# Princeton's Net-Zero America study

# Annex Q: Potential for Negative Emissions from Carbon Sequestration on US Agricultural Land


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## Introduction

Soils constitute the largest non-geologic terrestrial carbon stock on the planet, containing more carbon than exists in the atmosphere and the world's vegetation, combined. In agricultural systems in particular, soil carbon stocks are depleted relative to those under the original native ecosystems (forests, grasslands, wetlands) that were converted to agricultural use (arable cropping and grazing lands). Historically, many soil and crop management practices that were employed on agricultural lands (e.g., intensive tillage, monoculture cropping, bare fallowing, crop residue removal) were responsible for soil carbon losses. Most cropland top soils (ca. 0-30 cm depth) now contain less than 60% of their original (native) carbon stocks [1] and it's estimated that, world-wide, agricultural practices have resulted in the loss of ca. 130 billion tonnes of carbon since the origination of agriculture ca. 12,000 year ago [2].

Because of this enormous carbon 'debt' accumulated over the history of agricultural development, adoption of conservation or 'regenerative' agricultural management practices now have the capacity to rebuild much of this previous terrestrial carbon stock and in the process act to remove $CO_2$ from the atmosphere. In general, management practices that a) increase the amount of plant-fixed $CO_2$ and the amount of C added to soil via roots and plant residues, and/or b) reduce the relative rate of soil respiration and $CO_2$ release from soil organic matter (e.g. by reducing soil disturbance, reducing decomposition rates), will promote carbon sequestration and increasing soil carbon stocks.

The recent National Academies report [3] classified soil C sequestration technologies into two main categories: existing conservation practices and 'frontier technologies'. Frontier technologies included things like crop varieties with enhanced root phenotypes (i.e., larger, deeper), perennial grains, widespread utilization of biochar amendments and other approaches that are largely still in a research phase and not yet ready for widespread deployment in US agricultural systems. In contrast, existing conservation practices are relatively well understood and are being currently deployed in production agriculture (e.g., cover cropping, intensified rotations, minimum tillage, advance nutrient management, integrated crop-livestock systems) but are not widely practiced and are in an early phase of adoption. Since the assessment of carbon removal potential in this study is looking over the next 30-year time frame to 2050, we based our analysis solely on what would be achievable with widespread adoption of existing conservation management technologies, **without** considering potential future gains through deployment of frontier technologies. In addition, where the data supporting some practices – such as improved grazing systems on permanent pastures – are still relatively sparse as compared to that for annual cropping systems, for example, we chose to be conservative and not account for potential soil C removals in permanent pastures and rangelands. Ongoing research suggests that improved grazing systems may have considerable C sink capacity (M-F. Cotrufo, pers comm.), but also activity data (i.e., current baseline grazing management practices) are less well quantified and so we felt that not including C sequestration potential on permanent pasture and rangelands, at this time, was warranted in order to not risk overestimating the overall agricultural C sink capacity.

## Methods

The agricultural land carbon sink/net emission reduction potential includes managed soil carbon stock increases as well as greenhouse gas (GHG) emission reductions on croplands, agricultural land purposed for bioenergy crop production systems, pastures and rangelands, and lands set-aside from production for conservation purposes. To estimate the potential agricultural land negative emissions in 2050, we estimated the total land area available within each land use category, accounting for the bioenergy production scenarios in the net-zero emissions scenarios described in the Net-Zero America study report. We defined two mitigation scenarios, 'moderate' and 'aggressive', for achieving negative emissions on agricultural lands **not** utilized for bioenergy feedstocks.

Total baseline areas of cropland and pasture/rangeland were extracted at the county scale from the 2017 U.S. Agricultural Census [4]. The agricultural land areas that were considered as potentially contributing to soil C stock increases were grouped into four categories: 1) land currently used for corn ethanol production that could be converted to perennial grass biomass crops, 2) 'marginal' cropland and pasture that could be converted to perennial biomass feedstock crops, 3) annual cropland converted to 'within field' perennial vegetation for conservation purposes and 4) cropland remaining cropland but with adoption of soil conservation management practices.

Under the two bioenergy production scenarios analyzed, a portion of the land base in croplands and pasture were converted to bioenergy production. In the 'delimited bioenergy' scenario, only croplands currently used to produce corn grain for ethanol were converted to perennial, herbaceous biomass energy crops. The 'high bioenergy production' scenario included the same area of land converted from corn grain ethanol production in the delimited scenario, plus additional 'marginal' croplands and pastures that could be converted to biomass crops (mainly to perennial grasses but with a smaller area to woody crops), according to the most recent Billion-Ton Report [5], under their < $100/ton price scenario. In addition to land use changes to perennial biomass energy crops, we also assumed conversion of a small portion (<10%) of annual cropland to permanent herbaceous cover for conservation purposes, such as field borders, filter strips, grass waterway, riparian buffers, etc., within cropland landscapes. There are recent estimates that more than 20% of cropland in the Midwest, within an average field, has much lower productivity than other parts of the field and may often produce negative net revenues [6] and thus could be more profitably set aside as infield conservation set-asides.

Once the current and future agricultural land bases were established, we applied two mitigation scenarios on cropland remaining cropland, that assume moderate and aggressive adoption, respectively, of conservation practices demonstrated to sequester atmospheric carbon and reduce GHG emissions. Practices were chosen based on their potential to reduce emissions and the practical scalability of implementation (Table 1). Emission reduction coefficients associated with adoption of USDA-Natural Resource Conservation Service (NRCS) Conservation Practice Standards (CPS) were derived from the COMET-Planner Tool [7]. Values in COMET-Planner represent regionally-averaged soil C and GHG emissions computed with the DayCent biogeochemical simulation model within the COMET-Farm platform for field-scale GHG inventories [8]. The COMET-Planner tool reports net changes in soil carbon stocks and soil nitrous oxide emissions (as $CO_2$ equivalents) from implementation of soil conservation management practices. Negative values indicate a net reduction of GHG to the atmosphere, relative to baseline agricultural management. Emission reductions due to increases in soil carbon under consistent management may be expected to continue for approximately 20-30 years on average before reaching an equilibrium state [9]. Soil nitrous oxide emission reductions would continue indefinitely, under our assumptions of consistent management over time in baseline and conservation scenarios.

To avoid double-counting of emission reductions on lands already (currently) practicing conservation management, we removed those land areas from the future projections, to the extent possible. The 2017 Agricultural Census provides data on current use of no-till and cover crops, but does not provide data on areas under both no-till and cover crops. Because no-till is more extensively adopted than cover crops, we removed land areas already under no-till management from future projections. Similarly, we did not estimate future emission reductions for lands currently enrolled in the Conservation Reserve Program, which pays farmers for temporarily converting annual crop to perennial grass or tree cover.

To estimate emission reductions from conversion of annual croplands to perennial, herbaceous bioenergy crops, we applied the emission reduction factors from the Forage and Biomass Plantings (CPS 512) practice category in COMET-Planner. We did not estimate emission reductions or carbon sequestration on all lands, either because emissions reductions are likely near zero, or are unknown. For example, pastures converted to perennial, herbaceous bioenergy crops under the high bioenergy scenario likely do not sequester additional soil carbon as grasses since both systems have similar carbon inputs and minimal soil disturbance. Data are limited on the impacts on soil emissions of conversion of croplands and pastures to woody bioenergy crops, so carbon sequestration/emission reductions were assumed to be zero for these areas under the high bioenergy scenario.  As mentioned in the Introduction we did not assume any increases in soil C stocks on pasture/rangeland areas remaining as pasture/rangeland in the future.

*Table 1.  Summary of mitigation scenarios by land use category and the NRCS Conservation Practice Standards applied.  The two right columns are percent of land to which the standards are applied.*

| **Land Use** | **NRCS Conservation Practice Standard** | **Moderate Adoption** | **Aggressive Adoption** |
|---|---|---|---|
| Croplands Remaining Croplands | | *Percent Land Area* | |
| Humid climates | No-Till (CPS 329) + Cover Crops (CPS 340) | 50 | 100 |
| Dry climates | No-Till on Irrigated Croplands (CPS 329); Conservation Crop Rotation (CPS 328) on Non-Irrigated Croplands | 50 | 100 |
| Croplands Converted to Permanent Herbaceous Cover | Conservation Cover (CPS 327) | 5 | 10 |
| Cropland Converted to Biomass Energy Crops | | | |
| Delimited Scenario | Forage and Biomass Plantings (CPS 512) | 100 | 100 |
| High Scenario | Forage and Biomass Plantings (CPS 512) | 100 | 100 |

## Results

Under the scenario with aggressive adoption of conservation management in agricultural lands and conversions to bioenergy feedstock production, we estimated an approximate overall greenhouse gas emission change of -234 million metric $tCO_2e\ yr^{-1}$ (Table 2). We predict very similar rates of GHG reduction between the delimited and high bioenergy sub-scenarios with the aggressive adoption assumption, because the cropland areas converted to bioenergy crops are relatively small compared to the total cropland land base. On average across the U.S., we estimate a GHG emission change of -1.47 t $CO_2e\ ha^{-1}\ yr^{-1}$ (0.59 t $CO_2e\ ac^{-1}\ yr^{-1}$) relative to current agricultural management.

Moderate adoption of conservation practices is predicted to reduce total emissions by 133 million metric $tCO_2e\ yr^{-1}$ in the delimited bioenergy scenario and 141 million metric $tCO_2e\ yr^{-1}$ in the high bioenergy scenario.

*Table 2. Total land areas impacted by land use conversions and adoption of conservation management practices and resulting total net CO2e emission changes (as negative emissions). Note pasture/rangeland area with unchanged land use are included in the table but no net C removals are assumed.*

| **Agricultural Land Use** | **Delimited bioenergy** | | **High bioenergy (B+)** | |
|---|---|---|---|---|
| | Million hectares | Million $tCO_{2e}$/yr | Million hectares | Million $tCO_{2e}$/yr |
| ***Aggressive Adoption Scenario*** | | | | |
| Corn Ethanol Converted to Herbaceous Biomass Crops | 11 | -23 | 11 | -23 |
| Other croplands converted to | | | | |
| perennial energy grasses | 0 | 0 | 10 | -16 |
| woody energy crops | 0 | 0 | 1 | *not estimated* |
| permanent herbaceous cover | 13 | -7 | 12 | -7 |
| Pasture Converted to Biomass Crops | 0 | 0 | 15 | *not estimated* |
| Croplands Remaining Croplands | 136 | -204 | 127 | -189 |
| Pasture/Rangeland | 155 | *not estimated* | 140 | *not estimated* |
| **Total** | **315** | **-234** | **315** | **-234** |
| | | | | |
| ***Moderate Adoption Scenario*** | **Delimited bioenergy** | | **High bioenergy (B+)** | |
| Corn Ethanol Converted to Herbaceous Biomass Crops | 11 | -23 | 11 | -23 |
| Other croplands converted to | | | | |
| perennial energy grasses | 0 | 0 | 10 | -16 |
| woody energy crops | 0 | 0 | 1 | *not estimated* |
| permanent herbaceous cover | 6 | -4 | 6 | -3 |
| Pasture Converted to Biomass Crops | 0 | 0 | 15 | *not estimated* |
| Croplands Remaining Croplands | 71 | -106 | 66 | -99 |
| Pasture/Rangeland | 155 | *not estimated* | 140 | *not estimated* |
| **Total** | **167** | **-133** | **179** | **-141** |

Rates of net negative emissions per unit area, generally follow climate patterns in the US, with higher rates predicted in humid climates or irrigated systems (upwards of 4 t $CO_2e\ ha^{-1}\ yr^{-1}$), and lower rates predicted in drier climates under rain-fed conditions (< 1 t $CO_2e\ ha^{-1}\ yr^{-1}$) (Figure 1). When applied to agricultural lands, we see the highest potentials for carbon sequestration and

GHG emission reductions in the rain-fed (largely non-irrigated) croplands of the northern Great Plains, Midwest, and Mississippi Delta regions and irrigated croplands in the west (Figure 2).

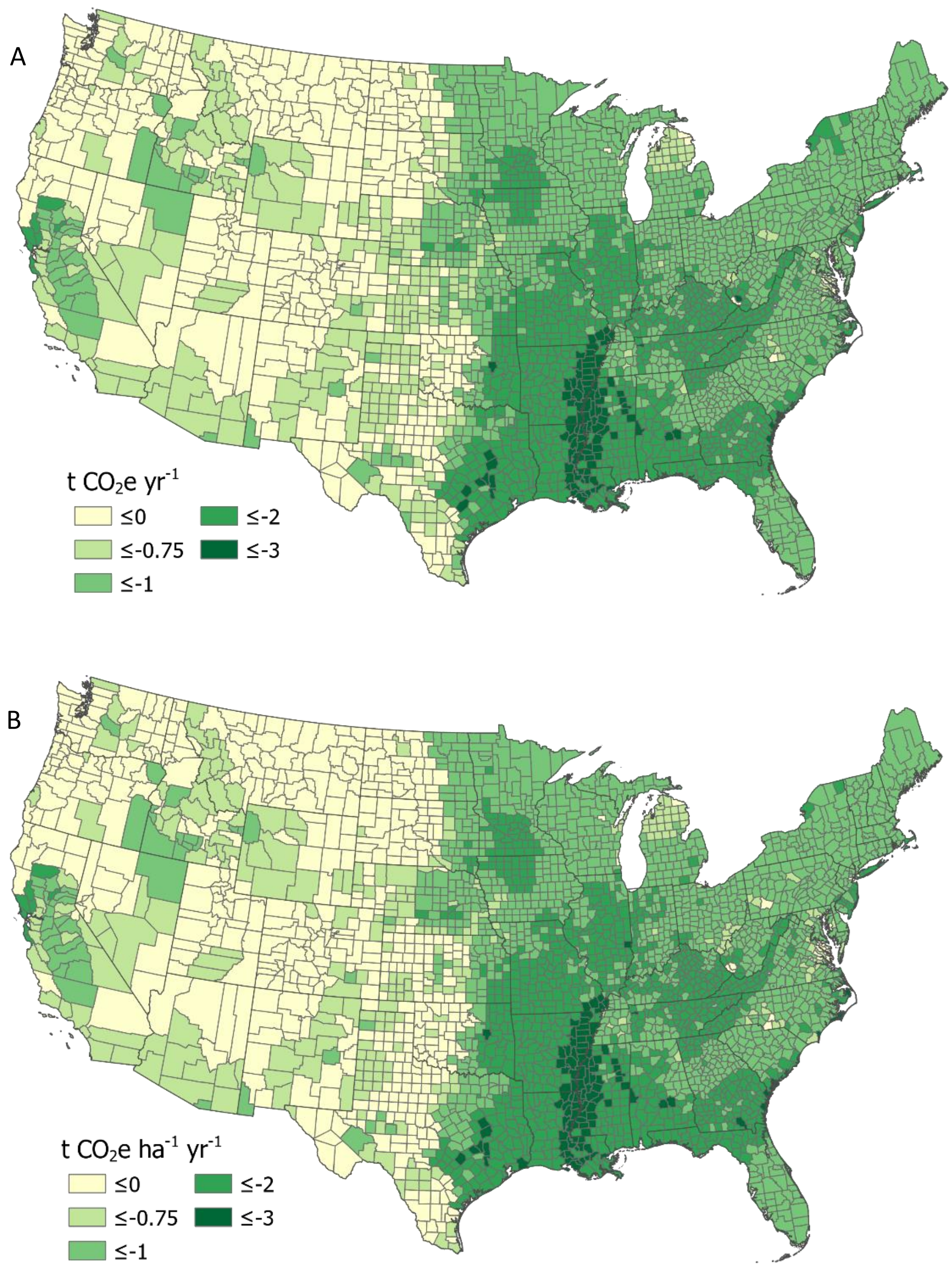


*Figure 1. Per unit area rates of net negative emissions (in t $CO_2e$ $ha^{-1}$ $yr^{-1}$) for all agricultural land uses (excluding pastures and rangeland) at the county scale for the high bioenergy and aggressive adoption scenario (A) and delimited bioenergy and aggressive adoption scenario (B). Negative emissions are relative to the baseline emission/removals.*

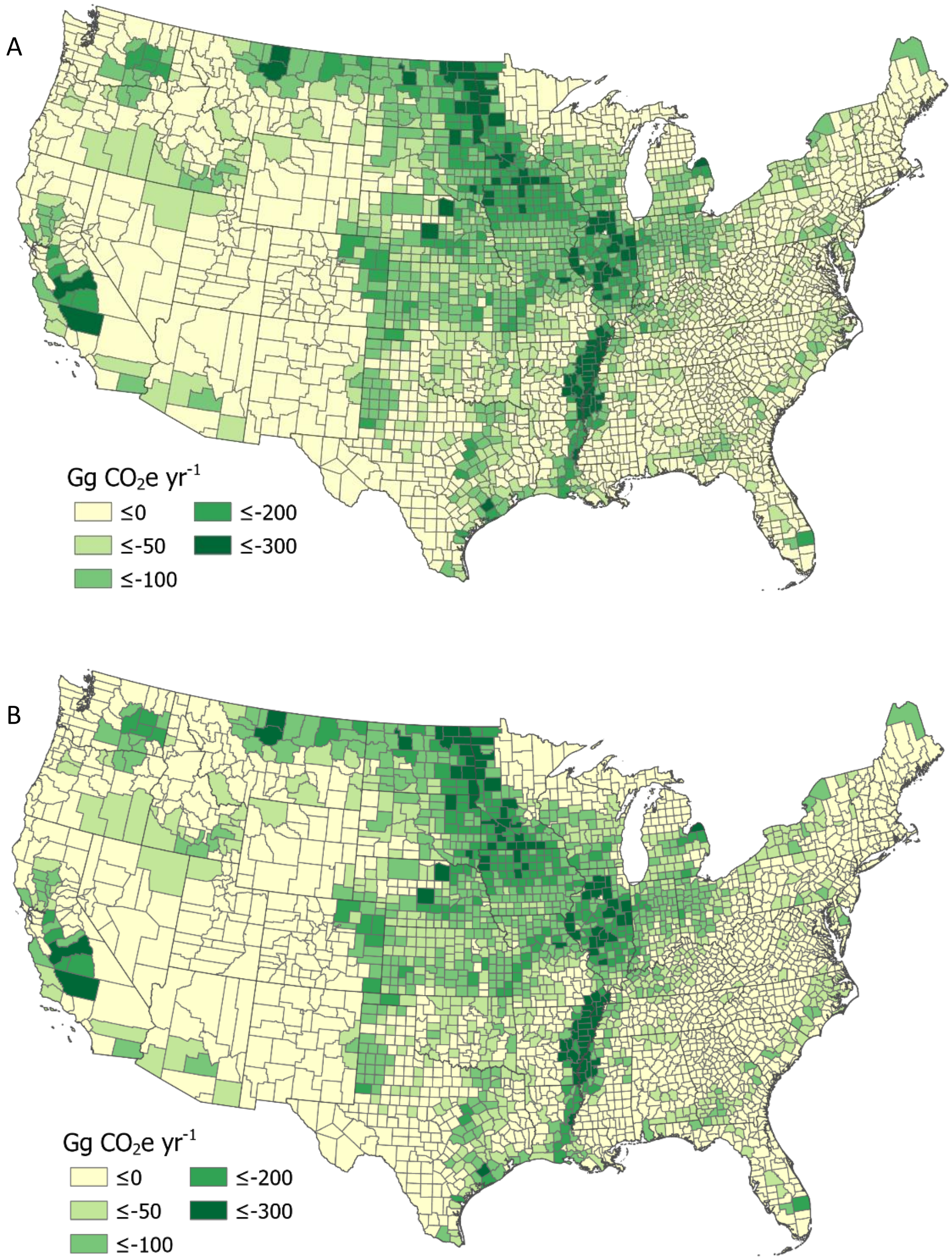


*Figure 2. Net negative emissions totaled at county scale (in Gg $CO_2e$ $yr^{-1}$ or $10^3$ t $CO_2e$ $yr^{-1}$) across all agricultural land uses, for the high bioenergy and aggressive adoption scenario (A) and delimited bioenergy and aggressive adoption scenario (B). Negative emissions are relative to the baseline emission/removals.*

Conversion of corn grain ethanol and other croplands to perennial energy grasses is estimated to reduce emissions by 36 MMT $CO_2e$ $yr^{-1}$, representing about 15% of total emission reductions under the high bioenergy/aggressive adoption scenario. Geographically, most of the perennial energy grass conversions are predicted to be in the Midwest due to higher existing ethanol corn production, with smaller areas spread throughout the eastern US (Figure 3).

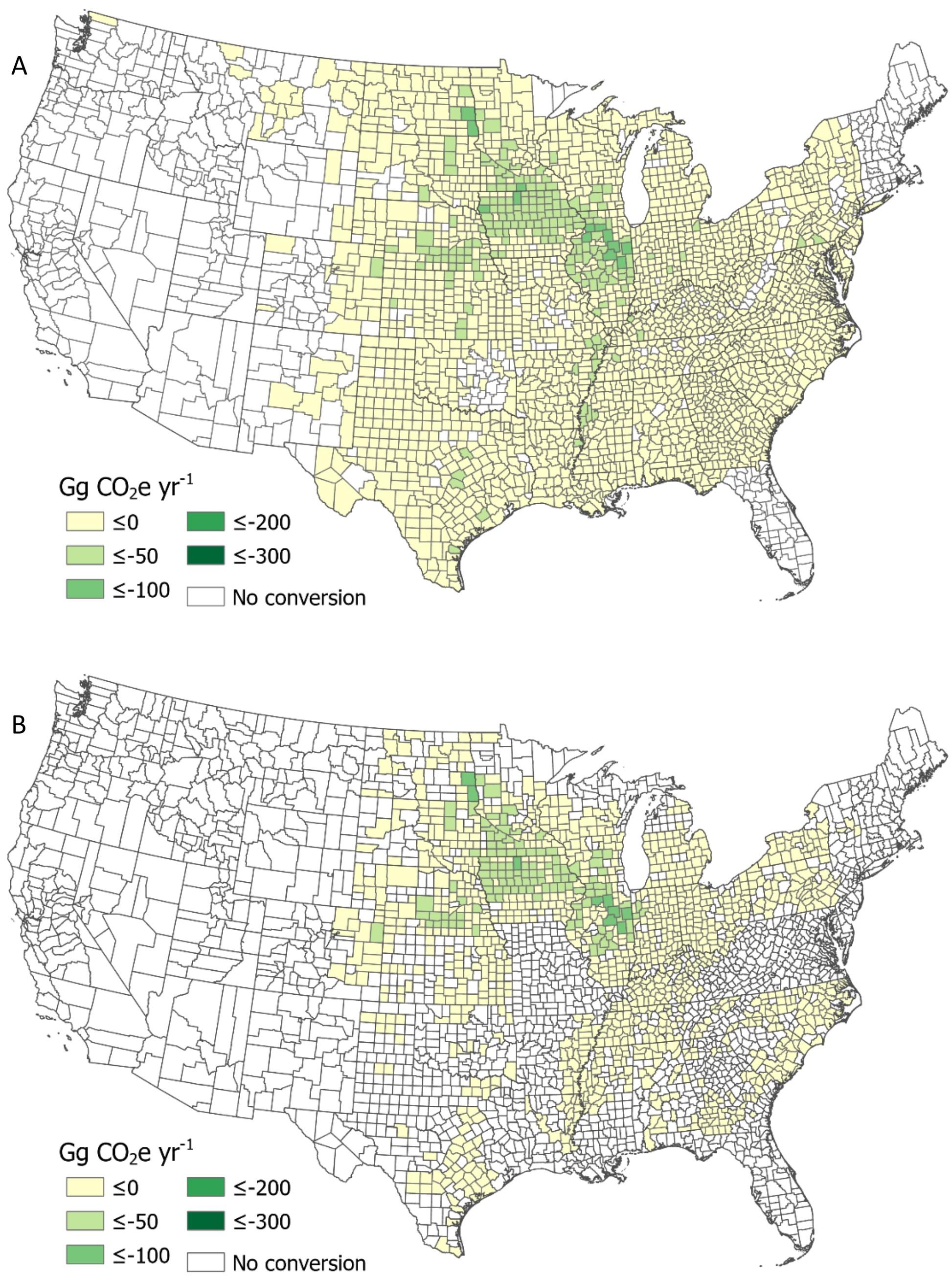


*Figure 3. Total greenhouse gas emission changes (in Gg $CO_2e$ $yr^{-1}$ or $10^3$ t $CO_2e$ $yr^{-1}$) due to conversion of corn grain ethanol and other croplands to perennial energy grasses at the county scale for the high bioenergy and aggressive adoption scenario (A) and delimited bioenergy and aggressive adoption scenario (B).*

When aggregated at the state level, Midwestern states such as Illinois, Iowa and Minnesota were predicted to have the highest emission reductions (Figure 4 and Table 3). These same regions also had the highest rates of ethanol-corn and other cropland conversion to perennial energy grasses.

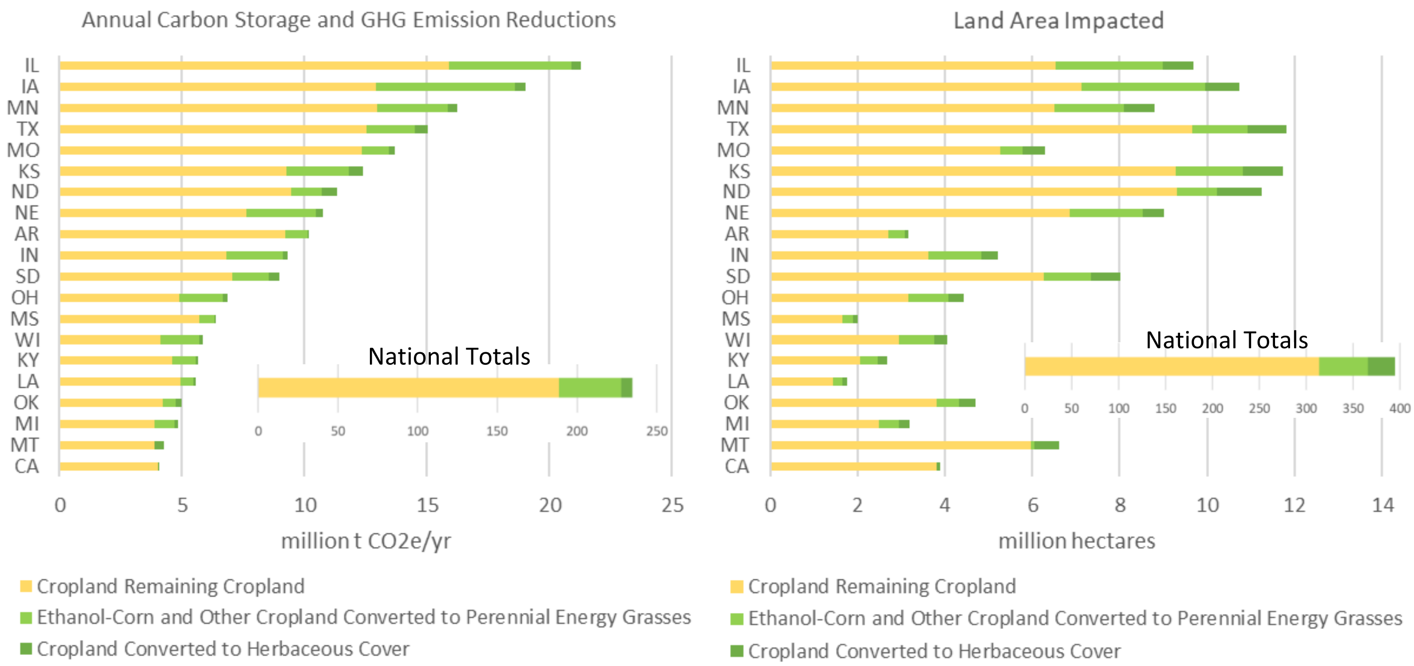


*Figure 4. State level totals for annual carbon storage and greenhouse gas emission reductions (left) and total acres impacted (right) for top states for the high bioenergy and aggressive adoption scenario.*

*Table 3. Total carbon storage and greenhouse gas emission reductions and area impacted by state for the delimited and high bioenergy scenarios, with aggressive conservation adoption.*

| | **Delimited bioenergy** | | **High bioenergy (B+)** | |
|---|---|---|---|---|
| State | Million hectares | Million $tCO_2e/yr$ | Million hectares | Million $tCO_2e/yr$ |
| AL | 1.1 | 2.3 | 1.1 | 2.3 |
| AR | 3.2 | 10.4 | 3.2 | 10.2 |
| AZ | 0.5 | 0.5 | 0.5 | 0.5 |
| CA | 3.9 | 4.1 | 3.9 | 4.1 |
| CO | 4.5 | 3.0 | 4.5 | 3.2 |
| CT | 0.1 | 0.1 | 0.1 | 0.1 |
| DE | 0.2 | 0.3 | 0.2 | 0.3 |
| FL | 1.1 | 2.1 | 1.1 | 2.1 |
| GA | 1.8 | 3.9 | 1.8 | 3.8 |
| IA | 10.7 | 18.8 | 10.7 | 19.0 |
| ID | 2.4 | 2.0 | 2.4 | 2.0 |
| IL | 9.7 | 21.8 | 9.7 | 21.3 |
| IN | 5.2 | 9.6 | 5.2 | 9.3 |
| KS | 11.8 | 11.6 | 11.7 | 12.4 |
| KY | 2.7 | 5.5 | 2.7 | 5.7 |
| LA | 1.8 | 5.7 | 1.8 | 5.5 |
| MA | 0.1 | 0.1 | 0.1 | 0.1 |
| MD | 0.6 | 0.6 | 0.6 | 0.7 |
| ME | 0.2 | 0.3 | 0.2 | 0.3 |
| MI | 3.2 | 5.0 | 3.2 | 4.8 |
| MN | 8.8 | 16.7 | 8.8 | 16.3 |
| MO | 6.3 | 13.8 | 6.3 | 13.7 |
| MS | 2.0 | 6.5 | 2.0 | 6.4 |
| MT | 6.6 | 4.3 | 6.6 | 4.3 |
| NC | 2.0 | 3.3 | 2.0 | 3.3 |
| ND | 11.3 | 11.3 | 11.3 | 11.3 |
| NE | 9.0 | 10.7 | 9.0 | 10.8 |
| NH | 0.0 | 0.1 | 0.0 | 0.1 |
| NJ | 0.2 | 0.3 | 0.2 | 0.4 |
| NM | 0.7 | 0.5 | 0.7 | 0.5 |
| NV | 0.3 | 0.2 | 0.3 | 0.2 |
| NY | 1.7 | 2.7 | 1.7 | 2.7 |
| OH | 4.4 | 6.9 | 4.4 | 6.9 |
| OK | 4.7 | 4.8 | 4.7 | 5.0 |
| OR | 1.9 | 1.2 | 1.9 | 1.2 |
| PA | 1.9 | 2.5 | 1.9 | 2.6 |
| RI | 0.0 | 0.0 | 0.0 | 0.0 |
| SC | 0.8 | 1.4 | 0.8 | 1.4 |
| SD | 8.0 | 9.0 | 8.0 | 9.0 |
| TN | 2.1 | 3.7 | 2.1 | 3.9 |
| TX | 11.9 | 14.5 | 11.8 | 15.1 |
| UT | 0.7 | 0.4 | 0.7 | 0.4 |
| VA | 1.2 | 1.9 | 1.2 | 2.0 |
| VT | 0.2 | 0.3 | 0.2 | 0.3 |
| WA | 3.0 | 2.1 | 3.0 | 2.1 |
| WI | 4.1 | 6.0 | 4.1 | 5.9 |
| WV | 0.4 | 0.5 | 0.4 | 0.5 |
| WY | 1.0 | 0.8 | 1.0 | 0.8 |

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