

# Supporting Information

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## SI Methods

**Land-Use Change** Greenhouse gas (GHG) emissions from land-use change are estimated from a baseline of land that has been enrolled in CRP for an average of 15 years and that will continue to be enrolled indefinitely. Upon enrollment, perennial plants remove atmospheric carbon and store it in their root structures at a rate of  $0.498 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ , reaching maximum root growth in  $\approx 10$  years (1). In addition, soil carbon increases at an estimated average rate of  $0.566 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$  for 0–100 cm depth over the first 50 years after conversion (1). On converting CRP land to corn production, carbon in both roots and soil is lost until levels revert to a pre-CRP equilibrium. This conversion not only releases carbon but also halts any further soil carbon sequestration, which we refer to as a carbon opportunity cost. This is likely even should conservation tillage regimes be used in place of conventional tillage (2). We amortize the difference in carbon soil and root structures between lands planted in corn versus a baseline of lands enrolled in CRP over a 50 year time period.

Carbon emissions from converting CRP land to biomass crop production are calculated in the same manner as with conversion to corn. Preparing CRP land for planting into switchgrass, prairie, or *Miscanthus* is assumed to expose bare soil such that soil carbon loss occurs over half of a year as biomass and cover crops become established. Biomass crop root structures are assumed to regrow to a mass equal to that of the roots of the CRP crop such that there is no net loss of root carbon over the 50 year time frame. An opportunity cost of a half year of carbon sequestration is also considered. As with CRP land, perennial bioenergy crops increase soil carbon levels. As there are a lack of studies showing side-by-side comparisons of soil carbon sequestration rates of switchgrass, diverse prairie, *Miscanthus*, and CRP, we assume their soil carbon sequestration rates to be equal. There is, therefore, no carbon opportunity cost of land conversion to perennial cellulosic feedstock.

**NH<sub>3</sub> Analysis.** Producing nitrogenous fertilizers for corn grain and stover releases between 0.0013 (3) and 0.0023 (4) kg NH<sub>3</sub> per kg N, as adjusted for the current mix of N use in U.S. corn farming (70.7% ammonia, 21.2% urea, and 8.2% ammonium nitrate). Once fertilizer is applied, an industry-weighted average of 0.038 kg of NH<sub>3</sub> are released per kg N applied (i.e., the average of 0.027 (5) and 0.049 (6)). For corn ethanol production, NH<sub>3</sub> emissions for fertilizer production and corn farming are reduced 17% to account for coproducts. For switchgrass and *Miscanthus* production, it is assumed nitrogen is applied as ammonium nitrate. Ammonium nitrate production emits an average of 0.0034 kg of NH<sub>3</sub> per kg N (3, 4). On application, an average of 0.024 kg of NH<sub>3</sub> are released per kg N applied as ammonium nitrate (5, 6). For diverse prairie, nitrogen is supplied by legumes with no additional NH<sub>3</sub> release (7).

For gasoline production, refining crude oil releases  $1.01 \times 10^{-5}$  kg of NH<sub>3</sub> per L of gasoline produced (8, 9). Upon combustion of gasoline, NH<sub>3</sub> is emitted at a rate of  $0.00116 \text{ kg L}^{-1}$  (10), equal to the amount from an energy-equivalent volume of ethanol (11). For both ethanol and gasoline, electricity generation and diesel use in transportation are both estimated to be trivial sources of NH<sub>3</sub> emissions with totals  $<0.1\%$  of life-cycle NH<sub>3</sub> emissions.

**Spatial Allocation of Emissions.** Locations of emission sources in fuel life cycles are determined by using publicly available data

(12–27). These data are used to translate descriptions of the quantities of fine particulate matter (PM<sub>2.5</sub>) related emissions emitted in each life-cycle stage as provided by GREET (28, 29) into quantities of PM<sub>2.5</sub> related emissions emitted in each of 3110 counties as needed for input into the Response Surface Model (RSM).

**RSM of PM<sub>2.5</sub> Formation.** The RSM is a reduced-form prediction model that uses statistical techniques to characterize the relationship between the detailed results of EPA's Community Multiscale Air Quality (CMAQ) model and emissions input parameters (30, 31). The RSM uses statistical correlation structures to approximate the more complex model functions through the design of multidimensional experiments. The range of experiments for which the RSM is calibrated, and for which results are considered reliable, include changes in emissions rates of from 0%–120% of estimated 2015 emissions for any combination of changes in the 12 categories noted below. Here, most emission changes are within this domain, and all of factors with the greatest influence on ambient PM<sub>2.5</sub> outcomes are within this domain.

The RSM provides  $36 \text{ km} \times 36 \text{ km}$  resolution in estimated changes of total PM<sub>2.5</sub> levels over a 2010 base case scenario in response to increased fuel production and combustion. The 2010 base case scenario is adjusted from the original 2015 base used in prior RSM applications. Inputs into the RSM include county level emissions of primary PM<sub>2.5</sub>, and the 4 precursors to secondary PM<sub>2.5</sub> formation (VOC, NO<sub>x</sub>, SO<sub>x</sub>, and NH<sub>3</sub>) as characterized by source type. Primary PM<sub>2.5</sub> emissions inputs are the sum of 2 primary constituents: organic carbon and elemental carbon, sometimes referred to as black carbon. Other types of primary emissions (e.g., those of crustal origin) and biogenics are included in the RSM base case as baseline emissions but are effectively held constant across all scenario variants analyzed here. RSM recognizes 4 source types: electrical generating unit (EGU), non-EGU, mobile, and area. The 12 emission categories used as inputs into the model are as follows:

- NO<sub>x</sub>—EGU
- NO<sub>x</sub>—NonEGU and Area
- NO<sub>x</sub>—Mobile
- SO<sub>x</sub>—EGU
- SO<sub>x</sub>—NonEGU
- SO<sub>x</sub>—Area and Mobile
- NH<sub>3</sub>—Area, EGU, and NonEGU
- NH<sub>3</sub>—Mobile
- Primary PM<sub>2.5</sub>—EGU and NonEGU
- Primary PM<sub>2.5</sub>—Mobile
- Primary PM<sub>2.5</sub>—Area
- VOC—EGU, NonEGU, Area, and Mobile.

**BenMAP Model of Health Impacts.** Damage cost estimates from changes in PM<sub>2.5</sub> levels impacting human health (32) are estimated by using BenMAP Version 2.4 (33, 34). BenMAP first generates estimates of avoided cases of each of the effects listed below based on a suite of concentration-response functions derived from the health science literature:

- Acute bronchitis
- Acute myocardial infarction
- Acute respiratory symptoms
- Asthma exacerbation
- Chronic bronchitis

- Emergency room visits, Respiratory
- Hospital admissions, Cardiovascular
- Hospital admissions, Respiratory
- Lower respiratory symptoms
- Premature mortality
- Upper respiratory symptoms
- Work loss days.

Damage costs are calculated based on estimates of the willingness-to-pay or medical costs to avoid a single case. Estimates

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reported here are mean estimates; confidence intervals reflect statistical measurement uncertainty in both the concentration-response and valuation steps. Parameter values for both steps reflect choices made in a recent EPA benefit-cost analysis (35). On average, mortality accounts for 93% of the total cost. Estimates of PM<sub>2.5</sub> costs do not include other environmental damages (e.g., lowered visibility).

**Table S1. Summary of lifecycle GHG emissions caused by production and combustion of an additional billion gallons of ethanol ( $3.78 \times 10^9$  L) or an energy-equivalent amount of gasoline ( $6.58 \times 10^8$  gal or  $2.49 \times 10^9$  L)**

Fuel	Life-cycle process emissions from biofuel production and combustion (Excluding land use)	Loss of soil and root carbon accumulated since land converted to CRP	Carbon opportunity cost of converting land from CRP to bioenergy production
Gasoline	7,520	0	0
Corn ethanol (Natural gas heat)	5,230	1,010	1,790
Advanced corn ethanol (Natural gas heat)	4,080	758	1,350
Corn ethanol (Coal heat)	7,660	1,010	1,790
Corn ethanol (Stover heat)	3,390	1,010	1,790
Cellulosic ethanol (Stover)	713	0	0
Cellulosic ethanol (Switchgrass)	1,680	20	20
Cellulosic ethanol (Prairie biomass)	590	20	20
Cellulosic ethanol ( <i>Miscanthus</i> )	786	7	7

Values expressed in Gg of CO<sub>2</sub> equivalent.

**Table S2. Cost estimates from increased GHG levels caused by production and combustion of an additional billion gallons of ethanol ( $3.78 \times 10^9$  L) or an energy-equivalent amount of gasoline ( $6.58 \times 10^8$  gal or  $2.49 \times 10^9$  L) using alternative methods**

Fuel	\$35 Mg <sup>-1</sup> C	\$120 Mg <sup>-1</sup> C	\$350 Mg <sup>-1</sup> C
Gasoline	\$ 72	\$246	\$718
Corn ethanol (Natural gas heat)	76	262	765
Advanced corn ethanol (Natural gas heat)	59	202	590
Corn ethanol (Coal heat)	100	342	997
Corn ethanol (Stover heat)	59	202	590
Cellulosic ethanol (Stover)	7	23	68
Cellulosic ethanol (Switchgrass)	16	56	164
Cellulosic ethanol (Prairie biomass)	6	21	60
Cellulosic ethanol ( <i>Miscanthus</i> )	8	26	76

Values expressed in millions of 2005 constant dollars. We use the cost of reducing carbon emissions via carbon capture and storage with a midpoint estimate of \$120 Mg<sup>-1</sup> C and estimates of the "social cost of carbon," which represents the expected future damages from GHG emissions. Nordhaus (36) estimated a relatively modest social cost of carbon of \$30 Mg<sup>-1</sup> C in 2005 that increases in real terms at a rate of roughly 2% per year. By 2010, this cost would increase to \$33–34 Mg<sup>-1</sup> C. The Stern Review by the UK Treasury (37) estimated far higher costs of \$312 Mg<sup>-1</sup> C in 2000 under business-as-usual emissions. Converting this estimate from 2000\$ to 2005\$ using the US Producer Price Index results in an estimate of \$352 Mg<sup>-1</sup> C. Using the Consumer Price Index instead results in an estimate of \$353 Mg<sup>-1</sup> C in 2005\$.

**Table S3. Summary of total lifecycle PM<sub>2.5</sub> related emissions caused by production and combustion of an additional billion gallons of ethanol (3.78 × 10<sup>9</sup> L) or an energy-equivalent amount of gasoline (6.58 × 10<sup>8</sup> gal or 2.49 × 10<sup>9</sup> L)**

Fuel	VOC	NO <sub>x</sub>	Primary PM <sub>2.5</sub>	SO <sub>x</sub>	NH <sub>3</sub>
Gasoline	4.78	5.78	0.55	1.55	0.79
Corn ethanol (Natural gas heat)	6.03	12.66	1.06	4.57	5.71
Advanced corn ethanol (Natural gas heat)	6.16	9.75	0.80	3.35	3.29
Corn ethanol (Coal heat)	6.18	17.48	4.70	12.81	5.71
Corn ethanol (Stover heat)	6.35	15.96	1.32	5.04	6.08
Cellulosic ethanol (Stover)	6.21	14.44	1.06	1.23	2.30
Cellulosic ethanol (Switchgrass)	6.65	15.63	1.05	0.18	3.96
Cellulosic ethanol (Prairie biomass)	5.95	13.63	1.00	-0.03	0.76
Cellulosic ethanol ( <i>Miscanthus</i> )	6.19	14.30	1.02	-0.03	1.83

Values expressed in Gg. For cellulosic ethanol from prairie biomass and *Miscanthus*, negative SO<sub>x</sub> emissions are the result of electricity production at biorefineries offsetting electricity generation from fossil fuels.

**Table S4. Human health cost estimates from increased PM<sub>2.5</sub> levels caused by production and combustion of an additional billion gallons of ethanol ( $3.78 \times 10^9$  L) or an energy-equivalent amount of gasoline ( $6.58 \times 10^8$  gal or  $2.49 \times 10^9$  L)**

Fuel	5 <sup>th</sup> Percentile	Mean	95 <sup>th</sup> Percentile
Gasoline	\$ 50	\$223	\$ 469
Corn ethanol (Natural gas heat)	77	352	727
Advanced corn ethanol (Natural gas heat)	57	270	531
Corn ethanol (Coal heat)	141	610	1,289
Corn ethanol (Stover heat)	87	387	797
Cellulosic ethanol (Stover)	39	176	363
Cellulosic ethanol (Switchgrass)	34	152	304
Cellulosic ethanol (Prairie biomass)	22	102	211
Cellulosic ethanol ( <i>Miscanthus</i> )	26	117	246

Values expressed in millions of 2005 constant dollars.