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Biofuels That Cause Land-Use Change May Have Much Larger Non-GHG Air Quality Emissions Than Fossil Fuels

C.-C. Tsao,*[,†] J. E. Campbell,[†] M. Mena-Carrasco,[‡] S. N. Spak,[§] G. R. Carmichael,[§] and Y. Chen[†]

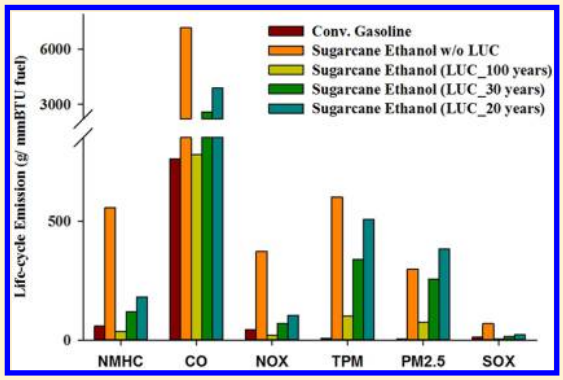
[†]School of Engineering, University of California, 5200 Lake Road, Merced, California 95343, United States

[‡]Center for Sustainability Research, Universidad Andrés Bello, Republica 440, Santiago, Chile

[§]The Center for Global and Regional Environmental Research, University of Iowa, 424 IATL, Iowa City, Iowa 52242, United States

Supporting Information

ABSTRACT: Although biofuels present an opportunity for renewable energy production, significant land-use change resulting from biofuels may contribute to negative environmental, economic, and social impacts. Here we examined non-GHG air pollution impacts from both indirect and direct land-use change caused by the anticipated expansion of Brazilian biofuels production. We synthesized information on fuel loading, combustion completeness, and emission factors, and developed a spatially explicit approach with uncertainty and sensitivity analyses to estimate air pollution emissions. The land-use change emissions, ranging from 6.7 to 26.4 Tg $PM_{2.5}$, were dominated by deforestation burning practices associated with indirect land-use change. We also found Brazilian sugar cane ethanol and soybean biodiesel including direct and indirect land-use change effects have much larger life-cycle emissions than conventional fossil fuels for six regulated air pollutants. The emissions magnitude and uncertainty decrease with longer life-cycle integration periods. Results are conditional to the single LUC scenario employed here. After LUC uncertainty, the largest source of uncertainty in LUC emissions stems from the combustion completeness during deforestation. While current biofuels cropland burning policies in Brazil seek to reduce life-cycle emissions, these policies do not address the large emissions caused by indirect land-use change.



1. INTRODUCTION

Expansions of biofuels production may provide benefits to energy security, greenhouse gas (GHG) emission reductions, and rural economic development.[1−3] Production of liquid biofuels including ethanol and biodiesel is expected to grow rapidly in the future in response to market forces and government mandates for fuel-blending.[4,5] Expansion in Brazil presents unique opportunities for both liquid fuel and electricity production.[6] Estimates of the life-cycle GHG emissions from biofuels are largely based on regional and global models of the land-use change (LUC) impacts from biofuels.[4,7,8] The climate effects of land-use changes from increasing biofeedstock acreage, both indirect and direct, have dominated policy discussion, and focused on comparisons in long-lived GHGs. However, the potential for land-use change to also cause important non-GHG air pollution emissions (e.g., particulate matter, carbon monoxide) has been largely overlooked. These non-GHG air pollutants may also lead to short-term impacts on local and regional climate. The present study estimates these non-GHG pollutant releases for an important biofuel pathway and compares them to analogous pollution from fossil fuel use.

Among the available biofuels on the market, sugar cane ethanol that is primarily produced in Brazil may result in lower life-cycle GHG emissions than other conventional biofuels such as corn ethanol.[9] However, sugar cane ethanol may be of particular concern with respect to non-GHG air pollution due to preharvest burning of sugar cane fields.[10] An additional driver of life-cycle non-GHG air pollution emissions from sugar cane ethanol may be the dLUC and iLUC emissions that could be incurred by an expansion of biofuel croplands.

Air pollution emissions from LUC are due to the open burning practices for land clearing, e.g., slash-and-burn.[11] Recent analyses of global biomass burning found that deforestation and degradation fire are the second largest sources of biomass burning emissions, following fires in grasslands and savannas.[12] These land clearing emissions have shifted toward areas with higher biomass density in tropical region, particularly in Amazonia.[13,14] Recent work shows that the prominent decrease in deforestation rates have been offset by the shifting of deforestation to areas with higher biomass density.[15,16] Burning practices are not limited to deforestation. In the Brazilian Amazon region, local farmers use fires as a conventional and cost-effective way to remove aboveground

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biomass on Cerrado savanna to prepare land for agricultural use.[17,18]

Non-GHG air pollution from LUC may be a significant problem if biofuel production continues to grow without effective controls on burning practice for LUC. Although previous biofuels studies focus on non-GHG air pollution from other life-cycle phases (sugar cane field burning, vehicle emissions, refinery emissions),[10,19−21] air pollution from land-use change is in general a significant global emissions source and thus may present an important impact in the biofuels life-cycle as well. The composition and magnitude of potential emissions from future biofuels LUC remains an important unknown for biofuels sustainability. In this paper, spatially explicit emissions from direct and indirect LUC due to the future expansion of biofuels production in Brazil are estimated using a bottom-up approach incorporating LUC maps, fuel loading, combustion completeness, and emission factors. These emissions are compared with other life-cycle phases and life-cycle emissions estimates for fossil fuels.

2. METHODOLOGY

A bottom-up estimation of dLUC and iLUC emissions based on multiple approaches for estimating non-GHG emissions from land-use is applied in this study. Spatially explicit emissions from LUC in Brazil due to incremental biofuels production are estimated by integrating predicted activities of LUC and emission factors. Equation 1 formulates the LUC emissions

$$E_i^{\mathrm{LUC}} = \sum_{j,k,s} [A_{js} \times F_{jks} \times \mathrm{CF}_{jk} \times \mathrm{EF}_{ijk}] \tag{1}$$

where E_i^{LUC} (Mg emitted) is the LUC emissions of pollutant i. E_i^{LUC} is the aggregation of the emissions from different types of LUC, j, including dLUC of forest to the cropland for biofeedstock for energy (i.e., sugar cane and soybean) (F2B), cropland to biofeedstock (C2B), ranchland to biofeedstock (R2B), wood savanna to biofeedstock (W2B), and other vegetation to biofeedstock (O2B), as well as iLUC of forest to ranchland (F2R), cropland to ranchland (C2R), wood savanna to ranchland (W2R), other vegetation to ranchland (O2R), and ranchland to cropland (R2C). A_{js} (ha) is the area for the j type LUC at location s. F_{jks} [(Mg dried matter) ha^{-1}] is the removed biomass as the available fuel loading per area for burning practices due to the j type LUC and the k type biomass (i.e., aboveground or belowground biomass) at location s. CF_{jk} (%) is the fraction of fuel consumption relative to the total available fuel loading for the j type LUC and the k type biomass. EF_{ijk} (Mg emitted × Mg^{-1} dried matter) is the emission factor of the ith pollutant for different types (i.e., j and k) of biomass burning.

The following sections (sections 2.1−2.4) describe the data sources and application of each parameter in eq 1. The parameter estimates for the baseline scenario and two additional scenarios for future burning controls are introduced in section 2.5. We normalize our estimates for LUC emissions using an energy functional unit, i.e., million British thermal unit (mmBTU) of fuel, in order to allow for comparison with other types of liquid fuels. The method for normalization is addressed in section 2.6. The approach to quantifying uncertainty in LUC emissions based on parameter uncertainty is introduced in section 2.7.

2.1. Projection of LUC Area. The LUC area (A_{js}) summarized in Table S-1 was based on spatially explicit results from a previous analysis of biofuels LUC in Brazil estimated from the LandSHIFT model.[4] This study used a spatially explicit modeling framework (5 arc-min resolution) to project direct and indirect LUC caused by biofuel cropland expansion, for an incremental biofuel production scenario of 39 billion liters per year (35 billion liters sugar cane ethanol and 4 billion liters biodiesel) in the 2003−2020 period . The estimates of production projection are similar to OECD predictions (38.2 billion liters ethanol and 3.1 billion liter biodiesel).[22] Several options of feedstocks for biodiesel including soybean, sunflower/rapeseed, Jatropha curcas, and oil palm were analyzed in this study. Herein, we chose soybean biodiesel because most of the biodiesel produced in Brazil in recent years is from soybean oil. The framework couples the LandSHIFT model with two other models, IMPACT (the International Model for Policy Analysis of Agricultural Commodities and Trade) and the LPJ for managed Lands (LPJmL, Lund-Potsdam-Jena managed Land Dynamic Global Vegetation and Water Balance Model) dynamic global vegetation model, to account for future changes in crop yield, population, food demand, and biomass productivity. The LandShift model simulates the interactions between anthropogenic and environmental drivers and their competition for land resources.[23] The study by Lapola et al.[4] explored two contrasting scenarios: (1) no avoidance of biofuel-driven ILUC; (2) all biofuel-driven ILUC avoided by intensifying cattle ranching. In this study we employ scenario 1. While model validation of indirect land-use at current biofuels product rates is challenging,[24] the LUC model has shown skill at reproducing more general trends in land-use (see Supporting Information).

The single land-use change scenario we employed in this study is subject to a wide range of uncertainties. Improved sugar cane yields and ethanol refinery conversion rates may reduce land-use impacts.[25] The published land-use change data we used assumed a 50% increase in yields from 2003 to 2020 as well as improved yields of a wide range of Brazilian crops (see Lapola et al. Tables S1 and S2). Improvements in refinery conversion rates have been proposed assuming that technology breakthroughs will allow cellulosic conversion (e.g., sugar cane bagasse to ethanol) to become commercially viable. The Lapola scenario is focused on sugar cane ethanol and not cellulosic ethanol. As new land-use change scenario data becomes available that accounts for such uncertainties, the emissions modeling conducted here should be repeated to provide revised estimates.

2.2. Estimates of Fuel Loading from LUC. Available fuel loading per area, F_{jks}, were derived from the difference of available aboveground and belowground biomass before and after LUC. The component of the removed biomass that was used as products (e.g., logs) rather than burned was subtracted from the fuel loading. In the IPCC approach, fuel loadings are summarized by vegetation type (tier 1 fire emissions).[26] An alternative approach by Fargione et al. calculated fuel loading from land clearing based on the evaluation and synthesis of published studies for relevant native habitats and land-uses.[27] Due to the potential spatial and temporal variations in biomass, other studies have applied remote-sensing techniques, direct measurements, or a combination of these two approaches to access spatially and temporally explicit biomass stocks.[12,28−31] Carbon stock modeling methods based on CASA (Carnegie Ames Stanford Approach), a satellite-driven biogeochemical

model, are commonly used for determining aboveground or belowground biomass.[12,28] Potter et al. developed a simulation model incorporating CASA and direct biomass measurements to examine monthly fire emissions in terrestrial ecosystems of the Brazilian Amazon and the Cerrado region.[28] The Global Fire Emissions Database (GFED) also applied CASA to estimate fuel loadings for use in modeling fire emissions.[12] Saatchi et al. combined remote sensing data with more than 500 plot measurements to determine the spatial distribution of forest biomass in the Amazon area and benchmark the forest carbon stocks with other regions in the world.[30,32]

In our study, we synthesized carbon stocks and fuel loading information from Saatchi et al. and Fargione et al. and developed a spatially explicit data set of potential fuel loadings for LUC. We used the Saatchi et al. data for forest conversion LUC (F2B and F2R) and Fargione et al. for nonforest LUC (R2B, R2C, O2B, O2R, C2B, C2R, W2B, and W2R). Table S-2 summarizes carbon changes for nonforest LUC and describes the methods of calculation. We assumed fuel loading consisted of 50% carbon relative to dry biomass. Available fuel loadings for forest LUC (F2B and F2R) were reduced by 14% of the dried matter due to removal for long-lived wood products.[26,27] For conversion to cropland, we assume all biomass except harvests (e.g., logs) is removed by fires. For conversion to rangeland, the available fuel loading is calculated as the difference between the fuel loading of the original land-use and the rangeland land-use. Figure S-4 shows the spatial distribution of fuel loading for LUC.

2.3. Emission Factors of Biomass Burning. Emission factors (EF_{ij}'s) representing emission intensity per unit fuel burned (g emission/kg dried matter burned) are obtained from the van der Werf et al.[12] and Wiedinmyer et al.[33] studies for biomass fire emissions. These emission factors have been applied in the calculation of fire emissions in the Global Fire Emissions Database (GFED) and the Fire Inventory from NCAR (FINN). The GFED and FINN models do not report separate emission factors for aboveground and belowground biomass, so we applied the same for both. Table S-3 compares the emissions factors from these two data sets for eight species and five types of LUC. Emission factors of CO, TPM, and $PM_{2.5}$ within a given LUC type are similar for both data sets (10%, 12%, and 18% average difference, respectively) while larger differences are found for NMHC (42% difference in average).

2.4. Combustion Completeness. The fraction of fuel consumption relative to the total available fuel loading is the combustion factor (CF), also known as combustion completeness.[33,34] The IPCC provides combustion completeness for non-GHG emission inventories of wild or prescribed fires, indicating that 50% of dried matter is burned for tropical rainforest.[26] Carvalho et al. conducted a forest clearing experiment in the Brazilian Amazon and found an average combustion completeness for land clearing of one-time fire of 20.5%.[35] Houghton et al. synthesized two studies and also found 20% of initial forest biomass is burned during deforestation.[36] Aboveground fire might also result in the burning of belowground biomass which can cause relatively small emissions.[37−39] Although a previous study has addressed that the pasture land in Brazil (Cerrado) has a high level of belowground biomass (around 20 Mg C ha^{-1}) and contributes significant emissions while burning,[40] the level of the emissions is still lower than deforestation due to lower fuel loadings and CF. Two studies, Tufekcioglu et al.[39] and Rau et al.,[38] investigate the characteristics of belowground biomass for forest and shrubland after burning. We apply their fractions of biomass burning, for calculating LUC emissions from belowground. Table S-4 summarizes the range and the mean of CF values for LUC occurring in each type of vegetation. We also assume no burning practices are required for land-use conversion from existing cropland to biofuels cropland.

2.5. Scenarios of Future Burning Controls. To project LUC emissions, a baseline estimate is calculated from the mean values and best guess parameter estimates addressed in the previous sections, and compared with different scenarios of burning controls. We assume there are no open burning controls as the baseline case, since open-field burning is one of the most common practices for LUC in Brazil.[17,18,41] Due to increasing concerns over air pollution from open biomass burning in several states of Brazil, we expect some actions on burning control might be adopted in the future. For example, preharvest burning practices for sugar cane crops are obliged to gradually shift to mechanized practices in São Paulo state. Preharvest burning will be banned by 2021 on cropland with slopes of less 12%. Both agriculture survey data and remote sensing studies for São Paulo state suggest that the use of open burning as a management practice has been reduced to 50% of sugar cane cropland area.[9,42] This measure of control or abolition on sugar cane preharvest burning might extend to other types of open-field burning (i.e., LUC fires) or even to the other states outside São Paulo state in the future. Therefore, we assume two scenarios of burning control on LUC emissions which are (A) 50% reduction of open burning practices in São Paulo state and (B) 100% reduction of open burning practices in São Paulo state and 50% reduction of burning practices in other states.

2.6. Normalization of LUC Emissions for Biofuels. LUC emissions as a part of the biofuel life-cycle emissions might be compared with other types of fuel based on the same functional unit, i.e., 1 mmBTU biofuel produced. However, unlike emissions from other life-cycle phases, LUC emissions largely occur in the first year of production and are much smaller in subsequent years. To normalize LUC emissions to the mmBTU functional unit, they must be amortized over the period that biofuels are produced in order to compare the upfront LUC emissions with the annual emissions associated with biofuels production. Thus, the amortization is sensitive to the assumed production period. We apply straight-line amortization of the LUC emissions over the biofuel production period. It should be noted that this amortization approach may underestimate the effects of air pollution from LUC emissions because LUC emissions are concentrated in the earlier part of the production period which can result in larger air pollution impacts than emissions that are evenly distributed over time.[43] Equation 2 formulates the amortization of LUC emission

$$\mathrm{NE}_i^{\mathrm{LUC}} = \frac{E_i^{\mathrm{LUC}} \times 10^{-6}}{\left(\sum_s \sum_{j=\mathrm{dLUC}} A_{js}\right) \times \mathrm{FY} \times \mathrm{PP}} \tag{2}$$

where $\mathrm{NE}_i^{\mathrm{LUC}}$ is the normalized value of LUC emissions (Mg emitted/mmBTU fuel) for the ith pollutant. $\mathrm{NE}_i^{\mathrm{LUC}}$ as the average LUC emissions per unit biofuel produced is the baseline LUC emissions divided by the net biofuel yields over the converted lands within the production period. The net biofuel yields are determined by the product of cropland expansion area associated with direct LUC (A, ha), fuel yield (FY, mmBTU fuel/ha × year), and production period (PP,

Table 1. Eight Combinations of Variables Used to Calculate a Range of Estimates of LUC Emission and a Sensitivity Index for Each Input Variable

	fuel loading (F_{jk})	emission factor (EF_{ij})	combustion completeness (CF_{ijk})	LUC emission (Tg $PM_{2.5}$ emitted)	comparison with baseline case
baseline	medium	medium	medium	14.7	1
1	high	high	high	26.4	1.80
2	medium	medium	high	19.4	1.32
3	medium	medium	low	9.6	0.65
4	high	medium	medium	19.4	1.32
5	low	medium	medium	11.1	0.76
6	medium	high	medium	15.3	1.04
7	medium	low	medium	14.0	0.96
8	low	low	low	6.7	0.46
sensitivity index (S_l)	0.22	0.01	0.73		

year). We use the average value for 2003 and future (2020 projection) fuel yield for soy biodiesel (15.79 mmBTU/ha × year) and sugar cane ethanol (143.29 mmBTU/ha × year) based on previous study.[4,9,44] We applied the assumption of 20-year and 30-year production periods for biofuels based on analyses chosen by USEPA and EU Renewable Energy Directive,[7,45,46] and consider 100-year production period as an upper bound to estimate long-term integrated effects. We also separate LUC emissions from sugar cane ethanol and soybean biodiesel, with emissions proportional to the LUC area for each type of LUC (see Table S-5).

2.7. Sensitivity and Uncertainty Estimates. The uncertainty of emissions estimates was determined by Monte Carlo simulations ($n = 10^6$) given uncertainties of each parameter. We assumed uniformly distributed input parameter distributions across the range of available estimates. The variation in parameter estimates are also assumed to be independent from from each other.

Sensitivity of LUC emissions to individual input variables (i.e., F_{jk}, EF_{ij}, and CF_{jk}) was reported using a sensitivity index for each variable

$$S_l = \frac{V[E(E^{LUC}|X_l)]}{V(E^{LUC})} \tag{3}$$

where S_l is the sensitivity index for the lth variable and X_l is the lth variable (i.e., F_{jk}, EF_{ij}, and CF_{jk}). $V[E(E^{LUC})|X_l)]$ is the expected value of variance that would be removed from the total output variance, $V(E^{LUC})$, given a true value of variable X_l. The measure of the sensitivity index indicates the relative importance of an individual input variable in driving the uncertainty of the output (E_i^{LUC}).

3. RESULT AND DISCUSSION

3.1. Net LUC Emissions. Baseline scenario estimates for each type of LUC emission, and aggregated iLUC and dLUC emissions, are provided in Figure S-5. Our best-guess estimate for iLUC emissions (13.5 Tg $PM_{2.5}$ emitted) is 12 times the estimated dLUC emissions (1.1 Tg $PM_{2.5}$). Among LUC emissions, F2R (forest converted to rangeland) as iLUC is the dominant source because of the large area and large fuel loading for this LUC type relative to the other dLUC and iLUC types. While dLUC from rangelands to biomass (R2B) croplands accounted for large areas relative to other LUC types, the low fuel loadings of rangelands resulted in emissions (1 Tg $PM_{2.5}$) that were small relative to forest conversion.

The influences of each input parameter on the emission estimates are summarized in Table 1. Uncertainties in the fuel loading, emission factor, and combustion completeness cause the baseline scenario estimates to range from 6.7 to 26.4 Tg $PM_{2.5}$ emitted. Among three variables, the combustion completeness causes the widest range of estimates from 65% to 132% of the baseline. Fuel loading (F_{jk}) is the next most important source of uncertainty, with a range of 76% to 132% of the baseline. The emissions factor is much less significant than the other two variables with respect to uncertainties. Results of sensitivity analysis for each input variable are also shown in Table 1. These results suggest that improvement in estimates of combustion completeness should reduce the uncertainty of LUC emission estimates. Projections of LUC areas (A_{js}) are another potentially significant source of uncertainty.[7] However, it is difficult to quantify aggregated uncertainty due to the inherent uncertainty in projecting LUC in Brazil and identifying the indirect component attributable to biofuels expansion.[4] Further qualitative analysis on the uncertainty of A_{js} is discussed in section 3.4.

Estimates among the baseline case and scenarios of open burning control are compared in Figure S-6. The open burning control scenario A reduces dLUC by nearly 10% but results in limited reduction in total LUC emissions. LUC emissions remain at a high level (7.4 Tg $PM_{2.5}$ emitted) even if burning practices are strictly controlled through scenario B.

In Figure S-6 we also compare the emissions associated with biofuels LUC to current total open burning emissions in Brazil associated with drivers other than biofuels. Current Brazilian emissions are obtained from the GFEDv3 database. Biofuels LUC emissions under the three burning scenarios are found to be similar in magnitude to the cumulative Brazilian emissions from deforestation from years 2000 to 2009 and much larger than annual Brazilian emissions.

3.2. Spatial Analysis of LUC Emissions. Figure 1 shows the spatial distribution of LUC emissions for the baseline case. Our results show that dLUC emissions mostly occur in southern Mato Grosso, Goiás, Minas Gerais, Rio de Janeiro, São Paulo, Mato Grosso do Sul, and some areas in southern and northeastern regions. iLUC emissions, which are more significant than dLUC emission, are concentrated along the frontier of the Amazonia rainforest (Northern Mato Grosso, Rondônia, Amazonas, Acre, and Pará). The largest LUC emissions occur in Mato Grosso State where nearly three million residents live, suggesting the potential for public health impacts. However, this population is dispersed and small compared to southern states. Local pollution includes effects experienced where biofuel is produced (dLUC and preharvest burning), but also far away locations (iLUC) affecting different

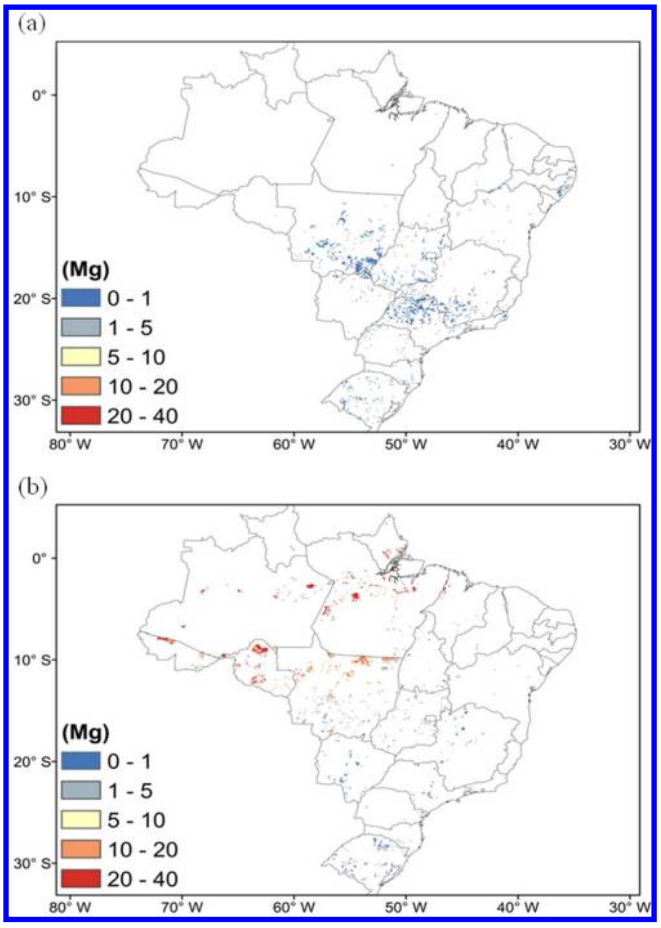

Figure 1. Spatial distribution of $PM_{2.5}$ emission (Mg per grid cell) from LUC during the period 2003−2020 including (a) dLUC, (b) iLUC. The grid resolution is 5 arc min (~80 km^2).

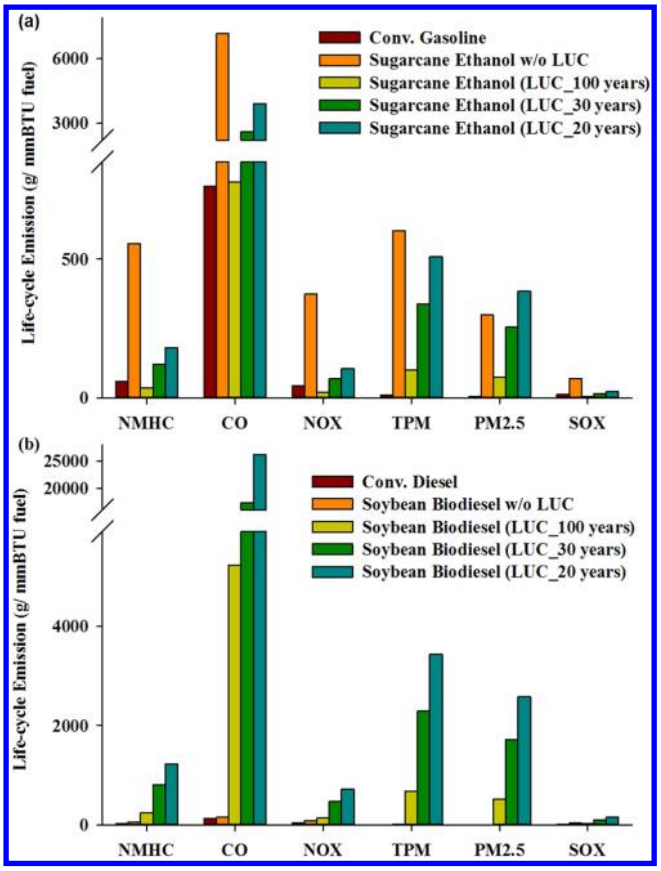

Figure 2. Comparisons of life-cycle emissions from LUC phase for (a) sugar cane ethanol and (b) soybean biodiesel.

populations (though much smaller ones, therefore with lower social cost per unit of emissions). The land-use scenario applied here only accounted for iLUC within Brazil, but iLUC may have a global influence, generating air pollution that are not in single jurisdiction of a policymaking authority.

3.3. Comparison of LUC and Life-Cycle Emission for Fuels. Normalized LUC emissions on the basis of a functional unit (1 mmBTU fuel) are further compared with non-LUC life-cycle stages of sugar cane ethanol and soybean biodiesel and with life-cycle emissions of gasoline and diesel (Figure 2). Life-cycle emissions are taken from the GREET model.[44] Normalized LUC emissions are based on three cases of production periods (20, 30, 100 years). Non-GHG LUC emissions from sugar cane ethanol have the same magnitude as the emissions from other life-cycle stages but are higher than conventional gasoline for six regulated air pollutants in the case of 20- and 30-year production period. Even in the 100-year case, LUC emissions in CO and particulate matter are still higher than that of gasoline. Life-cycle emissions of sugar cane ethanol with consideration of LUC effects (376−683 g $PM_{2.5}$ emitted per mmBTU fuel depending on production periods) are 75−136 times higher than the life-cycle emissions of conventional gasoline (5 g $PM_{2.5}$ emitted per mmBTU fuel). Biodiesel has much higher emissions of six regulated air pollutants than conventional diesel. For example, biodiesel LUC emission for $PM_{2.5}$ (515−2575 g $PM_{2.5}$ emitted per mmBTU fuel depending on production periods) is 103−515 times higher than diesel (5 g $PM_{2.5}$ emitted per mmBTU fuel). In general, including the LUC phase, sugar cane ethanol and soybean biodiesel have much larger life-cycle emissions than conventional gasoline and biodiesel for six regulated air pollutants. Although a previous study reported the success of the "Green Ethanol Protocol" which will eliminate sugar cane preharvest burning in the future,[47] Brazilian biofuels including sugar cane ethanol and soybean biodiesel are still likely to have higher air pollution impacts than conventional fossil fuels due to LUC effects if the LUC occurs as projected by LandSHIFT through 2020.

3.4. Discussion. We found that LUC emissions, particularly iLUC (F2R), associated with an incremental increase in the supply of biofuels may be significant under current burning practices, and if biofuels-driven iLUC is not avoided. According to our results, the planned reductions in preharvest burning will have positive impacts locally, but the LUC emissions will remain large unless deforestation (F2R) is eliminated. After LUC projections, the largest uncertainty in LUC emissions is from the CF for deforestation, ranging from 65% to 133% of baseline estimates. These LUC emissions may be underestimated as the CFs used in the analysis are measured from wild or prescribed fires.[26,35] The practices for LUC, unlike wild or prescribed fire, involve slash-and-burn to remove biomass. In some cases, additional burns may occur two or three more times if the first fire has not removed enough slash.[48]

Other important sources of uncertainty for LUC emissions are the magnitude and spatial distribution of the areas of LUC. However, LUC projections are inherently highly uncertain. As a result, the results of our study are conditional on the specific

LUC scenario applied here. The spatially explicit data for LUC expansion used in our study were previously published output from a modeling framework comprising a partial equilibrium model and a dynamic ecological model. The estimates of model uncertainties associated with this LUC modeling approach were assessed through a favorable comparison with historical cropland areas and regional 1992−2003 deforestation rates.[4] Recent records of crop area and biofuel yields and LUC data and their trends also show strong similarities to the projections and assumptions of the model (see Supporting Information). Plevin et al. have also examined the uncertainty of iLUC emissions (GHG) from U.S. corn ethanol derived by the product of five parameters (average fuel yield, net displacement factor, ecosystem conversion fractions, land conversion CO_2 emission factors, and production period).[7] These variables contribute to significant variation of global LUC emissions. Further work to determine the uncertainty and to improve the accuracy of LUC area projections is needed.

The emissions estimates presented here could provide valuable input to regional air quality models or general circulation models to assess human health outcomes and climate impacts. However, the temporal allocation of LUC emissions, another major factor influencing health outcomes, remains to be determined. Burning practices for LUC in Brazil are usually concentrated in the end of the dry season, August or September, depending on the location of LUC.[49,50] Temporal concentration of emissions could exacerbate air quality impacts. These results suggest that careful management of LUC is essential for ensuring the sustainability of Brazilian biofuels and for preventing potential hazards from non-GHG air pollution.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Additional details, figures, and tables. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*Phone: +1 209 2332261; e-mail: ctsao3@ucmerced.edu.

Notes

The authors declare no competing financial interest.

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