WORKING PAPER 2016-13

THE INTERNATIONAL COUNCIL
ON CLEAN TRANSPORTATION

A critique of soil carbon assumptions used in ILUC modeling

Authors: Stephanie Searle and Chris Malins

Date: June 13, 2016
Keywords: soil carbon, indirect land use change, corn ethanol, biofuels, policy

Summary

Recent estimates of land use change emissions associated with corn ethanol vary widely, even with analyses that use the same economic model. Differences in land use change results are driven by model inputs, including assumptions on soil carbon. In this report, we review a recent meta-analysis on soil carbon changes with land conversion and discuss its results in the context of the underlying literature studies it references. In particular, we assess a key underlying scientific question that appears to partially account for modeling differences: how the conversion of cropland to corn production affects soil carbon stocks.

We assess the data input related to soil carbon changes under corn, based on a 2015 meta-analysis by Argonne National Laboratory (ANL). We identify three main questions related to the application of the results of the meta-analysis within the ANL land use change modeling framework: (a) lack of comparison with other crops; (b) use of data from crop rotational systems; and (c) influence of short-term studies. Firstly, the studies referenced in the meta-analysis measure soil carbon at different points in time on plots under corn, and in several cases, corn grown in rotation with soy or other crops, but they do not compare soil carbon under corn with that under other types of annual crops. Land use change driven by corn ethanol demand would presumably either lead to the conversion of other annual crops to corn, or to the maintenance of corn when this land would otherwise have been converted to non-corn crops in the baseline scenario. In either case, it would be necessary to understand how soil carbon differs between corn cultivation and that of other annual crops. It is difficult to see how this assessment of soil carbon changes under corn over time can be used to understand how soil carbon would be affected with increased corn production compared to other crops.

Secondly, the results in the meta-analysis are skewed by data on crop rotational systems. While the literature referenced in this study finds that soil carbon increases significantly over time under crop rotation systems (usually corn/soy), the studies on continuous corn systems do not report soil carbon increases on average. Thus, the conclusion of soil carbon increase over time under corn is highly influenced by positive results in rotational systems. If anything, one would expect an increase in corn ethanol demand to drive the conversion of rotational systems to continuous corn, which according to these studies would tend to decrease soil carbon.

We also find that the conclusion of soil carbon increase is driven largely by experiments of short duration. Studies of 9 years or less find that soil carbon increases under corn, but with very high variation in results both among and within individual studies, while longer duration studies find no change in soil carbon under corn or rotational systems. The variance in the annual rate of soil carbon change is far lower in the longer duration studies, suggesting that results from shorter duration studies may be more significantly influenced by measurement error and natural variation among plots.

Overall, we do not believe that this meta-analysis adequately supports an assumption that the conversion of generic cropland to corn will increase soil carbon. The scientific literature points towards a consensus that continuous corn cultivation does not significantly affect soil carbon stocks over time, and there is not sufficient evidence to compare soil carbon under corn with that under other annual food crops. Assuming that soil carbon stocks increase when other crops are converted to corn is an unrepresentative treatment of the literature and would tend to underestimate land use change impacts from corn ethanol.

Introduction

Indirect land use change (ILUC) estimates vary depending on the modeling framework used, the region to which demand shocks are applied, and a large number of inputs and assumptions. ILUC is a market-mediated effect that occurs when increased demand for biofuel feedstocks results in agricultural expansion (Malins et al., 2014). Even given the wide range in ILUC estimates in the literature, there is a notable difference in estimated ILUC emissions for U.S. corn ethanol between analyses by the California Air Resources Board (ARB) and Argonne National Laboratory (ANL) scientists. In their latest analyses, ARB reports ILUC emissions of 19.8 $gCO_2e\ MJ^{-1}$ for corn ethanol (ARB, 2015), while ANL gives a range of 2.1-9.3 $gCO_2e\ MJ^{-1}$ for the same pathway (Qin et al., 2016), and the median of this range is about one third of ARB's estimate. These two analyses use the same model with the Global Trade Analysis Project (GTAP) general equilibrium modeling framework, GTAP-BIO-ADV, to estimate ILUC, and so the difference in results is striking.

There are differences in the parameterization of GTAP-BIO-ADV used in the two modeling exercises, and one important factor partially accounting for this difference in results is the emissions factor models used. GTAP-BIO-ADV projects the total area of land use change induced by biofuel expansion and where this land use change occurs around the world, and a separate model is needed to estimate the emissions from changing the land use of those areas. ARB uses the agroecological zone emission factor model (AEZ-EF) (Plevin et al., 2014), which provides carbon stock estimates for agroecological zones in world regions and emission factors that indicate carbon stock change with different types of land use conversion. In contrast, ANL uses the Carbon Calculator for Land Use Change (CCLUB) to predict carbon stock change. CCLUB in turn relies on a separate model, CENTURY, to assess changes in soil carbon stocks within the United States (Kwon & Hudson, 2010). CENTURY starts with assumed initial land characteristics, including soil type and soil carbon stocks, and combines this with an assumed land use history to simulate the state of the land at some later point in time (Plevin, 2016). Several aspects of CCLUB have been critiqued by Plevin (2016).

This latest ANL ILUC result (Qin et al., 2016) uses CENTURY and incorporates new inputs from a review paper on soil carbon changes under various types of land use change (Qin et al., 2015). The results in Qin et al. (2015) are based on meta-analysis of data on soil carbon changes with land use change in the literature. Qin et al. (2015) reviewed soil carbon changes with the cultivation of five different biofuel feedstocks (corn, switchgrass, Miscanthus, poplar, and willow) on land that was previously cropland, forest, or grassland. The study reported that the conversion of cropland to any of these feedstocks would result in an increase in soil carbon, and in particular that converting generic "cropland" to corn cultivation would result in an average soil carbon increase of 15%, or 0.43 $tC\ ha^{-1}\ yr^{-1}$. While there is consensus in the scientific literature that dedicated energy crops, including switchgrass, Miscanthus, poplar, and willow, increase soil carbon when grown on land previously used to produce food crops (reviewed in Searle et al. 2016), the finding that conversion of generic cropland to corn would increase soil carbon is surprising and contrary to results reported elsewhere. Generally, the soil carbon literature has shown that the conversion of any other land type to cropland will result in soil carbon loss, with soil carbon levels stabilizing after 10 or more years at a level lower than that under the pre-agricultural state (Don et al., 2011a,b; Guo & Gifford 2002; Murty et al. 2002). The standard assumption would be that the conversion of any annual food crop to another (e.g., wheat to corn) would not result in a significant further change in soil carbon, and in fact this is what the AEZ-EF model implicitly assumes (it does not calculate any soil carbon change for annual crop-to-crop land use conversions). In this context, the finding in Qin et al. that soil carbon would increase substantially when generic cropland is converted to corn is a rather unexpected result. We note that GTAP-BIO-ADV contains another cropland category, cropland-pasture, representing land that shifts between crop and pasture use. We do not assess soil carbon changes related to cropland-pasture in this study, as the research used in Qin et al.'s meta-analysis relates only to actively cropped agricultural land.

In this paper, we critique the general approach and the analysis in Qin et al. (2015). We examine the primary literature studies whose data were used in this meta-analysis, and place Qin et al.'s conclusions in the context of the original research.

Critique of Qin et al. (2015)

COMPARISON METHODOLOGY

We reviewed all studies included in Qin et al.'s analysis for the cropland to corn comparison, as listed in the Supporting Online Material of that paper. In our analysis, we included results from all studies that reported sufficient information on soil carbon stocks under corn cultivation and a reference system. Following Qin et al., we only included results from experiments that did not remove any stover. This reflects common practice for U.S. corn cultivation, where residues are typically retained in the field. Also following Qin et al., we included comparisons that applied any type of fertilizer or tillage treatment. Approximately two-thirds of the comparisons in our analysis were under some form of tillage treatment, while one-third were under no-till; this is also representative of agricultural practice in the United States (Horowitz et al., 2010).

Following Qin et al., we included results for continuous corn systems, as well as rotations with corn and other crops. As in Qin et al., we included each individual comparison as a separate datapoint; for example, if a study tracked soil carbon changes over time for corn under three different fertilizer treatments, we included the result for each fertilizer treatment as a separate datapoint. Following Qin et al., when studies reported soil carbon concentration but not total soil carbon stocks, we converted using the relationship in Guo & Gifford (2002), and standardized all results to soil carbon stocks in the top 30 cm following a conversion formula in Jobbagy & Jackson (2002). We make no note on the accuracy of these data standardization techniques. We corresponded with the authors in attempting to replicate as exactly as possible the list of observations used for the cropland-corn comparison in Qin et al., but we cannot confirm that our list was identical and there may be some differences among the datasets. However, our dataset likely contains most of the results used in Qin et al.'s analysis. The list of studies included in our analysis is provided in the Appendix.

THE APPROACH IN QIN ET AL. (2015)

Qin et al. included results from both paired site (comparing soil carbon under corn with that under a different crop on a nearby plot) and repeated sampling (measuring the change over time in soil carbon under corn cultivation) comparisons in their study overall, but for the cropland-corn studies in particular that were used in Qin et al.'s analysis, we only identified repeated sampling studies. All of these studies measured soil carbon on land that had previously been cultivated for agriculture, then grew corn on that land for a number of years, and measured soil carbon again on the same plot at the end of some time period. Each of these studies thus measured changes in soil carbon on the same plots of corn at time x and time y. We compare the soil carbon results at time x and time y to infer whether soil carbon increased or decreased as a result of corn cultivation. We note that in most studies, the previous crop that had been cultivated on the experimental plots was not specified, and in some cases was specified as corn (e.g., Nafziger & Dunker, 2011; Al-Kaisi et al., 2005; Halpern et al., 2010). We were not able to identify a single study used in this analysis that specified a switch from a non-corn system to corn.

This changes our understanding of what these results tell us in the context of land use change theory in general. Increasing demand for corn from a corn ethanol mandate will tend to drive the conversion of land under other agricultural crops to corn cultivation (as well as conversion of non-agricultural land to corn and to other crops that were displaced by corn). In this context, soil carbon change under a corn system that remains corn is not pertinent. Presumably, a scenario modeling a corn ethanol demand shock would have overall greater corn area and lower area of other annual crops than in the baseline scenario, and we would need to know how soil carbon under corn differs from soil carbon under other crops in order to understand the land use change emissions associated with increased corn ethanol.

From our review of the studies included in Qin et al.'s analysis, it appears that there is not sufficient information available to be able to conduct a meta-analysis of soil carbon changes under other annual crops converted to corn, or from paired site comparisons between corn plots and other crops. In the absence of such information, the natural assumption to make would be no soil carbon change between different types of annual crop systems. It is not clear that using data on soil carbon changes under corn systems over time to infer soil carbon changes with the conversion of other annual crops to corn is an improvement upon an assumption of zero change.

OVERVIEW OF SOIL CARBON CHANGE RESULTS

Qin et al. (2016) conducted a meta-analysis of the data on soil carbon presented in the referenced literature studies, comparing treatment soil carbon stocks (at the end of the experiment) with reference soil carbon stocks (before the experiment). The data were log-transformed to create a more normal distribution. Qin et al. reports two main results on soil carbon changes for cropland conversion to corn production: a 15% increase in soil carbon (regardless of experiment length); and an absolute rate of soil carbon increase of 0.43 tC ha^{-1} yr^{-1}. We were not able to replicate these results using a similar model, but the model description in Qin et al. (2016) was high level and so we likely are missing details of how exactly those authors constructed their model. Thus, we will simply discuss the main results in Qin et al. in the context of the individual studies we have analyzed.

Figure 1 summarizes all of the data points included in our analysis, shown as both percent change in soil carbon over the entire experiment on the left, and the rate of soil carbon change in tC ha^{-1} yr^{-1} on the right. Qin et al.'s results described above are shown in orange. Qin et al.'s result for the rate of soil carbon change (right) appears to be centered in the underlying data and so appears to be a reasonable conclusion from looking at these summary results. However, their result for the percentage change in soil carbon over the experiment lifetime appears to be higher than most of the underlying data points, and in fact is greater than two-thirds of the values. We note that while log-transforming the data will make the highest and lowest results appear closer to the mean, it will not affect the relative placement of Qin et al.'s result in the distribution of the data. We are unable to explain how one might arrive at the conclusions in Qin et al. from the summary data alone: the average change in soil carbon over the experiment lifetime was 5.6% in our analysis (compared to 15% in Qin et al.); and the median annual rate of soil carbon change was 0.17 t ha^{-1} yr^{-1} (compared to 0.43 t ha^{-1} yr^{-1} in Qin et al.).

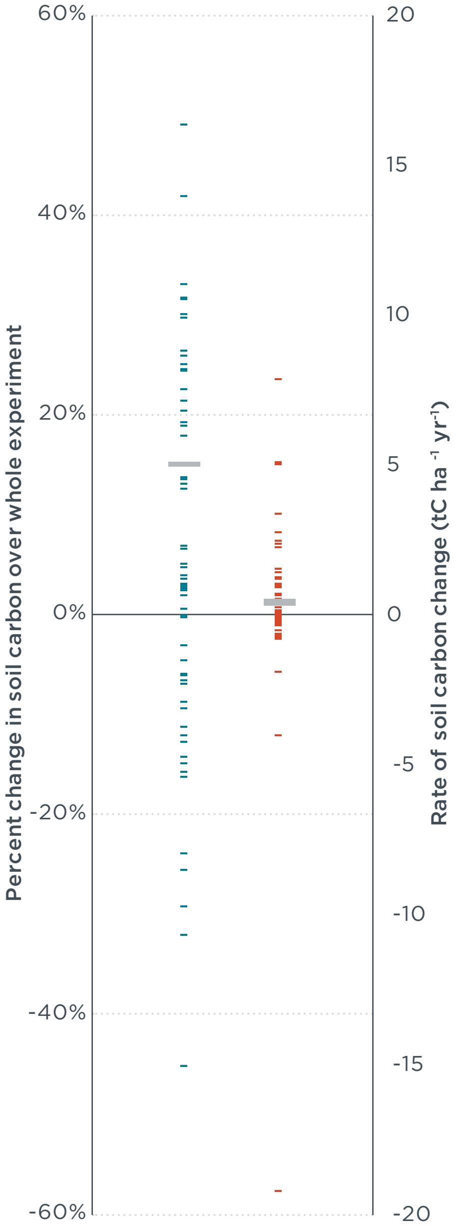

Figure 1: Summary of soil carbon change results in literature studies, presented as percent change over experiment lifetime in blue (left axis) and as an annual rate in orange (right axis). The result in Qin et al. (2015) for each metric is shown in the gray bars.

CROP ROTATIONS

Table 1 shows the results reported in Qin et al. (2015) compared to simple averages and medians of the data in the underlying literature studies according to our analysis. As observed above, the percent change in soil carbon (regardless of study duration) reported in Qin et al. (15%) is much higher than the simple average of the data in the underlying studies (5.6%). The mean and median rate of soil carbon change in Qin et al. is slightly positive, and is roughly similar to our findings. In our analysis, we followed Qin et al. in including data for both continuous corn systems, as well as systems where corn is grown in rotation with other crops, including mostly soy, but also oat and clover. If we separate out results for these two types of crop management, we see that soil carbon changes under continuous corn are lower than for rotational systems. In fact, it is not clear that there is any soil carbon sequestration in continuous corn systems. A t-test confirms that the soil carbon changes for continuous corn are not significantly different from zero, using any of these three metrics. While the total percent change and median annual soil carbon change rate are positive for studies on continuous corn, the mean annual soil carbon change rate is negative. This is because a number of studies reported soil carbon increases in soils with low starting soil carbon stocks, so the percent change was high but the absolute change was low.

It is clear that soil carbon results from crop rotations are skewing the overall result upwards. This is also shown in Figure 2. From these box plots, it is apparent that much of the distribution for rotations lies above even the maximum value for continuous corn (the whiskers represent maximum and minimum values for each dataset). Rotational systems are generally thought to increase crop yields for various reasons, including disease and pest suppression (Griffiths, 2009; Angus et al., 2008; Kirkegaard, 2005), and so it may be that the higher plant growth in these systems contributes more root biomass to soil carbon; however, we have not studied this issue in detail.

The difference in soil carbon results for continuous corn and rotational systems is important because continuous corn plots should be more relevant in interpreting the likely ILUC impacts of corn ethanol demand. Increased demand for corn for corn ethanol production should logically increase corn area relative to the baseline. If anything, one would expect an increase in corn demand to increase corn production area at the expense of soy, driving a conversion of corn-soy rotations to continuous corn. In fact, the U.S. Department of Agriculture's Economic Research Service predicts that higher demand for corn from the U.S. Renewable Fuel Standard will result in more continuous corn acres at the expense

Table 1: Summary of soil carbon results in Qin et al. (2015) and in our analysis using various metrics.

	Percent change in soil carbon over total study	**Percent change in soil carbon per year**	**Soil carbon change rate (tC ha^{-1} yr^{-1}) Median (Mean)**
Qin et al. (2015)	15%		0.43 (0.16)
Simple average of underlying studies	5.6%	1.0%	0.17 (0.37)
Average of studies on continuous corn	3.9%	0.3%	0.06 (-0.35)
Average of studies on rotational systems	7.9%	1.9%	0.51 (1.25)

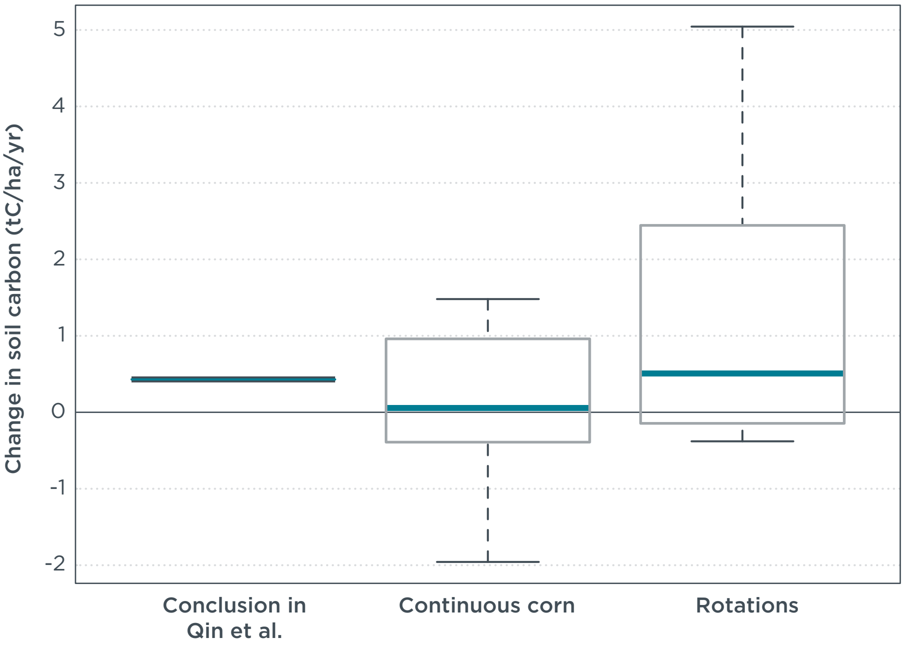

Figure 2: Box plot of the rate of soil carbon change in continuous corn studies and crop rotation studies, compared to the result in Qin et al. (2015)

of corn-soy rotations (Malcolm & Aillery, 2009). Including the soil carbon results for crop rotations is thus misleading in the context of assessing land use change emissions from corn ethanol demand.

TIME DEPENDENCE

The conclusions drawn in Qin et al. (2015) that soil carbon is 15% greater under corn cultivation than under generic "cropland" and that soils under corn cultivation sequester 0.43 tC ha^{-1} yr^{-1} imply that under corn, soil carbon should increase over time. [As discussed earlier, this interpretation actually implies that corn sequesters more soil carbon than other annual crops, which was not studied, but we will set aside this issue for this section.]

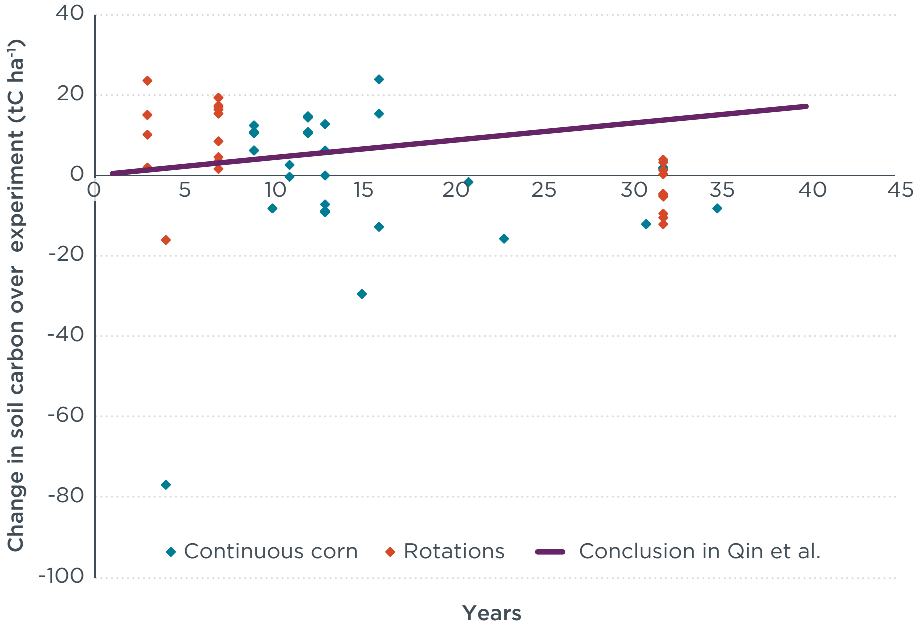

Figure 3: Total change in soil carbon over experiment duration for continuous corn and rotational systems in the reviewed studies, compared to the conclusion of soil carbon increases in Qin et al.

Put simply, one would expect experiments that measure soil carbon changes under corn over longer periods to find greater soil carbon increases compared to shorter experiments. However, this is not what we observe in the studies used in Qin et al.'s analysis. Figure 3 shows the total change in soil carbon over the duration of each experiment, compared to the soil carbon change one would predict using Qin et al.'s conclusion of an annual soil carbon increase of 0.43 tC ha^{-1} yr$^{-1,}$ represented by the orange line. It is apparent from this figure that pooled together, the reviewed studies do not indicate a soil carbon increase over time. This is true for both continuous corn and rotational systems. Total soil carbon gains are actually highest for the studies of shorter length and decrease with increasing study duration. The average annual change in soil carbon for all results from experiments lasting 9 years and less is 0.17% or 0.98 tC/ha; for all experiments lasting 10 years or more is -1% or -0.01 tC/ha; and for all experiments lasting 20 years or more is -6% or -0.15 tC/ha. We note that the 30-year amortization of ILUC emissions—used in both carbon accounting models—reflects an assumed 30 years of fuel and feedstock production. Thus the most relevant results indicate either no change or a loss of soil carbon.

If we took these results at face value we could interpret them as showing that growing corn very quickly increases soil carbon levels immediately after conversion, and they slowly decrease thereafter. However, this would be a surprising result with no obvious scientific explanation, especially given that in some studies the new corn system is replacing a previous system also involving corn cultivation.

There could be a simpler explanation for why shorter term studies may be showing apparent soil carbon increases under corn while longer term studies do not. The issue may be that measurement error and natural variation affect results from short-term studies to a greater degree than in longer-term studies. The spread in results for any one year is similar across study durations in Figure 3. Some of this is due to natural variation across study locations; soil carbon stocks can even vary from one plot to the next within the same experiment. When several data points are shown for one year, this usually shows different results within one study. In some cases, a single study reports results from experiments across a range of locations (e.g., in different U.S. states) and sometimes from adjacent plots that have received different fertilizer treatments. On the other hand, some of the variation is likely due to measurement error. It makes sense that this would be similar with study duration; if a certain method of estimating soil carbon stocks is accurate within 5 tC ha^{-1}, then the spread in results will be around 5 tC ha^{-1} no matter how long the treatment has been in place, or what the overall long-term change in soil carbon is.

This matters greatly when we divide the total change in soil carbon stocks by the study duration and try to interpret soil carbon changes over short timescales. Figure 4 shows the annual rate of soil carbon change by experiment duration. From this figure it is clear that the spread in results among studies and among plots within one study is far higher for experiments of shorter duration. One data point (-19 tC ha^{-1} yr^{-1}, 4 years) is omitted in order to improve the visual resolution of the remaining data; thus, the spread in short-term results is even greater than shown here. This is not surprising; if soil carbon changes under corn cultivation, one would expect to see that result clarified over longer time periods. As an analogy, consider testing the effects of irrigation on corn growth. After two days of the experiment, one may not be able to tell whether the irrigated plants are larger than the non-irrigated plants. The obvious solution is to wait. If irrigated plants do grow faster, one would expect to see a larger difference in total growth after two months. If, after two months, the corn plants still appear to be the same size, one would conclude that irrigation has no effect. In the studies reviewed here, we are seeing no effect of corn cultivation on soil carbon for longer-term studies, for both continuous corn and rotational systems. This suggests that the positive result for soil carbon increase under corn in shorter duration studies could be influenced by measurement error and natural variation.

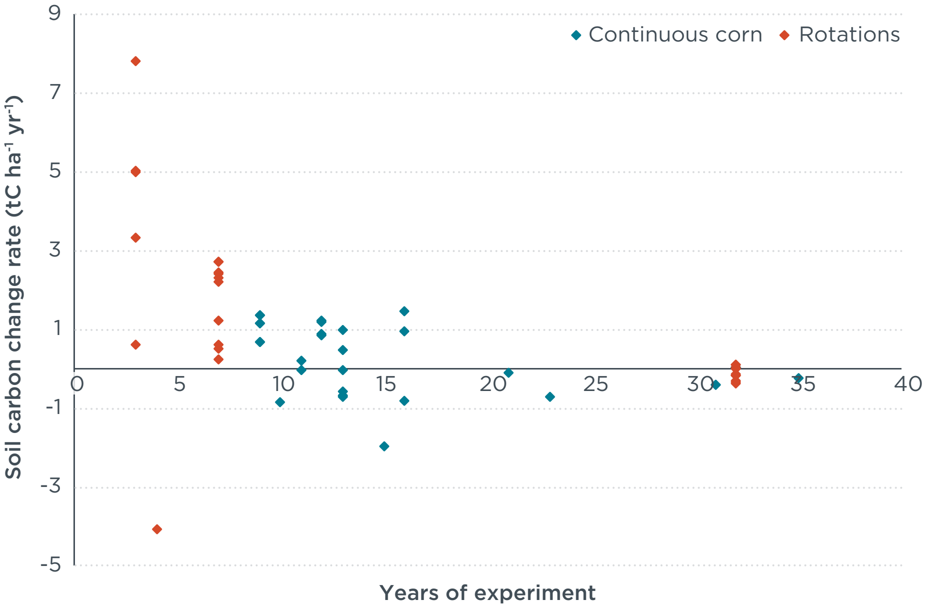

Figure 4: Annual rate of soil carbon change shown by experiment duration for continuous corn and rotational systems in the reviewed studies.

This brings us back to Qin et al.'s conclusion that soil carbon increases by 15% under corn cultivation regardless of time. We cannot explain how this number is derived by simply looking at total soil carbon changes across the referenced studies. The only way we can reproduce this number is by multiplying the annual soil carbon change rate of 0.43 tC ha^{-1} yr^{-1} reported by Qin et al. by precisely 25 years. Assuming an annual increase in soil carbon of 0.43 tC ha^{-1} yr^{-1} over 25 years yields a total soil carbon increase of 10.8 tC ha^{-1}, which is exactly 15% of the average reference soil carbon stock in the studies included in Qin et al.'s analysis.

We cannot confirm that this was Qin et al.'s approach in arriving at their final result of a 15% increase in soil carbon under corn. The methods in this paper were not detailed enough to understand exactly how the authors made their calculations. It is perfectly possible that the authors used a completely different analytical method to arrive at this result. However, we do note that using such a calculation would be an inappropriate extrapolation of data—if one purposefully wanted to estimate soil carbon changes after 25 years, it would make a lot more sense to look specifically at studies that measured soil carbon changes after around 25 years.

Conclusions

Our review of the assessment in Qin et al. (2015) and the underlying studies referenced in that paper does not support the conclusion that conversion of generic cropland to corn will lead to significant soil carbon sequestration. Our main criticisms of this analysis are:

- The general approach of analyzing soil carbon changes over time under corn cultivation does not answer the question of how the conversion of generic cropland to corn will affect soil carbon stocks.
- The finding of a soil carbon increase under corn results largely from measurements on corn rotations with soy and other crops, while studies on continuous corn do not support the conclusion of significant soil carbon sequestration.
- The finding that soil carbon increases over time under corn is also driven by studies of short (>10 years) duration, which would tend to be influenced by measurement error to a greater degree compared to longer term studies.

We do not believe that the assessment in Qin et al. (2015) adequately supports an assumption that the conversion of generic cropland to corn will increase soil carbon. Rather, based on our interpretation of the underlying literature and in the absence of further information, there is no reason to assume any change in soil carbon for land conversion between corn and other annual crops. This interpretation does not relate to cropland-pasture, which was not reviewed in this assessment nor in Qin et al. (2015).

Literature cited

Al-Kaisi, M. M., Yin, X., & Licht, M. A. (2005). Soil carbon and nitrogen changes as influenced by tillage and cropping systems in some Iowa soils. *Agriculture, Ecosystems & Environment*, *105*(4), 635-647.

Angus, J. F., Peoples, M. B., Kirkegaard, J. A., Ryan, M. H., & Ohlander, L. (2008, September). The value of break crops for wheat. In *Proceedings 14th Australian Agronomy Conference* (pp. 21-25).

Don, A., Schumacher, J., & Freibauer, A. (2011). Impact of tropical land-use change on soil organic carbon stocks–a meta-analysis. *Global Change Biology*, *17*(4), 1658-1670.

Griffiths, J. (2009, August). Legumes – benefits beyond nitrogen. In *Farming Ahead*, *211*, 57-58.

Guo, L. B., & Gifford, R. M. (2002). Soil carbon stocks and land use change: a meta analysis. *Global Change Biology*, *8*(4), 345-360.

Halpern, M. T., Whalen, J. K., & Madramootoo, C. A. (2010). Long-term tillage and residue management influences soil carbon and nitrogen dynamics. *Soil Science Society of America Journal*, *74*(4), 1211-1217.

Horowitz J, Ebel R, Euda K. (2010, November). “No-Till” Farming Is a Growing Practice. Washington DC: *United States Department of Agriculture*. Economic Information Bulletin Number 70.

Jobbágy, E. G., & Jackson, R. B. (2000). The vertical distribution of soil organic carbon and its relation to climate and vegetation. *Ecological Applications*, *10*(2), 423-436.

Kirkegaard, J. (2005, January). Unravelling the benefits of crop rotation. In *Farming Ahead*, *156*, 42-44.

Kwon, H. Y., & Hudson, R. J. (2010). Quantifying management-driven changes in organic matter turnover in an agricultural soil: An inverse modeling approach using historical data and a surrogate CENTURY-type model. *Soil Biology and Biochemistry*, *42*(12), 2241-2253.

Malcolm, S., & Aillery, M. (2009, March). *Growing Crops for Biofuels has Spillover Effects.* Washington, D.C.: United States Department of Agriculture Economic Research Service. Accessed June 2, 2016. Retrieved from http://www.ers.usda.gov/amber-waves/2009-march/growing-crops-for-biofuels-has-spillover-effects.aspx#.V1CZEZMrIWp.

Malins, C., Searle, S., & Baral, A. (2014). *A Guide for the Perplexed to the Indirect Effects of Biofuels Production.* Washington, D.C.: The International Council on Clean Transportation. Retrieved from http://www.theicct.org/guide-perplexed-indirect-effects-biofuels-production.

Murty, D., Kirschbaum, M. U., Mcmurtrie, R. E., & Mcgilvray, H. (2002). Does conversion of forest to agricultural land change soil carbon and nitrogen? A review of the literature. *Global Change Biology*, *8*(2), 105-123.

Nafziger, E. D., & Dunker, R. E. (2011). Soil organic carbon trends over 100 years in the Morrow plots. *Agronomy Journal*, *103*(1), 261-267.

Plevin, R., Gibbs, H., Duffy, J., Yui, S., & Yeh, S. (2014). Agro-ecological Zone Emission Factor (AEZ-EF) Model (v47). *Purdue University, West Lafayette, IN*. GTAP Technical Paper No. 34.

Plevin, R. (2016, October). *Comments on modeling biofuel-induced land-use change emissions.* Prepared for the Union of Concerned Scientists. Accessed on June 2, 2016. Retrieved from https://docs.google.com/a/plevin.com/viewer?a=v&pid=sites&srcid=cGxldmluLmNvbXxyaWNofGd4OjMwZDkwNjA4NjY1YzljY2Q.

Qin, Z., Dunn, J. B., Kwon, H., Mueller, S., & Wander, M. M. (2015). Soil carbon sequestration and land use change associated with biofuel production: empirical evidence. *GCB Bioenergy*. DOI: 10.1111/gcbb.12237.

Qin, Z., Dunn, J. B., Kwon, H., Mueller, S., & Wander, M. M. (2016). Influence of spatially-dependent, modeled soil carbon emission factors on life-cycle greenhouse gas emissions of corn and cellulosic ethanol. *GCB Bioenergy*. DOI: 10.1111/gcbb.12333.

Searle, S., Petrenko, C., Baz, E., & Malins, C. (2016). *Crops of the biofrontier: In search of opportunities for sustainable energy cropping.* Washington, D.C.: The International Council on Clean Transportation.

Appendix

Al-Kaisi, M. M., Yin, X., & Licht, M. A. (2005). Soil carbon and nitrogen changes as influenced by tillage and cropping systems in some Iowa soils. *Agriculture, Ecosystems & Environment*, *105*(4), 635-647.

Clapp, C. E., Allmaras, R. R., Layese, M. F., Linden, D. R., & Dowdy, R. H. (2000). Soil organic carbon and 13 C abundance as related to tillage, crop residue, and nitrogen fertilization under continuous corn management in Minnesota. *Soil and Tillage Research*, *55*(3), 127-142.

Collins, H. P., Christenson, D. R., Blevins, R. L., Bundy, L. G., Dick, W. A., Huggins, D. R., & Paul, E. A. (1999). Soil carbon dynamics in corn-based agroecosystems: results from carbon-13 natural abundance. *Soil Science Society of America Journal*, *63*(3), 584-591.

Follett, R. F., Vogel, K. P., Varvel, G. E., Mitchell, R. B., & Kimble, J. (2012). Soil carbon sequestration by switchgrass and no-till maize grown for bioenergy. *Bioenergy Research*, *5*(4), 866-875.

Halpern, M. T., Whalen, J. K., & Madramootoo, C. A. (2010). Long-term tillage and residue management influences soil carbon and nitrogen dynamics. *Soil Science Society of America Journal*, *74*(4), 1211-1217.

Karlen, D. L., Berry, E. C., Colvin, T. S., & Kanwar, R. S. (1991). Twelve-year tillage and crop rotation effects on yields and soil chemical properties in northeast Iowa 1. *Communications in Soil Science & Plant Analysis*, *22*(19-20), 1985-2003.

Karlen, D. L., Birell, S. J., & Hess, J. R. (2011). A five-year assessment of corn stover harvest in central Iowa, USA. *Soil and Tillage Research*, *115*, 47-55.

Nafziger, E. D., & Dunker, R. E. (2011). Soil organic carbon trends over 100 years in the Morrow plots. *Agronomy Journal*, *103*(1), 261-267.

Pikul, J. L., Johnson, J. M., Schumacher, T. E., Vigil, M., & Riedell, W. E. (2008). Change in surface soil carbon under rotated corn in eastern South Dakota. *Soil Science Society of America Journal*, *72*(6), 1738-1744.

Stewart, C. E., Follett, R. F., Pruessner, E. G., Varvel, G. E., Vogel, K. P., & Mitchell, R. B. (2015). Nitrogen and harvest effects on soil properties under rainfed switchgrass and no-till corn over 9 years: implications for soil quality. *GCB Bioenergy*, *7*(2), 288-301.

Tautges, N., Sanford, G., & Posner, J. (2009). Soil Organic Carbon Changes in Six Midwestern Cropping Systems in Southern Wisconsin. In *The Wisconsin Integrated Cropping Systems Trial, Thirteenth Report – 2009 & 2010.* Eds. Posner, J.L., & Hedtcke, J.L. (60-72).