Carbon debt of Conservation Reserve Program (CRP) grasslands converted to bioenergy production

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Over 13 million ha of former cropland are enrolled in the US Conservation Reserve Program (CRP), providing well-recognized biodiversity, water quality, and carbon (C) sequestration benefits that could be lost on conversion back to agricultural production. Here we provide measurements of the greenhouse gas consequences of converting CRP land to continuous corn, corn–soybean, or perennial grass for biofuel production. No-till soybeans preceded the annual crops and created an initial carbon debt of 10.6 Mg CO_2 equivalents (CO_2e)·ha^{-1} that included agronomic inputs, changes in C stocks, altered N_2O and CH_4 fluxes, and foregone C sequestration less a fossil fuel offset credit. Total debt, which includes future debt created by additional changes in soil C stocks and the loss of substantial future soil C sequestration, can be constrained to 68 Mg CO_2e·ha^{-1} if subsequent crops are under permanent no-till management. If tilled, however, total debt triples to 222 Mg CO_2e·ha^{-1} on account of further soil C loss. Projected C debt repayment periods under no-till management range from 29 to 40 y for corn–soybean and continuous corn, respectively. Under conventional tillage repayment periods are three times longer, from 89 to 123 y, respectively. Alternatively, the direct use of existing CRP grasslands for cellulosic feedstock production would avoid C debt entirely and provide modest climate change mitigation immediately. Incentives for permanent no till and especially permission to harvest CRP biomass for cellulosic biofuel would help to blunt the climate impact of future CRP conversion.

land-use change | renewable energy | carbon balance | agriculture | nitrous oxide

Projections of reduced fossil fuel availability and increasing appreciation of the environmental impacts of fossil fuel use have stimulated interest in renewable energy sources from agricultural crops (1, 2), which would likely lead to the expansion of cropland to satisfy new production demands (3). A likely side effect of cropland expansion is an increase in greenhouse gas (GHG) emissions due to land-use conversion (4, 5). In the United States, ∼13 × 10^6 ha of former cropland are in the Conservation Reserve Program (CRP) (6) but this amount is subject to change as CRP and additional acreage now unmanaged will increasingly be converted to biofuel crops in response to the current US ethanol mandate (7). Modeled estimates of the carbon cost (C debt) of converting CRP grassland to agriculture have ranged from ∼30 to 200 Mg CO_2 equivalents (CO_2e)·ha^{-1}, requiring from 3 to >50 y to repay depending on GHG emissions following conversion vs. the net production of biofuels to offset fossil fuel use (fossil fuel offset credit) (4, 8–10). However, the lack of direct measurements of GHG fluxes during conversion of CRP lands makes such estimates highly uncertain.

Here we report a full GHG accounting during the year of conversion of a 22-y-old CRP perennial grassland dominated by smooth brome grass (*Bromus inermis*) to a no-till soybean (*Glycine max*) system. No-till soybean is a recommended breakout crop for CRP conversion because of weed control and soil carbon conservation advantages. Our analysis includes all major components of the C balance including the CO_2e costs of agricultural inputs such as fuel, fertilizer, herbicides, seeds, and other agronomic inputs; changes in C storage as measured by net ecosystem CO_2 exchange adjusted for grain C; and net ecosystem fluxes of the greenhouse gases N_2O and CH_4. We credit the C balance with a fossil fuel offset credit based on biodiesel yield from soybeans grown at the converted sites and published life cycle comparisons of fossil vs. biodiesel production (11–13) (*SI Text*), which include coproduct credits. To calculate the C debt payback time we project forward from the conversion year using the life cycle analysis (LCA) of biofuel and fossil fuel production and long-term county crop yields, together with data for soil GHG fluxes and soil carbon from nearby fields on the same soil series studied for a decade or more.

We consider five contrasting scenarios for subsequent management: continuous corn and corn–soybean rotations, each either tilled or in permanent no-till. A fifth scenario is CRP grassland harvested for cellulosic ethanol production. We recognize that only a small fraction of US soils are today in permanent no-till and that even a single tillage event can rapidly destroy an accumulated soil C benefit (14, 15). We present the permanent no-till scenario as a best-practice option, agronomically realistic with the proper incentives (16). Likewise, using the grassland for cellulosic ethanol production will not be practical without nearby biorefineries that can accept cellulosic feedstocks. Nevertheless, such scenarios are important for framing potential outcomes in light of ongoing policy discussions.

Results and Discussion

The largest first-year C cost of CRP conversion to no-till soybean is the change in ecosystem C stocks as measured by net ecosystem CO_2 exchange (NEE) (defined here as positive for net C emission to the atmosphere and negative for net C sequestration from the atmosphere) (Fig. 1*A* and Table 1). Over the course of 2009, emissions in excess of photosynthetic uptake totaled 9.60 ± 0.35 Mg CO_2e·ha^{-1} (NEE_{adj}; Table 1 and Eq. **1**), which represents a net loss of ecosystem C for the conversion year. Additionally, the converted fields emitted a substantial amount of N_2O (Fig. 1*B* and Table S1), which contributed another 2.10 ± 0.58 Mg CO_2e·ha^{-1} to the net GHG balance. Methane oxidation, on the other hand, was negligible, on the order of −0.008 ± 0.005 Mg CO_2e·ha^{-1} (Table S1). GHG farming costs were also minor: the total CO_2e cost of fuel, fertilizer, pesticides, and seeds summed to 0.10 Mg CO_2e·ha^{-1} (Table S2 and *SI Text* for details). The direct first-year carbon cost of conversion was thus 11.80 ± 0.68 Mg CO_2e·ha^{-1} (Fig. 2).

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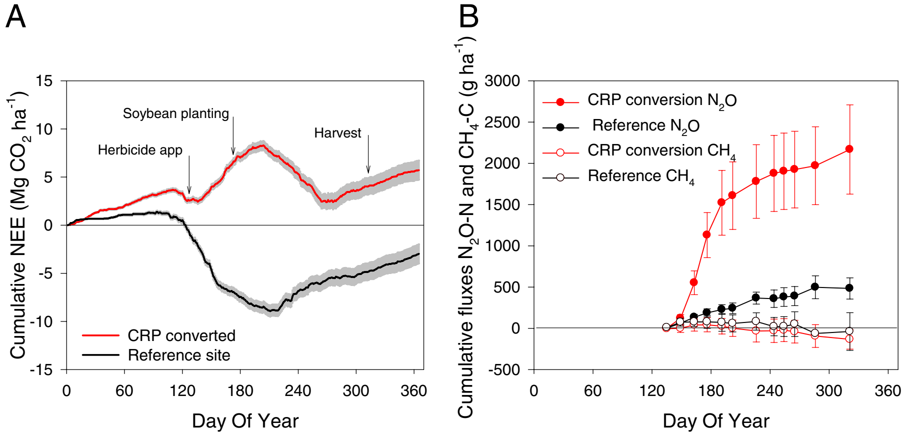

Fig. 1. Cumulative fluxes of greenhouse gases from the studied systems. (*A*) Average cumulative NEE from three CRP grasslands converted to no-till soybean (red line) compared with a CRP grassland reference site (black line) during 2009. Positive values indicate net CO_2 emission from the ecosystems. Gray areas show the SD of cumulative NEE. Herbicide was first applied to the CRP grassland on day of year (DOY) 125; soybeans were sown on DOY 160 and harvested on DOY 310. (*B*) Average cumulative emissions of N_2O (N_2O – N g·ha^{-1}; solid symbols) and CH_4 (CH_4 – C g·ha^{-1}; open symbols) at the study sites during the 2009 growing season. Black lines and symbols represent the CRP reference site and red lines and symbols represent converted sites. Error bars are quadratic sums of component SEs (n = 3 replicate fields for converted CRP and n = 4 replicates within one field for reference CRP; see *SI Text* for details). Note different units in *A* and *B*.

To this initial conversion cost an additional 2.50 ± 0.98 Mg CO_2e·ha^{-1} of foregone sequestration must be added. This is the amount of carbon that would have been sequestered during the conversion year by soil and plants in the converted sites had they been left unconverted and is based on the net greenhouse gas balance of the reference site (Fig. 2, *Inset*). This value includes the net amount of CO_2e captured by the reference site, measured as the cumulative annual NEE (−2.97 ± 0.97 Mg CO_2e·ha^{-1}; Fig. 1*A* and Table 1) less emitted N_2O (0.46 ± 0.10 Mg CO_2e·ha^{-1}) and methane (0.009 ± 0.022 Mg CO_2e·ha^{-1}) (Fig. 1*B* and Table S1). The total first-year carbon cost thus sums to 14.31 ± 0.86 Mg CO_2e·ha^{-1}.

Against this initial cost can be credited 3.66 ± 0.08 Mg CO_2e·ha^{-1} or 227 g CO_2e·MJ^{-1} for avoided fossil fuel C use following biodiesel production. To determine this fossil fuel offset credit we used published results of life cycle analyses and models to estimate the CO_2 displaced both by direct production of soybean biodiesel and by coproduct allocations based on mass and energy allocation methods (11) (*SI Text*). This method brings the net first-year carbon cost of conversion to 10.65 ± 0.79 Mg CO_2e·ha^{-1} (Fig. 2 and Table S3).

In addition to first-year carbon costs are two additional sources of C loss that will contribute to overall debt. The first is CO_2 that will be emitted in the years following conversion from the eventual decomposition of grass biomass killed during the conversion year. This estimate is based on the conservative assumption that ~33% of brome grass biomass fully decomposed during the conversion year (Table S4 and *SI Text*), yielding CO_2e that is already included in NEE measurements. The remaining 8.92 ± 0.22 Mg CO_2e·ha^{-1} would then decompose in subsequent years less a very small percentage that would be expected to become sequestered in passive soil carbon pools.

A second and substantially larger future cost is the loss of soil C sequestration in the converted sites that would have continued to have been sequestered had those sites not been converted. We estimate future foregone soil C sequestration to add an additional C debt equivalent to the difference in soil C concentration between the preconverted sites and the saturation C content of area soils of the same series in late successional, unmanaged ecosystems (18–21). We thus expect that future soil C sequestration would have been 49 ± 7 Mg CO_2e·ha^{-1} (Tables S5 and S6 and *SI Text*) on the basis of current soil concentrations of 25.5 g C·kg^{-1} for the Ap (surface) horizon that would eventually, in the absence of conversion, have reached a saturation soil C concentration of ~30 g C·kg^{-1} as for nearby soils of the same series (22). Other estimates of foregone soil C sequestration for conservation lands range from ~27 (10) to 104 (23) Mg CO_2e·ha^{-1}. Foregone soil C sequestration thus makes one of the largest contributions to overall C debt.

Summing both conversion year (Fig. 2) and future debt as discussed above brings the total C debt for CRP land converted to no-till agriculture to 68 ± 7 Mg CO_2e·ha^{-1}, with 9.6 Mg CO_2e·ha^{-1} from decomposing soil and plant carbon during the conversion year, 2.1 Mg from changes in N_2O and CH_4 fluxes, 0.1 Mg from farming activities, −3.7 Mg of conversion year fossil fuel offset credit, 2.5 Mg of foregone C sequestration during the year of conversion, 8.9 Mg of future brome grass decomposition, and 49 Mg of foregone future soil C sequestration.

Our calculation of C debt is higher than Piñeiro et al.'s estimate for conversion of CRP land (~30 Mg CO_2·ha^{-1}) (10) and similar to Fargione et al.'s (69 Mg CO_2·ha^{-1}) (9), even though our conversion entailed no-till management and thus conserved a substantial amount of soil C that was estimated to have been oxidized in the earlier studies. As well, our measurement is lower than that estimated by Searchinger et al. (4) for conversion of native grassland with its higher soil C content (111–200 Mg CO_2·ha^{-1}). Were our fields tilled rather than under no-till management during the conversion year, our debt would be substantially higher, as described below.

The time it takes for a biofuel cropping system to produce enough GHG savings to offset the GHGs emitted due to con-

Table 1. Net ecosystem exchange (NEE) for the year 2009 in CRP grasslands converted to no-till soybean and in an unconverted reference site

	Mg CO_2e·ha^{-1}·y^{-1}		
	NEE	C_{bio}	NEE_{adj}
CRP converted grassland	5.18 (0.30)	4.43 (0.01)	9.60 (0.35)
CRP reference*	−2.97 (0.97)	—	−2.97 (0.97)

NEE is measured by eddy covariance adjusted for harvested grain respired off site (C_{bio}) to provide NEE_{adj} (Eq. **1**) (mean ± SEM, n = 3 replicate sites except as noted). NEE as defined here is positive when the net flux is to the atmosphere.

*One replicate, error propagated by quadratic sum of component errors (17).

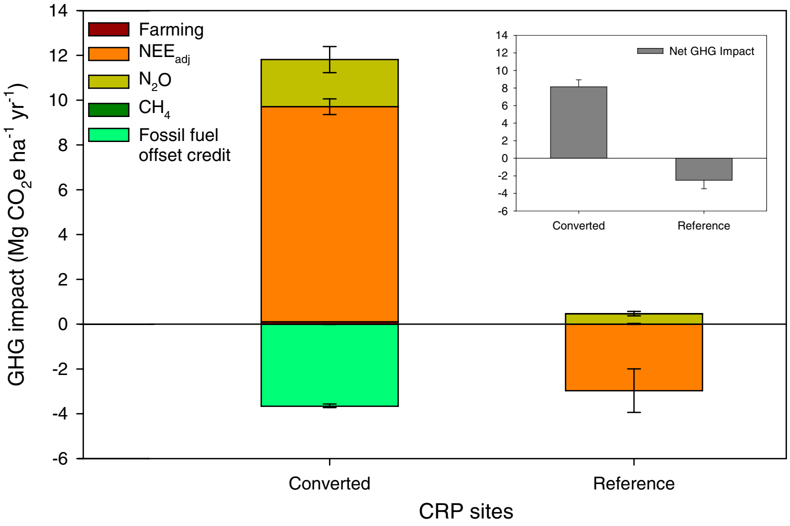

Fig. 2. Conversion year GHG impact for Conservation Reserve Program (CRP) fields converted to no-till soybeans in 2009. NEE$_{adj}$ includes the net release of soil and grain C in the converted site and the net capture of soil C in the reference site. Not shown for the converted sites is foregone C sequestration, which is equivalent to the net GHG impact for the reference site, shown in the *Inset*. Also not shown is future debt created by the subsequent decomposition of CRP biomass (8.9 Mg CO$_2$·ha^{-1}) and future foregone soil C sequestration (49 Mg CO$_2$·ha^{-1}). Error bars are quadratic sums of component SEs (see *SI Text* for details).

version is the C debt payback time. Payback time for a given debt depends on subsequent agricultural management practices and biofuel production offset credits. To bracket the range of times for a realistic range of grain-based production systems in our area we estimate payback times under four different rotation and tillage scenarios: continuous corn vs. corn–soybean rotations, each with either tillage or permanent no-till soil management. A fifth scenario is harvesting the CRP grassland directly for cellulosic ethanol production.

We base our estimates on long-term results from nearby experiments, as well as on average agricultural grain yields from 2007 to 2009 for Kalamazoo County, Michigan (7.7 ± 0.8 Mg·ha^{-1}·y^{-1} and 2.5 ± 0.2 Mg·ha^{-1}·y^{-1} for corn and soybean, respectively, at standard moisture contents) (Table S6). Under all four grain-based scenarios we assume grain is used for ethanol (corn) or biodiesel (soybeans). Additionally we assume that 17% of continuous corn residues are removed for the production of cellulosic ethanol and no residues are removed from corn–soybean rotations. These rates of stover removal leave sufficient corn residue to maintain (but not build) long-term soil carbon stores: 5.2 Mg·ha^{-1}·y^{-1} for continuous corn and 7.8 Mg·ha^{-1}·y^{-1} for corn–soybean rotations in southwest Michigan (24, 25).

Fossil fuel offset credits account for fossil fuel CO$_2$ emissions displaced by both direct production of renewable energy and feedstock coproducts. We used published results of life cycle analysis (LCA) and models (11–13) to estimate fossil fuel offset credits of 194 and 33 g CO$_2$e·MJ^{-1} for biodiesel from soybeans and ethanol from corn grain, respectively (*SI Text*). For cellulosic ethanol from stover and CRP grasses we used the GREET model (GREET 1.8d.0) (11) to estimate fossil fuel offset credits of 101 and 90 g CO$_2$e·MJ^{-1}, respectively (*SI Text*).

If postconversion-year management were permanent no-till continuous corn, we estimate that our system's C debt of 68 Mg CO$_2$·ha^{-1} could be repaid within 40 ± 11 y (Table 2, Table S6, and *SI Text*). Including a no-rotation yield penalty of 10% of harvestable biomass (26, 27) (*cf.* ref. 16), our estimate of a 40-y payback time for no-till continuous-corn ethanol is somewhat shorter than Fargione et al.'s (8) estimate of 48 y. This result is in part due to our assuming no additional soil C loss on the basis of no-till results at nearby sites (22) vs. their assuming loss of all CRP-accumulated soil C due to tillage. Our estimate would be substantially shorter without the inclusion of foregone future soil C sequestration, as in Fargione et al. (8), i.e., an additional loss of ~49 Mg CO$_2$e·ha^{-1} (Table S5 and *SI Text*) that must also be repaid.

If subsequent management were a corn–soybean rotation under permanent no-till, we estimate that our system's C debt of 68 Mg CO$_2$·ha^{-1} would require 29 ± 5 y to repay (Table 2). This faster payback is because the corn–soybean rotation produces higher average fossil fuel offset credits (301 ± 35 g CO$_2$·MJ^{-1}·y^{-1} for bioethanol plus biodiesel averaged over 2 y vs. 232 ± 43 g CO$_2$e·MJ^{-1}·y^{-1} for bioethanol from continuous corn; calculated by Eq. **3**, Eq. S5, and Eq. S6) (*SI Text*). Annual net CO$_2$e balances are −2.37 ± 0.36 and −1.69 ± 0.44 Mg CO$_2$e·ha^{-1}·y^{-1} for corn–soybean and continuous corn, respectively (Table S6 and *SI Text*).

Tillage, for either rotation scenario, increases the payback time substantially. Were the subsequent agricultural systems to be tilled following our no-till conversion year, the payback times would be ~123 and 89 y for the continuous corn and corn–soybean rotations, respectively (Table 2 and Table S6). This payback time is two to four times longer than those estimated by Piñeiro et al. (~30 y) (10) and Fargione et al. (48 y) (9) and is closer to that estimated by Searchinger et al. (167 y) (4), which, unlike others, including ours, also includes the cost of indirect land-use change. Our longer payback time is because tillage will cause the complete oxidation of the soil carbon pool accumulated under CRP management (25) (Table S5), much of which will be released during the first 2–3 y of initial tillage (15). This will add consid-

Table 2. Carbon debt payback times under different scenarios of conversion of Conservation Reserve Program (CRP) grassland to annual cropping systems at a site in southwest Michigan

	Carbon debt payback time: years	
Agronomic management	Conventional tillage	Permanent no-till
Continuous corn	123 (43)	40 (11)
Corn–soybean rotation	89 (26)	29 (5)

The management system noted follows a first-year conversion of grassland to no-till soybeans as noted in Fig. 1. Projections are based on observations made during the establishment year plus projections of historical productivity and greenhouse gas fluxes from nearby sites under conventional tillage and permanent no-till rotations. Carbon debt payback times include coproduct offsets (*SI Text*). SEs (in parentheses) are based on the propagation of errors associated with the various components of carbon debt.

erably to the system's carbon debt, increasing payback time accordingly: Soil C differences between our CRP sites and nearby historically tilled fields under continuous cultivation indicate that at least 4.2 kg C·m^{-2} to 1-m depth (Table S5) will be lost; oxidation of this amount of soil C is equivalent to ~153 Mg CO_2e·ha^{-1} of additional debt.

Thus, if the biofuel production entails annual tillage, the system's resulting carbon debt will triple from 68 ± 7 Mg CO_2e·ha^{-1} for no-till conversion to 222 ± 56 Mg CO_2·ha^{-1}, not including the additional debt associated with the increase in N_2O emissions likely to occur following tillage (15). Tillage of CRP lands thus creates substantial local C debt—not repayable for almost a century if subsequent crops are used for biofuel and never repaid if intermittently tilled and used for food crop production. Irrespective of future crop use, policies to protect CRP carbon on conversion should be a national priority to avoid further atmospheric CO_2 loading.

An alternative to converting CRP grasslands to annual crops for biofuel production is to use these lands to produce perennial crop biomass for cellulosic biofuel feedstocks (5, 28). The aboveground net primary production of our unfertilized reference site was 3.86 Mg dry mass·ha^{-1} in 2009 (Table S4). This dry biomass is sufficient to produce between 17 ± 1 and 25 ± 1 GJ·ha^{-1} of cellulosic ethanol depending on harvest efficiencies (55–83%) (29, 30), resulting in fossil fuel offset credits between 1.53 ± 0.05 and 2.31± 0.08 Mg CO_2e·ha^{-1} (Table S6).

Additionally, the soil C sequestration potential of our sites is 6.97 Mg CO_2e·ha^{-1}·y^{-1} (to 1 m depth) on the basis of the rate of soil C accumulation over 22 y at our CRP reference site (Table S5). This potential will diminish over time, eventually to nil as soil C concentrations reach equilibrium (21). After this point, our CRP land would provide a continuous GHG mitigation capacity of at least 2.33 Mg CO_2e·ha^{-1}·y^{-1} from fossil fuel offset credits and lower N_2O emissions, together with other ecosystem services (Tables S1, S3, and S6 and *SI Text*). This mitigation could be significantly greater were the fields fertilized or coplanted to legumes to increase productivity (so long as N_2O production does not increase substantially as a result) or were they replanted without tillage to a more productive species mix (5, 31). Additionally, cellulosic biofuel crops could be grown on land less or not suitable for food crops—a criterion for CRP lands, thus avoiding food vs. fuel competition for highly productive land as well as the GHG emissions associated with indirect land use change (4), whereby land elsewhere is converted to agricultural production to offset the loss of food production where biofuels are newly grown.

Estimation of net CO_2e emissions per unit of biofuel energy produced (GHG emission intensity; Eq. S4) allows comparison of the environmental impacts of different energy sources (12). We estimate that production of 1 MJ of biofuel energy from CRP conversion to grain-based biofuel crops would emit 661 g CO_2e (Table S7) during the year of conversion alone. This GHG impact is seven times higher than the emissions from an equivalent amount of fossil fuel-derived gasoline, including production, distribution, and combustion (94 g CO_2e·MJ^{-1}) (12). Even with the establishment of a no-till continuous-corn system, the GHG impact of biofuel production will stay very high, 1148 g CO_2e·MJ^{-1} in the first year and decreasing thereafter until the C debt of conversion and foregone C sequestration are repaid, and only after that would it stabilize at −39 g CO_2e·MJ^{-1}. During this same period, the use of CRP lands for cellulosic biofuel feedstock production from perennial grassland would result in a consistently negative GHG emission intensity of −121 to −137 g CO_2e·MJ^{-1} of energy produced (Table S7), although at a lower energy yield (17 ± 1 to 26 ± 1 GJ·ha^{-1} for CRP biomass vs. 60 ± 10 GJ·ha^{-1} for continuous corn grain; Table S7) in the absence of improved cellulosic crop varieties and management to provide better yields.

Overall, our results show that no-till conversion of CRP grassland to an annual bioenergy crop will create a C debt of 68–222 Mg CO_2·ha^{-1} depending on postconversion tillage management. Payback times likewise depend on tillage: Shorter payback times are achievable only with permanent no-till, for which 29–40 y would be required if subsequent rotations were no-till corn–soybean or no-till continuous corn, respectively. If managed with conventional tillage, the repayment period triples to 89–123 y, respectively. The direct use of unconverted CRP grasslands for cellulosic feedstock production, on the other hand, would avoid C debt entirely and provide significant climate change mitigation immediately. Policy incentives for permanent no-till would help to attenuate the climate impact of future CRP conversion and permission to harvest CRP biomass for cellulosic biofuel would provide a net climate benefit.

Materials and Methods

Experimental sites were located in southwest Michigan, in the northeastern part of the US Corn Belt (Fig. S1). The experiment is part of the Great Lakes Bioenergy Research Center (GLBRC) and located at the W. K. Kellogg Biological Station (KBS) Long-Term Ecological Research (LTER) site (www.lter.kbs.msu.edu; 42° 24′ N, 85° 24′ W, and 288 m above sea level). Mean annual air temperature is 9.7 °C and annual precipitation is 920 mm, evenly distributed throughout the year. Soils are well-drained Typic Hapludalfs developed on glacial outwash (32).

Three CRP fields (13–19.5 ha; Fig. S1) were converted to no-till soybeans in spring 2009. Glyphosate was applied at a rate of 0.5 kg active compound·ha^{-1} [Touchdown HiTech (*N*-(phosphonomethyl); Syngenta Agro] at day of year (DOY) 125, with subsequent no-till planting of glyphosate-tolerant soybeans at DOY 160 with a seed drill; there was no further soil disturbance. Glyphosate-tolerant soybeans are a recommended break crop for CRP lands because perennial grasses can be effectively controlled with herbicide applications throughout the growing season as needed. All three fields had been in USDA-contracted CRP grasslands since 1987, as was an additional 9-ha field used as a reference site; before CRP enrollment the fields were in corn–soybean production for at least 50 y and in other corn–small grain rotations since first farmed in the 1800s. During CRP enrollment all sites were planted with monocultures of smooth brome grass (*Bromus inermis*) (33), maintained following the USDA criteria for CRP lands (www.fsa.usda.gov/FSA/).

Measurements and Calculations of Net Ecosystem CO_2 Exchange. The turbulent exchange of CO_2 between the canopy and the atmosphere was measured throughout 2009 using the eddy covariance (EC) technique (Fig. 1) (34–36). The EC system consisted of a LI-7500 open-path infrared gas analyzer (Li-Cor Biosciences), a CSAT3 three-dimensional sonic anemometer, and a CR5000 data logger (Campbell Scientific). The LI-7500 was calibrated every 4 mo in the laboratory with National Oceanic and Atmospheric Administration precision CO_2 standards.

The 30-min mean flux of CO_2 was computed as the covariance of vertical wind speed and the concentration of CO_2 after removing spikes in raw data (>6 SDs) and correcting sonic temperatures for humidity and pressure (37), with additional correction of the coordinate system with the planar fit method. The correction algorithm uses the formulation of ref. 38 in the planar fit coordinate system (39), which was defined from the entire year's mean wind data in all studied sites. The correction was performed using the EC processor software package available at http://research.eeescience.utoledo.edu/lees/. The 30-min mean fluxes were corrected for fluctuations in air density using the Webb–Pearman–Leuning expression (40), including the term for the warming of the infrared gas analyzer above air temperature (41).

The resulting NEE of CO_2, compiled at 0.5-h intervals, was averaged across the three converted fields to estimate the annual C flux for each field. We compared this C flux with the flux of the unconverted (reference) CRP field. The C debt calculations were based on these NEE estimates of replicate plots (Table 1).

For the estimation of the C debt of the CRP land conversion we calculated adjusted NEE (NEE_{adj}; Mg CO_2e·ha^{-1}·y^{-1}) (Table 1) from measured NEE (Mg CO_2e·ha^{-1}·y^{-1}) plus harvested grain or biomass C (C_{bio}; Mg CO_2e·ha^{-1}·y^{-1}):

$$\mathrm{NEE_{adj}} = \mathrm{NEE} + C_{\mathrm{bio}}. \qquad [1]$$

Carbon in the grain or grass biomass, representing organic C removed in soybean or grass harvest, was calculated as

$$C_{\mathrm{bio}} = f_c \times Y, \qquad [2]$$

where C_{bio} is the measured C fraction in soybean grain (0.53 ± 0.05 g C·g^{-1} dry mass) and the C concentration in brome grass [0.44 ± 0.00 g C·g^{-1} dry biomass (*SI Text*)], and Y is soybean grain or grass yields (Mg·ha^{-1}·y^{-1}) (for detailed information on soybean and grass yields see Table S6). For use in Eq. **1**, C_{bio} is recalculated to CO_2.

The fossil fuel offset credit is defined here as the sum of all potential avoided CO_2 emissions due to the displacement of production and combustion of fossil fuels or their coproducts by biofuels. We used results of published life cycle analyses and models for calculation of fossil fuel and coproduct offset credits (11–13). For fossil fuel offset credits associated with biodiesel we used published results from comparison of life cycle analyses by the GREET model (11). The fossil fuel offset credits estimated in this study sum to 7.60 kg CO_2e·kg^{-1} of biodiesel, or 193.9 g CO_2e·MJ^{-1}, using a biodiesel energy content of 34.5 MJ·L^{-1} and a density of 0.88 g·mL^{-1} (42, 43) (*SI Text*). For the conversion year we added an additional 33.0 g CO_2e·MJ^{-1} to the offset due to lower than assumed in GREET agricultural inputs to our site (*SI Text*).

For corn grain ethanol, avoided CO_2e emissions were calculated from a comparison of life cycle analyses of ethanol and petroleum gasoline. Gasoline emits 94 g CO_2e·MJ^{-1} of petroleum gasoline produced, distributed, and combusted (12), whereas the cost of bioethanol is 61.3 g CO_2e emissions per MJ produced and distributed (calculated from the comparison between BESS, EBAMM, and GREET models) (12, 13), for an ethanol fossil fuel offset credit of 32.7 g CO_2e·MJ^{-1}. For cellulosic ethanol we used results of GREET (11), which show for our systems that production of 1 MJ of cellulosic ethanol will offset 90 and 101 g CO_2e, for ethanol produced from grasses and stover, respectively (*SI Text*). To calculate energy produced from ethanol we used average corn yields (Table S6), harvestable biomass from the unconverted CRP site (Table S4), and ethanol energy content [lower heating value (LHV)] assumed to be 21.1 MJ·L^{-1} bioethanol. We assumed a biorefinery yield of 0.43 L bioethanol·kg^{-1} dry corn grain and 0.38 L bioethanol·kg^{-1} dry corn stover and grass biomass (GREET) (44).

The energy-equivalent amounts of fossil fuel use avoided due to the use of biofuels were calculated using LHV energy contents (34.5 and 21.1 MJ·L^{-1} for biodiesel and bioethanol, respectively) and the specific densities of each fuel (42, 43),

$$\text{Energy equivalent }(\text{MJ}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}) = \text{DM}\times X\,\frac{\text{kg Fuel}}{\text{kg DM}}\times Y\,\frac{\text{L Fuel}}{\text{kg Fuel}}\times \text{Biofuel}_{\text{energy}}, \qquad [3]$$

where DM is biomass yield as dry matter (kg·ha^{-1}·y^{-1}; Tables S4 and S6); X is the conversion factor for biofuel production from grain, stover, or cellulosic feedstocks; Y is a factor accounting for fuel-specific density; and $\text{Biofuel}_{\text{energy}}$ is biofuel energy content (MJ·L^{-1} fuel).

Soil GHG Emission Measurements and Farming C Costs. We measured soil N_2O and CH_4 fluxes in four replicate locations in each of the studied fields during the 186-d growing season. Biweekly fluxes were measured with static chambers (45) placed within the footprint of the eddy covariance towers (see *SI Text* for detailed information about methods). We calculated CO_2e of soil GHG emissions using a 100-y global warming potential (GWP) time horizon as recommended by the Intergovernmental Panel on Climate Change (IPCC) (46). Other C costs were based on detailed information documenting actual farming practices in these systems in the year of conversion (Table S2). For all systems, contributions of farming practices to the net C balance (in Mg CO_2e·ha^{-1}·y^{-1}) were based on our agronomic practices, which are typical of the region, and standard conversion factors for the production costs of fertilizers, herbicides, and field fuel use (Table S2).

Calculation of GHG Balances for Scenarios. For the no-till and conventional tillage scenarios (*SI Text*), we used the average yields of either corn or soybeans for the years 2007–2009 in Kalamazoo County, Michigan (47). For estimation of CO_2e emissions associated with production of biodiesel and corn ethanol from feedstocks, we used published results of LCAs (*SI Text*) (11–13, 45). For scenarios with conventional tillage, we assumed soil C losses to the level of nearby agricultural sites (Table S5). We estimated conversion year foregone sequestration as the cumulative annual CO_2e balance of the reference site. For scenarios with no-till management, we assumed that soils maintain soil C at the levels of the conversion year (Table S5). In the calculation of payback times for all scenarios, we included potential loss of future soil C sequestration by CRP lands (*SI Text*).

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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):

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

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

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),

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

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 $MJ{\cdot}m^{-2}{\cdot}y^{-1} \times$ 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 $\text{balance}_{\text{postconversion}}$ 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).

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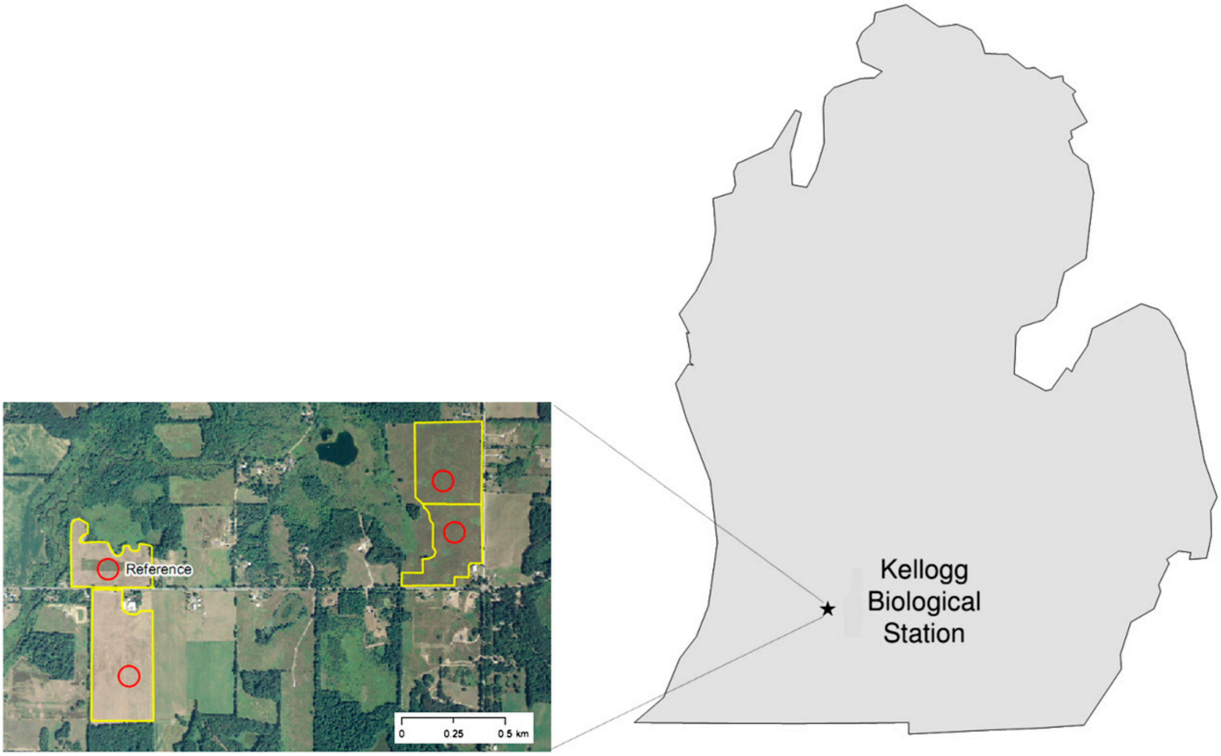

Fig. S1. Location of CRP converted fields and reference site in lower Michigan. Circles (200 m diameter) indicate positions and footprints of eddy-covariance towers.

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·ha^{-1}	g CO_2e·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·m^{-2}·y^{-1})		10.4	

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

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

[†] Totals of 370 × 10^{3} seeds·ha^{-1}, 56 kg seeds·ha^{-1}, 0.25 kg CO_2e·kg^{-1} of seeds.

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

[§] A total of 0.5 kg·ha^{-1} of active ingredient; glyphosate was used.

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

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

	Mg CO_2e·ha^{-1}·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}·y^{-1}		
Site	ANPP	Harvestable biomass	Mg CO$_2$·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·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·m^{-2}) from harvested grain we used the factor 0.18 (4). A total of 228.3 g grain·m^{-2} can produce 41.1 ± 0.9 g biodiesel·m^{-2} or 411.0 ± 9.0 kg biodiesel·ha^{-1}, with a biodiesel density of 0.88 g·ml^{-1} (4), bringing biodiesel production to 467.0 ± 10.2 L biodiesel·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).

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Table S5. Soil carbon concentrations (g C·kg·soil^{-1}), bulk density (BD; g·cm^{-3}) and total C pools (kg C·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·kg^{-1} soil)	25.50 (4.40)	13.70 (2.90)	6.50 (1.40)	2.50 (0.80)	
BD (g·cm^{-3})	1.29 (0.05)	1.63 (0.03)	1.74 (0.02)	1.29 (0.05)	
Total C (kg C·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·kg^{-1} soil)	10.4 (0.30)		4.2 (0.70)	1.8 (0.20)	
BD (g·cm^{-3})	1.6 (0.05)		1.7 (0.05)	1.6 (0.03)	
Total C (kg C·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: $C_{\text{accumulation}} = \frac{\text{Total } C_{\text{CRP}} - \text{Total } C_{\text{Agriculture}}}{22\text{y}}$.

[†] 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 CO$_2$e·ha^{-1}·y^{-1}			Mg·ha^{-1} dry biomass[‡]		
Scenario	Fossil fuel offset credit[*]	Net GHG balance[*]	Mg CO$_2$·ha^{-1}: foregone soil C sequestration[†]	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$_2$O 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$_2$O and CH$_4$ fluxes in the unconverted CRP grassland, 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·ha^{-1}·y^{-1} and soybean yields of 2.5 ± 0.2 Mg·ha^{-1}·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·kg^{-1} (*SI Text, Foregone Soil Carbon Sequestration and Soil Carbon Loss on Tillage*).

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

	MJ·m^{-2}·y^{-1}		
	Biodiesel energy production	Ethanol energy production[*]	CO$_2$e·MJ^{-1}: GHG emission intensity[*]
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·ha^{-1} (fossil diesel equivalents); for postconversion continuous corn, ethanol production is estimated to be 2,934 L·ha^{-1}·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 CO$_2$e·MJ^{-1} from the atmosphere.

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