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Reducing the negative human-health impacts of bioenergy crop emissions through region-specific crop selection

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Abstract

An expected global increase in bioenergy-crop cultivation as an alternative to fossil fuels will have consequences on both global climate and local air quality through changes in biogenic emissions of volatile organic compounds (VOCs). While greenhouse gas emissions may be reduced through the substitution of next-generation bioenergy crops such as eucalyptus, giant reed, and switchgrass for fossil fuels, the choice of species has important ramifications for human health, potentially reducing the benefits of conversion due to increases in ozone (O₃) and fine particulate matter (PM_{2.5}) levels as a result of large changes in biogenic emissions. Using the Community Earth System Model we simulate the conversion of marginal and underutilized croplands worldwide to bioenergy crops under varying future anthropogenic emissions scenarios. A conservative global replacement using high VOC-emitting crop profiles leads to modeled population-weighted O₃ increases of 5–27 ppb in India, 1–9 ppb in China, and 1–6 ppb in the United States, with peak PM_{2.5} increases of up to 2 µg m⁻³. We present a metric for the regional evaluation of candidate bioenergy crops, as well as results for the application of this metric to four representative emissions profiles using four replacement scales (10–100% maximum estimated available land). Finally, we assess the total health and climate impacts of biogenic emissions, finding that the negative consequences of using high-emitting crops could exceed 50% of the positive benefits of reduced fossil fuel emissions in value.

1. Introduction

As bioenergy crops continue to replace both existing agricultural crops and natural landscapes, the choice of crop species will become increasingly important given their likely impacts on air quality and climate. The use of crops such as poplar, eucalyptus, and switchgrass as bioenergy feedstocks has increased globally over the past decade, and while ongoing adoption trends are highly dependent on both economic outcomes and policy decisions, significant increases are expected to continue (Energy Information Administration 2013). The large scale land-use changes associated with bioenergy production will have consequences on many aspects of environmental and human health, including food supply, watershed cleanliness, soil quality, and ecological diversity (e.g.

Service 2007, Dominguez-Faus *et al* 2009, Ditomasso *et al* 2010, Pedrolí *et al* 2013). In some cases, the environmental costs associated with bioenergy production and consumption have been estimated to outweigh the benefits of reduced fossil fuel combustion completely (Hill *et al* 2009, Tessum *et al* 2014). In addition to these concerns, many of the most popular candidates for bioenergy crop feedstocks are high-emitters of isoprene, monoterpenes, and other biogenic volatile organic compounds (BVOCs), precursors of surface-level ozone (O₃) and fine particulate matter (PM_{2.5}). Recent observational and modeling studies of existing bioenergy crop plantations have highlighted the importance of examining ambient chemical and climatological conditions, along with crop emission profiles, when assessing the potential for large-scale cultivation to effect negative air quality

consequences in any given area (Hewitt *et al* 2009, Porter *et al* 2012). Thus far, however, strategies to inform regional energy crop selection and limit the negative impacts of bioenergy cultivation on air quality and human health have not been adequately addressed.

With a global single-year death toll of seven million, air pollution has now been identified as the most significant environmental risk to human health (WHO 2014). Over half of the total estimated air pollution related deaths are linked to outdoor exposure, particularly to elevated levels of O₃ and PM_{2.5} (Brauer *et al* 2012). These pollutants largely are secondary, forming *in situ* as a result of chemical reactions involving both naturally and anthropogenically emitted precursors (Sillman 1999, de Gouw and Jimenez 2009), making effective control of their ambient concentrations particularly challenging. For both O₃ and PM_{2.5}, fluxes of BVOCs can play a crucial role in determining peak daily pollutant concentrations. While all plants emit BVOCs to some extent, there is enormous variability in the magnitude of emission rates between different plant species (Guenther *et al* 1995). Thus, large-scale landscape-level changes in the type and quantity of plants can have profound consequences on regional air quality by affecting the rates of BVOC emissions, and therefore rates of O₃ and PM_{2.5} formation (Wiedinmyer *et al* 2006, Ashworth *et al* 2012).

While recent work has examined the air quality consequences of both theoretical and observed land-use changes driven by bioenergy crop cultivation (Porter *et al* 2012, Ashworth *et al* 2013), a global study comparing targeted likely bioenergy crop emission profiles has not yet been performed. This comparison is important, since the differences between the highest and lowest emitting candidate crops are large: eucalyptus and other woody energy crops rank among the highest of known BVOC emitters (Guenther *et al* 1994, Street *et al* 1997, Padhy and Varshney 2005, Hewitt *et al* 1990, Winters *et al* 2009, Owen 2001), while rapidly growing cellulosic alternatives such as switchgrass (*Panicum sp.*) and Miscanthus (*Miscanthus x Giganteus*) are among the lowest (Graus *et al* 2011, Eller *et al* 2011). Since the conversion of existing fossil-fuel based energy sources to these modern bioenergy cropping systems will presumably be driven by climate and air quality concerns, choosing feedstocks that do not undermine these efforts through drastic changes in biogenic emissions will be critical. As modern bioenergy methods continue to be developed and applied, the regional selection of feedstock crop will naturally be based on a number of agronomic criteria, including growth rates, hardiness, ease of cultivation and harvesting, and suitability for efficient conversion to energy. It is the purpose of this paper to assess whether biogenic emissions must also be added to emerging feedstock crop-selection criteria in areas demonstrating high air quality sensitivities.

2. Methodology

In this work, the air quality and climatic impacts of increased biogenic emissions due to a global transition to bioenergy crop cultivation are examined, and considerations for reducing these impacts are proposed and evaluated. To compare these impacts, we model the climate and air quality consequences of large-scale conversion of underutilized land to bioenergy crop cultivation using the NCAR chemistry climate model Community Earth System Model (CESM) 1.1, including version 4 of the Community Atmosphere Model (Lamarque *et al* 2012, Neale *et al* 2013; additional model and crop replacement details available in supplementary data available at stacks.iop.org/ERL/10/054004/mmedia). We use three characteristic replacement crop emission profiles representing a range of emission types: trace isoprene emissions (LOW case), high isoprene emissions (ISO case), and high isoprene and monoterpene emissions (ISO + MT case). We also generate a fourth case using an average of all three emission types to represent an intermediate emissions scenario (MIXED). We then use each of these four profiles to simulate varying degrees of land-use change in areas identified as underutilized (Cai *et al* 2010) under both current and projected future anthropogenic emissions scenarios (Meinshausen *et al* 2011), and compare them to base cases using non-emitting land rather than a replacement crop.

We run a total of three base cases and 48 replacement cases (table 1), representing a wide range of total replaced area (143–1430 Mha) and emissions profiles (low to high BVOC emitters) using both current and projected anthropogenic emissions and ambient temperatures. Projections of future total biomass energy production potentials are highly variable, mostly due to uncertainties in quantifying land availability and likely crop yields (Berndes *et al* 2003). For much of this study, the ‘Moderate’ replacement scale, representing 25% of the full potential area, or around 277 Mha (supplementary table 1 available at stacks.iop.org/ERL/10/054004/mmedia), is examined in detail. Recent literature estimates the area of global abandoned agricultural land at approximately 400 Mha (Campbell *et al* 2008), making the Moderate case a relatively conservative estimate. We analyze the global model results for six regions with the largest estimates of potentially available land area: Africa, China, Europe, India, South America and the United States. Estimates of net energy gain (NEG) per hectare of energy crop vary widely, even within individual species (Collura *et al* 2006, Lewandowski and Schmidt 2006, Angelini *et al* 2009, Schmer *et al* 2009, 2014, US Department of Energy 2011), but conservative NEG values suggest that land-use conversion in the most aggressive scenarios could generate approximately 10% of current global electricity production.

In addition to comparing pollutant changes between crop profiles and anthropogenic emissions

Table 1. Settings used for all 46 simulated cases (above), and changes to population-weighted NO_x resulting from modified anthropogenic emissions (below).

Crop emission types (4 + base)	Replacement scales (4)	Anthropogenic emissions (3)
Base	none	current ^a , RCP4.5 ^b , RCP8.5 ^b
ISO + MT	100%, 50%, 25%, 10%	current ^a , RCP4.5 ^b , RCP8.5 ^b
ISO	100%, 50%, 25%, 10%	current ^a , RCP4.5 ^b , RCP8.5 ^b
LOW	100%, 50%, 25%, 10%	current ^a , RCP4.5 ^b , RCP8.5 ^b
MIXED (average of above profiles)	100%, 50%, 25%, 10%	current ^a , RCP4.5 ^b , RCP8.5 ^b
Region	RCP4.5 NO _x	RCP8.5 NO _x
Africa	−5%	−3%
China	+3%	+59%
Europe	−41%	−35%
India	+47%	+53%
South America	−17%	−13%
United States	−49%	−42%

^a Default CESM emissions via POET, REAS, GFED2.^b Lamarque *et al* (2011).

scenarios, we perform an analysis of human-health impacts of alternative cropping scenarios. Using population distribution data and concentration response estimates we estimate the number of lives affected by degraded air quality and assess a health cost on a regional basis (Jerrett *et al* 2009, Krewski *et al* 2009, Anenberg *et al* 2010). We then weight changes in O₃ and PM_{2.5} by population density and normalize results by replacement scale to generate an aggregate ‘energy crop air quality score’ (ECAQS) for each crop and region. Following the examination of urban tree selection and air quality effects presented in Donovan *et al* 2005, the ECAQS score can be understood as the population-weighted average change in air quality (measured relative to WHO standards for O₃ and PM_{2.5}) per 10 Mha of energy crop planted in that region, allowing for a normalized measure of AQ sensitivity to variation in crop type and regional abundance. An ECAQS score of negative ten, for example, indicates that the population will see an average increase in pollutant concentrations equivalent to 10% of their respective standards.

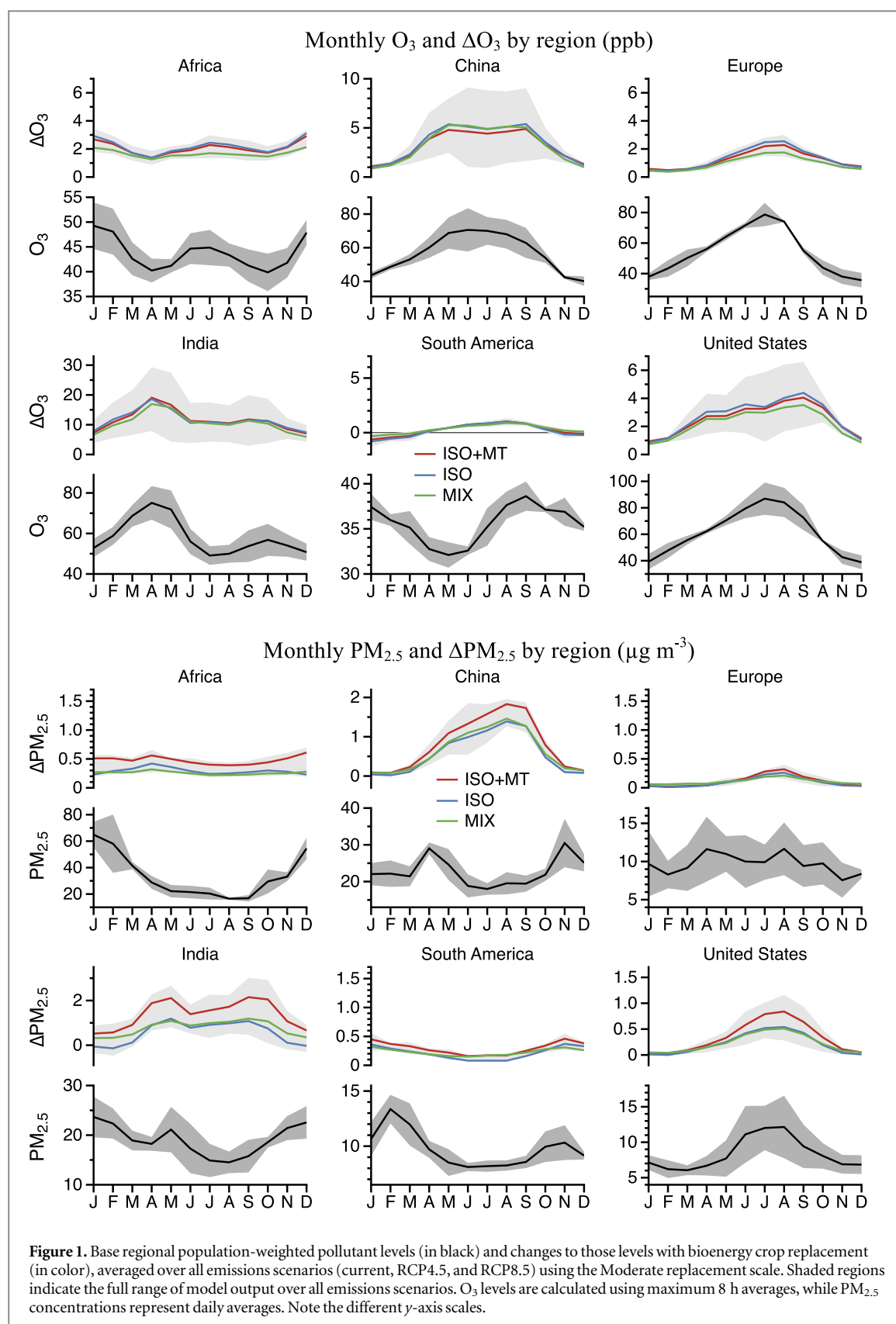
3. Results and discussion

3.1. Air quality impacts

Our model results show highly non-linear, region-specific air quality impacts of bioenergy crop selection (figure 1), demonstrating the need for regional crop selections taking local sensitivities into account. Simulated O₃ generally increase for all three high-emitting crop types, with especially large summertime effects predicted in the following regions: India (average increases of 5–27 ppb population-weighted summertime O₃ for the Moderate replacement cases), China (1–9 ppb O₃), and the United States (1–6 ppb O₃). However, changes in O₃ levels are low or even negative in areas exhibiting already low NO_x/volatile organic

compound (VOC) ratios, such as South America, where changes in O₃ range from −1 ppb in the summer to +1 ppb in the winter for the Moderate replacement scale ISO and ISO + MT cases, respectively. Secondary organic aerosol formation in all regions is primarily driven by monoterpene emissions, characteristic of the ISO + MT and MIXED cases. ISO replacement cases show some PM_{2.5} response, but at much reduced levels, while the LOW cases show negligible impacts on PM_{2.5} concentrations. Unlike O₃, PM_{2.5} levels consistently increase with greater crop replacement area. PM_{2.5} levels also show much less sensitivity to future changes in climate and emissions. In China and India maximum population-weighted changes in PM_{2.5} approach 2 μg m^{−3} for the ISO + MT case.

Since the health risks associated with PM_{2.5} exceed those of tropospheric O₃ relative to the magnitudes of changes evident in this study, the high monoterpene emissions of the ISO + MT cases result in the greatest estimated health costs among the four crop types, with over 410 000 premature deaths worldwide associated with the Moderate replacement level (see supplementary data for more details on mortality estimate calculations (available at stacks.iop.org/ERL/10/054004/mmedia)). Using the reduced emissions of the ISO-only profile leads to 328 000 premature deaths, while conversion of land using LOW emissions shows only very small changes in O₃ and PM_{2.5}, and therefore negligible increases in premature deaths. Notably, mixing the three crop types (MIXED) proves to be more detrimental than might be expected, with mortality increases almost identical to those of the ISO case worldwide, and greater than the average of the three emissions cases for each individual region. This may be related to nonlinearities in pollutant formation, and therefore in the resulting changes in mortality estimates. The scale of estimated land availability and dense population distributions in India, Africa, and

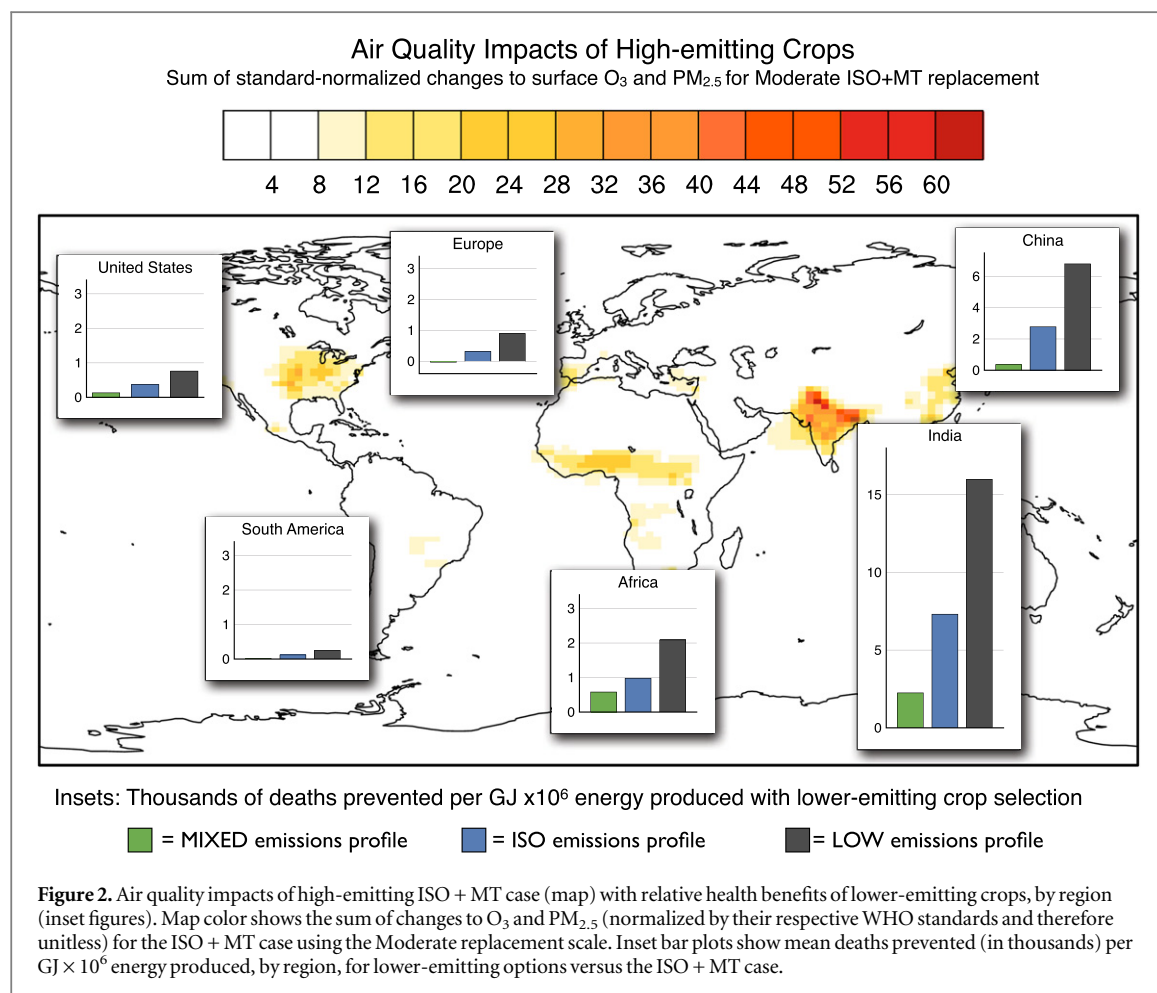


China makes health effects in those areas the most sensitive to increased VOC emissions from bioenergy crops. These areas, already among the most affected by outdoor air pollution (Cohen *et al* 2005), account for approximately 70% of the increased mortality worldwide.

The extent to which air quality concerns should be taken into account in the selection of bioenergy crops on a regional basis can be evaluated quantitatively by comparing differences in the ECAQS for each crop and region (table 2). Total scores for ISO + MT emissions at the Moderate replacement scale range from

Table 2. Average Energy Crop Air Quality Scores by region and pollutant for the Moderate replacement scale cases. ECAQS represents change in population-weighted, standard-normalized air quality per 10 Mha of energy crop planted. Peak column represents the maximum monthly average change by crop and region.

	Africa				China				Europe			
	O ₃	PM _{2.5}	Total	Peak	O ₃	PM _{2.5}	Total	Peak	O ₃	PM _{2.5}	Total	Peak
ISO + MT	−0.6	−1.0	−1.6	−2.2	−1.8	−2.1	−3.8	−6.1	−0.8	−0.6	−1.4	−3.1
ISO	−0.6	−0.6	−1.2	−1.7	−1.9	−1.1	−3.0	−4.7	−0.8	−0.5	−1.4	−3.0
LOW	0.0	0.0	0.0	0.0	0.0	0.0	0.0	−0.1	0.0	0.0	0.0	0.0
MIX	−0.5	−0.5	−1.0	−1.3	−1.8	−1.2	−3.0	−4.8	−0.6	−0.4	−1.0	−2.3
	India				South America				United States			
	O ₃	PM _{2.5}	Total	Peak	O ₃	PM _{2.5}	Total	Peak	O ₃	PM _{2.5}	Total	Peak
ISO + MT	−7.5	−6.9	−14.4	−23.1	−0.1	−0.8	−0.9	−1.2	−1.2	−1.7	−2.9	−5.2
ISO	−7.6	−3.8	−11.4	−18.3	−0.1	−0.6	−0.7	−1.0	−1.3	−1.0	−2.3	−4.2
LOW	0.0	−0.1	−0.1	−0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MIX	−6.7	−3.6	−10.3	−16.4	−0.1	−0.5	−0.5	−0.8	−1.1	−1.0	−2.1	−3.7



−0.9 in South America, where low NO_x levels and a fairly disperse human population keeps health impacts modest; to −14.4 in India, where the density of human population and replacement areas make the air quality consequences of crop selection an especially important factor.

The potential increase in productivity of higher-emitting crops when compared to low-emitting crops such as miscanthus or switchgrass may be justifiable

when the population-weighted impacts of the higher emissions are relatively low, as in Africa and South America. On the other hand, the larger impacts shown in the other four regions suggest that finding low-emitting solutions may be crucial for any region-wide implementation of a bioenergy cultivation strategy. Furthermore, comparing the ISO + MT and ISO cases highlights the relative importance of monoterpene and isoprene emissions in each region. While PM_{2.5}

impacts are larger for the ISO + MT case in all regions, in some areas the health effects of increased O_3 may outweigh those of $PM_{2.5}$, reducing the difference between isoprene-only emitters such as giant reed and monoterpene emitters such as eucalyptus. The combined health benefits of using lower-emitting crops for bioenergy production is evident in figure 2, where summed impacts of O_3 and $PM_{2.5}$ changes for the ISO + MT case are shown in red, with regional benefits of lower-emitting options (in deaths prevented per energy produced) shown as inset bar plots.

3.2. Climatic impacts

In addition to local air quality effects, a worldwide shift towards high VOC-emitting bioenergy crop cultivation would have global climatological impacts, including possible changes to methane (CH_4) lifetimes and the aerosol radiative effect. The highest crop emission case (100% ISO + MT replacement) results in globally averaged OH levels reduced by approximately 20% compared to the base simulation after correcting for estimated HO_x recycling impacts (Lelieveld *et al* 2008, Petters *et al* 2009, da Silva *et al* 2010; see supplementary data available at stacks.iop.org/ERL/10/054004/mmedia). While CH_4 emissions worldwide are projected to decline over the 21st century under all but the highest emitting scenarios (Meinshausen *et al* 2011), a reduction in the OH concentration of this magnitude as a result of bioenergy crop emissions would increase average CH_4 lifetimes by up to two years, leading to higher concentrations and a corresponding increase in CH_4 -induced warming. Although reduced replacement areas and lower-emitting crops would have a lesser impact on CH_4 , the inclusion of even small impacts on CH_4 may be important additions to the overall cost-benefit calculations associated with bioenergy crop selection. Based on OH reductions in the simulations for current atmospheric conditions, changes to the CH_4 radiative effect could be as high as 0.19 W m^{-2} in the Maximum ISO + MT case. Such values would represent over 1/3 of the total modern CH_4 radiative forcing estimates, highlighting the potentially significant impact that large-scale increases in high VOC-emitting bioenergy crops can have on Earth's climate system. Peak changes for the ISO and MIXED cases are predicted to be less than that, at 0.13 and 0.12 W m^{-2} respectively, with reduced-scale replacement schemes scaling down nearly linearly.

The increase in total organic aerosol burden would have complex effects on the net energy budget of the atmosphere, affecting not only incoming radiation directly, but also a variety of cloud properties such as albedo and lifetime. Greater levels of $PM_{2.5}$ are predicted for most replacement scenarios, contributing an overall cooling effect. Taken together, the increased CH_4 lifetime and aerosol burden resulting from enhanced BVOC emissions would be expected to have competing effects on radiative forcing, with the CH_4

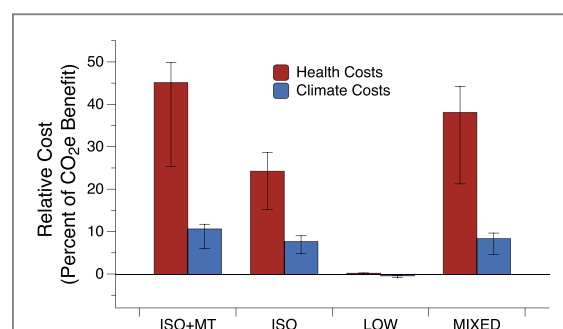


Figure 3. Climate and human health costs related to biogenic emissions for simulated emissions types. All impacts are normalized to equivalent CO_2 emissions (CO_2e) and compared to estimated benefit of an associated reduction in coal emissions. Error bars reflect uncertainties in crop yield and variability in modeled output across the full set of simulated scales and emissions scenarios.

effect greater by a factor of approximately five in these simulations. Since the reduction of radiative forcing from greenhouse emissions is one of the main goals driving the present move towards bioenergy development and expansion, taking such BVOC related feedbacks into account will be important when assessing bioenergy crop selection and expansion from a global perspective.

3.3. Total costs

Finally, we perform economic assessments of climatic and human-health impacts using estimates for the social cost of carbon, and value of a statistical life. Literature values for both of these costs vary greatly, depending heavily upon future economic and atmospheric assumptions. For this work we use conservative, low-end estimates of \$21 per ton CO_2 (IAWG 2010) and \$1 million per statistical life (Viscusi and Aldy 2003). We then convert the climatic and human health costs associated with each modeled crop type into equivalent CO_2 (CO_2e) and compare them to estimated benefits of coal combustion reductions (Burnham *et al* 2012), to produce a comparison of costs and benefits for each crop emission type (figure 3). Costs associated with increased CH_4 (minus the cooling effects of increased organic aerosol) are approximately 8–10% of the expected value of reduced fossil fuel emissions for ISO + MT, ISO, and MIXED emission cases, and negligible for the LOW case. Globally summed health costs are larger, totaling 24–45% of the dollar value of reduced fossil fuel emissions for the high BVOC-emitting cases. These costs make the reduction in negative climate and human health impacts associated with a low-emitting bioenergy crop like switchgrass especially attractive. Under these assumptions, high-emitting crops would dramatically mitigate any net benefits of greenhouse gas emission reductions, primarily through impacts on human health.

3.4. Land-use change assumptions and uncertainties

In simplifying and evaluating the impacts of large-scale global trends as we have done here, important assumptions must be made. For one, we use a single land-availability map to determine replacement areas worldwide, scaling each grid cell down uniformly for reduced area cases. In practice, bioenergy crops will probably not be distributed in this manner, and are more likely to be clustered in dense areas around processing facilities. This difference in distribution and density would likely affect the resulting air quality impacts. Likewise, land-use change consequences will be highly dependent on the original land being replaced, a sensitivity that remains unexplored in our study.

While we have chosen values representative of typical candidate crops, the specific phenology, yields, and cultivation needs of selected feedstocks will also vary greatly between species and regions. For this reason, the comparisons presented here should be considered emblematic of the wide-ranging bioenergy crop options available, rather than evaluations of specific crops.

4. Summary

As alternatives to fossil fuels are increasingly adopted, it will be crucial to do so in ways that seek to maximize carbon reduction while also minimizing associated negative consequences. The results of this study suggest that, while cultivation of high productivity bioenergy crops may offer an attractive option for biomass-based energy production in many areas of the world, air quality and climate impacts of crop emissions must also be considered alongside other concerns such as water availability, biodiversity, and food security. In terms of biogenic emissions, using a low-emitting crop such as switchgrass or *Miscanthus* rather than a higher-emitting alternative could maximize any expected environmental benefits of reduced fossil fuel use. However, the possibility of lower potential yields of these crops compared to higher VOC-emitting options may affect the final cost-benefit analysis of any proposed bioenergy development. By evaluating the local and global consequences of crop selection on a case-by-case basis, including calculation of ECAQS values for candidate crops as performed here, these considerations can help to further inform energy policy and maximize the benefits of alternative energy production while minimizing the negative impacts of bioenergy crop cultivation on air quality, human health, and climate.

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