Measuring and mitigating agricultural greenhouse gas production in the US Great Plains, 1870–2000

William J. Parton, Myron P. Gutmann, Emily R. Merchant, Melannie D. Hartman, Paul R. Adler, Frederick M. McNeal, and Susan M. Lutz

The Great Plains region of the United States is an agricultural production center for the global market and, as such, an important source of greenhouse gas (GHG) emissions. This article uses historical agricultural census data and ecosystem models to estimate the magnitude of annual GHG fluxes from all agricultural sources (e.g., cropping, livestock raising, irrigation, fertilizer production, tractor use) in the Great Plains from 1870 to 2000. Here, we show that carbon (C) released during the plow-out of native grasslands was the largest source of GHG emissions before 1930, whereas livestock production, direct energy use, and soil nitrous oxide emissions are currently the largest sources. Climatic factors mediate these emissions, with cool and wet weather promoting C sequestration and hot and dry weather increasing GHG release. This analysis demonstrates the long-term ecosystem consequences of both historical and current agricultural activities, but also indicates that adoption of available alternative management practices could substantially mitigate agricultural GHG fluxes, ranging from a 34% reduction with a 25% adoption rate to as much as complete elimination with possible net sequestration of C when a greater proportion of farmers adopt new agricultural practices.

Significance

The US Great Plains is a globally important agricultural region, providing both the US and world economies with grain, fiber, and meat. This region contains more than 30% of the US agricultural land area, and accounts for more than 50% of winter wheat and more than 30% of beef production in the country. The Great Plains region is located in the central United States, generally west of the 98th meridian and east of the Rocky Mountains (Fig. 1). The semiarid temperate climate of this region encompasses enormous subregional diversity, reflected in mean annual temperatures ranging from more than 20 °C in Texas to less than 0 °C in North Dakota, with annual precipitation levels ranging from 700 to 200 mm along an east-west gradient. The native vegetation is primarily grassland, with mixed-grass prairie in the east and shortgrass steppe in the west (3, 4).

Agricultural production in the Great Plains increased dramatically between 1870 and 2000, facilitated by changes in farming techniques, all of which have led to significant GHG releases. Historically, soil cultivation has represented the largest agricultural source of GHGs, producing both C (30–50% soil C losses) and nitrous oxide (N₂O) (5). N mineralization rates, enhanced by cropping, increase the N₂O released from the soil, with the application of N fertilizer causing further N₂O emissions (6). The other major sources of GHGs include CH₄ from cattle and other livestock production (7); fossil fuels used in fertilizer


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production; and C released from burning of fossil fuels by tractors, irrigation pumps, and other farm equipment.

Agricultural GHG production in the Great Plains is also tightly tied to public policy actions, primarily those of the US government. The plow-out of the plains would not have been as rapid without the Homestead Act of 1862, which distributed land at no cost to those homesteaders willing to cultivate it. In addition, the 20th century reduction in the extent of cropland (described later) was spurred by agricultural support policies that arose out of the rapid adoption of such new agricultural technologies as (i) mechanical cultivation equipment, (ii) inorganic fertilizers, (iii) pump irrigation, and (iv) new high-yielding crop varieties bred for synergy with other new inputs (22–24). This period has also seen a substantial increase in beef cattle production in the Great Plains, both in absolute numbers and as a proportion of all livestock, especially from the 1940s to the 1960s (Fig. 2D).

The dominant crops in the northern and central Great Plains are winter wheat, spring wheat, and corn. Winter wheat, sorghum, corn, and cotton are the most prevalent crops in the south (23). Dryland cropping predominates, except along the major river systems and over the Ogallala aquifer, where irrigation water is available. The amount of irrigated agricultural land increased substantially in the 1950s, and then stabilized by the 1980s, with over 15 million acres irrigated with pumped water (Fig. 24). Land was increasingly retired from crop production beginning in the 1950s, largely through enrollment in federally sponsored conservation programs. An analysis of the most recent US Census of Agriculture (through 2012) suggests that about 20% of the 1950s dryland cropping area is no longer used for that purpose, with about half of that change a result of increased irrigated cropping and about half a result of a long-term reduction in cropland. The data also show a 31% decrease in land in the Conservation Reserve Program (CRP) between its maximum in 2007 and 2012. We suspect that improved corn prices have led farmers to convert CRP land into cropland. The consequence of plowing out CRP land would be to release C from the soil and increase N\textsubscript{2}O emissions (25).

Total production for all crops was low before 1940. Production rose thereafter as farmers experienced rapid increases in corn, hay, cotton, and wheat yields from the 1940s to the 1970s; corn and hay yields have continued to grow since then (Fig. 2B). Parton et al. (6) attribute the larger crop yields to the increased use of fertilizer (Fig. 2C), new crop varieties (22), improved soil tillage practices for wheat, use of herbicides and insecticides, and the expansion of irrigation, all of which generates a yield increment of 100–300% in cotton, hay, and corn production.

Patterns of livestock raising have also changed over the past 150 y. The number of domestic animals rapidly increased from 1870 to 1900 (Fig. 2D), by which time more than 12 million beef cattle had replaced the bison herds on the Great Plains. After a period of stability from 1900 to 1935, the number of beef cattle increased by 120% from 1935 to 1970, whereas the number of horses and dairy cattle declined due to the substitution of mechanical power for horse power in agriculture and the concentration of dairies in other parts of the country. Many of these cattle reside in feedlots, a major consumer of the increasing quantities of corn and hay produced under irrigation.

Although many of the changes in agricultural practices just described were accomplished by the 1970s, change has continued, and efforts to improve agricultural productivity and efficiency are reflected in the results reported here. The previously unidentified estimates stated in this article were made using the

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**Fig. 1.** Irrigation in the US Great Plains. Counties shaded in light blue irrigated at least 25% of cropland area in 2007; in the unshaded counties, dryland cropping accounts for 75% or more of cropland (2).
farm equipment and increase both soil water storage and yields in dryland wheat systems. Currently, no-tillage cultivation is used by fewer than 15% of wheat farmers (the dominant crop) in the Great Plains (31). Recent papers suggest the previous estimates of soil C storage under no-till agriculture have been overestimated (32, 33) because most of the soil C measurements did not consider the changes to soil C below the plow zone (0- to 20-cm layer). In contrast to that finding, a recent review paper supports the results from earlier studies that show substantial increases in soil C under no-tillage cultivation for dry agricultural regions similar to the Great Plains (34, 35).

Results

GHG Fluxes by Land Use Category. Estimates of GHG fluxes related to cropping are combined from separate analyses of four agricultural land use systems (dryland cropping, irrigated cropping, land removed from crop production, and pasture land). Fig. 3 shows GHG emissions annually by land use category, with separate results for system C [positive when lost (released) and negative when sequestered (stored)], soil N2O emissions (always positive), and CH4 absorbed by the soil (always negative). The GHG fluxes for N2O and CH4 are shown as CO2-Ce fluxes using standard corrections needed to account for the differential GHG warming potentials of N2O and CH4 (N2O is 298-fold more effective than CO2, and CH4 is 25-fold more effective than CO2). System C includes soil C (>95% of total C) and live and dead plant C pools, with most of the changes in system C resulting from changes in soil C. These results are weighted to reflect the actual amount of land in each use category across the region. Because a relatively small amount of land was used for irrigated cropping or taken out of production (Fig. 3), the scale for Fig. 3 B and C is an order of magnitude smaller than the scale for the panels representing dryland cropping (Fig. 3A) and pasture (never-cropped) land (Fig. 3D).

Simulated soil GHG fluxes from dryland cropping in the Great Plains (Fig. 3A) show a steady increase in system C loss (primarily from the soil C pool) and N2O fluxes from 1900 to 1930, a result of the progressive plow-out of native prairie grasslands that culminated in most parts of the region during the 1930s. System C losses slowed after the 1930s, partly as a result of the stabilization of the amount of land in crop production and partly because the loss of soil C from cultivation markedly diminished after the first 20 y of cultivation (36). A general pattern of low-level system C sequestration began in the 1960s, resulting from a reduction in the number and intensity of soil tillage events. At the same time, however, soil N2O fluxes increased by as much as 100% due to an increase in the use of N fertilizer (Fig. 2C).

Model results for irrigated cropping systems in the Great Plains (Fig. 3B) show low levels of system C loss before the 1950s because relatively few counties irrigated before that time. Irrigated agriculture was initiated after 1950 in most areas where land had already been plowed for dryland cultivation, and thereby depleted of soil C. As irrigation became more widespread on former dryland cropping areas between the 1950s and the 1970s, both system C storage (removing GHGs from the atmosphere) and soil N2O fluxes (releasing GHGs into the atmosphere) increased dramatically (6). These increases reflect the enhancement of plant production and C inputs to the soil associated with irrigation (6, 37), as well as the expansion of irrigated land (Fig. 2A). System C storage peaked in the 1970s and then decreased as the soil C storage potential of the irrigated soils was reached. Soil N2O fluxes increased in tandem with N fertilizer application beginning in the 1950s (Fig. 2C). Irrigated cropping represents a net sink of GHGs from 1950 through the 1980s, with fluxes reaching their lowest negative values in the 1970s and then turning positive by the 1990s as the soil saturated with C and N2O fluxes continued to increase.
Simulations of the abandonment of dryland cropping (out of production; Fig. 3C) show a dramatic increase in system C storage, resulting from the accumulation of soil C with the cessation of cropping and tillage (38–40). Increases in C storage over time reflect both the restoration of grassland (perennial grasses have more root growth than annual crops) and increases in the amount of land taken out of production, particularly during the 1960s and then again with the implementation of the CRP in the 1980s (41). Restoration of native soil fertility takes 100 y or more unless fertilizer is added to the system. However, even the slow accumulation of C more than offsets soil N2O fluxes, which remain low in the restored grassland because of low soil fertility. Net GHG fluxes in this system are therefore negative throughout the period.

Modeled GHG fluxes for pasture (Fig. 3D) are neutral on the whole, with positive GHG emissions from soil N2O balanced by negative fluxes from CH4 uptake by the soil. System C fluxes vary substantially from year to year with precipitation, showing a general pattern of net C losses during dry years and net C gains during wet years. Growing season precipitation is negatively correlated with growing season maximum air temperature (42, 43). System C storage is positively correlated with growing sea-

All Sources of GHG Emissions. Fig. 4 A summarizes the results from Fig. 3. As cropping expanded from the late 19th century into the 20th century, an ever-larger quantity of GHG emissions was released into the atmosphere, peaking in the 1930s at levels as high as 35,000 Gg of CO2-Ce per year. The most prominent source of GHG emissions during this period was the loss of soil C associated with the plowing of native grasslands, a practice that had nearly ended by the early 1930s. Soil C losses diminished rapidly from 1930 into the 1950s, with soil C sequestration starting after the 1960s, as a result of both soil C stabilization in dryland systems and soil C storage in irrigated cropland and restored grasslands (cropland out of production). The cultivation of native grasslands also produced a pattern of increasing soil N2O fluxes beginning in 1900. N2O emissions rose by another 30% between 1940 and 2000 due to increased fertilizer application in irrigated and dryland cropping systems. After 1970, C sequestration in restored grasslands and irrigated cropland offset N2O emissions and produced net negative GHG fluxes in the system as a whole. This pattern of GHG sequestration was enhanced in the 1990s when above-average rainfall increased C storage in native prairie and restored grasslands.

Since the 1930s, farmers have increased plant productivity by (i) using gasoline and diesel equipment to cultivate, plant, and harvest their lands; (ii) applying synthetic fertilizer to raise crop productivity; and (iii) irrigating fields to ensure sufficient moisture for plant growth. GHG fluxes from tractor fuel peaked in the 1950s and then declined, with most energy used throughout the period for cultivation rather than planting or harvesting (Fig. 4B). The decline since the 1950s is largely due to less intensive cultivation and a shift from gasoline to more energy-efficient diesel engines. The scale of GHG fluxes from equipment is relatively small, with the peak just over 3,500 Gg of CO2-Ce per year, compared with peaks from the soil systems 10-fold as high in the 1930s (Fig. 4A). GHG fluxes from energy used for fertilizer production and irrigation pumping increased steadily after onset of use in the 1940s (Fig. 4B). Fluxes from irrigation pumping have remained constant since the 1970s, as the amount of irrigated land has stabilized and pumps have shifted from gasoline to electric power. At the same time, GHG emissions associated with fertilizer production increased rapidly from virtually nothing in the 1930s and 1940s to a peak in the late 1960s of nearly 4,700 Gg of CO2-Ce per year, followed by a slow decline to about 3,500 Gg of CO2-Ce per year in the late 1990s.

The last element in our comprehensive estimate of GHG emissions from Great Plains agriculture is the CH4 produced by the livestock sector. Overall, livestock numbers increased slowly but steadily in the area during the 20th century (Fig. 2D). The use of horses for maintaining agricultural lands decreased as tractors were adopted. In addition, the number of dairy cattle decreased as other regions of the United States began to specialize in dairy production. Nondairy cattle were quickly substituted, becoming consumers of the region’s increasing corn production. As generators of enteric and manure CH4, livestock are large and growing contributors to regional GHG fluxes (Fig. 4C).

Fig. 4D combines all of the elements discussed above into previously unidentified estimates of annual net GHG emissions from US Great Plains agriculture between 1870 and 2000 (presented numerically in Table 1). Early exploitation of the soil by agriculture (from the late 19th century until the 1930s) produced
a net positive GHG flux, peaking in the particularly dry 1930s at an average rate of 45,000 Gg of CO$_2$-Ce per year. After that time, contributions from soil systems diminished, whereas contributions from livestock increased, reaching 12,000 Gg of CO$_2$-Ce per year in the 1990s due to extensive use of the region for cattle feeding. By the 1950s, fuel consumed for irrigation, mechanized cultivation, and fertilizer production had also become an important source of net GHG emissions, at about 7,000 Gg of CO$_2$-Ce per year by the end of the century. Total GHG fluxes have decreased since the period of soil plow-out (they are now close to 12,000 Gg of CO$_2$-Ce per year) but are nonetheless steady and positive.

The uncertainty in these results is presented in SI Materials and Methods, which shows that the absolute value of the uncertainty generally increases from 1860 to 2003, with secondary uncertainty maxima from 1915 to 1935. Absolute uncertainty ranges from 239 Gg of CO$_2$-Ce per year in 1871 to 877 Gg of CO$_2$-Ce per year in 1975. Increasing absolute uncertainty after the 1950s is correlated with increases in livestock CH$_4$; soil N$_2$O emissions; and fuel consumed for irrigation, cultivation, and fertilizer production. The high uncertainty in GHG fluxes from 1915 to 1935 is associated with the high soil C losses resulting from cultivation of the soil and expansion of agriculture. The relative annual uncertainty of total GHG fluxes (annual absolute uncertainty divided by observed annual net GHG flux) ranges from 1 to 206%, with the highest relative uncertainty associated with low net GHG fluxes (values close to zero).

**GHG Reductions Using Best-Management Practices.** The combined impact of best-management practices for Great Plains farming in the 1990s (current GHG fluxes from farming) was determined by (i) assuming that no-tillage practices would lead to an additional storage of 50 g of C per m$^2$·y$^{-1}$ in irrigated cropping (29, 30) and an additional storage of 10.0 g of C per m$^2$·y$^{-1}$ in dryland cropping (27, 28), (ii) a 30% reduction in soil N$_2$O fluxes by using improved fertilizer techniques (26), and (iii) a 30% reduction in CH$_4$ (7) due to improved cattle management (the method of estimation is provided in SI Materials and Methods). Due to the uncertainty of farmer adoption rates, we made our assessments assuming a range of 25%, 50%, 75%, and 100% (44). Results (Table 2) show a 34% reduction in net GHG fluxes, with 25% of farmers adopting the new methods. Most of the reduction (60%) resulted from the use of no-tillage cultivation practices, 25% resulted from the CH$_4$ mitigation from cattle, and 15% resulted from the use of improved fertilizer. A 75% increase in farmer adoption rates resulted in a 102% reduction, whereas a 100% rate increase resulted in a 136% reduction (C sequestration).

**Discussion**

The results of this research reveal a complex picture, which is neither optimistic nor pessimistic, regarding agriculture’s contribution to net GHG emissions, especially if we look to the future. If we begin with the historical account of estimated emissions from land management (Fig. 4), the conclusion may be encouraging, suggesting that after a century of soil exploitation through cropping, the agricultural systems of the Great Plains had begun to stabilize by the 1970s, with relatively modest emissions of GHGs and the potential for C sequestration to offset soil N$_2$O emissions. However, Table 1 shows that conclusion to be inappropriate. Even if cropping systems have sequestered some C since the 1960s, all other parts of the agricultural system (including those parts that facilitated C sequestration) continue to produce net positive GHG fluxes, with the largest contributions coming from livestock production and smaller, yet nontrivial, amounts coming from equipment use, fertilizer, and irrigation. Although there is uncertainty in these estimates, that uncertainty is small compared with the historical changes in GHG fluxes over 130 y. The historical patterns described here show the important roles played by the series of technological transformations that have swept over agriculture since 1870. The patterns themselves partly reflect public policies that have altered where and how these lands have been used for agriculture. Within this human-dominated system, however, it is critical to notice the fundamental influence of climatic variation, which is apparent in Daycent model results for never-cropped land (pasture; Fig. 3D). Independent of technological change and policy impacts, when precipitation was high and temperature was low, C was stored. Conversely, when temperature was high and precipitation was low, C was released. Interannual changes in system C on pasture land ranged from a storage of 41 g of C per square meter in the wet year of 1942 to a release of 27 g of C
per square meter in the dry year of 1934. Table 1 indicates that in the 1990s, fuel (tractor and irrigation), fertilizer, and livestock in the Great Plains produced 19,263 Gg of CO$_2$-Ce of GHG emissions (Fig. 4D). Because it was a particularly wet decade, 21% of this release was absorbed by the pasture system, but results for pasture in the dry 1930s suggest that the pasture system could also increase the release of GHG emissions by the same percentage under less favorable weather conditions. Climatic changes, therefore, have the potential to alter yearly net GHG fluxes greatly.

Our results suggest that use of best agricultural management practices has the potential to reduce net GHG fluxes from the Great Plains agricultural system greatly, depending on the rate of adoption by farmers (a 34–136% reduction as rates of adoption increased from 25–100%). Most of the reduction (60%) resulted from the use of no-tillage cultivation practices, 25% resulted from the CH$_4$ mitigation from cattle, and 15% resulted from the use of improved fertilizer. The use of no-tillage cultivation has increased over the past 10 y (44), and has the potential to reduce GHG fluxes for the Great Plains greatly, because only 14% of land planted in wheat, the dominant crop, used no-tillage practices during 2008 (31). The reduction in GHG fluxes from C sequestration due to the use of no-tillage practices primarily occurs during the first 20 y following initiation of the practice; however, the GHG reductions from the use of CH$_4$ mitigation from cattle and improved fertilizer result in permanent annual reductions. These reductions from the Great Plains agricultural system could potentially contribute to the goal of the Obama administration to reduce GHG fluxes from agricultural systems in the United States by more than 25% during the next 10 y (45, 46). The technologies to implement these best-management practices are currently available; however, farmers will not adopt them unless financial incentives are offered, given the resultant cost increase for raising both crops and livestock.

This research has estimated the overall production of positive net GHG fluxes from Great Plains agriculture at about 2.9 million Gg of CO$_2$-Ce between 1870 and 2000. Although this figure is large, almost 50% of the total emissions are a result of the expansion of dryland agriculture before 1950. Clearly, the major sources of GHG fluxes have evolved over time. Before 1950, most emissions came from soil C losses related to cultivation. Currently, the majority of GHG fluxes result from livestock production and energy used by farm equipment, fertilizer synthesis, and irrigation (Table 1). As a result of these findings, this article suggests that the use of existing best-management practices could greatly reduce GHG emissions from US Great Plains agricultural systems if economic incentives were available to promote their use.

### Materials and Methods

The Daycent ecosystem model was used to estimate soil GHG fluxes associated with cropping in each of 476 Great Plains counties (19). The model is driven by county-level weather and soil data (42, 43, 47) and detailed assumptions about daily agricultural management practices. These practices include cultivation, planting, irrigation, fertilizer application, and harvesting over the simulation period, and were derived from historical documents reflecting historical changes in crop varieties, technology, and cropping techniques (37). Each major dryland and irrigated rotation system, as well as unplowed native grassland, was modeled separately, as was land removed from crop production either before or under the CRP. The model was verified and validated with yield data from national agricultural databases (19) (www.nass.usda.gov) and scaled to the county level using historical agricultural census data (20). Daycent output includes interannual change in system C and annual amounts of N$_2$O release and CH$_4$ absorption. GHG flux is calculated by converting each component to CO$_2$-Ce and summing over components. Calculation of the uncertainty in our estimates of GHG fluxes from each component of agriculture and for the total annual agricultural GHG flux in the Great Plains is detailed in SI Materials and Methods.

The assumptions about agricultural management practices that drive the Daycent model also provided estimates of historical amounts of tractor use, irrigation, and fertilizer application in each county over the simulation period. Fuel consumed during tractor use was estimated using the Agricultural Machinery Management Data from the American Society of Agricultural and Biological Engineers Standards (48, 49). Fuel consumed in irrigation pumping was estimated by combining data from the National Agricultural Statistics Service’s 2008 Farm and Ranch Irrigation Survey (50) with energy price data from the Energy Information Administration (51–53). Historical GHG emissions from methane were estimated from national inventories available from the American Electric Power System (54). Historical inventories of atmospheric nitrous oxide and N$_2$O production from the combustion of fossil fuels were estimated from the historical carbon cycle (55). Historical land-use histories were estimated from published data (56).

### Table 1. Net GHG fluxes from all sources (gigagrams of CO$_2$-Ce): Annual average by decade

<table>
<thead>
<tr>
<th>Decade</th>
<th>Pasture</th>
<th>Dryland</th>
<th>Irrigated</th>
<th>Out of production</th>
<th>Tractor</th>
<th>Irrigation</th>
<th>Fertilizer</th>
<th>Livestock</th>
<th>Total</th>
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<td>1870</td>
<td>−1,491</td>
<td>441</td>
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<td>1880</td>
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<td>8,266</td>
<td>28</td>
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<td>0</td>
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<td>0</td>
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<tr>
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<td>13,328</td>
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<td>0</td>
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<td>1900</td>
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<td>15,597</td>
<td>109</td>
<td>0</td>
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<td>0</td>
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<td>1,651</td>
<td>22,027</td>
<td>83</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>9,205</td>
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<td>31,230</td>
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<td>18</td>
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<td>455</td>
<td>55</td>
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<td>376</td>
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<td>−352</td>
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<td>1,101</td>
<td>2,527</td>
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<td>2,969</td>
<td>−872</td>
<td>−2,457</td>
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<td>1,659</td>
<td>3,960</td>
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<td>18,341</td>
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<td>1970</td>
<td>−945</td>
<td>−937</td>
<td>−1,017</td>
<td>−1,910</td>
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<td>−2,311</td>
<td>293</td>
<td>−2,919</td>
<td>1,574</td>
<td>1,890</td>
<td>3,500</td>
<td>12,300</td>
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### Table 2. Summary of mitigation best practices

<table>
<thead>
<tr>
<th>Scenario</th>
<th>System before improvements</th>
<th>Reduction from no-till</th>
<th>Improved fertilizer</th>
<th>Improved livestock feed</th>
<th>Total change</th>
<th>System total with improvements</th>
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<tr>
<td>Current practices</td>
<td>102,177</td>
<td>−20,788 (−20%)</td>
<td>−5,401 (−5%)</td>
<td>−8,604 (−8%)</td>
<td>−34,794 (−34%)</td>
<td>102,177</td>
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<tr>
<td>25% use best practices</td>
<td>102,177 (0%)</td>
<td>−20,788 (−20%)</td>
<td>−5,401 (−5%)</td>
<td>−8,604 (−8%)</td>
<td>−34,794 (−34%)</td>
<td>67,383</td>
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<td>50% use best practices</td>
<td>102,177 (0%)</td>
<td>−41,576 (−41%)</td>
<td>−10,803 (−11%)</td>
<td>−17,208 (−17%)</td>
<td>−69,587 (−68%)</td>
<td>32,590</td>
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<td>75% use best practices</td>
<td>102,177 (0%)</td>
<td>−62,364 (−61%)</td>
<td>−16,204 (−16%)</td>
<td>−25,812 (−25%)</td>
<td>−104,381 (−102%)</td>
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</tr>
<tr>
<td>100% use best practices</td>
<td>102,177 (0%)</td>
<td>−83,153 (−81%)</td>
<td>−21,606 (−21%)</td>
<td>−34,416 (−34%)</td>
<td>−139,174 (−136%)</td>
<td>−36,997</td>
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</tbody>
</table>
Potential reductions in GHG fluxes due to improved agricultural practices were estimated by taking the calculated GHG contributions by agricultural category for the 1990s and reducing them by fixed amounts of C stored from no-tillage cropping practices and by percentages of GHG flux for improved fuel use, fertilizer, and cattle management. Because we do not know the proportion of farmers who might make use of these improved practices, we then estimated the overall and agricultural category impacts on GHG fluxes assuming that 25%, 50%, 75%, and 100% of farmers would do so. A more detailed description of the methods used can be found in SI Materials and Methods.

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