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Global impacts of surface ozone changes on crop yields and land use

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HIGHLIGHTS

- We estimate ozone impacts on crop yields using high and low air pollution scenarios.
- Substantial crop losses can be avoided by air pollution control, especially in Asia.
- Climate policies can have co-benefits for crops due to reduced co-emissions.
- Reduced ozone damage will also reduce land use and associated carbon emissions.

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ABSTRACT

Exposure to surface ozone has detrimental impacts on vegetation and crop yields. In this study, we estimate ozone impacts on crop production and subsequent impacts on land use in the 2005–2050 period using results of the TM5 atmospheric chemistry and IMAGE integrated assessment model. For the crops represented in IMAGE, we compute relative yield losses based on published exposure-response functions. We examine scenarios with either constant or declining emission factors in a weak climate policy future (radiative forcing target of 6.0 W/m^2 at the end of the century), as well as co-benefits of stringent climate policy (targeted at 2.6 W/m^2). Without a large decrease in air pollutant emissions, higher ozone concentrations could lead to an increase in crop damage of up to 20% locally in 2050 compared to the situation in which the changes in ozone are not accounted for. This may lead to a 2.5% global increase in crop area, and a regional increase of 8.9% in Asia. Implementation of air pollution policies could limit crop yield losses due to ozone to maximally 10% in 2050 in the most affected regions. Similar effects can be obtained as a result of co-benefits from climate policy (reducing ozone precursor emissions). We also evaluated the impact of the corresponding land-use changes on the carbon cycle. Under the worst-case scenario analysed in this study, future ozone increases are estimated to increase the cumulative net CO_2 emissions between 2005 and 2050 by about 3.7 Pg C, which corresponds to about 10% of baseline land use emissions over the same period.

1. Introduction

Anthropogenic emissions of ozone precursors have increased surface ozone concentrations in many areas of the world (Royal Society, 2008). It has been demonstrated in field experiments conducted mostly in Europe and North America that exposure to elevated ozone concentrations has detrimental effects on plants (e.g., Heck et al., 1983; Fuhrer et al., 1997; Pleijel et al., 2002; Karlsson et al., 2007; González-Fernández et al., 2008; De Bock et al., 2011). This ozone impact on plants has different implications: Firstly, it affects the productivity of crops and thus the global production of food. Secondly, it also negatively impacts natural vegetation. This may reduce biodiversity and contribute to global warming by reducing the CO_2 uptake by plants (Sitch et al., 2007). Finally, ozone impacts on crops may also necessitate the need for additional agricultural cropland to meet food demand thus resulting in land use changes.

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Future changes in surface ozone are expected to vary regionally depending on the evolution of ozone precursors emissions. It is expected that the implementation of stringent air pollution policies will lead to a reduction in episodic peak ozone concentrations in Europe and North America (Ellingsen et al., 2008; Royal Society, 2008). At the same time, surface ozone concentrations are projected to increase in regions with rapidly growing economies in South and East Asia, at least in the near term. Young et al. (2013) presented multi-model projections of surface ozone concentrations based on the representative concentration pathways (RCPs). Chuwah et al. (2013) recently presented projections based on an extended set of RCP-like scenarios and showed that both air pollution and climate policy could significantly affect ozone precursor emissions and consequently ozone concentrations in the coming decades.

There have been a number of studies on present-day ozone impacts on crop yields, such as the global studies of Van Dingenen et al. (2009) and Avnery et al. (2011a) and the regional study for the United States by Yue and Unger (2014). In addition, scenario studies have investigated the possible impacts of future ozone levels on crop yields, such as the global studies by Avnery et al. (2011b; 2013) and the regional study for Asia by Wang and Mauzerall (2004), both based on the IPCC SRES scenarios (Nakićenović et al., 2000), the global study by Van Dingenen et al. (2009) based on emission scenarios from the International Institute for Applied Systems Analysis (IIASA), and the global study of Tai et al. (2014) based on the Representative Concentration Pathways (RCPs). Other studies have looked at the impacts of future changes in land use on ozone precursor emissions and ozone concentrations (Lathière et al., 2006; Ganzeveld et al., 2010; Wu et al., 2012). However, no attention has been given to the impacts of changes in surface ozone on land use via crop yield losses. In this study, we use a wider set of scenarios with respect to air pollution (Chuwah et al., 2013) developed using the Integrated Model to Assess the Global Environment (IMAGE, Bouwman et al., 2006) to assess the possible impacts of ozone concentration changes on future crop yields and consequently land use under different climate and air pollution policy regimes.

To do so, we make use of established exposure-response functions (ERFs) based on field experiments. The relative yield loss (RYL) factors for different crop types have been calculated from hourly ozone fields simulated with the atmospheric chemistry and transport model TM5 (Huijnen et al., 2010; Van Noije et al., 2014). The resulting crop production losses and the subsequent impact on land use were calculated by feeding back the results to the IMAGE model. This modelling setup allows us to assess the potential of different scenarios in reducing crop losses and subsequent impacts on land use for the first half of the century.

The paper is structured as follows: Section 2 describes the methodology. In Section 3 we present results on the simulated ozone indicators. Results on ozone impacts on crop production and land use, and the associated net CO_2 emissions for the different scenarios are presented in Section 4. A discussion and conclusions of our results are given in Section 5.

2. Methodology

2.1. Models and emission scenarios

The ozone concentrations used in this study were calculated by Chuwah et al. (2013) using TM5, driven by present-day meteorological fields. This is justified by the fact that in most regions the impacts of climate change on ground-level ozone concentrations are expected to be much smaller than the impacts of future changes in ozone precursor emissions (see e.g. Fiore et al., 2012).

The three emission and land-use scenarios considered in this study have been developed using the IMAGE model, as described by Chuwah et al. (2013). We consider two scenarios that are similar to the RCP6.0 and RCP2.6, which lead to a radiative forcing of 6.0 and 2.6 W m^{-2} in 2100 respectively (Van Vuuren et al., 2011). The scenarios, called IM6.0 and IM2.6, differ in terms of energy use and land use as a consequence of the assumed climate policy. The IM6.0 is a scenario with very mild climate policy, while the IM2.6 scenario resembles the most ambitious climate policy scenarios in the literature. To assess the importance of air pollution policy we designed variants of these two climate scenarios with different trends in emission factors for ozone precursor gases and other short-lived air pollutants (Chuwah et al., 2013). The low air pollution scenarios assume that emission factors will decline following the implementation of currently formulated air pollution legislation up to 2030, followed by a further decline assuming that increasing levels of welfare lead to a higher valuation of air quality (similar to the Kuznets hypothesis). This is similar to the original RCPs, used in climate research (see Van Vuuren et al., 2011). In the high-pollution variants of these scenarios, current and planned legislation is assumed to be implemented until 2010, after which emission factors are taken to be constant. In this study, the following three scenarios are considered:

1) IM6.0-high (RCP6.0 type scenario, i.e. weak climate policy with high air pollutant emissions)
2) IM6.0-low (RCP6.0 type scenario, i.e. weak climate policy with low air pollutant emissions)
3) IM2.6-low (RCP2.6 type scenario, i.e. stringent climate policy with low air pollutant emissions).

A detailed description of the models and key assumptions about the emissions scenarios can be found in the Supplementary

Table 1
Overview of crop types in IMAGE, the different ozone indicators used to estimate ozone impacts and the exposure-response functions (ERFs) used to evaluate the relative yield loss (RYL). The mean of the RYL based on AOT40 and M7or M12 has been taken in the cases of rice and maize. Note that maize is both a food and energy crop in IMAGE.

IMAGE crop types	Crop types used for ERFs	Ozone indicator	ERFs used for RYL calculation	References
Rice	Rice	AOT40 M7	0.00415*AOT40 $\mathrm{Exp}[-(M7/137)^{2.34}]/\exp[-(25/137)^{2.34}]$	Mills et al. (2007) Wang and Mauzerall (2004)
Maize	Maize	AOT40 M12	0.00356*AOT40 $\mathrm{Exp}[-(M12/124)^{2.83}]/\exp[-(20/124)^{2.83}]$	Mills et al. (2007) Wang and Mauzerall (2004)
Temperate cereals	Barley	AOT40	0.00061*AOT40	Mills et al. (2007)
Tropical cereals	Barley/wheat	AOT40	0.00061*AOT40	Mills et al. (2007)
Pulses	Pulses	AOT40	0.0172*AOT40	Mills et al. (2007)
Oil crop	Soybean	AOT40	0.0113*AOT40	Mills et al. (2007)
Grass	Ryegrass/clover mixture	AOT40	0.00003*AOT40	González-Fernández et al. (2008)
Root and Tuber	Potato	AOT40	0.0058*AOT40	Mills et al. (2007)
Sugar cane	Cotton	AOT40	0.0150*AOT40	Mills et al. (2007); Grantz et al. (2009)
Woody bio-fuel crops	Broadleaves and conifers	AOT40f	0.00162*AOT40f	Karlsson et al. (2007)
Non-woody bio-fuel crops	Maize	AOT40	0.00356*AOT40	Van Dingenen et al. (2009)