Supporting Information

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SI Text

N_2O and CH_4 CO_2-Equivalents Calculation. The CO_2 equivalents ($g\ CO_2e{\cdot}m^{-2}{\cdot}y^{-1}$) for N_2O and CH_4 emissions were calculated using the IPCC 100-y horizon (factors 298 for N_2O and 25 for CH_4) (1):

$$CO_2e(N_2O) = \frac{x_1 gN_2O-N}{ha\times d}\times\frac{44gN_2O}{28gN_2O-N}\times\frac{365d}{1y}\times\frac{1ha}{10^4m^2}\times\frac{298gCO_2}{1gN_2O} \quad \textbf{[S1]}$$

$$CO_2e(CH_4) = \frac{x_2 gCH_4-C}{ha\times d}\times\frac{16gCH_4}{12gCH_4-C}\times\frac{365d}{1y}\times\frac{1ha}{10^4m^2}\times\frac{25gCO_2}{1gCH_4}, \quad \textbf{[S2]}$$

where x_1 is average daily N_2O-N emission rate ($g\ N{\cdot}ha^{-1}{\cdot}d^{-1}$) and x_2 is average daily CH_4-C emission rate ($g\ C{\cdot}ha^{-1}{\cdot}d^{-1}$). Average fluxes of N_2O and CH_4 for all studied systems are given in Table S1; for main text discussion and Table S3 areal values were converted from $g{\cdot}m^{-2}$ to $Mg{\cdot}ha^{-1}$ to make them consistent with other parameters.

Farming CO_2e Calculation. Total GHG emissions in CO_2 equivalents associated with farming during the conversion year were calculated as the sum of CO_2e emissions from the production of fertilizers and herbicides and from farm agricultural machinery fuel use. Calculations were based on actual field practices at the study sites, with average fuel use and production costs from standard tables (2–4), as presented in Table S2. CO_2e emitted by diesel fuel (represented by the formula $C_{16}H_{34}$) is assumed to be oxidized 100% to CO_2 (5),

$$CO_2e(diesel) = \frac{x_1 LC_{16}H_{34}}{ha\times y}\times\frac{832gC_{16}H_{34}}{1LC_{16}H_{34}}\times\frac{192gC}{226gC_{16}H_{34}}\times\frac{44gCO_2}{12gC}\times\frac{1ha}{10^4m^2}, \quad \textbf{[S3]}$$

where: x_1 is average annual diesel use for the field operations ($L{\cdot}ha^{-1}{\cdot}y^{-1}$). The CO_2e emissions of nitrogen fertilizer production and application were calculated on the basis of 1.44 mol of CO_2 released per mol of N produced and transported to field crops, or 4.5 kg $CO_2{\cdot}kg^{-1}$ N (5). Conversion year farming inputs summed to 10.4 g $CO_2e{\cdot}m^{-2}{\cdot}y^{-1}$ (Table S2) or 0.10 Mg $CO_2e{\cdot}m^{-2}{\cdot}y^{-1}$ for the production of 228 ± 5 g $soybean{\cdot}m^{-2}$ (Table S4) or 45.6 g $CO_2e{\cdot}kg^{-1}$ soybean grain.

Calculation of Fossil Fuel Displacement Due to the Use of Renewable Fuels. We used results of published analyses for calculation of fossil fuel displacement due to use of renewable fuels and their coproducts, which results in a fossil fuel offset credit for displaced fossil fuel C emissions. Offsets produced during the conversion year reduce the carbon debt and were calculated by the GREET model (6) less its agricultural input emissions, for which we instead used measured values (see *SI Text, Farming CO2e Calculation*, above). Offsets produced subsequent to the conversion year reduce the payback time and were calculated from the GREET model including its agricultural input emissions.

For fossil fuel offset credits associated with biodiesel production we used published results of life cycle analysis by the GREET model (6), which compares five different approaches for crediting GHG emissions allocations to coproducts: a displacement approach, an allocation approach based on the energy value of coproducts, an allocation approach based on the market value of coproducts, and two hybrid approaches that integrate the displacement and allocation methods. The fossil fuel offset credit so estimated sums to 7.6 kg $CO_2e{\cdot}kg^{-1}$ soybean diesel or 193.9 $gCO_2e{\cdot}MJ^{-1}$ using a biodiesel energy yield of 34.5 $MJ{\cdot}L^{-1}$ and a diesel volumetric density of 0.88 $g{\cdot}mL^{-1}$ (7, 8). Of this sum, 1.16 kg $CO_2e{\cdot}kg^{-1}$ biodiesel is allocated to soy meal, 1.29 kg $CO_2e{\cdot}kg^{-1}$ to glycerin, 1.08 kg $CO_2e{\cdot}kg^{-1}$ to fuel gas (displacing natural gas), 0.76 kg $CO_2e{\cdot}kg^{-1}$ to heavy oil, 0.20 kg $CO_2e{\cdot}kg^{-1}$ to propane fuel mix, 0.96 kg $CO_2e{\cdot}kg^{-1}$ to product gas, 0.99 kg $CO_2e{\cdot}kg^{-1}$ to light cycle gas, and 1.15 kg $CO_2e{\cdot}kg^{-1}$ to clarified slurry oil (6). Average soybean yields for our converted site (2.28 $Mg{\cdot}ha^{-1}{\cdot}y^{-1}$ or 228 $g{\cdot}m^{-2}{\cdot}y^{-1}$; Table S4), which could produce 41.1 g $biodiesel{\cdot}m^{-2}$ or 1.6 $MJ{\cdot}m^{-2}$, would thus offset 312 g $CO_2e{\cdot}m^{-2}{\cdot}y^{-1}$ or 3.12 Mg $CO_2e{\cdot}ha^{-1}{\cdot}y^{-1}$.

For calculation of fossil fuel offset credits during the conversion year we substituted our measured emissions from agricultural inputs for the 39.4 g $CO_2e{\cdot}MJ^{-1}$ estimated by the GREET model on the basis of emissions of 278 g $CO_2e{\cdot}kg^{-1}$ for produced soybean grain (GREET Version 1.8d.0). More specifically, GREET assumes farm energy use of 825.9 $kJ{\cdot}kg^{-1}$ soybean grain produced (21,310 $Btu{\cdot}bushel^{-1}$); additionally GREET assumes the following farming inputs (per kilogram of soybean grain): 1.9 g N fertilizer, 5.6 g P_2O_5, 11.2 g K_2O, 157.0 g $CaCO_3$, 0.5 g herbicides, and 0.001 g insecticide. One kilogram of soybean grain can produce 0.205 L of biodiesel (using conversion factors as above), which will contain 7.1 MJ energy. For conversion of GREET assumptions to an areal basis, we assume an average soybean production of 2.47 $Mg{\cdot}ha^{-1}$ (Table S6). Thus, using average soybean yields and GREET assumptions, we can calculate that GREET assumes the use of 2,038 $MJ{\cdot}ha^{-1}$ energy for farming, which is the equivalent of 56 L of fossil diesel vs. our 28 L (Table S2). Other emissions from field practices during the conversion year at our site were also substantially lower that those assumed in GREET: At our fields we applied 1.6 kg $N{\cdot}ha^{-1}$ vs. 4.7 kg $N{\cdot}ha^{-1}$ in GREET, 0 vs. 13.8 kg $P_2O_5{\cdot}ha^{-1}$, 0 vs. 27.6 kg $K_2O{\cdot}ha^{-1}$, 0 vs. 387.4 kg $CaCO_3{\cdot}ha^{-1}$, and 0.5 vs. 1.2 $kg{\cdot}ha^{-1}$ herbicides.

Using a similar procedure to that for GREET above, we calculate that emissions from farming during the conversion year sum to 6.5 g $CO_2e{\cdot}MJ^{-1}$. Thus, we added the difference between emissions from agricultural inputs in both cases (33.0 g $CO_2e{\cdot}MJ^{-1}$) into the fossil fuel offset credit of biodiesel produced during the conversion year. This calculation makes our first-year fossil fuel offset value greater than those estimated by GREET. For our postconversion years we conservatively base our fossil fuel offset values on the GREET model as presented in ref. 6 as we do not have measured values and use of the model facilitates comparison with fossil fuel offset credits reported elsewhere. For fossil fuel offset credits associated with production of corn grain bioethanol we used a comparison of published results of life cycle analyses by the EBAMM and GREET models (6, 9, 10). We estimate the CO_2e cost of producing, distributing, and combusting fossil gasoline at 94.0 g $CO_2e{\cdot}MJ^{-1}$ of gasoline, calculated from the EBAMM model as reported in ref. 9. For estimation of the CO_2e costs of production and distribution of corn ethanol we used the GREET model estimate of 61.3 g $CO_2e{\cdot}MJ^{-1}$, as presented in ref. 10. This analysis accounts for CO_2e emissions from farm operations, transportation, and biorefinery operations (mainly from natural gas for heating and electricity). Both models credit coproducts (avoided life cycle CO_2e emissions for products displaced by biorefinery distiller's grains) at 17 g $CO_2e \cdot MJ^{-1}$ of produced anhydrous bioethanol (10). Thus, we estimate the net reduction of CO_2e emissions as the difference between emissions from the production, distribution, and combustion of fossil gasoline (94.0 g $CO_2e \cdot MJ^{-1}$) and the distribution and production of corn bioethanol (61.3 g $CO_2e \cdot MJ^{-1}$), for a net savings of 32.7 g $CO_2e \cdot MJ^{-1}$ of corn bioethanol energy produced.

For fossil fuel offset credits associated with cellulosic ethanol production we used results of the GREET model (GREET Release 1.8d.0). The GREET model assumes fermentative production of cellulosic ethanol and calculates GHG emissions associated with biomass harvest, ethanol production, coproducts offset (combustion for power and steam generation), and ethanol combustion to be −6.6 g $CO_2 \cdot MJ^{-1}$ and 4.3 g $CO_2e \cdot MJ^{-1}$, for corn stover and herbaceous (cellulosic) ethanol. Thus, by comparison between CO_2e emissions from fossil gasoline and cellulosic ethanol, we estimate a net savings of 89.7 and 100.6 g $CO_2e \cdot MJ^{-1}$ energy produced for grass and stover ethanol, respectively.

Production of bioethanol energy was calculated using average corn grain and stover yields of Kalamazoo County, Michigan (see below and Table S6) and harvestable grass biomass from the unconverted CRP site (Table S4). As an example, average corn yields for the corn–soybean rotation of 6.6 $Mg \cdot ha^{-1} \cdot y^{-1}$ (Table S6) and a conversion factor of 0.43 L bioethanol$\cdot kg^{-1}$ dry corn grain (see main text, Eq. **3**) result in the production of 2,842 L of bioethanol$\cdot ha^{-1} \cdot y^{-1}$. Using the energy content of ethanol, 21.1 $MJ \cdot L^{-1}$ (main text Eq. **3**) yields energy production on an areal basis of 6.0 $MJ \cdot m^{-2} \cdot y^{-1}$, which together with a corn grain ethanol offset of 32.7 g CO_2e per each megajoule of produced renewable energy provides an offset of 196 g $CO_2e \cdot m^{-2} \cdot y^{-1}$ (6.0 $MJ \cdot m^{-2} \cdot y^{-1}$ × 32.7 g $CO_2e \cdot MJ^{-1}$) or 1.96 Mg $CO_2e \cdot ha^{-1}$.

Calculated fossil fuel offset credits were thus as follows: corn grain bioethanol, 32.7 g $CO_2e \cdot MJ^{-1}$; soybean grain biodiesel during the conversion year, 226.9 g $CO_2e \cdot MJ^{-1}$; soybean grain biodiesel postconversion year, 193.9 g $CO_2e \cdot MJ^{-1}$; corn stover bioethanol, 100.6 g $CO_2e \cdot MJ^{-1}$; and cellulosic bioethanol, 89.7 g $CO_2e \cdot MJ^{-1}$.

Foregone Soil Carbon Sequestration and Soil Carbon Loss on Tillage. We estimated foregone soil C sequestration as the difference between the soil C content of preconverted sites and the equilibrium C content of soils of the same series in unmanaged midsuccessional vegetation on a site never tilled (11). We estimated soil C loss on tillage by comparing the soil C content of preconverted sites and the C content of the same soils under long-term (>100 y) tillage (11).

The soil C content of preconverted sites was measured by removing from each site 10 soil cores 6 cm in diameter × 1 m depth, using a hydraulic probe. Each core was divided in the laboratory into depth intervals of 0–10, 10–25, 25–50, and 50–100 cm and weighed for bulk density analysis. Soils were sieved to pass a 4-mm mesh and a subsample was oven dried at 60 °C. Triplicate subsamples from each dried sample were finely ground in a roller mill and 10-mg aliquots weighed into each of three tinfoil cups, which were placed in desiccators before CN analysis. Each was analyzed for C and N using a Costech Model ECS 4010 CHNSO Analyzer (Costech Analytical Tech; see details in ref. 11).

We estimated total C (kg $C \cdot m^{-2}$) by layer (i.e., 0–10 cm, 10–25 cm, etc.), using soil bulk density ($g \cdot cm^{-3}$) and soil C concentration ($g \cdot kg^{-1}$) and compared these values to total C concentration of soil profiles at the nearby Kellogg Biological Station Long-Term Ecological Research (KBS LTER) site for soils of the same series under either long-term conventional tillage (to estimate C loss on tillage) or never-tilled midsuccessional herbaceous vegetation (to estimate foregone C sequestration) (Table S5) (11).

Soil C concentrations at the never-tilled midsuccessional sites, which can be assumed to be at or near equilibrium, are 29.5 ± 1.1 g $C \cdot kg^{-1}$ (A/Ap horizon) (11). Similar equilibrium levels have been estimated for other upper Midwest US grasslands (29.9 and 35.3 g $C \cdot kg^{-1}$) (12, 13).

There is evidence that rates of soil C accumulation in the CRP sites were already slowing toward the end of the first 22 y since planting. The inferred rate of soil C accumulation in the CRP reference site over the 22 y since it was set aside was 191 g C or 697 g $CO_2 \cdot m^{-2} \cdot y^{-1}$, on the basis of comparison of its soil C concentration in 2009 (11.1 ± 1.4 $kg \cdot m^{-1}$) with that of nearby conventionally farmed and tilled fields on the same soil series (6.9 ± 0.6 $kg \cdot m^{-1}$; Table S5). In 2009 the cumulative NEE at the CRP reference site was measured by eddy covariance to be −297 g $CO_2 \cdot m^{-2} \cdot y^{-1}$ or −29.7 Mg $CO_2 \cdot ha^{-1}$ (Table 1). This rate is ∼40% of the historical soil C accumulation rate, suggesting that the field is approaching soil C equilibrium (14).

The current soil C concentrations in the upper 0- to 10-cm and 10- to 25-cm layers at the CRP reference site (which together constitute most of the 29-cm Ap horizon; Table S5) are 25.5 ± 4.4 and 13.7 ± 2.9 g $C \cdot kg^{-1}$, respectively. We assume that the Ap horizon of our CRP grasslands would have accumulated C until reaching an equilibrium concentration of 30 g $C \cdot kg^{-1}$ soil; deeper horizons (Bt and Bt2) are conservatively assumed not to change significantly on the basis of whole-profile comparisons at the nearby KBS LTER site (11). For our estimation of forgone sequestration, then, we used the proportional increase of current C concentrations toward equilibrium C concentration of 30 g $C \cdot kg^{-1}$ soil and current bulk densities of soils under CRP grasslands for the Ap horizon only.

To reach a C equilibrium level of 30 g $C \cdot kg^{-1}$ the Ap horizon would need to accumulate an additional 17.7% or 1.3 ± 0.2 kg $C \cdot m^{-2}$ (or 4.9 ± 0.7 kg $CO_2e \cdot m^{-2}$; Table S6), bringing the total soil C stock of the Ap horizon to 8.9 ± 1.1 kg $C \cdot m^{-2}$. This estimation is based on the current concentration of C in the Ap horizon, adjusted to a 0- to 29-cm depth by proportionately extending the 10- to 25-cm layer by an additional 4 cm. Thus, our estimation of the current C concentration in the Ap horizon of preconverted sites is 7.5 ± 1.1 kg $C \cdot m^{-2}$.

Payback Time Calculation. For calculation of the C debt payback time we used two different management scenarios, no-till and conventional tillage, and two common annual cropping systems, continuous corn and corn–soybean rotations. Following the year of conversion, N_2O and CH_4 fluxes were assumed to reach the levels measured in similar cropping systems on the same soil series at the nearby KBS LTER site, where GHG fluxes have been the subject of intensive study for 20 y (5) (Table S1). Soils under no-till management were assumed to maintain current soil C levels (Table S5) (11). Soils under conventional tillage were assumed to equilibrate to soil C levels equivalent to plots under conventional management at the nearby KBS LTER site (Table S5) (11).

We used the following formula for calculation of payback time,

$$\text{Payback time} = \frac{\text{Total } CO_2e \text{ debt}_{\text{LUC}}}{\text{Net } CO_2e \text{ balance}_{\text{postconversion}}}, \qquad \textbf{[S4]}$$

where Total CO_2e debt $_{\text{LUC}}$ (g $CO_2e \cdot m^{-2}$) is the net C balance of the conversion year plus subsequent year C costs. Included are NEE_{adj}, soil GHG emissions, CO_2e emitted by farming activities, CO_2e offset by conversion year soybean production, and during subsequent years the further decomposition of killed brome grass and foregone soil C sequestration. Net CO_2e balance$_{\text{postconversion}}$ is the net CO_2e balance of the continuous corn or corn–soybean rotation, including soil GHG fluxes and CO_2e savings associated with the displacement of fossil fuels with bioethanol or biodiesel, as well as coproducts.

Scenario Calculations. For all scenarios we assumed corn and soybean yields to be the average of yields in Kalamazoo County, Michigan, for years 2007–2009 (Table S6). The corn harvest index (HI) was assumed to be 0.51, and a minimum amount of stover was assumed left on the fields to maintain soil fertility and no-till soil C levels: 5.15 Mg·ha^{-1} (2.3 tons·acre^{-1}) and 7.84 Mg·ha^{-1} (3.5 tons·acre^{-1}) for continuous corn and corn–soybean rotation, respectively (15).

We assumed no net change in soil C under no-till management following conversion (Table S5). For the scenario with conventional tillage, we assumed full soil C oxidation to the levels of nearby agricultural fields that are in long-term conventional tillage, i.e., the loss of 4.2 kg C·m^{-2} (Table S5).

GHG Emission Intensity of Biofuel Energy Production. To compare the sustainability of biofuel production between different land uses we estimated the GHG emission intensity (g CO_2e·MJ^{-1}), defined here as the net CO_2e balance per unit of biofuel energy produced in the system,

$$\text{GHG emission intensity} = \frac{\text{Net CO}_2\text{e balance}}{\text{Biofuel energy content}}, \quad \textbf{[S5]}$$

where Net CO_2e balance (g CO_2e·m^{-2}·y^{-1}) is

$$\text{Net CO}_2\text{e balance} = \sum \text{CO}_2\text{e}(\text{GHG, FF, Farm, Soil C, FCS, NEE}_{\text{adj}}), \quad \textbf{[S6]}$$

where GHG represents greenhouse gas fluxes from the agricultural fields (N_2O and CH_4), FF is the fossil fuel offset credit, Farm is CO_2 emissions associated with agricultural practices, Soil C is changes in soil C concentrations under different tillage practices, FCS is foregone soil C sequestration, NEE_{adj} is net ecosystem exchange adjusted to include harvested C in grain (Eq. **1**), all in g CO_2e·m^{-2}·y^{-1}. Biofuel energy content is the net biofuel energy yield of the system in MJ·m^{-2}·y^{-1}.

GHG Flux Measurements. Fluxes of greenhouse gases (GHG) were measured biweekly with static chambers in four replicate locations in each of the four fields, within the footprint of the eddy-covariance towers, using static chamber GHG flux protocols of the KBS LTER site (http://lter.kbs.msu.edu/protocols/113) (16). The results of the measurements were linearly interpolated between the measurement dates to calculate daily fluxes during the growing season, and data from replicate fields were averaged to yield one mean value for each land-use type (Table S1). For the estimation of GHG fluxes during postconversion years we used GHG fluxes from the conventional (tilled) and no-till plots of the LTER site (Table S1).

1. Forster P, et al. (2007) *IPCC, Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, eds Solomon S, et al. (Cambridge Univ Press, Cambridge, UK, and New York, NY), pp 129–234.
2. Lal R (2004) Carbon emission from farm operations. *Environ Int* 30:981–990.
3. Stein D (2009) 2008-2009 machine custom and work rate estimates. District farm business management (Michigan State University Extension, East Lansing, MI). Available at https://www.msu.edu/user/steind/. Accessed July 21, 2011.
4. West TO, Marland G (2002) A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. *Agric Ecosyst Environ* 91:217–232.
5. Robertson GP, Paul EA, Harwood RR (2000) Greenhouse gases in intensive agriculture: Contributions of individual gases to the radiative forcing of the atmosphere. *Science* 289:1922–1925.
6. Huo H, Wang M, Bloyd C, Putsche V (2009) Life-cycle assessment of energy use and greenhouse gas emissions of soybean-derived biodiesel and renewable fuels. *Environ Sci Technol* 43:750–756.
7. Sheehan J, et al. (1998) *Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus* (National Renewable Energy Laboratory, Golden, CO).
8. Patzek TW (2009) A first law thermodynamic analysis of biodiesel production from soybean. *Bull Sci Technol Soc* 29:194–204.
9. Farrell AE, et al. (2006) Ethanol can contribute to energy and environmental goals. *Science* 311:506–508.
10. Plevin RJ (2009) Modeling corn ethanol and climate, a critical comparison of the BESS and GREET models. *J Ind Ecol* 13:495.
11. Syswerda SP, Corbin AT, Mokma DL, Kravchenko AN, Robertson GP (2011) Agricultural management and soil carbon storage in surface vs. deep layers. *Soil Sci Soc Am J* 75:92–101.
12. Knops JM, Tilman D (2000) Dynamics of soil nitrogen and carbon accumulation for 61 years after agricultural abandonment. *Ecology* 81:88–98.
13. McLauchlan KK, Hobbie SE, Post WM (2006) Conversion from agriculture to grassland builds soil organic matter on decadal timescales. *Ecol Appl* 16:143–153.
14. West TO, Six J (2007) Considering the influence of sequestration duration and carbon saturation on estimates of soil carbon capacity. *Clim Change* 80:25–41.
15. National Research Council (2009) *Liquid Transportation Fuels from Coal and Biomass* (National Academies Press, Washington, DC).
16. Holland EA, et al. (1999) Soil CO_2, N_2O, and CH_4, exchange. *Standard Soil Methods for Long-Term Ecological Research*, eds Robertson GP, Bledsoe CS, Coleman DC, Sollins P (Oxford Univ Press, Oxford, UK), pp 185–201.

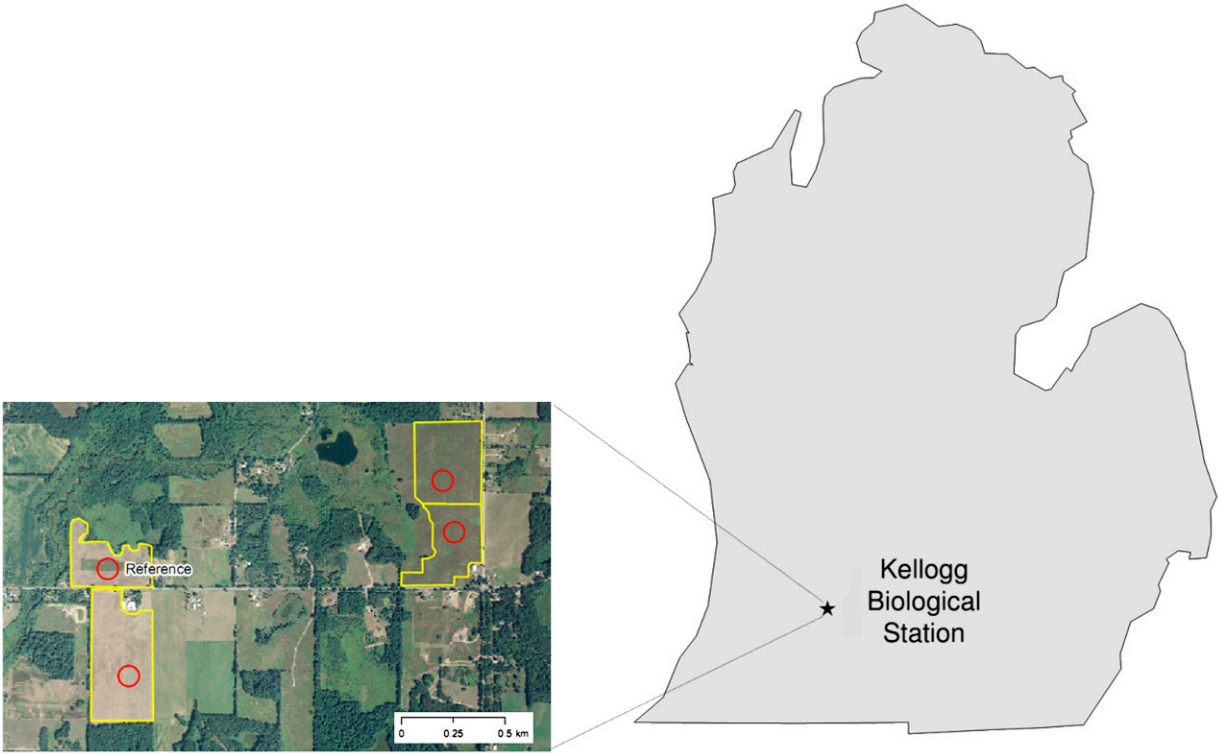

Fig. S1. Location of CRP converted fields and reference site in lower Michigan. Circles (200 m diameter) indicate positions and footprints of eddy-covariance towers.

Table S1. Greenhouse gas (GHG) fluxes and CO_2 equivalents (CO_2e, calculated by Eqs. S1 and S2) in the different ecosystems

	$g \cdot ha^{-1} \cdot d^{-1}$		$g\ CO_2e \cdot m^{-2} \cdot y^{-1}$	
	$N_2O - N$	$CH_4 - C$	$N_2O - N$	$CH_4 - C$
CRP converted grassland	12.3 (3.4)^a	−0.7 (0.4)^a	210.3 (58.3)	−0.8 (0.5)
CRP reference*	2.7 (0.7)^b	0.8 (1.8)^a	45.8 (9.9)	0.9 (2.2)
Conventional tillage	3.1 (0.6)^b	−1.2 (0.2)^a	52.8 (10.3)	−1.4 (0.2)
No-till	3.8 (0.5)^b	−1.2 (0.2)^a	64.9 (8.6)	−1.4 (0.2)

CRP converted grassland and reference GHG fluxes are for the conversion year (2009); results shown are mean (± SEM), $n = 3$. Postconversion year fluxes are from KBS LTER long-term averages (1989–2009) for conventional tillage and no-till systems (see ref. 5 and *SI Text* for details); results are shown as mean (± SEM), $n = 4$. GHG fluxes with different lowercase letters within columns are significantly different from one other ($P < 0.05$); similar lowercase letters within columns indicate that these GHG fluxes are not significantly different from each other. GHG fluxes (mean ± SEM, $n = 3$) were measured in four replicates per field and then averaged for each treatment to calculate the land-use change effect (CRP to agriculture conversion).

*CRP reference field results are means ± SEM of four replicates within the single field (9-ha size).

Table S2. Estimates of equivalent CO_2 emissions for agricultural operations during CRP grassland conversion to biofuel production (all fuel was petroleum-based diesel; see *SI Text* for further information)

Field operation	$L \cdot ha^{-1}$	$g\ CO_2e \cdot kg^{-1}$ soybean*	Source
Fuel use			
Herbicide application	1.8	2.0	(1)
Planting (no-till drill)	7.6	8.6	(2)
Soybean harvest	18.9	21.5	(3)
Chemicals and seeds			
Soybean seeds†		9.1	(1)
N fertilizer‡		3.1	(4)
Herbicide§		1.2¶	(3, 5)
Total agronomic operations	28.3	45.6	
Net total ($g\ CO_2e \cdot m^{-2} \cdot y^{-1}$)		10.4	

All reported values were converted to $L \cdot ha^{-1}$ if reported otherwise. The diesel C and energy contents were estimated to be 85% and 36.4 $MJ \cdot L^{-1}$, respectively (6).

*The soybean yield at our site is 228.3 ± 5.0 $g \cdot m^{-2}$ (Table S4).

†Totals of 370×10^3 seeds$\cdot ha^{-1}$, 56 kg seeds$\cdot ha^{-1}$, 0.25 kg $CO_2e \cdot kg^{-1}$ of seeds.

‡A total of 0.5 g CO_2e per application of 1 kg $N \cdot ha^{-1}$; ammonia was applied as surfactant for herbicide at 1.6 kg $N \cdot ha^{-1}$.

§A total of 0.5 $kg \cdot ha^{-1}$ of active ingredient; glyphosate was used.

¶A total of 2.3 g $CO_2e \cdot m^{-2} \cdot y^{-1}$ per application of 1 $kg \cdot ha^{-1}$ of herbicide, including production CO_2 costs.

1. West TO, Marland G (2002) A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. *Agric Ecosyst Environ* 91:217–232.
2. Stein D (2009) 2008-2009 machine custom and work rate estimates. District farm business management (Michigan State University Extension, East Lansing, MI). Available at https://www.msu.edu/user/steind/. Accessed July 21, 2011.
3. Lal R (2004) Carbon emission from farm operations. *Environ Int* 30:981–990.
4. Schlesinger WH (1999) Carbon and agriculture: Carbon sequestration in soils. *Science* 284:2095.
5. Syngenta Crop Protection Canada (2009) Material Safety Data Sheet for Touchdown Total Herbicide. Syngenta, Guelph, Ontario. Available at http://www2.dupont.com/Crop_Protection/en_CA/assets/downloads/Touchdown_Total_28072_en_msds_20080301.pdf. Accessed July 21, 2011.
6. Oak Ridge National Laboratory (ORNL) (2003) Bioenergy conversion factors. Available at http://www.localenergy.org/pdfs/Document%20Library/Bioenergy%20conversion%20factors.pdf. Accessed July 21, 2011.

Table S3. Detailed C debt of the CRP converted and reference sites for the conversion year

	$Mg\ CO_2e \cdot ha^{-1} \cdot y^{-1}$							
	Net ecosystem exchange (NEE)			Greenhouse gases (GHG)				
	NEE	C_{bio}	NEE_{adj}	N_2O	CH_4	Farm inputs	Fossil fuel offset credit*,†	Net GHG balance
CRP converted grassland	5.18 (0.30)	4.43 (0.10)	9.60 (0.35)	2.10 (0.58)	−0.008 (0.005)	0.10	−3.66 (0.08)	8.14 (0.79)
CRP reference	−2.97 (0.97)	—	—	0.46 (0.10)	0.009 (0.02)	—	—	−2.50 (0.98)
Total first year C cost								10.65 (0.79)
CRP with cellulosic ethanol production	−2.97 (0.97)	1.70 (0.97)	−1.27 (1.25)	0.46 (0.10)	0.009 (0.02)	—	−1.53 (0.05) to −2.31 (0.08)	−2.33 (1.25) to −3.11 (1.26)

Future debt from foregone soil C sequestration and decomposition of brome grass after the conversion year is not shown (see text). NEE_{adj} is net ecosystem exchange adjusted to include offsite grain respiration (converted sites) or biomass C (CRP reference site in the scenario with cellulosic ethanol production) as described in main text (Eq. **1**). Total first year C cost is the net GHG balance for CRP converted grassland less foregone sequestration represented by the net GHG balance of the CRP reference site (mean ± SEM, $n = 3$ replicate sites except as noted). NEE as defined here is positive when the net flux is to the atmosphere.

*See Tables S4 and S6 for detailed explanation of fossil fuel offset credit calculation.

†Reflects a range of possible harvest efficiencies (Table S6).

Table S4. Aboveground net photosynthetic productivity (ANPP) from CRP fields converted to a soybean production system and ANPP and harvestable biomass of the CRP reference system for 2009 (mean ± SEM, *n* = 3 fields converted, 1 as reference)

	$Mg\ ha^{-1}\cdot y^{-1}$		
Site	ANPP	Harvestable biomass	$Mg\ CO_2\cdot ha^{-1}$: decomposition*
CRP converted	2.28 (0.05)[†]	—	—
CRP reference[‡]	3.86 (0.13)	2.13 (0.07)–3.21 (0.11)[§]	8.92 (0.22)

The CRP reference site ANPP was used to estimate potential biofuel ethanol production if CRP lands had not been converted.

*Carbon debt from postconversion years due to decomposition of *Bromus inermis* biomass killed during conversion. We assume decomposition of 33% for below- and aboveground biomass of *B. inermis* during first year and residual 67% decomposition during subsequent years, on the basis of the field incubation experiments (1). We assumed 1.13 for the root-to-shoot ratio (2, 3) and 441.2 ± 1.4 $g\cdot kg^{-1}$ carbon concentration for *B. inermis* biomass (measured at our site).

[†] Soybean grain yields were measured in 10 replicates per field and then averaged for three converted fields. Soybean grain yields are given at 13% moisture. To calculate soybean oil and biodiesel yield ($g\cdot m^{-2}$) from harvested grain we used the factor 0.18 (4). A total of 228.3 g $grain\cdot m^{-2}$ can produce 41.1 ± 0.9 g $biodiesel\cdot m^{-2}$ or 411.0 ± 9.0 kg $biodiesel\cdot ha^{-1}$, with a biodiesel density of 0.88 $g\cdot ml^{-1}$ (4), bringing biodiesel production to 467.0 ± 10.2 L $biodiesel\cdot ha^{-1}$ at our sites.

[‡] ANPP, one field, 10 replicates manually harvested (mean ± SEM, *n* = 10). Grass yields are given as oven-dry mass.

[§] Harvestable biomass assumes a harvest efficiency of 55–83% (5, 6).

1. Knops JMH, Naeem S, Reich PB (2007) The impact of elevated CO_2, increased nitrogen availability and biodiversity on plant tissue quality and decomposition. *Glob Change Biol* 13:1960–1971.
2. Bolinder MA, et al. (2002) Root biomass and shoot to root ratios of perennial forage crops in eastern Canada. *Can J Plant Sci* 82:731–737.
3. Barbour MG (1973) Desert dogma reexamined: Root/shoot productivity and plant spacing. *Am Midl Nat* 89:41–57.
4. Patzek TW (2009) A first law thermodynamic analysis of biodiesel production from soybean. *Bull Sci Technol Soc* 29:194–204.
5. Heaton EA, Dohleman FG, Long SP (2008) Meeting US biofuel goals with less land: The potential of Miscanthus. *Global Change Biol* 14:2000–2014.
6. Monti A, Fazio C, Venturi G (2009) The discrepancy between plot and field yields: Harvest and storage losses of switchgrass. *Biomass Bioenergy* 33:841–847.

Table S5. Soil carbon concentrations ($g\ C\cdot kg\cdot soil^{-1}$), bulk density (BD; $g\cdot cm^{-3}$) and total C pools ($kg\ C\cdot m^{-2}$) to 1-m soil depth at the CRP grassland sites preconversion (*n* = 4) and in agricultural fields at the Kellogg Biological Station LTER site under conventional tillage in 2001 (*n* = 6)

	Soil depth				
	Ap (0–28.8 cm)		Bt (28.8–63 cm)	Bt2 (63–100 cm)	Total profile C*
CRP grassland sites preconversion	0–10 cm	10–25 cm	25–50 cm	50–100 cm	
C ($g\cdot kg^{-1}$ soil)	25.50 (4.40)	13.70 (2.90)	6.50 (1.40)	2.50 (0.80)	
BD ($g\cdot cm^{-3}$)	1.29 (0.05)	1.63 (0.03)	1.74 (0.02)	1.29 (0.05)	
Total C ($kg\ C\cdot m^{-2}$)	3.29 (0.70)	3.35 (0.80)	2.83 (0.60)	1.61 (0.60)	11.1 (1.2)
Annual grain crops under conventional tillage[†]	A/Ap (0–19.9 cm)		B/Bt (19.9–55.7 cm)	Bt2/C (55.7–100 cm)	
C ($g\cdot kg^{-1}$ soil)	10.4 (0.30)		4.2 (0.70)	1.8 (0.20)	
BD ($g\cdot cm^{-3}$)	1.6 (0.05)		1.7 (0.05)	1.6 (0.03)	
Total C ($kg\ C\cdot m^{-2}$)	3.2 (0.10)		2.4 (0.40)	1.2 (0.20)	6.9 (0.6)

Results shown are means (± SEM).

*For calculation of carbon accumulation in the CRP grassland since set aside: $C_{accumulation} = \frac{Total\ C_{CRP} - Total\ C_{Agriculture}}{22y}$.

[†] Data are from ref. 11.

Table S6. GHG balances with fossil fuel offset credits, foregone soil C sequestration, and biomass yields (dry biomass) in the conventional tillage, no-till, and cellulosic ethanol scenarios

	Mg $\mathrm{CO_2e\cdot ha^{-1}\cdot y^{-1}}$		Mg $\mathrm{CO_2\cdot ha^{-1}}$: foregone soil C sequestration[†]	Mg·$\mathrm{ha^{-1}}$ dry biomass[‡]		
Scenario	Fossil fuel offset credit*	Net GHG balance*		Corn grain yield	Stover removed	Soybean yield
Conventional tillage						
Continuous corn	2.32 (0.43)	−1.81 (0.45)	49 (7)	5.9 (0.6)	1.0 (0.6)	—
Corn–soybean	3.01 (0.35)	−2.49 (0.36)	49 (7)	6.6 (0.7)	—	2.5 (0.2)
Permanent no-till						
Continuous corn	2.32 (0.43)	−1.69 (0.44)	49 (7)	5.9 (0.6)	1.0 (0.6)	—
Corn–soybean	3.01 (0.35)	−2.37 (0.36)	49 (7)	6.6 (0.7)	—	2.5 (0.2)
CRP grassland						
83% harvest efficiency	2.31 (0.08)	−3.11 (1.26)	—	—	—	—
55% harvest efficiency	1.53 (0.05)	−2.33 (1.25)	—	—	—	—

*Fossil fuel offset credits were calculated from agricultural yields; corn biomass used as dry biomass and soybean biomass used at standard moisture content of 13% since the LCI analysis of biodiesel production include changes of moisture content in soybeans during the biodiesel production process (1). For CRP grassland fossil fuel offset credit was calculated from harvestable biomass (Table S4), and the GREET model (see *SI Text* and main text for details). Net GHG balance was calculated as the sum of GHG impacts of soil N_2O and CH_4 emissions (Table S1) and fossil fuel offset credit. Net GHG balance for CRP grassland was calculated as the sum of GHG impacts of soil N_2O and CH_4 fluxes in the unconverted CRP grassland, $\mathrm{NEE_{adj}}$ (Table S3), and fossil fuel offset credit.

[‡] Biomass values used for calculation of scenarios are mean (± SEM) of 2007, 2008, and 2009 average yields for Kalamazoo County, Michigan (2), and a harvest index of 0.51 (corn grain yields of 7.7 ± 0.8 Mg·$\mathrm{ha^{-1}\cdot y^{-1}}$ and soybean yields of 2.5 ± 0.2 Mg·$\mathrm{ha^{-1}\cdot y^{-1}}$ at standard moistures). Soybean and corn grain yields were obtained from the US Department of Agriculture website, soy bean at 13% moisture, and corn grain yields at 15.5% moisture (2), and recalculated to dry biomass. Corn grain yield in continuous corn rotation was assumed to have a 10% yield penalty (3, 4). From corn stover we removed the amount of stover that should be left on the field to retain long-term soil carbon stores (see main text for detailed explanation).

[†] Assuming eventual approach of the Ap horizon to a saturation soil C concentration of 30 g·$\mathrm{kg^{-1}}$ (*SI Text, Foregone Soil Carbon Sequestration and Soil Carbon Loss on Tillage*).

1. Sheehan J, et al. (1998) *Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus* (National Renewable Energy Laboratory, Golden, CO).
2. Agricultural Statistics (2010) Available at www.nass.usda.gov/Statistics_by_State/Michigan/Publications/Annual_Statistical_Bulletin/index.asp. Accessed July 21, 2011.
3. Trenton F, Stanger TF, Lauer JG (2008) Corn grain yield response to crop rotation and nitrogen over 35 years. *Agron J* 100:643–650.
4. Vyn TJ, West TD, Steinhardt GC (2000) Corn and soybean response to tillage and rotation systems on a dark prairie soil: 25 year review. *15th Conference of International Soil Tillage Research Organization* (Fort Worth, TX), pp 1–10. Available at www.agry.purdue.edu/staffbio/ISTROConf.2000Manuscript.pdf. Accessed July 21, 2011.

Table S7. Greenhouse gas emission intensity of energy production from converted and unconverted CRP grassland

	$\mathrm{MJ\cdot m^{-2}\cdot y^{-1}}$		$\mathrm{CO_2e\cdot MJ^{-1}}$: GHG emission intensity*
	Biodiesel energy production	Ethanol energy production*	
Conversion year	1.6 (0.1)	—	661
Postconversion year, continuous corn	—	6.0 (1.0)	1,148[†]
Unconverted CRP grassland[‡]	—	1.7–2.6	−121 to −137

*Energy production calculations based on average yields for 2007–2009 in Kalamazoo County, Michigan (Table S6) and harvestable biomass from CRP reference site (Table S4). Total fuel production for conversion year is estimated to be 443 L·$\mathrm{ha^{-1}}$ (fossil diesel equivalents); for postconversion continuous corn, ethanol production is estimated to be 2,934 L·$\mathrm{ha^{-1}\cdot y^{-1}}$ (main text and Table S6).

[†] After all C debt associated with CRP conversion is repaid the production of 1 MJ of renewable energy from no-till continuous corn will sequester 39 g $\mathrm{CO_2e\cdot MJ^{-1}}$ from the atmosphere.

[‡] Range reflects different harvest efficiencies (Table S6).