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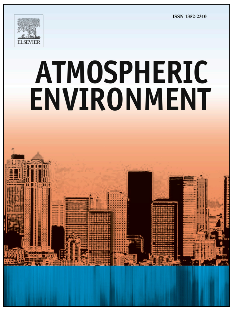

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Ozone concentrations and damage for realistic future European climate and air quality scenarios

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Abstract

Ground level ozone poses a significant threat to human health from air pollution in the European Union. While anthropogenic emissions of precursor substances (NO_x, NMVOC, CH_4) are regulated by EU air quality legislation and will decrease further in the future, the emissions of biogenic NMVOC (mainly isoprene) may increase significantly in the coming decades if short-rotation coppice plantations are expanded strongly to meet the increased biofuel demand resulting from the EU decarbonisation targets. This study investigates the competing effects of anticipated trends in land use change, anthropogenic ozone precursor emissions and climate change on European ground level ozone concentrations and related health and environmental impacts until 2050. The work is based on a consistent set of energy consumption scenarios that underlie current EU climate and air quality policy proposals: a current legislation case, and an ambitious decarbonisation case. The Greenhouse Gas-Air Pollution Interactions and Synergies (GAINS) integrated assessment model was used to calculate air pollutant emissions for these scenarios, while land use change because of bioenergy demand was calculated by the Global Biosphere Model (GLOBIOM). These datasets were fed into the chemistry transport model LOTOS-EUROS to calculate the impact on ground level ozone concentrations. Health damage because of high ground level ozone concentrations is projected to decline significantly towards 2030 and 2050 under current climate conditions for both energy scenarios. Damage to plants is also expected to decrease but to a smaller extent. The projected change in anthropogenic ozone precursor emissions is found to have a larger impact on ozone damage than land use change. The increasing effect of a warming climate (+ 2 to 5 °C across Europe in summer) on ozone concentrations and associated health damage, however, might be higher than the reduction achieved by cutting back European ozone precursor emissions. Global action to reduce air pollutant emissions is needed to make sure that ozone damage in Europe decreases towards the middle of this century.

Keywords: Ozone; air quality; energy scenario; land use change; GAINS; GLOBIOM; LOTOS-EUROS; CTM

Introduction

Ozone is a natural component of the troposphere and necessary because of its cleansing role. However, since pre-industrial times concentrations have risen to levels harmful to human health, crops and ecosystems (Fowler et al., 2008). In the EU28, ground-level ozone is associated with at least 16 thousand excess deaths each year, making it the second most important pollutant in terms of health damage after particulate matter (EEA, 2014). Ozone production is driven by emissions of the ozone precursor substances nitrogen oxides (NO_x), methane (CH_4), non-methane volatile organic compounds (NMVOC) and the availability of light. While NO_x has some natural sources, the vast majority of the emissions in Europe is of anthropogenic origin (Sutton et al., 2011). For NMVOCs, emissions from vegetation make up about 90% of total emissions globally, whereas in Europe anthropogenic and biogenic emissions contribute about equally to the total (Guenther et al., 1995). Biogenic NMVOC emissions (of which isoprene and monoterpenes are the most important) are driven by the type and density of vegetation as well as temperature and light.

EU climate and energy policies promote renewable energy production and increased energy efficiency measures (European Commission 2009). One expected effect of these policies is a significant expansion of commercial bioenergy crop production such as short-rotation coppice (SRC) plantations and an increasing use of forests (European Commission, 2014). Bioenergy crops and trees typically emit more isoprene than the crops or grassland they replace because of a higher isoprene emission factor as well as higher leaf density, whereas monoterpene emissions are equal or reduced since bioenergy species have generally low monoterpene emission factors (Benjamin and Winer, 1998; Steinbrecher, 2009). The increase in isoprene emissions could increase ground level ozone production and concentrations. Previous studies have explored the impact of a significant increase in SRC bioenergy plantations on ozone in Europe using chemistry transport models (CTMs) concluding that the increase in ground level ozone damage for human health and crop production could be significant (Beltman et al., 2013; Ashworth et al, 2013; Lathière et al., 2006). While some of these studies used country-specific projections of future SRC plantation areas (Ashworth et al., 2013), most used general and/or extreme assumptions about the amount and location of SRC plantations and used a CTM at a coarse scale, limiting the extent to which regional ozone formation is resolved (Wild and Prather, 2006; Emery et al., 2012).

The EU air quality directive (EC, 2008) restricts emissions of air pollutants from anthropogenic sources, leading to a significant decrease in European NO_x and NMVOC emissions in the near future (Amann et al., 2014). Results of energy policies such as an increasing share of renewable sources in the energy mix or increasing use of electric vehicles could cause a further decline in emissions of NO_x, NMVOCs and methane from the energy and transport sector (Cofala et al., 2012). These trends in anthropogenic emissions act towards a reduction in ground level ozone formation (Lacressonnière et al., 2014). Because some steps in the ground level ozone formation process are driven by absorption of light and/or proceed faster with higher temperatures, climate conditions influence ozone formation and ground level ozone concentrations could increase in future due to climate change nonetheless (Varotsos et al., 2013; Katragkou et al., 2011). The combined effect of increasing global ozone precursor emissions and climate change has been studied by Revell et al. (2015), who project a significant increase in ground level ozone concentrations and damage globally.

While the isolated impacts of changing land use and anthropogenic emissions on ozone levels have been investigated before (in- or excluding the possible impacts of a changing climate), the combined effect of these two correlated trends has not received a lot of attention so far. In this work, we investigate the change in ozone concentration and associated health and vegetation damage caused by the combined land use and emission changes projected by policy-relevant EU energy and emission scenarios. For this, we use the regional CTM LOTOS-EUROS at a 0.5 x 0.25 degree resolution (approx. 28 x 28 km) to model ground level ozone concentrations and damage indicators SOMO35 and POD_1 (a health and ecosystem damage indicator, respectively) based on consistent and policy-relevant emission and land use scenarios for the EU28. Also, we provide a decomposition of the total effect on ozone levels and explore the impact of the projected trend in hemispheric background concentrations as well as the possible effects of climate change.

Methods

The LOTOS-EUROS model

In this study, the 3D regional chemistry transport model (CTM) LOTOS-EUROS v.1.10 (Beltman et al., 2013) was used to assess the influence of EU climate and air quality policies on ground level ozone concentrations. Previous versions of the model have been used for air pollution assessments, some of which were aimed at ozone (e.g. Manders et al., 2012), NO_x (Curier et al., 2014; Schaap et al., 2013), and scenario studies (Mues et al., 2013; Hendriks et al., 2015). LOTOS-EUROS is used to provide operational forecasts of ozone, nitrogen dioxide and particulate matter within the CAMS (Copernicus Atmosphere Monitoring Service) ensemble (Curier et al., 2012; Marecal et al., 2015). Furthermore, LOTOS-EUROS has frequently participated in international model comparisons concerning ozone (Hass et al., 2003; Van Loon et al., 2007; Solazzo et al., 2013; Schaap et al., 2015). For a detailed model description we refer to Schaap et al. (2009) and Wichink Kruit et al. (2012). Here, only the most relevant aspects for the current study are presented.

The model uses a normal longitude–latitude projection and was run at a resolution of 0.5x0.25 degrees over Europe (15°W-25°E, 35-70°N). For boundary conditions of O_3 and NO_x, monthly climatological steady state values were used. The model top is placed at 3.5 km above sea level and consists of three dynamical layers: a mixing layer and two reservoir layers on top. The height of the mixing layer at each time and location is extracted from ECMWF meteorological data used to drive the model. The height of the reservoir layers is set to the difference between ceiling (3.5 km) and mixing layer height. Both layers are equally thick with a minimum of 50 m. If the mixing layer is near or above 3500 m high, the top of the model exceeds 3500 m. A surface layer with a fixed depth of 25 m is included in the model to monitor ground-level concentrations. Advection in all directions is represented by the monotonic advection scheme developed by Walcek (2000). Gas phase chemistry is described using the TNO CBM-IV scheme (Schaap et al., 2009), which is based on Whitten et al. (1980). The isoprene chemistry description follows Adelman (1999) and N_2O_5 hydrolysis is described in Schaap et al. (2004a). Dry deposition for gases is modeled using the DEPAC3.11 module (Van Zanten et al., 2010), while the description of particle deposition follows Zhang et al. (2001). Stomatal resistance is described by the parameterization of Emberson et al. (2000a,b) and the aerodynamic resistance is calculated for all land use types separately. Wet deposition of trace gases and aerosols are treated using simple scavenging coefficients for gases (Schaap et al., 2004b) and particles (Simpson et al., 2003).

Biogenic NMVOC emissions are calculated based on detailed information on tree types in Europe because the biogenic emission factors are extremely variable between species. Therefore, the CORINE land use dataset (Büttner et al., 2012) is combined with the distributions of 115 tree species over Europe (Koeble and Seufert, 2001). During each simulation time step, biogenic isoprene and monoterpene emissions are calculated as a function of the biomass density and standard emission factor of the species or land use class (Schaap et al., 2009), taking into account the growing season of deciduous trees and agricultural crops. The role of local temperature and photo-synthetically active radiation are taken into account in the biogenic emissions by following the empirically designed algorithms described by

Guenther et al. (1993) and Tingey et al. (1980). The implementation of biogenic NMVOC emissions is very similar to the approach by Steinbrecher et al. (2009).

Anthropogenic emissions per country and sector (SNAP1 level) for the EU28 for 2010 as well as country-specific NO/NO_2 ratios for NO_x emissions from transport are taken from the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model (Amann et al., 2011). Sector and country totals for non-EU countries were taken from the TNO-MACC emission database (Kuenen et al., 2011). The sector and country emission totals were gridded following the allocation procedures representative for 2005 of the latter. Temporal variability is included using sector specific monthly, daily and hourly factors (Builtjes et al., 2003) to divide the annual emissions over the year.

To evaluate the vegetation damage due to exposure to ozone, the indicator Phytotoxic Ozone Dose (POD_1 or accumulated stomatal flux above a threshold of 1 nmol m^{-2} s^{-1})(Emberson et al, 2000b) is calculated within the LOTOS-EUROS model. Relative Risk of mortality (based on overall mortality) is used as a human health indicator. This is calculated from SOMO35 (the sum of daily maximum 8-hour means over 35 ppb, or 70 μg/m^3) by multiplying SOMO35 (in μg/m^3) by $1.51 \cdot 10^{-6}$, the WHO-recommended relation between SOMO35 and Relative Risk of mortality (WHO, 2013).

Scenario implementation and model setup

Two energy scenarios for the EU28 developed with the PRIMES energy model (Antoniou and Capros, 1999) were used as input to the GAINS model to generate air pollutant emissions for 2030 and 2050. In the first, EU energy policy does not put additional climate change mitigation targets beyond commitments implemented and adopted by spring 2012 (current legislation or CLE scenario in this study, “reference scenario” in the original publication; European Commission, 2013), while in the second a target of 40% reduction in greenhouse gases (GHGs) is achieved in 2030 (and 80% in 2050), including extra energy efficiency measures (hereafter called the decarbonisation scenario; European Parliament, 2014). For air quality policy, no further measures beyond current legislation were assumed in both scenarios.

The abovementioned energy scenarios (especially the demand for bioenergy) were also used to drive the Global Biosphere Model (GLOBIOM) (Havlik et al., 2014), that analyses the competition for land use between agriculture, forestry and bioenergy, providing land use change projections until 2050 for each EU28 member state. The land use maps used in LOTOS-EUROS for 2030 and 2050 for both energy scenarios were produced by taking the total area of natural land, grassland and cropland in each country that was converted into forest and short rotation coppice plantations by GLOBIOM. For each country, the land use change was divided proportionally over all grid cells containing natural, grassland or cropland. To calculate isoprene and monoterpene emissions from SRC plantations, they are assumed to consist of poplar trees, which is a representative tree species for SRC plantations in terms of isoprene emissions. Monoterpene emissions of tree species used in SRC plantations are small or negligible (Benjamin and Winer, 1998). CTM model runs for both energy scenarios were performed for 2030 and 2050. A run for 2010 was also performed to establish the current situation and to evaluate the CTM performance. For the scenario runs, two meteorological years were used to explore the possible impact of a warming climate on ground level ozone concentrations. Meteorological year 2010 (which had an average summer in terms of temperatures and dominant weather patterns in Europe) was used to represent 'current climate', whereas the year 2003 was taken to represent a possible 'future climate' situation. Temperatures in the European 2003 summer were significantly higher than the long-term average (2 – 5 °C depending on region and month, Black et al., 2004) and are in the range of what could be expected for Europe in 2050 (Kirtman et al., 2013).

To be able to distinguish the contributions of land use change and anthropogenic emission change to the total signal for the 2050 decarbonisation scenario, two additional runs were performed in which only the land use change or the anthropogenic emission scenario was used, while the other was kept at 2010 level.

Another factor that influences future ground level ozone concentrations are trends in hemispheric background ozone levels that are determined by global long-term trends of precursor emissions. To investigate the extent to which this will influence European ozone levels, a model run was carried out in which the boundary conditions were scaled to fit the 2050 ECLIPSE v5(a) CLE emission scenario (IIASA, 2015; Stohl et al., 2015). This was done using monthly O_3 distributions from 14 independent CTMs and Global Circulation Models (GCMs) under 2001 meteorological conditions, along with the O_3 responses associated with 20% changes in anthropogenic precursor emissions from 5 world regions, and in global CH_4 emissions. The responses were averaged over the 14 models and scaled by the actual changes in regional emissions (global for CH_4) according to the ECLIPSE v5(a) CLE scenario, thus accounting for the non-linear response of O_3 to NO_x and CH_4. The general approach is documented in Wild et al., (2012). For ozone, the impact on the boundary conditions is –5.0 to + 4.4 µg/m^3 on average for the period April-September, depending on location. Changes in NO_x are in the order of –3.5 to 3.5 µg/m^3.

To explore to what extent emission reductions beyond CLE of O_3 precursors in the EU28 could contribute to a reduction in ground level ozone concentrations, a sensitivity run was performed in which the anthropogenic emissions of the 2050 decarbonisation scenario were replaced by those of a maximum technically feasible reduction (MTFR) scenario developed in the ECLIPSE project for 2050 developed with the GAINS model, while for the hemispheric background also the impacts of a global MTFR scenario were considered (IIASA, 2015).

In Table 1 an overview of all the LOTOS-EUROS model runs performed in this study is presented. All scenarios were performed for the period April-September, because ozone pollution is mainly an issue during the summer and as harmful concentrations of ozone in winter hardly occur.

Table 1. Overview of LOTOS-EUROS model runs and settings performed for this study.

Run ID	Meteorological year	GAINS scenario and year	Land use scenario and year	Boundary conditions
2010	2010	2010	Standard LOTOS-EUROS	2010
CLE-2030	2010	CLE 2030	CLE 2030	2010
CLE-2050	2010	CLE 2050	CLE 2050	2010
Decarb-2030	2010	Decarbonisation 2030	Decarbonisation 2030	2010
Decarb-2050	2010	Decarbonisation 2050	Decarbonisation 2050	2010
Future climate	2003	Decarbonisation 2050	Decarbonisation 2050	2010
GAINS-only	2010	Decarbonisation 2050	Standard LOTOS-EUROS	2010
Bound-2050	2010	Decarbonisation 2050	Decarbonisation 2050	Eclipse v5(a) 2050
Landuse-only	2010	2010	Decarbonisation 2050	2010
MTFR	2010	MTFR 2050	Decarbonisation 2050	MTFR

Validation approach

Modelled ground level ozone and nitrogen dioxide concentrations for the baseline run for April-September 2010 are compared with hourly measurements at EMEP rural background stations (www.emep.int). Only stations below 700 m elevation were taken into account. For NO_2, 25 measurement stations were available, 83 for ozone.

Results

Anthropogenic and biogenic emissions

Total anthropogenic emissions in EU28-countries calculated with GAINS for 2010 and the scenarios studied are shown in Table 2. NO_x, NMVOC and CH_4 emissions are the most relevant in terms of ozone formation. Of these, both NO_x and NMVOC emissions are projected to decline strongly (by 61-70 and 38-48 %, respectively) until 2050 under both the CLE and the decarbonisation scenario. For CH_4, emission reductions of 16-17 % are projected for 2050. For all species the largest reductions take place before 2030. Within the EU28, regional differences in emission trends occur. For example, in the decarbonisation scenario for 2050, methane emission for Cyprus are increased by 32% compared to 2010 (mainly due to increased emissions from transport), while Hungary shows a reduction of 54%. NMVOC emissions decrease in all countries in this scenario, ranging from -7 to -70 % (Ireland and Cyprus, respectively). For NO_x, the smallest reduction relative to total emissions is seen for the Netherlands (44%) whereas in Malta and Luxemburg less than 10% of the 2010 NO_x emissions remain. Differences in projected emission reductions also exist across economic sectors. Methane emissions from industry (which in 2010 are less than 1% of the total CH_4 emissions) are projected to increase over fivefold while e.g. residential combustion and transport show strong declines in emissions going from 2010 to 2050 in the decarbonisation scenario. For NMVOC and NO_x, emissions from road transport are projected to decrease by 80% resp. 85%, while those from agriculture increase by 15% resp. 17%.

Table 2. Anthropogenic emissions of air pollutants and their precursors (in kiloton) for the scenarios used in this study. CLE = Current legislation, Decarb = 40% decarbonisation by 2030 including energy efficiency measures, MFR = maximum feasible reduction for air pollutants.

Scenario	CH_4	CO	NH_3	NMVOC	NO_x	SO_2	$PM_{2.5}$	$PM_{2.5-10}$
2010	19659	24377	3780	4010	7392	4688	1530	745
CLE 2030	15759	17454	3767	2661	3365	2228	1180	764
CLE 2050	16334	16068	3866	2475	2892	1843	1089	812
Decarb 2030	16597	11587	3671	2486	3073	2046	1053	750
Decarb 2050	16572	9016	3760	2092	2193	1160	907	790
MFR 2050	16572	5519	2477	1381	1583	700	507	614

GLOBIOM calculations project an increase in short rotation coppice and forests at the cost of (in this order) other natural land, grassland and cropland. Figure 1 displays the amount of land use change implemented in LOTOS-EUROS for each scenario and the effect of the land use change on biogenic isoprene emissions. The extra isoprene emissions produced in a hot summer ('future climate', 2003 meteorology) is also shown. The growth of forest area is almost independent of the scenario used, because the modelled change in revenues from agricultural land or forests is small, leading to a fairly constant amount of afforestation and deforestation over time under both scenarios. The extra amount of biomass required in the decarbonisation scenario compared to the CLE case comes from plantations, a more intensive use of forests as well as the use of waste streams and agricultural products. Especially for 2050, a large increase in biomass plantation area is seen for the decarbonisation scenario. This is directly driven by the need for bioenergy to reach the EU target of 80% GHG emission reduction in 2050. Total isoprene emissions for the EU28 increase by 20-51% depending on scenario and scenario year compared to 2010. For all scenarios, a warmer climate increases total isoprene emissions by a further 9%. The highest isoprene emissions are seen for the model run for 2050 using the decarbonisation scenario and including future climate conditions, which shows a 56% increase compared to the 2010 baseline run. Figure 2 shows the geographical pattern of biogenic isoprene emissions across Europe. The countries with the largest increase in biomass plantations and forests in the scenarios are generally also the ones with the largest increase in emissions, as is shown in Figure 3. Because isoprene emissions increase with temperature, the emission increase per added hectare of biomass production area is higher in southern Europe. Modeled isoprene emissions in North Africa could be overestimated due to uncertainties in the land use database underlying the model results in this area; the amount of agricultural land might be lower than what is recorded in the CORINE database for this part of the domain.

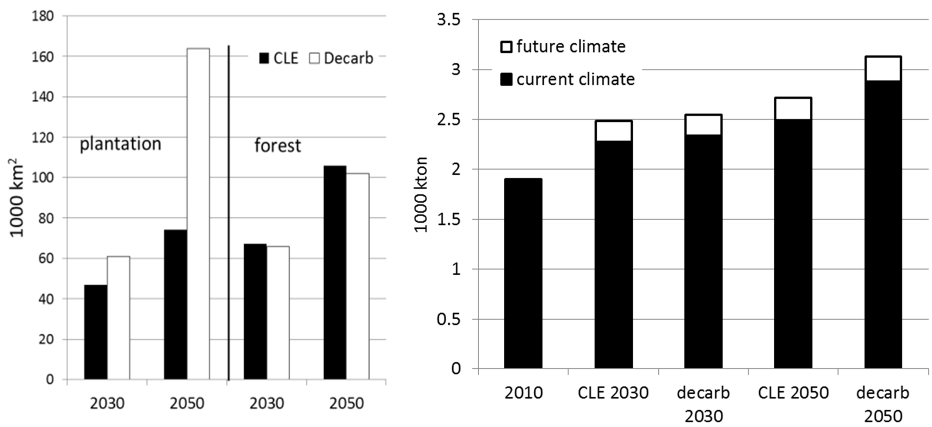

Figure 1. Left: area of other natural land, grassland and cropland and replaced by short rotation coppice plantations and forests in EU28 for the CLE and decarbonisation scenario as calculated by GLOBIOM. Right: corresponding effect on biogenic

isoprene emissions calculated in LOTOS-EUROS, for current and 'future' climate conditions (meteorological years 2010 and 2003, respectively).

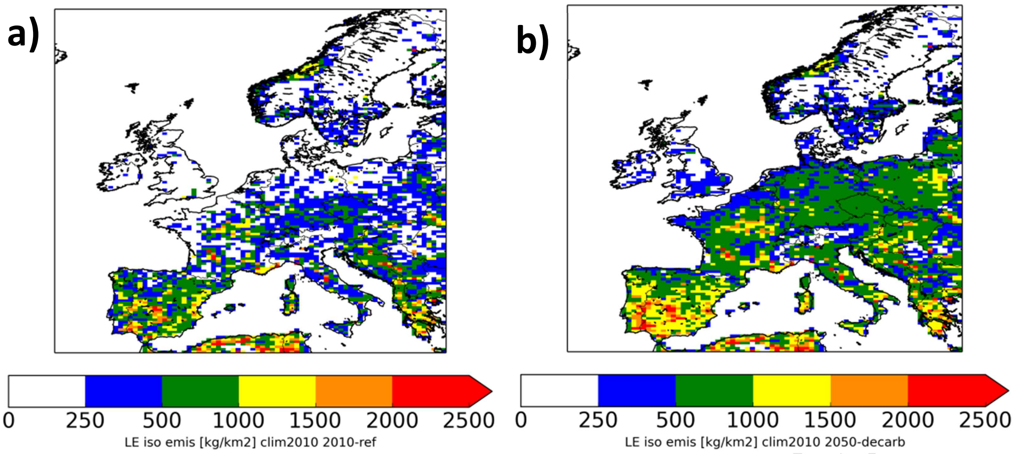

Figure 2. Biogenic isoprene emissions [kg/km^2] across Europe for 2010 (a) and for 2050 under the decarbonisation scenario and 2010 meteorology (b).

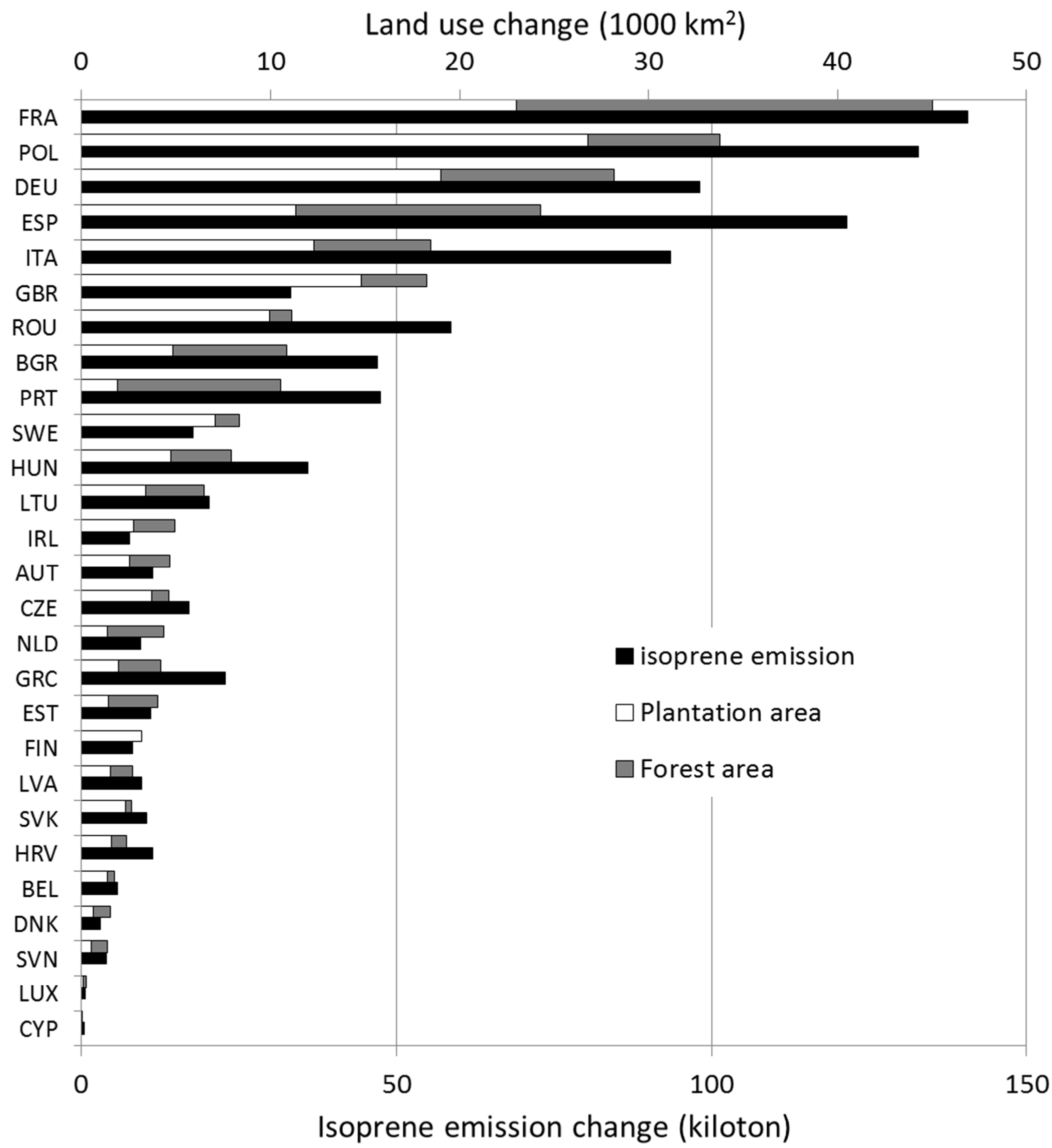

Figure 3. Overview of land use change and corresponding change in isoprene emissions (for 2010 meteorology) for each EU28 country (except Malta, for which no land use change was modelled)

LOTOS-EUROS validation

The comparison of average modelled and measured ground level concentrations of NO_2 and O_3 for the period April-September for rural background stations is shown in Figure 4. LOTOS-EUROS captures the spatial variability of NO_2 well (R^2 = 0.64) but on average measurements are about 20% underestimated. The average temporal correlation coefficient is for NO_2 is 0.12; such low temporal correlations for hourly

NO_2 over Europe is seen for most CTMs (Vautard et al., 2009). The spatial variability of ozone concentrations is underestimated in the model and the average bias is about 10% (6.3 µg/m^3). Spatial and average temporal coefficient of determination (R^2) are both 0.36. As health and vegetation damage mainly occur at high ozone concentrations, daily maximum concentrations for model and measurement are compared, as well as damage indicators AOT40 and SOMO35. Model performance for these indicators is higher than for the hourly ozone concentrations, with R^2 values between 0.7-0.73 and a bias of 2.06 µg/m^3 for daily maximum concentrations. Table 3 summarizes the performance parameters.

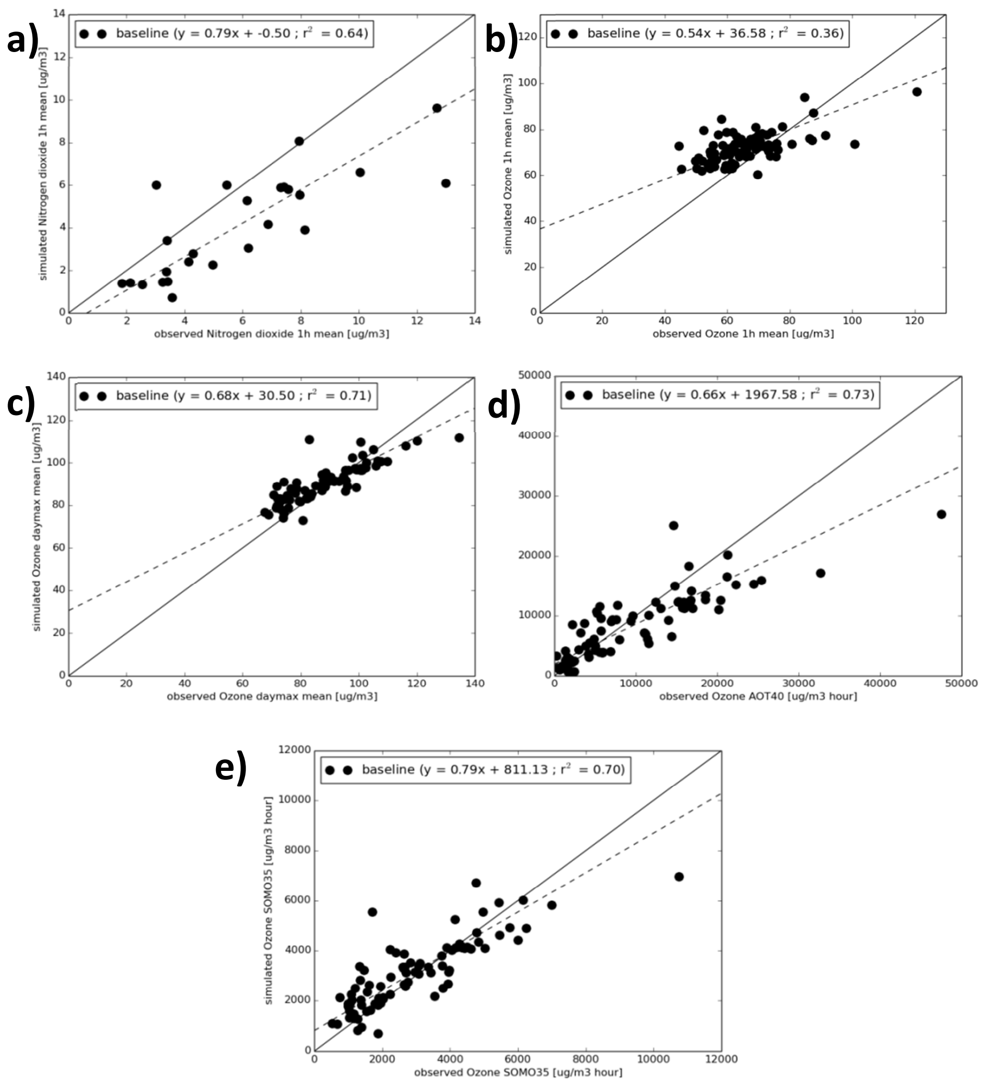

Figure 4. Comparison of modelled and observed average concentrations for April-September 2010 for EMEP rural background stations for, NO_2 (a) O_3 daily mean (b), O_3 daily maxima (c), AOT40 (d) and SOMO35 (e).

Table 3. LOTOS-EUROS performance for ozone concentrations and indicators and hourly NO_2 concentrations. Obs mean, bias and RMSE for O_3 hourly concentrations, daily maxima and maximum 8hr means are in µg/m^3, AOT40 in µg/m^3 hour and SOMO35 in µg/m^3 day.

	Obs mean	bias	RMSE	corr (R)	# stations
O_3 hourly	65.9	6.3	21.9	0.6	83
O_3 daymax	88.5	2.06	16.2	0.7	83
O_3 max8hrmean	82.9	3.8	15.6	0.7	83
AOT40	10033	-1419	n.a.	n.a.	83
SOMO35	2962	186	n.a.	n.a.	83
NO_2 hourly	5.86	-1.75	5.13	0.35	25

Modelled ozone concentrations and damage indicators for energy scenarios

Figure 5 displays modeled average ozone concentrations over Europe for April-September 2010 (panel a) and the change in concentration compared to 2010 for 2050 for the CLE scenario (panel b), decarbonisation scenario (bottom left) and decarbonisation scenario with a warmer climate (bottom right). Modeled ozone summer mean concentrations are lowest (around 60 µg/m^3) in densely populated areas such as central England, the Benelux and Ruhr area, where ozone is titrated away at night during the conversion of NO to NO_2. Across the rest of north-western Europe, concentrations are around 70 µg/m^3, increasing toward southern Europe to 80-85 µg/m^3. The highest values are seen over sea because ozone deposition, one of the most important loss processes, does not occur over water.

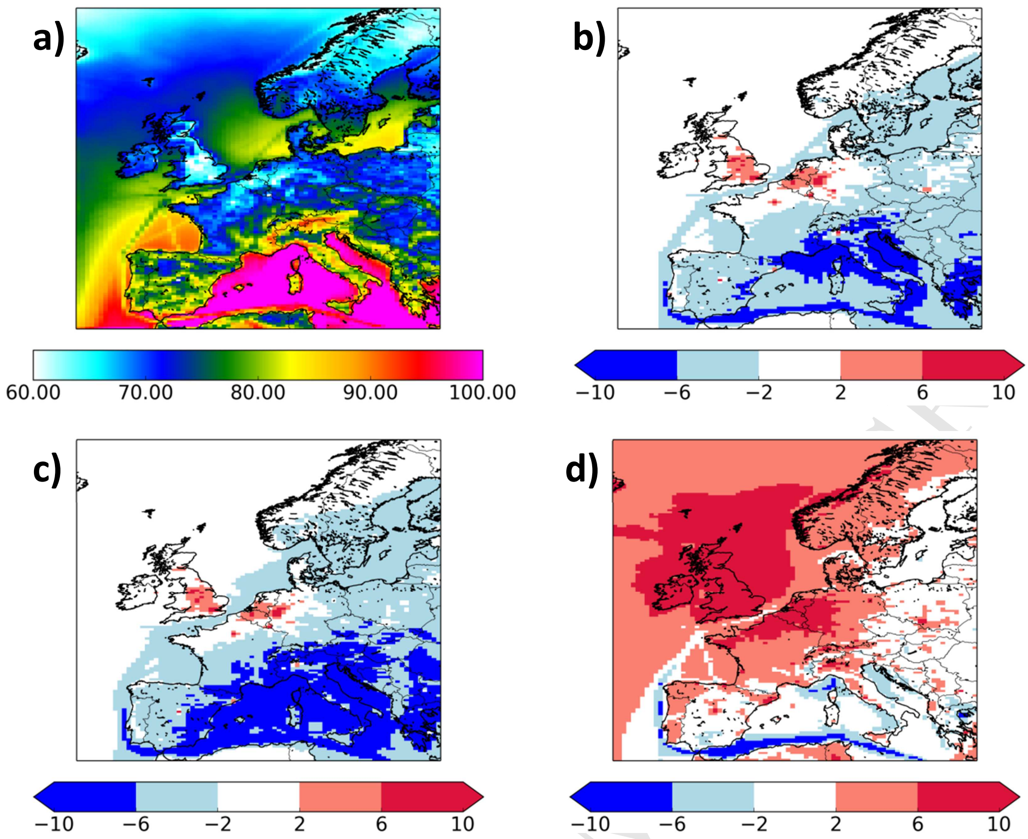

Figure 5. Modelled average ambient O_3 concentrations (in µg/m^3) for April-September for 2010 (A); Absolute change (in µg/m^3) from 2010 for 2050 CLE scenario (2010 meteorology) (B), 2050 decarbonisation scenario (2010 meteorology) (C) and 2050 decarbonisation scenario (2003 meteorology) (D).

For the CLE energy scenario in 2050 average ozone levels increase by 2-10 µg/m^3 in the high-NO_x regions in north-western Europe because night-time titration is reduced when NO_x emissions are lowered. Reductions during the daytime are small, since these high-NO_x regions are NMVOC-limited and ozone concentrations are not very sensitive to changes in NO_x levels and changes in NMVOC emissions in these regions are limited. Across the rest of Europe, ozone concentrations are lower compared to 2010 because of the lower precursor emissions (mainly NO_x, as for large regions in Europe, O_3 formation is NO_x-limited). Differences between the CLE and decarbonisation scenario (panel C) are limited although average ozone concentrations are reduced more strongly in southern Europe for the decarbonisation case. Results for both scenarios for 2030 (not shown) for each scenario are very similar to the 2050 concentrations, except for some Mediterranean shipping tracks. For the 2050 decarbonisation case under "future climate" conditions (2003 meteorology), we see an increase in average ozone concentration across the whole of Europe compared to the 2010 situation, except for the shipping tracks in the Mediterranean sea. The modelled increase is up to 20% in some regions in north-western Europe. This suggests that the influence of climate change on average ozone levels may overcompensate the reduction achieved by emission reductions of ozone precursors.

A model run using anthropogenic emissions from 2010 but land use data from the 2050 decarbonisation scenario (lu_only) as well as a run with 2010 land use but the 2050 decarbonisation emission data (emis_only) were performed to make a decomposition of the change observed in Figure 5C. Figure 6 shows the difference in average O_3 concentration for emis_only (panel A) and landuse-only (panel B) runs with the 2010 reference run. This shows that because of land use change and the corresponding increase in biogenic isoprene emissions, ozone concentrations are increased by 2-6 µg/m^3 for a few regions in central and southern Europe whereas ozone levels in the rest of the domain show a response below 2 µg/m^3. The anticipated decrease in NO_x, NMVOC and methane emissions from anthropogenic sources gives a much stronger signal: a decrease in average ozone concentrations of 2-10 µg/m^3 across the whole of Europe except for the NO_x-dominated regions in north-western Europe and metropolitan areas.

Changes in the hemispheric background at the boundaries of our model domain under the global CLE scenario causes an increase of 1-2 µg/m^3 for ozone levels across Europe. A sensitivity run for 2050 was performed in which the land use scenario for the decarbonisation case was combined with a maximum technically feasible reduction (MTFR) scenario for emissions of air pollutants for the EU28. This shows that there is additional potential for a reduction of ozone concentrations by about 2 µg/m^3 across Europe when more stringent European air quality policies are adopted. If the rest of the world also adopts stringent air quality measures (represented by a global MTFR scenario), the hemispheric ozone background around Europe could decrease by 6 to 20 µg/m^3 in 2050, following the methodology of Wild et al. (2012). Such a strong reduction in hemispheric background ozone concentrations could cause a further reduction of about 10 µg/m^3 on average, highlighting the importance of global efforts to reduce air pollution. The bottom panels of Figure 6 show the change in average ozone concentration for the global and European MTFR scenario for current (panel C) and future (panel D) climate in 2050.

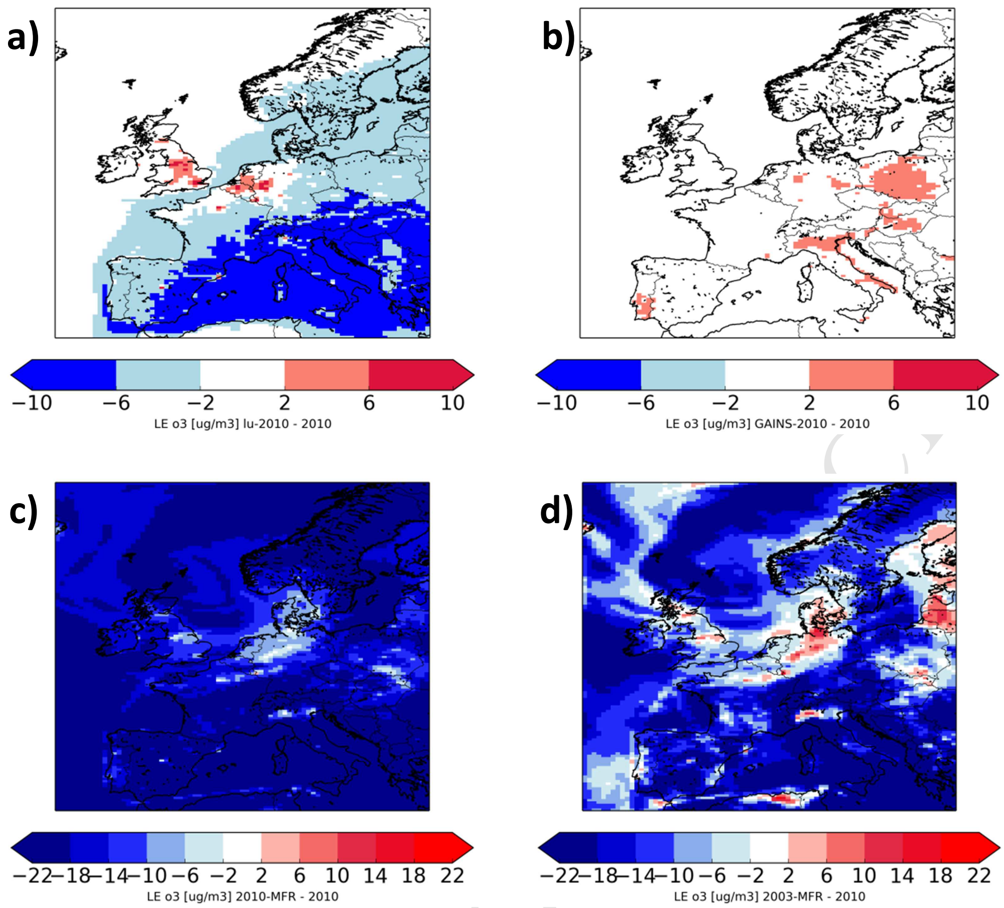

Figure 6. Change in average ground level ozone concentration for April-September compared to 2010 for model runs with (A) anthropogenic emissions of 2050 decarbonisation scenario and 2010 landuse; (B) 2010 anthropogenic emissions and landuse for 2050 decarbonisation scenario; (C) 2050 decarbonisation scenario for land use change; 2050 MTFR scenario for anthropogenic emissions and hemispheric ozone background; current climate (D) 2050 decarbonisation scenario for land use change; 2050 MTFR scenario for anthropogenic emissions and hemispheric ozone background; future climate. Note the different scales for panels A/B and C/D.

The effect of the emission and land use scenarios on modeled health indicator Relative Risk (in %, all-cause mortality) and vegetation damage indicator POD_1 (Phytotoxic Ozone Dose above 1 μmol/m^2) for damage to deciduous trees is shown in Figure 7. The basis of Relative Risk as health impact indicator is SOMO35 (Sum of Ozone Means Over 35 ppb), which is the WHO-recommended health indicator and defined as the yearly sum of the daily maximum of 8-hour running average over 35 ppb (70 μg/m^3). For both health and vegetation damage, the 2050 decarbonisation run with 2010 meteorology shows a significant decrease in damage compared to 2010 over the whole domain: modeled health damage is halved for a large part of Europe. The POD_1 values for the reference case calculated with LOTOS-EUROS

(Figure 7, panel B) agrees well with values calculated with the EMEP model (EMEP, 2015). The effect of the energy scenarios and climate change on POD_1 values is smaller than the effect on relative risk, but it is also significant. While for health damage the modeled values increase under future climate conditions, this is not the case across the whole domain for POD_1. In southern Europe POD_1 values are actually lower for the future climate compared to the current climate case because plants under heat and water stress will close their stomata, thus limiting ozone uptake.

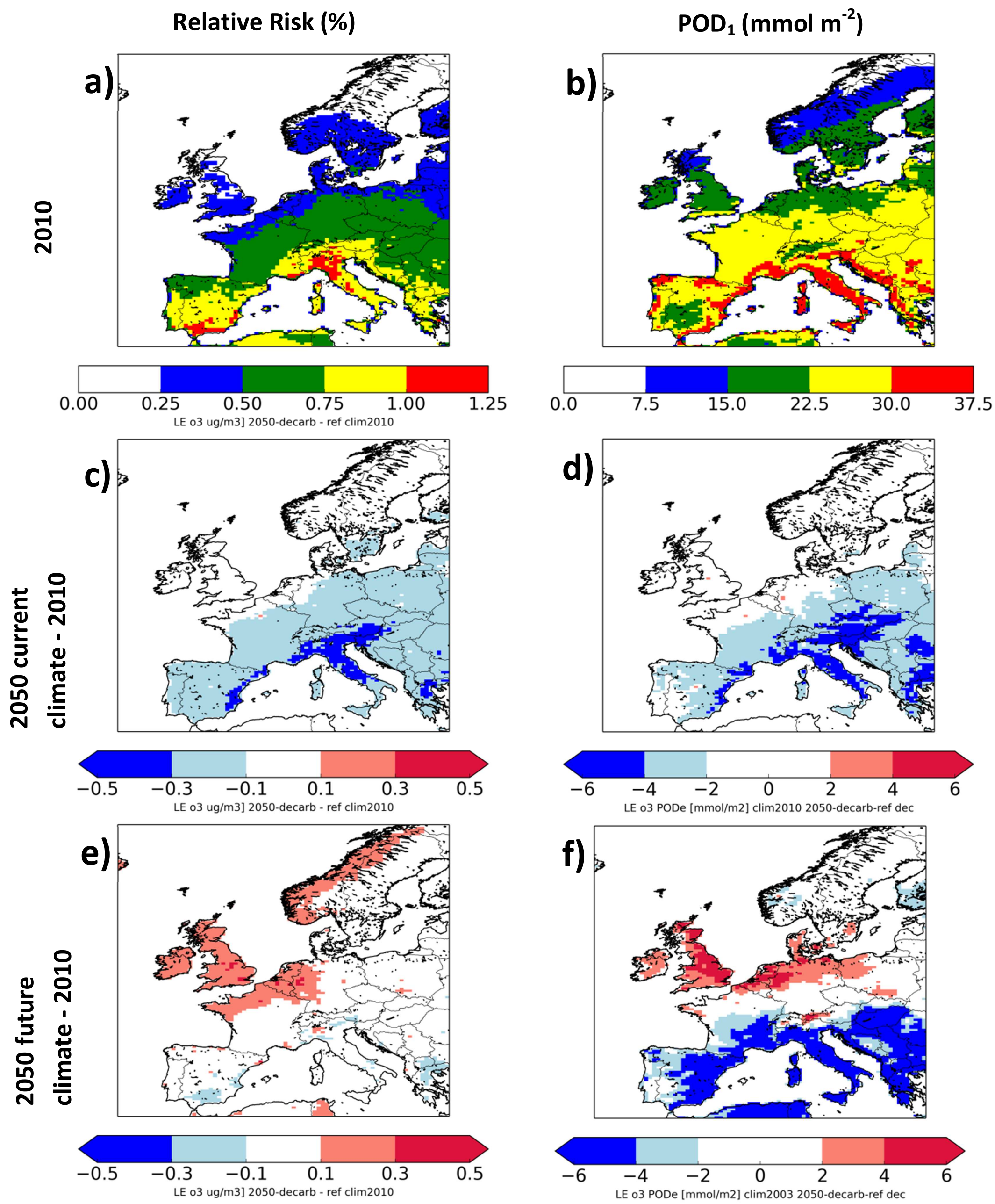

Figure 7. Relative Risk (in %-points, left) and POD_1 (in mmol/m^2, right) for 2010 (top), and the difference between the 2050 decarbonisation scenario under current (middle) and future (bottom) climate conditions and 2010.

For some example countries, the average Relative Risk is shown in Figure 8. This figure illustrates the differences in impact of land use change and decreasing anthropogenic emissions between regions as well as the decomposition of the total effect into the solitary impacts of land use change and emission change. This shows clearly that the magnitude of the effects found are different for different regions, but that the impact of a decrease in emissions from anthropogenic sources exceeds that of land use change for all countries.

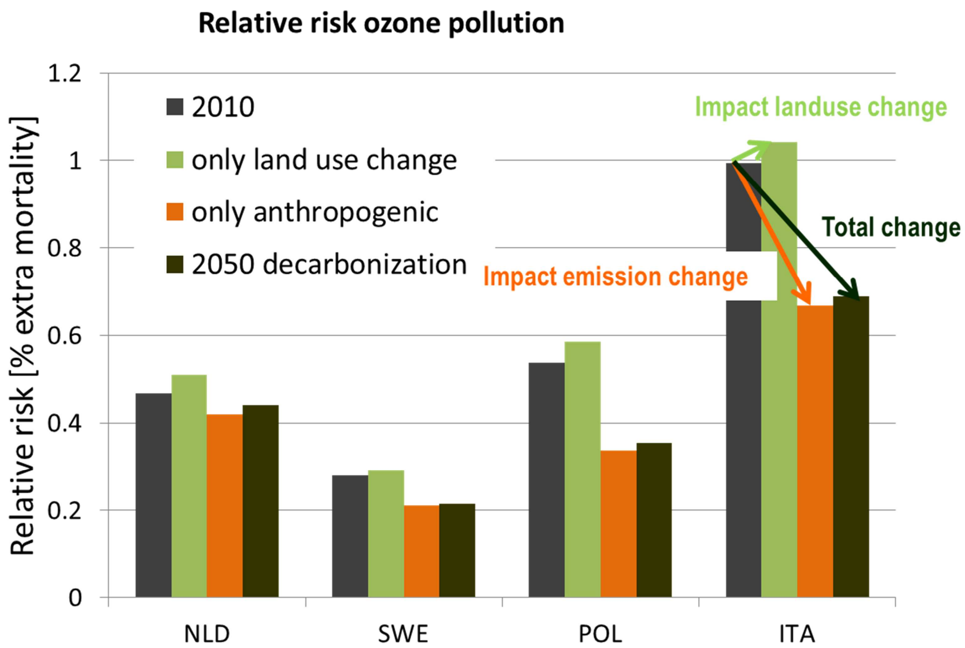

Figure 8 Decomposition of Relative Risk (% extra all-cause mortality) for a few example countries. NLD = the Netherlands, representative for north west Europe, SWE = Sweden, representative for Scandinavia, POL = Poland, representative for central Europe, ITA = Italy, representative for the Mediterranean region.

Discussion

Previous modelling studies focusing on the possible future impact of bioenergy plantations on isoprene emissions and O_3 levels did not take changing emissions from other sources or climate change into account. Beltman et al. (2013), Ashworth et al. (2012) and Lathiere et al. (2006) use straightforward assumptions on the amount of land use change with no clear policy underpinning. Beltman et al. (2013) assumed a conversion of 5% of agricultural and grassland into poplar plantations across Europe while Ashworth et al. (2013) converted 72Mha (45 of which in EU28 countries) of agricultural land into bioenergy plantations. In the present work, in total 7% (16 Mha) of agricultural and grassland in the EU28 is converted into poplar plantations and an additional 4 % (10 Mha) into forests (for the 2050 decarbonisation case). The increases in isoprene emissions and ozone levels found in the abovementioned studies are comparable with the impacts of land use change found in this study.

Ashworth et al. (2013) and Beltman et al. (2013) find isoprene emission increases of 40 and 45%, respectively, which agrees well with the increase of 50% for the 2050 decarbonisation case found in this work, taking into account the differences in land use change assumptions and geographical area covered in these studies. The resulting impact on ozone concentrations and damage found by previous studies also correspond with our results. This indicates that different models agree on the responses in ozone levels because of an isoprene emission increase.

The connection between high temperatures and increased ground level ozone concentration is well established (Smith and Tirpak, 1989; Wackter and Bayly, 1988; Wakim, 1989), although the exact relation is difficult to define because many other meteorological factors (e.g. wind, cloud cover, relative humidity) also play a role and the strength of the signal is also determined by atmospheric-chemical conditions. Katragkou et al. (2011) found the impact of climate change on ground level ozone concentrations to be below 2 $\mu g/m^3$ increase in the 2040s but up to 6-10 $\mu g/m^3$ towards the end of the century, for which an average temperature increase of 2.7 °C was calculated in the climate scenario they used. This corresponds well with the response of ground level ozone concentrations to higher temperatures and lower cloud cover found in the present work, where we use the extreme summer of 2003 to represent 'future climate' rather than a climate scenario. Most Global Circulation Models agree that because of climate change, the occurrence of stagnant weather conditions over the northern mid-latitude regions will increase (Jacob and Winner, 2009). Since the 2003 summer featured significantly more stagnant weather than normal in the current climate and temperature increases correspond with what is expected around 2050 (Kirtman et al., 2013), taking the 2003 summer is a fair choice to explore the effects of climate change on air quality in 2050. LOTOS-EUROS underestimates the variability in the observations between 2003 and more 'average' summers in the period 2003-2008 (Mues et al., 2013), which means that the effect of climate change calculated in this study may be underestimating the real effect of more frequent occurrence of summer conditions like in 2003.

Varotsos et al. (2013) model an increase in 8-hour maximum ozone concentrations for north-western Europe because of climate change in 2050, but find a decrease in central and southern Europe which they attribute to increasing water vapor over sea and increased wind speeds in these regions. They also take a global scenario for future emissions of air pollutants into account, which shows increasing emissions of ozone precursors and corresponding increases in ozone levels. Lacressonnière et al. (2014) take a similar approach but use an emission scenario projecting significant reductions in anthropogenic emissions for Europe. Their results are comparable to those presented in this paper both in absolute increase / decrease of average ozone concentrations found and in the geographical patterns of the response.

This comparison to other studies that investigated part of the effects included in this work shows that the responses in ozone concentrations to the separate effects of changes in land use, decreasing anthropogenic emissions and climate change correspond well with those found by other authors. This increases the confidence in the ozone response to the combined changes in land use, anthropogenic emissions and climate found in this study.

Conclusions

This study explores for the first time the combined impacts of changing land use and anthropogenic emissions on ground level ozone concentrations and damage for energy scenarios in Europe, using a consistent and policy-relevant combination of land use and emission datasets and taking into account the possible impacts of climate change as well. For both energy scenarios studied here, health damage because of high ground level ozone concentrations is projected to decline significantly towards 2030 and 2050, especially for central and southern Europe where health damage due to ozone might be halved in 2050. Damage to crops and ecosystems is also expected to decrease but to a smaller extent. The differences in ozone impact between the CLE and decarbonisation scenario were limited, indicating that the results presented here are robust for several possible European energy futures. The projected change in anthropogenic ozone precursor emissions, caused by current European air quality legislation rather than energy policies, was found to be a more important factor for resulting ozone levels than the projected land use change. Under an MTFR scenario for air quality, even further reductions of ozone damage in Europe are possible. Hemispheric background concentrations of ozone are expected to increase in a CLE scenario which leads to an increase of a 2-4 $\mu g/m^3$ in European ozone levels and causing a small but significant increase in Relative Risk and POD_1 as well. The increasing effect of a warming climate (+ 2 to 5 °C across Europe in summer) on ozone concentrations and associated health damage might be higher than the reduction that is achieved by cutting back ozone precursor emissions; ambitious air quality measures close to the MTFR scenario would be required to do that. However, if strong global action to reduce air pollutant emissions is taken, ozone damage in 2050 could be lower than at present.

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Highlights of manuscript "*Impact of EU climate and air quality policy on future ozone concentrations in Europe*" by Carlijn Hendriks, Nicklas Forsell, Gregor Kiesewetter, Martijn Schaap, Wolfgang Schöpp

Evaluating the impact of EU's energy and air quality policy on ground-level ozone damage.

Combined impacts of land use change, trend in anthropogenic emissions and climate change.

Effect of trend in emissions on ozone is more important than effect of land use change.

Impact of climate change may outweigh effect of reduced ozone precursor emissions.