Scenarios for low carbon corn production

Modeled results for 35 farms in the southwest Minnesota feedstock shed for a corn-based biorefinery

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Executive summary

In 2011, researchers at the University of Minnesota collected and analyzed detailed survey data from over 40 farms that had been suppliers to an ethanol biorefinery in Luverne, MN. That study clearly demonstrated the importance of characterizing individual farm performance, which varied tremendously based on specific farm management practices.

In this follow-on study, we conduct "cyber experiments" on 35 of these farms to assess the effect of key management strategies on the net carbon footprint of the corn grain produced on these farms. Included in the net carbon footprint are modeled estimates for soil carbon and soil nitrogen emissions (expressed as grams of CO2 equivalents per kilogram of grain) and life cycle greenhouse gas emissions associated with major inputs for each farm (fertilizer, chemicals, fuel, etc.).

Our results illustrate the critical importance of tilling practice and nitrogen application rate in reducing the carbon footprint of the grain harvested and delivered to the biorefinery (see Figure 1).

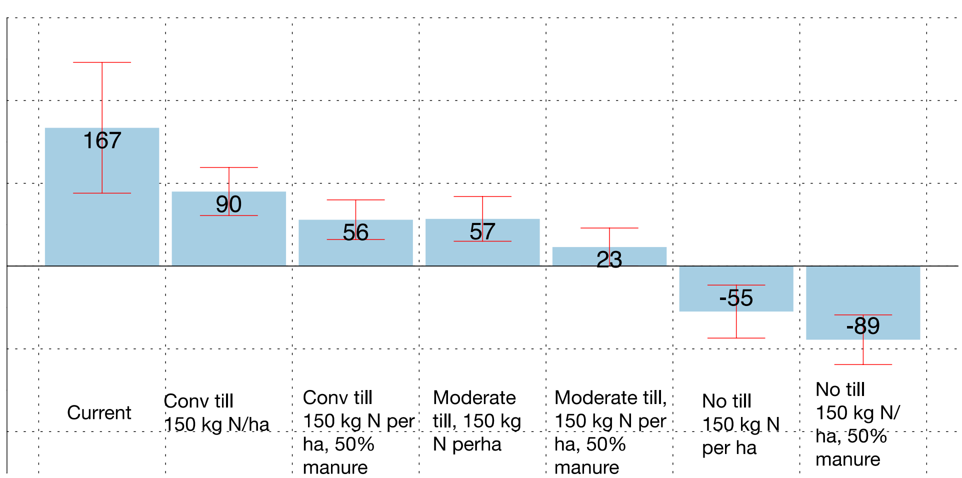

Figure 1. Average net carbon footprints of surveyed farms as a function of tillage[1], nitrogen usage rate and animal manure utilization. Error bars represent one standard deviation from the mean value.

Supplying half of the fertilizer in the form of animal manure has significant benefits as well, but the major benefit appears to be enhanced soil carbon sequestration associated with the use of no till practices.

The current mix of practices on the surveyed farms results in a farm-averaged net carbon footprint of 167 grams of CO2 per kg of grain harvested. We found that simply backing off on nitrogen application rate from the current average level of 225 kg per hectare (ha) to 150 kg per ha could reduce the net carbon footprint by 46% (from 167 to 90 gCO2 per kg) with no effect on yield—even under conditions of conventional tillage. Use of manure to supply half of the farm's fertilizer demand reduces the average net carbon footprint of these farms by 66% to 56 gCO2eq per kg of grain.

More importantly, we found that adoption of no till practices could turn these farms from net carbon sources to net carbon sinks. While we model standard no till operations, it is more likely that these farmers would use something akin to strip till practices in which a narrow strip of residue is cleared from where the seeds are planted. From a carbon management perspective, this type of tillage has the same effect on carbon accumulation as the no till practice we modeled. Under no till operation and under the reduced nitrogen application rate of 150 kg per ha, these farms provide a net reduction of 56 grams of CO2eq per kg, and reach a net reduction of almost 90 grams CO2eq per kg when half of the fertilizer demand is met with animal manure.

[1] Model results include conventional approaches to no till operations, though (due to climate conditions in Minnesota) it is likely that farmers would use a functionally equivalent form of no till known as strip till which promotes faster plant establishment.

Finally, a preliminary look at the potential impact of collecting and using residue (corn stover) suggests that: 1) it is possible to remove as much as 50% of the stover without causing a loss in soil organic matter, and 2) if the stover is used as an energy source to replace natural gas, its fossil carbon savings per kg of harvested grain are huge. Collection and use of stover for heat and/or power generation (either in a biorefinery or other applications) is not, however, widely practiced commercially.

This preliminary analysis captures only a small fraction of the total number of scenarios that have been modeled to date. The purpose of this report is establish the magnitude of the impact associated with farm management changes, and, based on that impact, to decide whether more comprehensive optimization of farm operations is worth pursuing. We conclude that the benefits of better farm management in the form of significantly reduced carbon footprints are potentially very high, and recommend that a more comprehensive assessment be carried out.

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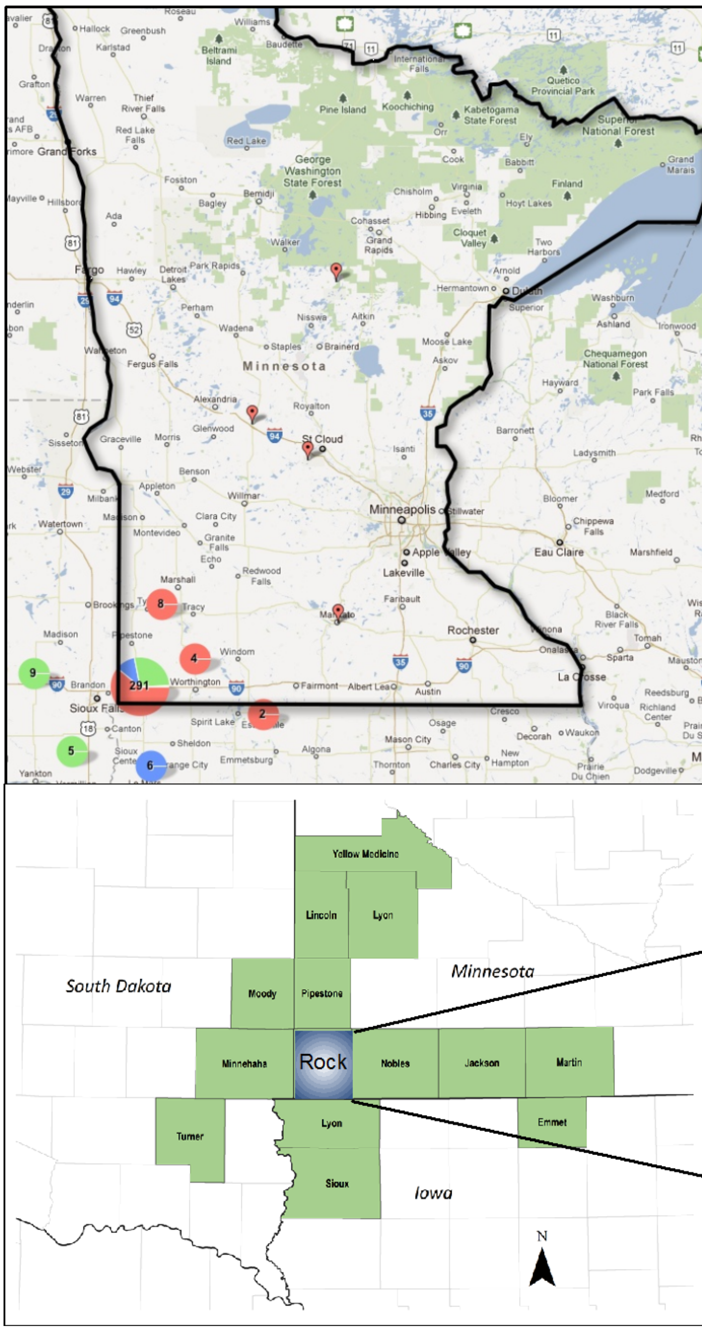
Figures

Farms modeled in this study

As part of a previous study (Sheehan et al, 2013), researchers at the University of Minnesota sent out over 300 surveys to farms that were listed as suppliers to a former 20 million gallon per year ethanol plant located in Luverne, MN.



County	Response*
Rock (MN)	32
Lyon (IA)	2
Yellow Medicine (MN)	1
Nobles (MN)	6
Lincoln (MN)	1
Turner (SD)	1
Minnehaha (SD)	2
Sioux (IA)	1
Pipestone (MN)	2
Martin (MN)	1
Jackson (MN)	1
Emmet (IA)	1
Moody (SD)	1
total	52

*more than one answer per farmer

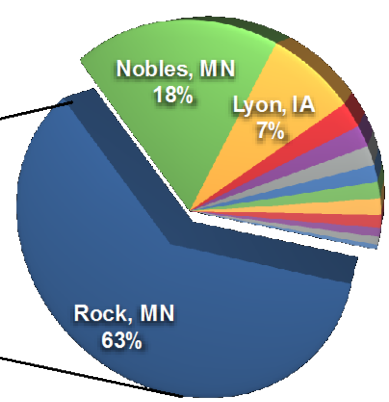


Figure 2. Farms surveyed by the University of Minnesota

Figure 2 shows the distribution of farmers who were requested to fill out the survey. As the map shows, 291 of the farms were within a close radius of the Luverne-based ethanol facility, with a handful of farms located in South Dakota and Iowa. Fifty one farmers actually responded. After a careful process of quality control, we winnowed down these responses to a set of 43 farms that had provided reliable data on all or most of the questions asked. This represents about a 13% response rate, which is considered quite high for such surveys. Total grain output of the surveyed farms represents about half of the total supply for the biorefinery.

A subset of 35 farm surveys had sufficient data to use for modeling soil carbon and soil nitorgen emissions (see model description below). The previous study established the baseline carbon footprint for each farm based on modeled estimates of their current soil emissions and on life cycle emissions associated with reported inputs for fuel, fertilizer and chemicals.

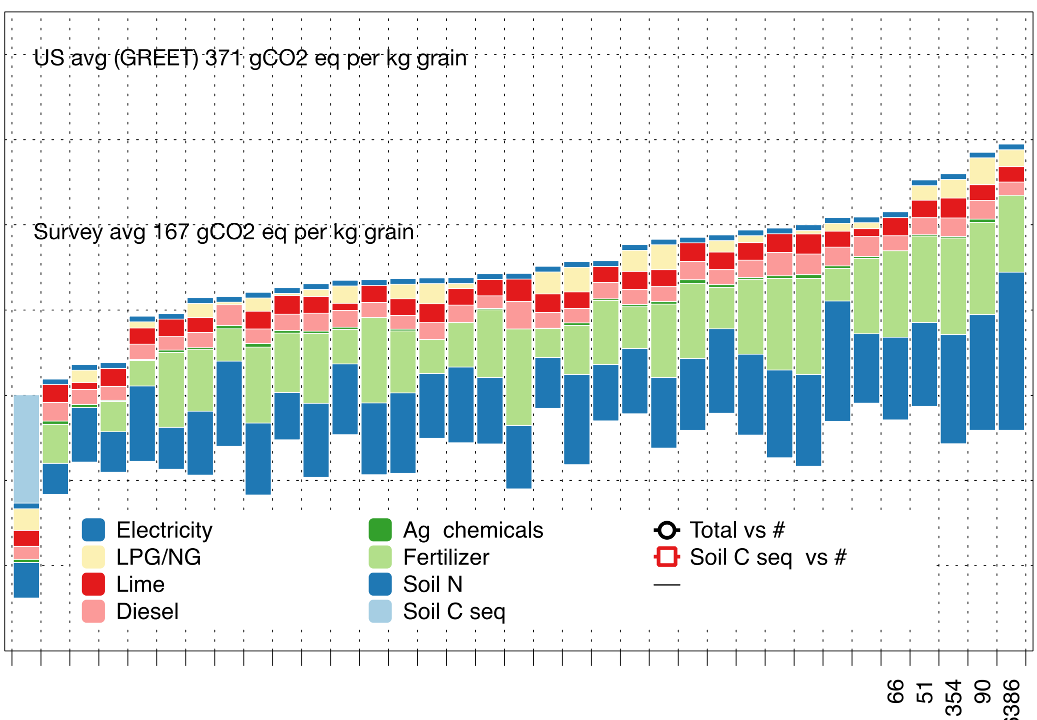


Figure 3. Baseline carbon footprints for 35 farms surveyed in 2011. Arbitrary ID numbers were assigned to each farm (as shown on the x-axis).

Their baseline carbon footprints are summarized in Figure 3. The farms have been ordered from lowest to highest net carbon footprints. A few observations are worth noting. First, all of the farms surveyed have net carbon footprints that are lower than the average US carbon footprint as estimated by Argonne National Laboratory using its GREET model. One explanation for the consistently lower footprint of this group of farmers is that they achieve yields that are substantially higher than the national average. For the period of 2008 to 2010—the years covered by the survey—US corn yields averaged 158 bushels per acre, while yields in Rock County and for this subgroup of farmers were 183 and 193 bushels per acre, respectively.

Second (and more importantly), the farm-to-farm variability among the 35 farms is extremely high. The best of these farms has a net negative carbon footprint of almost 250 gCO2eq per kg, while the worst of the farms has a net positive footprint of around 300 gCO2eq per kg. It is this diversity among the surveyed farmers that prompted our interest in more carefully identifying which farm management practices had the greatest influence on the carbon footprint of each farm.

Third, the largest contributors to the carbon footprint are soil N2O emissions and fossil CO2 emissions associated with fertilizer production. Soil N2O emissions occur as a result of microbial conversion of nitrogen present in the soil that has been fixed naturally from the atmosphere or has been added to the soil in the form of fertilizer or manure. N2O is a potent greenhouse gas—almost 300 times more potent than CO2. This points to the need for efficient and frugal use of nitrogen fertilizer.

Modeling soil emissions

Greenhouse gas emissions from crop land soil on each farm were estimated by researchers at Colorado State University using the DailyDayCent model, the latest version of the DayCent model ((Parton et al., 1998, Del Grosso et al., 2000). DayCent is a general biogeochemical model that simulates daily fluxes of carbon and nitrogen among the atmosphere, vegetation, and soil. The model simulates plant growth, decomposition and soil organic matter dynamics, mineral nitrogen transformation and soil water and temperature dynamics for cropland, grassland, forest and savanna ecosystems. DayCent is used by a number of research groups world-wide and is used for the US national GHG inventory (Del Grosso et al. 2010, EPA 2012). Note that our ability to predict and understand soil carbon dynamics is constantly evolving. Debates in this regard continue, in particular with respect to our understanding of how tilling practices affect soil carbon pools at depths below 30 cm. The soil carbon changes estimated by DayCent are limited to a depth of 30 cm. Nevertheless, there is good evidence in the literature to suggest that soil carbon changes in this upper layer are the most important and that the benefits of low and no till systems predicted by DayCent are consistent with real world experience (see Box 1 entitled "Soil carbon dynamics").

Box 1—Tillage impacts on soil carbon dynamics

Reducing the amount and intensity of soil tillage – particularly the use of no-till – helps increase carbon (C) storage in soil by reducing the turnover rate of soil organic matter in the upper layers of the soil where disturbance by tilling occurs, and by increasing the stabilization of organic matter in soil aggregates (Six et al. 2000, Ogle et al. 2012). Additional benefits of no-till and other conservation tillage include reduced soil erosion, increased water storage and decreased fuel use (Peterson et al. 1998, West and Marland 2002). This increased C storage along with reduced fuel consumption by machinery acts to reduce the' net carbon footprint' of no-till systems.

Numerous publications and meta-analysis of long-term field experiments demonstrate that, in most cases, conversion of intensively tilled soils to no-till increases net soil C storage in soils (e.g., Paustian et al. 1997, West and Post 2002, Ogle et al. 2005, Eagle et al. 2012, Franzluebbers 2010). Increases in soil C stocks with no-till adoption are generally restricted to surface soil layers (e.g. top 20 cm) and average net soil C storage rates for US croplands are typically in the range of 0.2 – 0.5 Mg C ha^{-1} yr^{-1} (Johnson et al. 2005, Franzluebbers 2010, Eagle et al. 2012). The soil carbon benefits estimated in this report fall within this range. However, changes in soil C storage due to changes in tillage can vary considerably for different soils and locations, depending a number of variables including climate, soil texture, plant productivity and previous land use history. Furthermore, in some soils, increases in C storage in surface layers may be offset by higher C stocks deeper in the profile under tilled systems, yielding little or no net increase in soil C due to no-till (Anger and Eriksen-Hamel 2007). A lack of C increase under no-till is most likely for soils having already high C contents in the surface layers (Gregorich et al. 2009), such that there is little capacity to stabilize additional soil C (Six et al. 2002, Stewart et al. 2008) or in systems where crop productivity is less under no-till (compared to conventional practices) such that less C in crop residues is being returned to the soil (Ogle et al. 2012).

Soil types reported in the original farm surveys were used whenever possible to pull texture data from county soils survey reports. When soil types reported in the surveys were vaguely described or were of a type not found in the county soil surveys a comparable soil series was used. Where no data on parcel soil was available the dominant soil in the county was used. All soils were simulated as non-hydric soils.

The plant growth submodel in Daycent was calibrated to more accurately reproduce reported yields for the 2008-2010 period for the surveyed farms as well as longer-term yields reported by USDA NASS for Rock County, MN. The fit to county and farm level yields is shown in Figure 4.

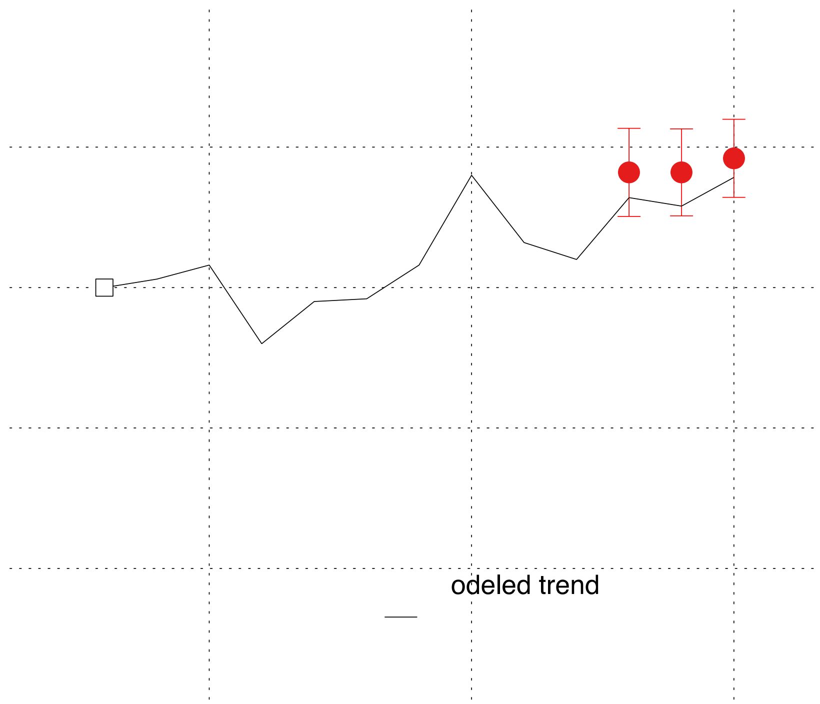


Figure 4. Comparison of modeled and reported yield data from 1998 to 2010. The red circles are average yields for the surveyed farms. Error bars reflect minimum and maximum values in the actual and modeled yield results for the surveyed farms. Black squares are USDA NASS reported yields for Rock County, MN

Each management scenario on each farm is modeled for 30 years. In other words, the specific assumptions for tillage, planting, fertilizer use and other pertinent parameters are introduced in 1979, and these conditions are maintained through 2009. This provides model output on 30 rotations of corn in the case of continuous, but only 15 rotations in alternating years for the corn-soy rotation. The last corn-soy rotation occurs in 2008. Historical climate data is based on weather files obtained from NOAA's North American Regional Reanalysis (NARR) weather database, which has gridded daily weather data, were based on county centroids. Initial analysis of these data for the study area showed some bias compared to data from other sources, including a data set from University of Minnesota, and therefore the precipitation values in these NARR weather files were adjusted to more closely match reported historical records.

Farm management permutations for soil modeling

Table 1 summarizes the management parameters that were modeled using DayCent, along with the range of values and assumptions included. Continuous corn is not common in the US, though the economics of the corn markets have led many farms to plant multiple years of corn between soy plantings. In our baseline modeling, carried out previously, 2008-2010 crop rotation information led us to model a simple corn-soy rotation. In this study we modeled rotation extremes, continuous corn and a corn-soy rotation. For timing of nitrogen fertilizer application, "N at plant" refers to application of all fertilizer at planting. "Split N" refers to a scenario in which half of the fertilizer is applied at planting, and the remainder is applied one month later. In the "Fall N" scenario, all fertilizer is applied in the Fall season prior to planting of corn. Ten kg N per ha of starter fertilizer is applied at soy planting.

The three tillage levels simulated correspond approximately to the following field management practices:

- Conventional-till: plowing, heavy disking and other substantial disturbances to soil surface, most crop residues are buried.
- Reduced-till: moderate soil disturbance from various implements, reduces soil disturbance and burial of residues relative to conventional-till practices.

- No-till: only soil disturbance is due to planter and herbicide/pesticide applicators, most crop residues are left on soil surface.

Minnesota farmers are more likely to use strip tilling rather than the standard no till practice modeled in this study. In terms of carbon management, strip till is functionally the same as standard no-till. Strip till operations clear a narrow strip of residue from the soil where planting occurs. This maintains a high degree of residue cover and very little soil disturbance. While there is no difference in soil carbon response between no till and strip till, strip till ensures better plant establishment in colder climates.

Table 1. Farm management scenarios

Parameter	Description	Values	Number of cases
Rotation	Year to year choice of crops	• Continuous corn • Corn-soy rotations	2
Nitrogen fertilizer timing	Timing of nitrogen fertilizer application	• N at plant • Split N • Fall N	3
Nitrogen rate	Kg per hectare of nitrogen applied	• 5, 10, 15, 20, 25	5
Manure use	Fraction of nitrogen supplied by manure	• 0, 0.2, 0.4 and 1.0	4
Tillage	Field preparation	• Conventional till • Reduced till • No till	3
Nitrification Inhibitor	Use of chemical to retard microbial nitrification in the soil	• Use of inhibitor • No inhibitor	2
Stover removal	Fraction of above ground crop residue removed	• 0, 0.25, 0.5, and 0.75	4
Total permutations	Number of scenarios per farm		2,880

Farm management scenarios for full carbon footprint

In this preliminary evaluation, we present results for a limited subset of management scenarios. Based on a more detailed assessment of the results for a single farm (see section entitled "A closer look at a single farm"), we focused on the set of conditions described in Table 2.

Table 2. Choices and justification for farm management scenarios considered for full carbon footprint analysis in this report

Parameter	Justification and range of values
Crop rotation	Corn-soy in alternating years. While our model results show that a continuous corn rotation leads to more rapid build up of soil carbon, we assume that continuous monocultures are more susceptible to pest and disease and would be considered less sustainable than a system in which corn is rotated with at least one other crop. Future work may include analysis of the effect of continuous corn rotations on soil carbon and carbon sequestration.
Tillage	Conventional, reduced and no till.
Fertilizer source	All industrial fertilizer vs. 50% animal manure. The manure case ignored soil carbon benefits associated with organic carbon contained in the manure, as this effect appears to be small and the uncertainty about values for carbon content is high. Instead, the effect of manure was measured in terms of avoided fossil inputs associated with the displaced industrial fertilizer associated with each farm.
Nitrogen timing	All cases are assumed to be split N. This parameter shows only a small effect on carbon footprint.
Nitrification inhibitor	All cases are assumed to include the use of a nitrification inhibitor. This parameter shows only a small effect on carbon footprint.
Nitrogen rate	Fixed at 150 kg per ha based on minimum rate required to maintain maximum yields.
Time frame	While the DayCent model was run for thirty years, we evaluate the emissions associated with the simulation year 2008 in order to be able to compare our results with the 2008-2010 data reported by farmers and used our previous study. The dynamics of soil carbon emissions are such that they decline in magnitude over time after introduction of a change in management. Focusing on the final year of the corn rotation

minimizes the effect of large changes at the start of a model run that are associated with the short term dynamic response. In addition, by focusing on 2008, we capture the effect of improvements in yield over time (see Figure 4). Future work will consider the sensitivity of the results to the choice of time frame.

Life cycle emission estimation

Life cycle greenhouse gas emissions associated with farm inputs is based on analysis described in our previous report (Sheehan et al 2012). Life cycle emissions are based on modeling results using SimaPro™ life cycle assessment software. The inputs for each farm are adjusted to reflect changes in fertilizer application rate and manure substitution in each scenario. We assume that each farm continues to use the type and mix of fertilizers specified in their respective surveys. Likewise, soil emissions for the new scenarios are used in lieu of the baseline emissions for each farm reported previously. We do not account for changes in fossil energy (diesel fuel) use associated with changes in tilling practices. Diesel fuel use reported in the farm surveys are assumed to remain the same. This is a refinement in the analysis that should be considered for future work, but (as Figure 3 suggests) diesel fuel use is a relatively small contributor to the farms' carbon footprints.

Results and discussion for tilling and fertilizer effects

Figure 1 in the Executive Summary provides a high level perspective on our findings. The results illustrate the potential importance of adopting no till practice as a means of rebuilding soil organic matter, with the resulting benefit that these farms become net carbon sinks rather than net emitters of carbon to the atmosphere, even after accounting for the highly potent greenhouse gas effect of nitrous oxide emissions from the soil.

Here, we discuss thee results in more detail. Figure 5 illustrates the benefits of reducing nitrogen fertilizer rate. The top chart shows the distribution of net carbon footprints under the current mix of farm management practices. Its wide distribution of footprints reflects the diverse nature of the farm operations. Average nitrogen fertilizer use is around 225 kg of N per ha and the predominant (but not exclusive) tillage practice is conventional. The bottom chart shows the net carbon footprint distribution for the farms when all are assumed to practice conventional till, but the total nitrogen application rate is dropped to 150 kg per ha. Even with the slightly more conservative assumption of 100% conventional tillage, the net carbon footprint drops from 167 to 91 grams CO_2eq per kg of grain. The spread of net carbon footprint values in the conventional till scenario is narrower than that observed in the current case , reflecting the fact that tillage, nitrogen application rate and timing have been eliminated as a source of variability among the farms.

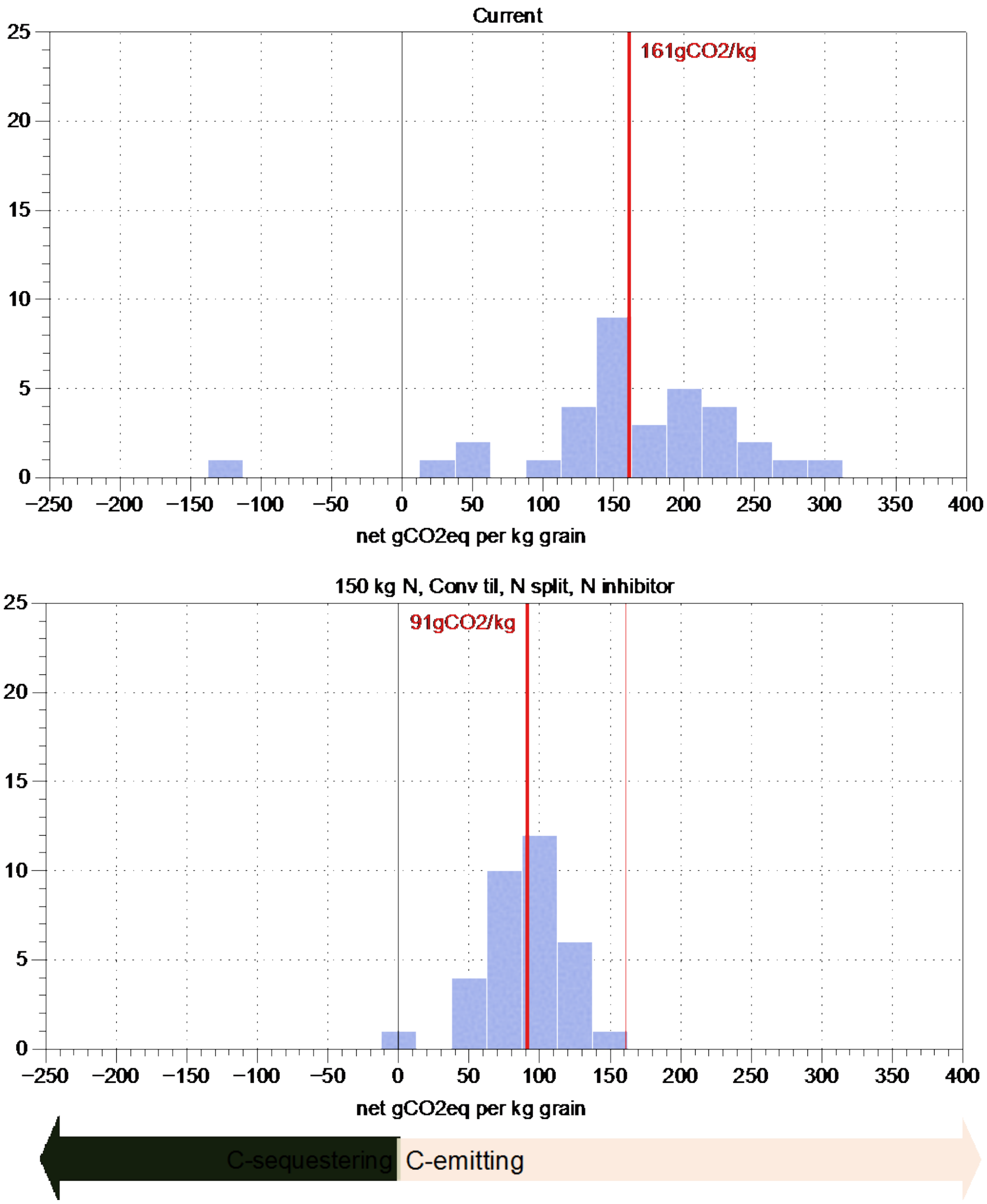


Figure 5. Current versus conventional till with reduced nitrogen usage. Histograms show number of farms corresponding to various ranges of net carbon footprint. All modeled scenarios are corn-soy rotations,150 kg per ha total N, with split application of nitrogen and use of a nitrification inhibitor.

Figure 6 illustrates the impact of tillage practice and manure use. As with the previous figure, each chart is a histogram showing the distribution of net carbon footprints among the 35 farms included in this analysis. Comparison of charts on a given row shows the change in the distribution of net carbon footprints associated with the replacement of half the nitrogen fertilizer applied with animal manure.

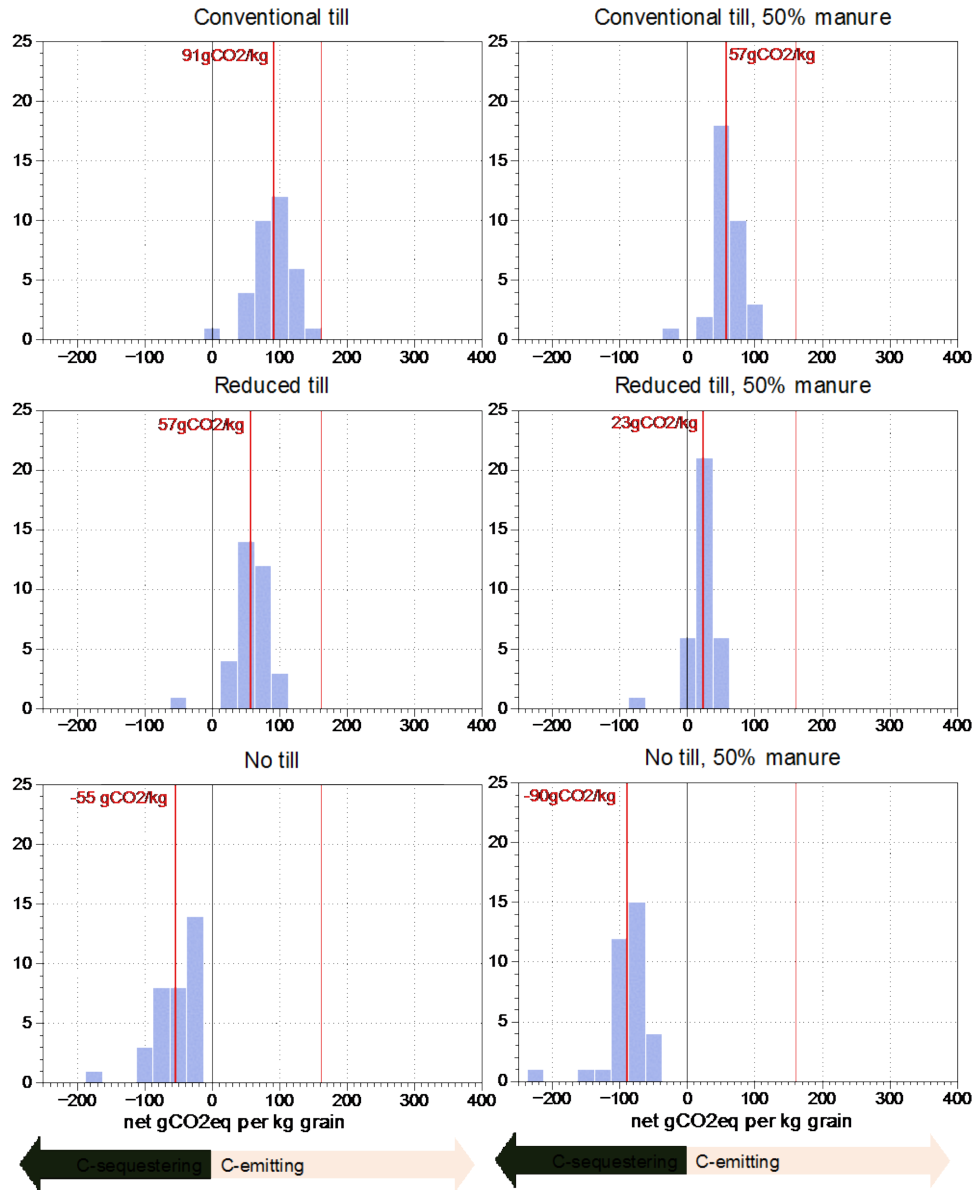


Figure 6. Comparison of tillage effects (charts in columns top to bottom) and manure integration effects (charts across rows) on net carbon footprints. All scenarios are corn-soy rotations,150 kg per ha total N, with split application of nitrogen and use of a nitrification inhibitor.

Comparing the three charts in each column from top to bottom shows the effect of adopting tilling methods with decreasing levels of soil disturbance (i.e. the change from conventional till to reduced till to no till practices).

The shift from conventional to reduced till reduces the net carbon footprint on average by 37 grams of CO_2eq per kg. The impact of shifting to no till is almost four times greater—reducing the net carbon footprint by 146 grams of CO_2eq per kg. All farms under the no till scenarios have net negative carbon footprints. Meeting half of the nitrogen fertilizer demand with animal manure contributes an additional 34 grams of CO_2eq per kg savings. This saving reflects avoided fossil CO_2 emissions associated with the production of commercial fertilizer. Manure also contains potassium and phosphate. Credit for reduced use of potash and phosphate is also included in this credit.

We note that controlling for management practices in these modeled scenarios does not eliminate farm-to-farm variability of the carbon footprint (as is obvious from the histograms in Figure 5 and Figure 6). Important sources of variability in the modeled scenarios include:

- **The type of fertilizer used** (e.g., ammonia versus urea and various forms of phosphate). Each farm is assumed to continue using the same mix of fertilizers as reported in the original survey study. If no commercial fertilizer was reported, then anhydrous ammonia and diammonium phosphate are assumed.
- **The source of animal manure.** Similarly, in scenarios where half of the nitrogen is met with manure, farms that reported some use of animal manure are assumed to use the same mix of animal sources. Farms that did not report using animal manure are assumed to use liquid swine manure delivered to the farm from local hog operations. Differences in fossil credits for each manure source are due to differences in the relative content of nitrogen, potassium and phosphate.
- **Soil types.** Reported soil types for each farm will impact the dynamics of soil carbon and nitrogen flows in the soil.

A first look at stover removal

The DayCent model scenarios included a range of stover removal rates of up to 75%. Here we consider the impact of removing 50% of the available stover on each farm under no till conditions.

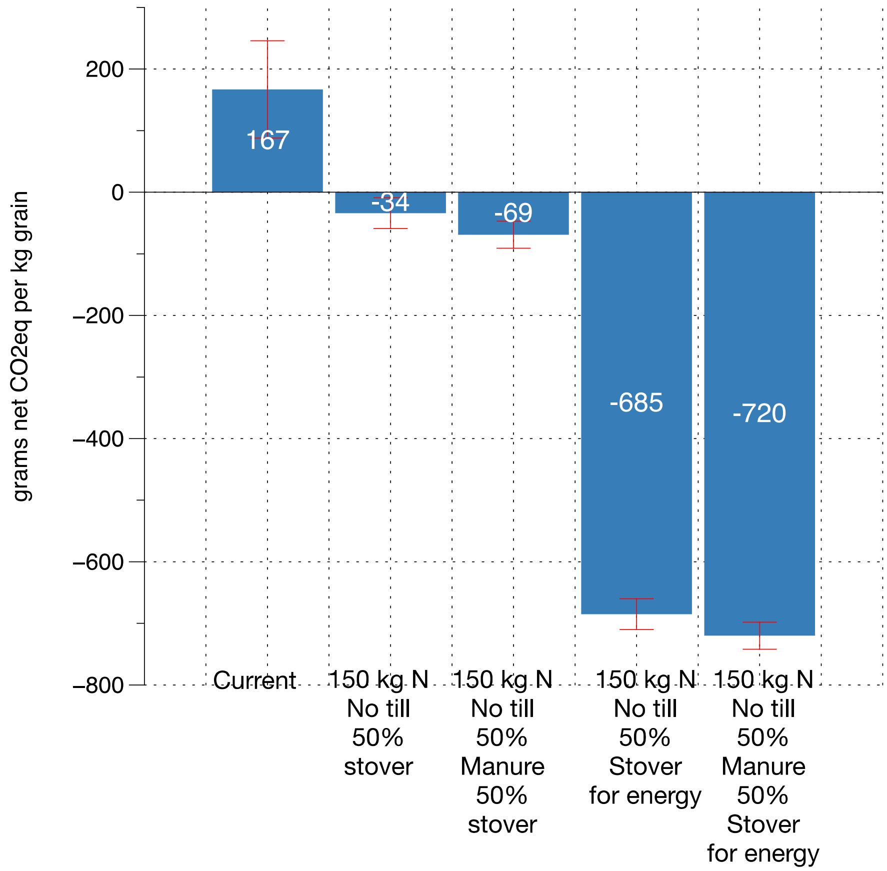


Figure 7. Impact of stover collection and use on carbon footprints for corn. Error bars represent one standard deviation. All modeled scenarios are corn-soy rotations,150 kg per ha total N, with split application of nitrogen and use of a nitrification inhibitor.

Figure 7 shows the carbon footprints for four stover removal scenarios. For reference, this chart also shows the current average net carbon footprint. The four stover scenarios represent two possible uses for stover. In the first, the stover is used as bedding or animal feed for which we conservatively assume no net savings in CO2. In the second scenario, we assume that the stover finds use as a fuel for energy production in which it receives a credit for avoided fossil CO2 emissions from natural gas. For each of these two end-use scenarios for stover, the net carbon footprint is shown with and without use of animal manure to replace 50% of the fertilizer. In the non-energy scenarios for stover removal, we see a small penalty in lost potential for carbon capture in the soil. The stover-for-energy scenarios offer dramatic improvements from a greenhouse gas perspective. Indeed, its energy value is a major reason why EPA and California regulators have both evaluated stover-fueled corn ethanol facilities as having substantial benefits for greenhouse reduction. Compared to the effect of using stover for energy production, manure use impacts are small. The commercialization of corn stover collection and use as an energy resource, however, remains a largely untapped opportunity.

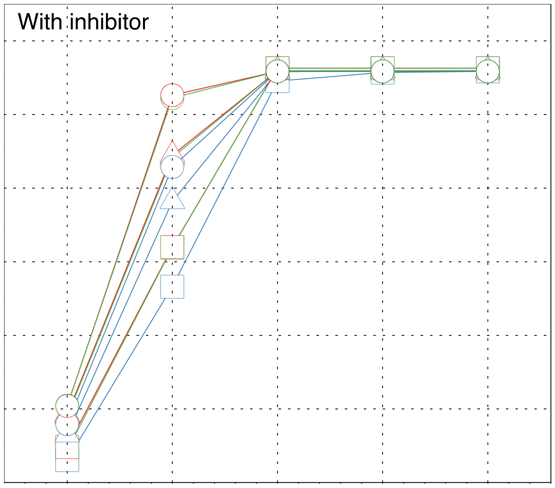
A closer look at a single farm

As part of the initial scoping of scenarios to analyze in this preliminary study, we probed the DayCent model output to identify important farm management factors for an individual farm. Figure 8 shows grain yield response to nitrogen fertilizer rate and timing for each crop rotation (continuous corn and corn-soy) for Farm ID 10. Yield on the y-axis is presented for an expanded range of 4 to 10 Mg per ha in order to highlight subtle differences in the response curves. All scenarios assume the use of a nitrification inhibitor. We note that the use of an inhibitor proved to have negligible effects on yield (see Appendix Figure A- 1).

As expected, nitrogen fertilizer rate has a large effect on yield. However, beyond a level of 150 kg per ha of nitrogen (as N), yield response is flat. This suggests that use of fertilizer at levels greater than 150 kg per ha is pointless, and likely to result only in leaving excess nitrogen in the soil that would then be subject to microbial activity and its consequent release into the air and into water. This pattern is very consistent. We see it in all of the farms.

As a result of these observations, we concluded that it makes most sense to set the nitrogen fertilizer rate at 150 kg her ha for all of the analyses presented in this preliminary study. While somewhat arbitrary, we feel that, at least for this first phase of the study, it does not make sense to evaluate lower fertilizer rate farm management scenarios in which farmers would be forced to accept an economic penalty due to reduced yields.

Grain yield is most sensitive to tillage and fertilizer timing at 100 kg N per ha, where yield varies from around 6-7 Mg per ha under no till conditions up to almost 9.5 Mg per ha under conventional till conditions. The sensitivity to yield at this intermediate nitrogen level probably reflects soil temperature effects. Under no till conditions, soil in the field takes longer to warm up. At 50 kg N per ha, nitrogen limitation becomes the dominant factor. Finally, we note that yield is more sensitive to nitrogen application rate under continuous corn rotations than it is under a corn-soy rotation. We attribute this to greater availability of nitrogen from previous rotations of soybean.



on at planting

Figure 8. Yield response to nitrogen fertilizer rate, tillage practice, fertilizer timing and use of nitrification inhibitor and crop rotation

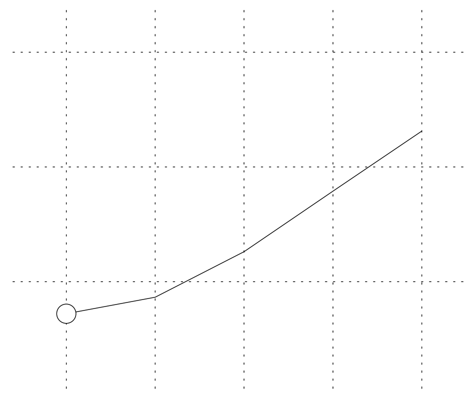
Figure 9 offers a closer look at the effects of fertilizer timing and the use of a nitrification inhibitor on soil N2O emissions (expressed as grams of CO2 equivalents per kg). We show results only for a corn-soy rotation, since we have chosen in this analysis to avoid continuous monoculture of corn, which may be viewed as less sustainable. Each chart shows individual response curves for conventional, reduced and no till conditions. Looking at the charts from top to bottom in a given column, we can see that soil N2O emissions do respond differently for different timing of fertilizer application. Applying nitrogen in the Fall prior to corn planting appears to reduce soil N2O emissions, but only when nitrogen application rates are in excess (at levels above 150 kg per ha). At or below 150 kg N per ha, there is no effect. There is little difference in response between applying fertilizer at planting and splitting the fertilizer application between planting and one month after planting.

Comparing charts on the left and right in a given row highlights the effect of the nitrification inhibitor. The use of an inhibitor showed little effect on N2O emissions when applying fertilizer at planting or when applying fertilizer in a split mode. When fertilizer was applied in the Fall, we actually saw an increase in soil N2O emissions when the inhibitor was used. We will need to explore more carefully what is going on in these cases.

Tilling practices also have significant impacts on N2O emissions. Differences in N2O emissions across tilling practices show up under all scenarios, but the differences shrink with decreasing levels of nitrogen fertilizer. No till scenarios consistently result in the lowest emissions.

At 150 kg N per ha (or less), the effect of the inhibitor and the effect of fertilizer timing are both negligible. For simplicity, we therefore maintained the same conditions for fertilizer timing and inhibitor use in all of the results presented in this study. Fertilizer application was split, and the inhibitor was assumed to be used in all cases.

Nitrogen fertilizer (kg per ha)



Nitrogen fertilizer (kg per ha)

Nitrogen fertilizer (kg per ha)

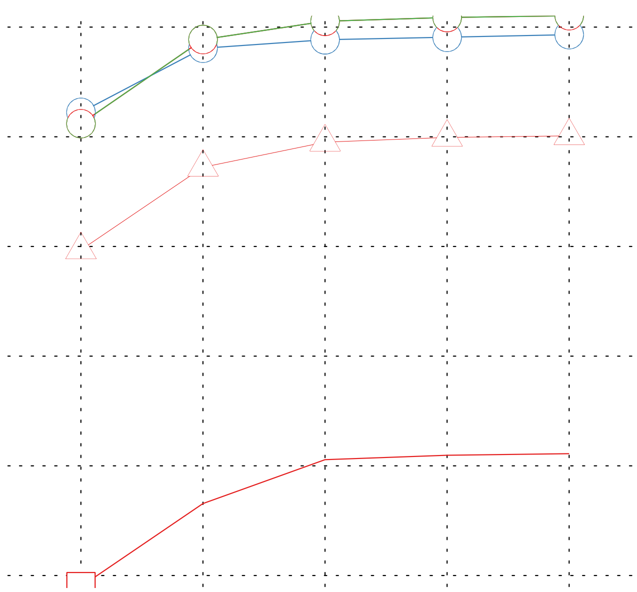
Nitrogen fertilizer (kg per ha)

Figure 9. Soil N2O response to tillage, fertilizer timing, fertilizer rate and use of a nitrification inhibitor. All scenarios are for corn-soy rotations.

Soil CO_2 emissions for corn-soy rotations are shown in Figure 10. In all cases, carbon is sequestered in the soil (that is, soil CO_2 rates are negative). Sequestration rates are actually higher (soil CO_2 rates are more negative) at lower nitrogen application rates. Above 150 kg N per ha, sequestration rates are relatively flat. The degree of soil carbon sequestration is highly dependent on tilling practice, with no till showing substantially higher rates of sequestration than either conventional or reduced till practices. The higher rates of sequestration observed at lower nitrogen application rates seem counter-intuitive, since soil carbon accumulation would seem more likely to be proportionate to overall yield of biomass, which declines significantly below 150 kg N per ha. In fact, the reverse trend is seen for continuous corn systems (see xx).

Net soil CO_2eq rates (combined CO_2 and N_2O) for corn-soy rotations are shown in Figure 11. The combined effects of soil CO_2 and soil N_2O displays a consistent linear increase with nitrogen fertilizer. Below 100 kg N per ha, most scenarios exhibit negative soil CO_2 emissions (that is, the soil serves as a sink in which there is a net flow of carbon from the atmosphere to the soil). Above 100 kg N per ha, conventional tillage scenarios show a net loss of carbon from the soil. By contrast, the no till scenarios all exhibit a negative carbon flow (from the atmosphere to the soil). Applying nitrogen in the Fall seems to weaken the response of soil CO_2 to nitrogen application rate.

Nitrogen fertilizer (kg per ha)



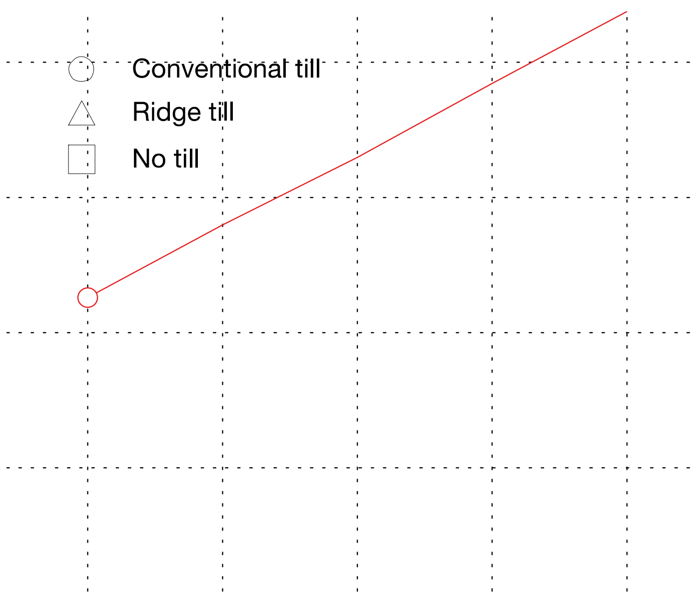
Nitrogen fertilizer (kg per ha)

on at planting

Figure 10. Soil CO_2 emissions response to nitrogen fertilizer rate, fertilizer timing, tillage, and nitrification inhibitor. All scenarios are for corn-soy rotations.

Conventional till
Ridge till
No till

Nitrogen fertilizer (kg per ha)



Nitrogen fertilizer (kg per ha)

nting

Figure 11. Net soil emissions (combined CO_2 and N_2O) response to nitrogen fertilizer rate, fertilizer timing, tillage, and nitrification inhibitor

Conclusions

After a detailed review of model outputs for a single farm (see previous section), we concluded that, for this preliminary study, it made most sense to focus on tillage, manure use, stover (residue) management and a reduced fertilizer application rate fixed at 150 kg N per ha. All other management parameters were held constant as discussed previously. We show that the combination of lower nitrogen fertilizer use, substitution of half the fertilizer with manure and no till practice can reduce average net carbon emissions among the 35 farms studied by 153% from 167 gCO2eq per kg to -89 gCO2eq per kg (see Figure 1). Collection and use of corn stover as an energy source could also dramatically change the carbon footprint by displacing natural gas see Figure 7). These encouraging results lead us to recommend a more comprehensive study of the management impacts on the net greenhouse gas emissions of these farms.

While the analysis presented in this study is specific to the 35 farms in the feedstock shed of a Luverne, MN-based biorefinery, it also offers broader lessons for corn production and utilization in a biorefinery:

1. Average US values for net carbon footprints of corn do not capture the rich diversity in farm practices and performance that exists among US corn farmers. It is therefore important to evaluate the carbon footprint of corn grain feedstocks on a farm-specific basis.
2. While climate and local natural endowments of soil and water are important influences on farm specific performance, our modeling also points out the importance of farm management practices. Adoption of no till practices or similar soil carbon management strategies is key.
3. As other studies have found, we see tremendous benefits to using a portion of corn stover for energy production. While the amount of sustainably removable stover varies from farm to farm (and even field to field), our modeling results show that adoption of no till or other similar soil carbon management strategies may allow many farms to

collect a significant fraction of corn stover with little effect on soil organic matter.

4. Finally, our study results point to the need for regulators, policymakers and industry leaders to stop thinking about the "average" corn farmer, and think instead about individual farms. At a minimum, we need to adopt policies that promote low carbon farm management strategies at the level of the individual biorefinery feedstock shed.

Peer review panel

Name	Organization
Keith Alverson	K2 Farms, Inc.
Joe Fargione	The Nature Conservancy
Suzy Friedman	Environmental Defense Fund
Alix Grabowski	World Wildlife Fund
Franklin Holley	World Wildlife Fund
Mike Huisenga	WSP Environment and Energy
David Kolsrud	DAK Renewable Energy
Robert Parkhurst	Environmental Defense Fund

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Appendix

The following figures provide an expanded view of the effects of nitrogen fertilizer rate, fertilizer timing, use of a nitrification inhibitor, rotation choice and tillage practice. Each of the 12 charts in each figure captures 5 N rates x 3 timings or 15 scenarios. Each figure contains charts representing rotation, tillage choice and use/no use of inhibitor. In total, each figure provides a view of 180 individual scenarios from the set of DayCent model runs. In Figure A- 1, reported values for total nitrogen fertilizer rate and grain yield are shown as red vertical and horizontal lines. The DayCent model appears to predict maximum yield reasonably well.

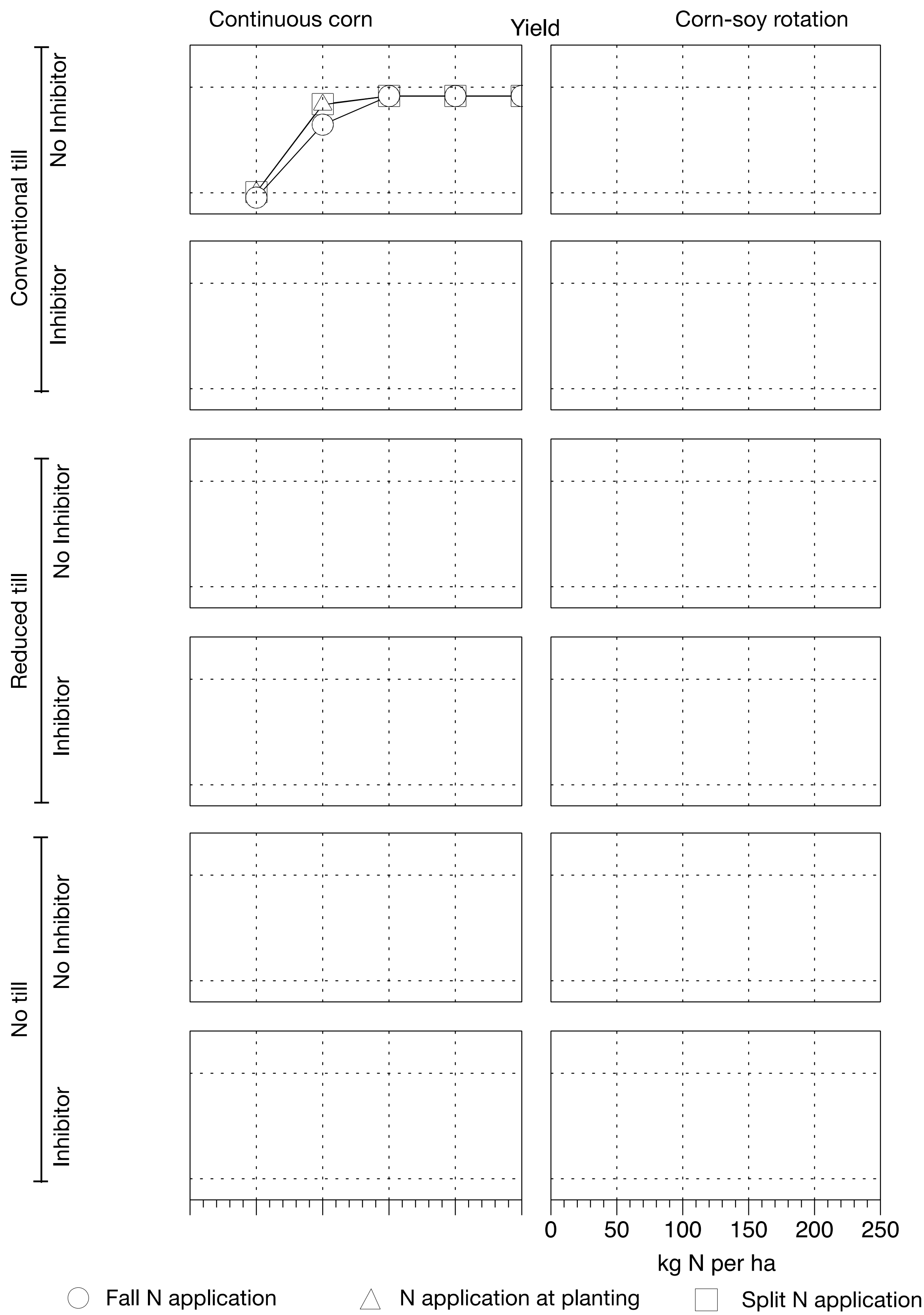

Figure A- 1. Selected yield response curves for Farm ID 10.

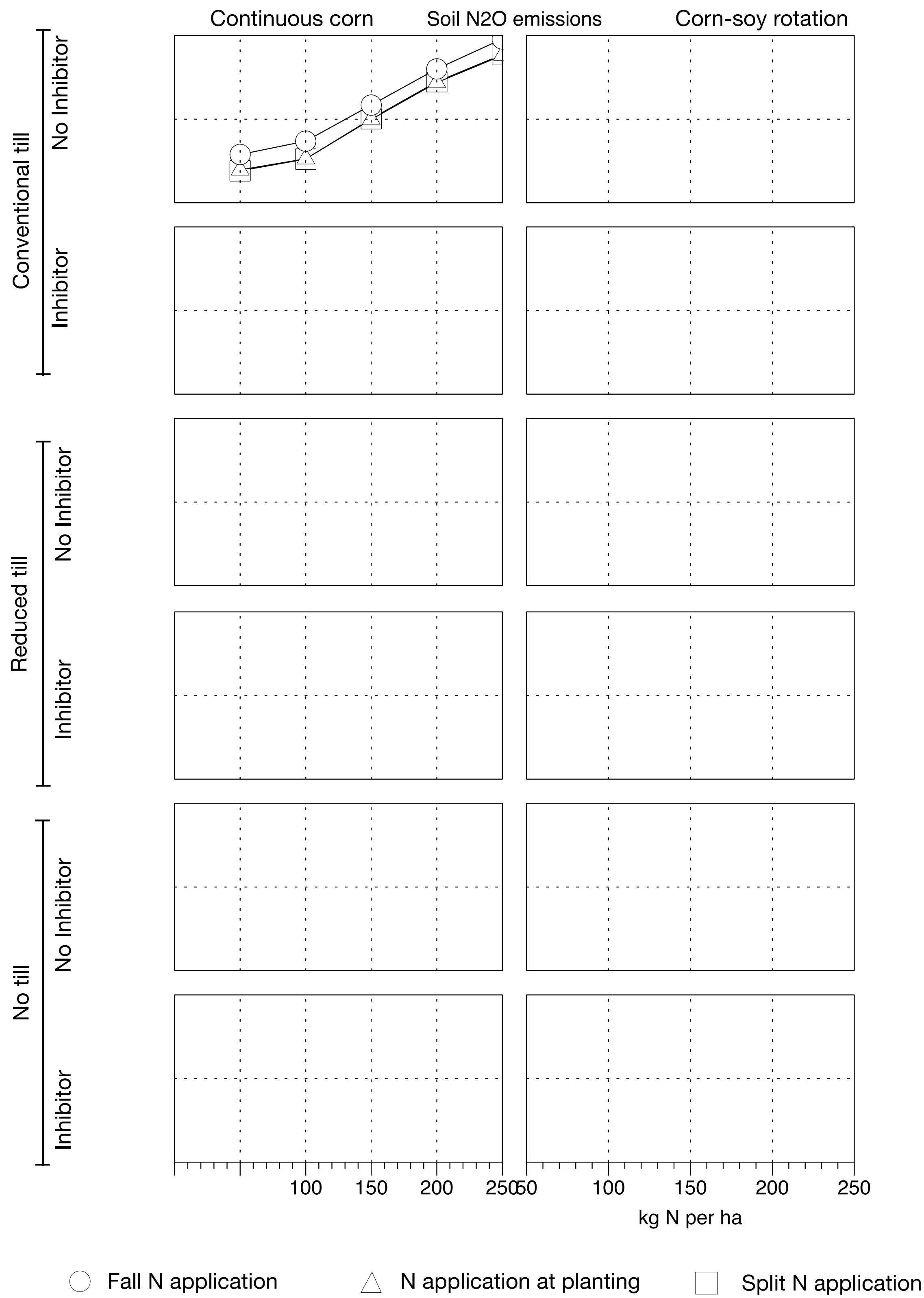

Figure A- 2. Selected Soil N2O response curves for Farm ID 10.

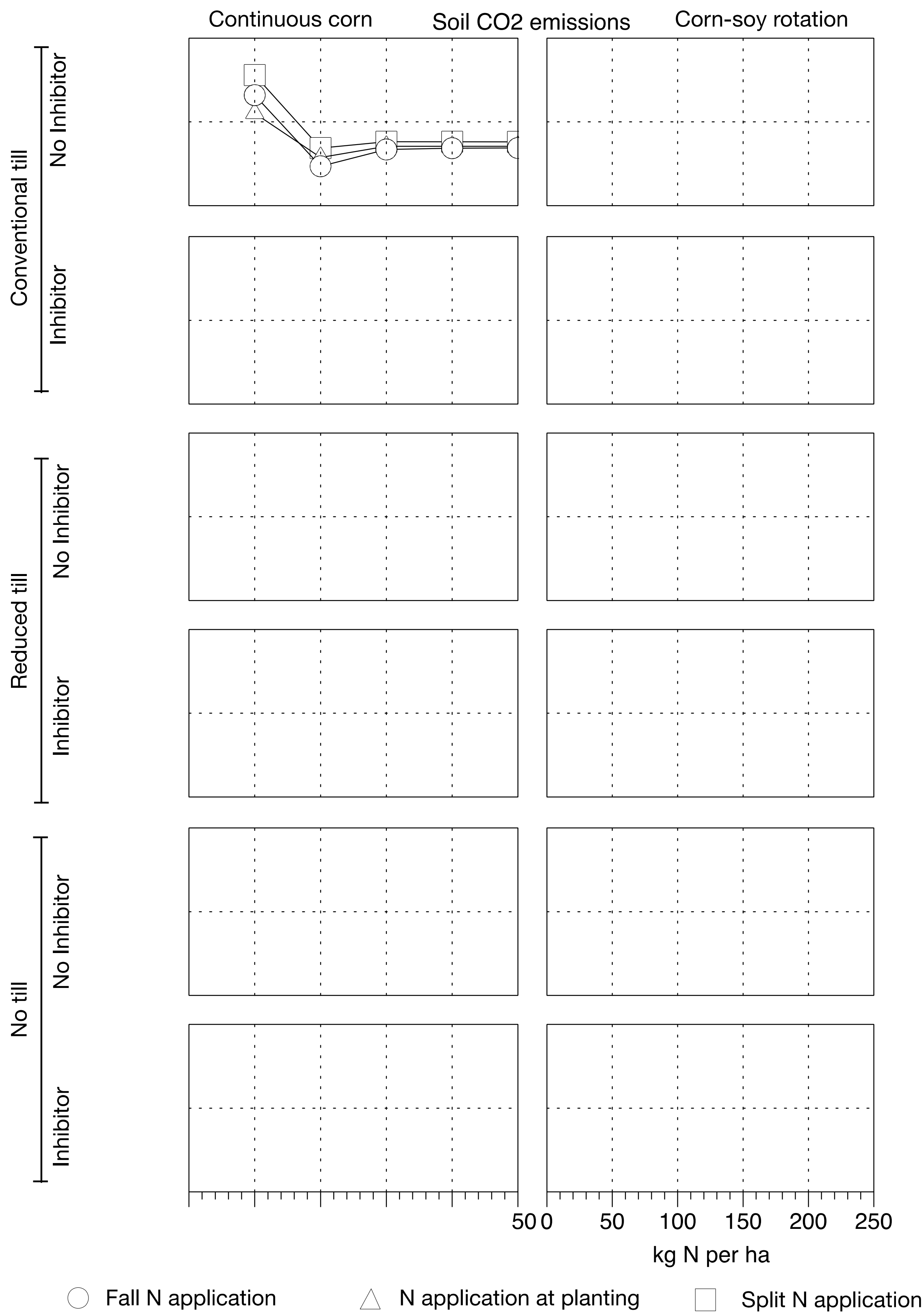

Figure A- 3. Selected soil CO2 response curves for Farm ID 10

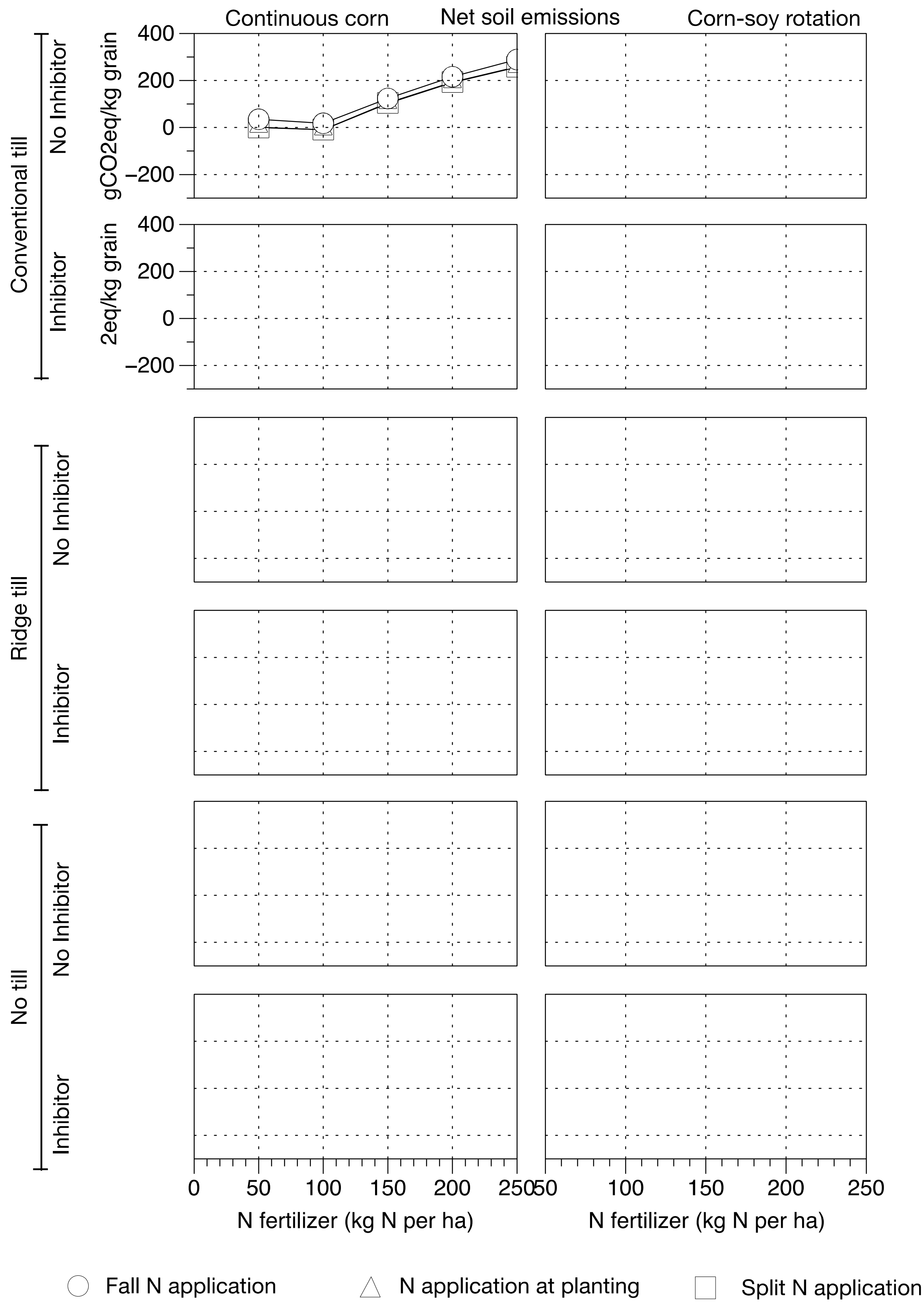

Figure A- 4. Select net soil emissions (combined soil CO2 and soil N2O) for Farm ID 10