locations of large plantations.

Recent international efforts to mitigate greenhouse gas emissions and climate change, coupled with concerns about the wider environmental impacts of first-generation biofuels, and concerns regarding fuel security, have led the EU to re-affirm its commitment to the increasing use of second-generation biofuel feedstocks to meet its renewable energy policy and reduce its dependence on fossil fuels (*42*). While the land currently under poplar cultivation in Europe is reported to be low (<5Mha) (*43*), several further initiatives by the EU are likely to drive a rapid expansion in poplar plantations. Small trial plantations of both poplar and willow have demonstrated that yields are high even on degraded and other marginal land, and that both species have beneficial effects on such poor quality land (*43*). Furthermore, both can be used as a component of wastewater treatment processes. In addition, the re-classification of the use of so-called short rotation coppice species such as poplar and willow as agricultural practice, thereby including these as crops eligible for subsidies (*43*), makes their cultivation economically attractive (particularly on poor quality land) and is likely both to drive an expansion in the area of land under cultivation and encourage full and accurate reporting of this land use. While the LULCC scenarios adopted in this study assume a highly aggressive expansion from the current situation, the land used has been identified as available for conversion by previous research (*18*). It is assumed here that all biofuel plantations are poplar, rather than a mix of poplar and willow in order to demonstrate the effect of the use of different cultivars for which we have experimentally determined yields and isoprene emission rates. It should be noted that the average yield and emission from willow species (*9,15,21*) is almost the same as that of our medium-yielding poplar cultivar type.

The current focus within both policy-making circles and the biomass industry is on maximizing yields at all stages of fuel production. Here we show that the choice of poplar cultivar has wider socio-economic implications than climate change mitigation and profit – cultivars that are high-yielding also produce most isoprene and hence have the greatest impacts on air quality. Our results clearly demonstrate that perturbations in the emissions of VOCs arising from the cultivation of poplar for biofuel in Europe result in adverse effects on air quality that are both cultivar and location dependent.

We show that the environmental conditions (light and temperature) associated with the proposed site of poplar cultivation are of greatest importance in determining the effects of that site on local and regional air quality. But, the impacts of the deterioration in air quality depend critically on the population density and agricultural crops in the region. Further, we demonstrate that mitigation of these impacts could be achieved through European-wide strategic planning of plantation siting. For example, a decision could be made to cultivate poplar on a large scale in areas of Europe with low population density and geographically removed from areas of high population and intensive agriculture.

Our findings indicate the need for a wide-reaching in-depth assessment of the implications of the cultivation of biofuel feedstocks, and highlight the need for detailed local impact assessments accounting for specific cultivar to be conducted on an individual case-by-case basis. Such assessments should be fully inter-disciplinary in approach and include cost-benefit analyses of all aspects of the replacement of fossil fuels with cultivated biofuels, including environmental effects (climate, air quality and ecosystem services), human behavior, dynamics and public opinion, human health, ecosystem health and biodiversity, economic costs, energy and food security, and feedbacks between changes in atmospheric composition and the Earth system. Assessments such as these should focus on specific local situations, but must also consider the region as a whole, as air pollutants are transported long distances and transport of the feedstock to the final market should also be a consideration.

In addition, research is required to constrain the substantial uncertainties involved in such assessments (*44*). These include uncertainties in the modeled ozone concentrations due to up-scaling of experimentally determined isoprene emission rates and biomass yields, assumptions regarding planting location and density, uncertainties associated with risk analysis using dose-response relationships derived for the population as a whole, and the use of absolute concentrations rather than fluxes to assess damage to vegetation. As we account only for the effects of changes in ozone our work should be seen as a lower bound estimate for the impacts associated with the effect of land use change on air quality in Europe..

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Supporting Information Available

Supporting Information is available as a single 6-page Word document containing 1 figure (Figure S1) and 3 tables (Tables S1-S3). This information is available free of charge via the Internet at http://pubs.acs.org.

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