15-2-4
Colin Murphy

NEXTGEN CLIMATE
AMERICA

February 18, 2015

NextGen Climate America
111 Sutter St.
San Francisco, CA 94104

Chair Mary Nichols
California Air Resources Board
1001 I St.
Sacramento CA, 95814

Dear Chair Nichols:

On behalf of NextGen Climate, I would like to thank the Air Resources Board for the opportunity to comment on the proposed re-adoption of the Low Carbon Fuel Standard. NextGen Climate America is dedicated to preventing climate disaster and enabling American prosperity. We recognize the critical role transportation plays in climate policy and we strongly support extending California's Low Carbon Fuel Standard (LCFS). Fuel carbon policies, like the LCFS, are a critical element in a comprehensive climate policy and provide an essential incentive for bringing advanced low-carbon technologies into commercial deployment as economies transition to long-term sustainability.

California's s Low Carbon Fuel Standard Shows Leadership on a Key Climate Issue

Transportation accounted for approximately 37% of California's greenhouse gas (GHG) emissions[1]. The share of emissions from transportation is generally expected to go up over the next decade in western U.S. states due to reductions in emissions from non-transportation sectors of the economy. Recognizing the critical need for carbon reduction policies California joined Oregon, Washington and British Columbia in agreeing to groundbreaking climate policy through participation in the Pacific Coast Collaborative (PCC). The success of the PCC efforts towards sustainable fuels policy is a direct result of the leadership the Air Resources Board showed in implementing the first-of-its-kind Low Carbon Fuel Standard. Low carbon fuels policy is necessary element in achieving long term climate sustainability. If the emissions from transportation are not substantially reduced, it is virtually impossible for any state to meet its climate goals. California can set an example the rest of the world can follow by continuing this groundbreaking policy.

Low Carbon Fuel Standards Enable a Smooth Transition to a Sustainable Future

Low carbon fuel policies achieve two goals: direct reduction of carbon emissions and incentivizing commercial deployment of advanced technologies. The latter goal is a niche that few other options in the policy toolkit can address in as direct, efficient and timely a fashion. By creating a market-based incentive structure that provides greater rewards for

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[1] CARB (2014) *California's Greenhouse Gas Emission Inventory*
http://www.arb.ca.gov/cc/inventory/inventory_current.htm

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fuels which yield greater carbon reductions, the Low Carbon Fuel Standard would help the most advanced technologies reach market sooner, so that future, bigger reductions can be attained in a cost effective manner. Without technology-promoting policies like a Low Carbon Fuel Standard, there is a risk that highly efficient technology will not develop quickly enough to meet long term goals.

Recent Research Has Demonstrated that California's Targets Can be Met with Likely Fuel Supplies

Several recent research reports, including the *Pacific Coast Collaborative Low Carbon Fuel Availability Study* from the International Council on Clean Transportation and E4tech, and from Promotum have demonstrated that there are a variety of technological and supply pathways which can meet California's low-carbon fuel demands in a cost-effective manner[2,3]. Already, electric vehicles, including plug-in hybrids, are demonstrating that they are cost-competitive and commercially attractive options in the passenger vehicle market. Existing biofuel production facilities are reducing their carbon emissions through efficiency enhancements and greater use of renewable energy. The first two advanced cellulosic ethanol production facilities in the U.S. came online in the last quarter of 2014, with other projects in various stages of demonstration or commercialization, including in California[4]. There are many combinations of fuels and technologies which would allow California to meet its goals under the proposed Low Carbon Fuel Standard. This flexibility will help minimize cost by allowing fuel markets to find the lowest cost pathways for decarbonization.

Cost Containment through a Credit Clearance Market Will Mitigate the Effect of Price Spikes

While there is a growing body of evidence to indicate that the LCFS credit market is appropriately regulated and balanced[5], we recognize that there is value in providing additional levels of cost containment. In order to protect California consumers and businesses, we support the creation of a Credit Clearance Market, to effectively cap the LCFS credit prices in times of excessive demand.

A Credit Floor Price Would Give Needed Certainty to Prospective Advanced Low-Carbon Fuel Producers

While the fundamental nature of the LCFS provides a critical incentive for advanced fuels (e.g. cellulosic biofuels, renewable diesel or hydrogen) to enter the market, this incentive often lacks the certainty required for prospective fuel producers to access capital markets

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[2] ICCT & E4Tech (2015) *Potential Low Carbon Fuel Supply to the Pacific Coast Region of North America* http://www.theicct.org/potential-low-carbon-fuel-supply-pacific-coast-region-north-america

[3] Promotum Group (2015) *California's Low Carbon Fuel Standard: Evaluation of the Potential to Meet or Exceed the Standards* http://www.ucsusa.org/sites/default/files/attach/2015/02/California-LCFS-Study.pdf

[4] E2 (2014) *Advanced Biofuel Market Report* https://www.e2.org/ext/doc/E2AdvancedBiofuelMarketReport2014.pdf

[5] UC Davis ITS (2014) *Status Review of California's Low Carbon Fuel Standard* http://www.its.ucdavis.edu/wp-content/themes/ucdavis/pubs/download_pdf.php?id=2253

and build commercial-scale production facilities. Part of this uncertainty revolves around the value of LCFS credits. Credit values have been relatively low for most of the program's history and the best projections indicate an over-supply of credits for the next 2-3 years[6]. This over-supply could risk a decline in credit prices during this period. At the same time, it is critical that advanced, low-carbon fuel producers expand production capacity during this time in order to meet stricter targets in the 2019-2020 timeframe.

Creating a floor price on LCFS credits can help create this certainty and bring more advanced fuel producers into commercial production. This would not only help the LCFS program meet its goals, but would create a more robust and liquid market for low carbon fuels, which would protect California's consumers and businesses from supply-related price increases in the future.

Carbon Intensities Need to be Regularly Re-Evaluated

Low carbon fuel production is still an emerging field, particularly as it relates to advanced biofuels. Scientific understanding of biofuel production processes is rapidly improving, as are the tools for conducting objective and accurate life cycle analyses. It is very likely that as our understanding of these systems, and our tools for evaluation improve, existing Carbon Intensity (CI) values will be revised. We urge the board to include a regular review process and procedure for modifying existing carbon intensities as better information emerges. We recognize the need to provide long term certainty to fuel providers regarding the value of their fuels and urge the board to find a balanced solution that allows for appropriate revision of CI numbers with a sufficient lead-in or phase-in time to allow producers to compensate for any changes and react appropriately.

Soil Carbon Changes May be Insufficiently Addresses by Current CI Calculations

Agricultural residues are thought to be a critical feedstock for biofuel or bioenergy production[7]. Emerging science is starting to question the assumption that agricultural residues can be removed for biofuel use without impacting soil characteristics, such as stored soil carbon[8,9]. While there is still substantial research ongoing, depleting soil carbon as a result of residue removal can result in fuels which offer limited value towards carbon reduction and may even be worse than the fuels they replace[10]. Given the critical importance of California's LCFS in setting standards for similar policies on the West Coast and beyond, it is absolutely essential that this determination be made with the greatest level of scientific certainty. Please review Attachment 1[11], research which aggregates data from several existing

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[6] *Ibid.*

[7] U.S. D.O.E. (2011) *Billion Ton Update* http://www1.eere.energy.gov/bioenergy/pdfs/billion_ton_update.pdf

[8] Anderson-Teixeira, K. J., Davis, S. C., Masters, M. D., & Delucia, E. H. (2009). Changes in soil organic carbon under biofuel crops. *GCB Bioenergy*, *1*(1), 75–96. doi:10.1111/j.1757-1707.2008.01001.x

[9] Liska, A. J., Yang, H., Milner, M., Goddard, S., Blanco-Canqui, H., Pelton, M. P., ... Suyker, A. E. (2014). Biofuels from crop residue can reduce soil carbon and increase CO2 emissions. *Nature Climate Change*, *4*(5), 398–401. doi:10.1038/nclimate2187

[10] Murphy, C., & Kendall, A. (2014). Life Cycle Analysis of Biochemical Cellulosic Ethanol under Multiple Scenarios. *GCB Bioenergy*, Accepted, in press. doi:10.1111/gcbb.12204

studies of the effect of corn stover removal on soil carbon levels, which finds evidence of significant soil carbon loss even at moderate levels of corn stover removal. This research is not, by itself, definitive on the subject but it indicates that there is a substantial risk here, which has not been adequately addressed by existing models or agricultural practice. We urge the board to exercise extreme caution when determining CI values for residue-derived fuels where the residues would previously have been returned to the soil. We also urge the Board to regularly review research on this subject and revise CI values promptly when sufficient evidence exists to justify such.

The LCFS is a Strong Policy Which Should be Re-Adopted

The current LCFS has, according to the overwhelming preponderance of evidence, achieved its goals and when the benefits to public health and energy security are considered, it has been a strong investment for the state. Already, tens of thousands of Californians are employed by jobs related to sustainable transportation in the state[12] The California Air Resources Board now has the opportunity to extend this success to 2020 and beyond and cement the state's leadership in this critical area of climate policy.

We would be happy to discuss any of these issues with the Board at your convenience. Please do not hesitate to contact us if there is anything else we can add.

Sincerely,

Colin W. Murphy
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NextGen Climate America, Inc.
cmurphy@nextgenamerica.org
(415) 802-2405

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[11] Excerpted from Murphy, C. W. (2013). *Modeling the Environmental Impacts of Cellulosic Biofuel Production in Life Cycle and Spatial Frameworks by*. University of California, Davis.

[12] Advanced Energy Economy (2014) *California Advanced Energy Employment Survey* http://info.aee.net/hs-fs/hub/211732/file-2173902479-pdf/PDF/aeei-california-advanced-energy-employment-survey-fnl.pdf

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Chapter 4: Analysis of Soil Organic Carbon Changes from Corn Stover Harvest

4.1 Introduction

Biofuels are thought to be a promising technology for reducing greenhouse gas (GHG) emissions from the transportation sector. The U.S. Revised Renewable Fuel Standard (RFS2) calls for a substantial increase in biofuel utilization over the next 10 years. At least 16 billion gallons (61 billion liters) of biofuels made from lignocellulosic feedstocks ("cellulosic biofuels") are specifically mandated by RFS2 (Renewable Fuels Association, 2010). Cellulosic biofuels have the potential to meet RFS2 GHG reduction goals (Bracmort, 2012; Farrell et al., 2006; C. Murphy & Kendall, n.d.; Tao & Aden, 2009; Viikari et al., 2012), but substantial uncertainty remains, particularly surrounding soil organic carbon (SOC) changes from producing and harvesting lignocellulosic feedstocks (Anderson-Teixeira et al., 2009; Lemke et al., 2010; P. Smith, 2007). In fertile soils, organic matter from root growth and above-ground litter is incorporated into the soil over time. Some of this carbon remains in the soil for long periods of time (Humberto Blanco-Canqui & Lal, 2009; J. M.-F. Johnson, Barbour, & Weyers, 2007). When undisturbed, carbon content in soils often reaches equilibrium, where the amount of soil carbon being added approximately equals that being lost (Buyanovsky & Wagner, 1997).

Disturbing these pools of SOC through changes in land coverage or agronomic management, such as removing large amounts of biomass for biofuel production, can alter soil carbon balances. This is of particular interest to biofuel analysts and policy makers, since the magnitude of these changes can be quite significant (Fargione et al., 2008). Cultivating feedstock crops for cellulosic biofuels typically requires a substantial change in management since, at present, virtually no cellulosic biofuel capacity is operating in the U.S. (Advanced Ethanol Council, 2013). Even where specific agronomic practices for biofuel crops are similar to food ones, biomass harvest removes much more biomass from the field than food harvest.

Corn stover, the above-ground, non-grain part of the corn plant, is thought to be a promising feedstock for biofuel production because substantial acreage of corn is already cultivated in the U.S. and stover is typically left on the field as residue (Graham et al., 2007). If harvesting stover causes a loss of soil organic carbon, through oxidation or reduction and volatilization to CO_2 or CH_4, then the life-cycle GHG impact of stover-based biofuels would increase. SOC changes are affected by local soil and climatic conditions as well as the type of organic matter in the soil, some forms, such as lignin, are typically much more recalcitrant than others. Understanding the SOC change is, therefore, an important element in accurate life-cycle assessment of biofuels.

This paper focuses on the following question: Does removing some part of the corn stover from corn fields reduce SOC? If so, under what conditions and by how much is it reduced? To answer this, we collect data from 21 studies of corn stover removal and SOC changes. 17 of these studies were from peer-reviewed publications, two were unpublished data from authors which had published in this field before (and which are intended for publication in the future), one was a M.S. thesis and one a PhD Dissertation.

4.2 Methodology

4.2.1 Data Collection

A literature search was conducted of studies quantifying changes in SOC from the harvest of corn stover. Google Scholar and ISI Web of Science were searched using the keywords "soil carbon" and "corn stover". This returned several hundred results, so a set of criteria was established to limit the inclusion to papers which would most directly reflect the effects of corn stover removal on SOC. These criteria were:

- Inclusion of at least two levels of stover removal, including zero.
- Corn must be grown continuously or must represent at least 50% of any crop rotation.
- Sampling depth must be at least 5 cm.

- Agronomic parameters including soil classification, tillage and nitrogen (N) fertilization must be reported or obtainable through other sources.
- Must be unique data; literature reviews and meta-analyses were used to identify potential studies, though all data in the dataset was copied from the original publication.

Only studies reporting empirical data were selected for this analysis; a comparison between measured and modeled studies is planned for future work. The 5cm sampling depth was picked to minimize the transient effects of surface litter. The crop rotation condition was set to allow corn-soy rotations, which are common. When a paper met these criteria, the relevant data were extracted to a MS-Excel data file (Microsoft, 2006). Additional papers were discovered by examining the works citing and cited by papers which were included in the study, as well as several literature reviews on the subject (Anderson-Teixeira et al., 2009; Humberto Blanco-Canqui, Lal, Post, Izaurralde, & Owens, 2006; Powlson, Glendining, Coleman, & Whitmore, 2011; W W Wilhelm, Johnson, Hatfield, Voorhees, & Linden, 2004; Zanatta, Bayer, Dieckow, Vieira, & Mielniczuk, 2007). When many sampling depths were reported in the same study and field, no more than two were included in this study, to avoid overrepresentation of any single study.

21 suitable studies were identified, which included data from 22 experimental fields (Appendix 8.2). These studies identified several factors thought to impact SOC changes from stover removal: soil clay content, biomass removal rate, initial SOC content, crop rotation practice, N fertilization, tillage practice, sampling depth, soil bulk density and duration of the study. Values for these parameters were extracted from the papers in the study. Where data were not reported, study authors were contacted to attempt to fill in gaps. If this failed, values were estimated from other sources, such as companion studies or earlier or later work from the same research plots. Soil conditions, such as bulk density and clay content were estimated by referencing the soil series and study location in the USDA Web Soil Survey (Soil Survey Staff, 2013).

Residue removal rates were given in the constituent papers, however not all were given as the fraction of above-ground biomass; some were based on surface area measurements or on the percent of mechanically-harvested stover, which excludes a stubble under the cutting height of a harvester. These were converted to mass fractions based on the 1:1 relationship between cut height and stover mass reported in Wilhelm, et al. (2010) and the average "Low-Cut" height for mechanical silage harvesters reported by Wu and Roth (Z. Wu & Roth, n.d.). Where corn height was unavailable, it was assumed to be equal to that of the average in the nearest test field reported in Wilhelm, et al. (Wally W. Wilhelm et al., 2010).

SOC is typically reported in one of two forms, as a mass fraction (g SOC/kg soil, or % SOC) or as a mass-per-area (typically Mg SOC/ha). The mass fraction form was used as the functional unit for our analysis, which reduces covariance between SOC levels and sampling depth. Where mass fractions were not available, the following relationship was used to convert between the two:

$$SOC_m \ \left(\frac{Mg}{ha}\right) = 10{,}000\frac{m^2}{ha} \times SD\ (m) \times BD\left(\frac{Mg}{m^3}\right) \times SOC_f\left(\frac{kg_{soc}}{kg_{soil}}\right) \qquad (1)$$

where SOC_m is SOC mass per area, SD is sampling depth, BD is soil bulk density and SOC_f is SOC mass fraction.

Tillage practices were grouped into three classes: (1) conventional tillage (CT - which includes continuous tillage using moldboard plow); (2) reduced tillage (RT - which includes conservation tillage; chisel plow; strip tillage; mulch tillage; ridge tillage); and (3) No tillage (NT). Conventional tillage has been widely reported as contributing to SOC loss; several studies find that tillage has a greater affect on SOC than residue removal (Clapp et al., 2000; Dick et al., 1998; Reicosky & Evans, 2002). This effect varies with soil depth, since tillage induces mixing of soils and rapidly moves stover carbon downwards, as well as reducing particle size (Anderson-Teixeira et al., 2009; Dolan, Clapp, Allmaras, Baker, & Molina, 2006). We control for the different tillage classes using indicator variables for which tillage method was used on a field.

Nitrogen fertilization may have an effect on SOC concentrations; this is examined in this study. The effect of nitrogen fertilizer on soil microbial activity and carbon dynamics will depend strongly on biogeochemical conditions, including the amount of available nitrogen in the soil prior to fertilization. Previous literature has been mixed and uncertain regarding the effect of nitrogen on SOC levels (Dolan et al., 2006). There is relatively little variation in nitrogen treatment rates, so it is uncertain whether treating this as a continuous parameter will identify any meaningful effects. Accordingly, two specifications are presented, one with nitrogen treated as a binary qualitative variable and one as a numeric rate (Specifications 4 and 5, respectively).

Soil classes are grouped into 7 categories, corresponding with USDA soil textural classes (Soil Conservation Service, 1987); not every class was observed in this dataset. Indicators for each class and type are included in regressions with appropriate exclusions to avoid perfect multicollinearity.

4.2.2 Analytical Methods and Identification

A reduced form regression approach was used to study the effect of various factors on SOC content in soil. The approach allows for flexible control of a number of factors which may affect SOC. In addition, cluster robust standard errors, clustered at the study level, were used to construct confidence intervals which account for idiosyncratic differences across studies as well as correlation in observations over time within studies (Cameron & Trivedi, 2005). In order to produce results that are relevant for prospective modeling of SOC changes, two types of SOC change are considered. In some cases, the important characteristic is the net gain or loss of SOC after a period of corn stover recovery. This "Within-Field" (WF) change is estimated using a differences-in-differences regression, where the dependent variable is the initial SOC and the initial SOC is controlled for as an explanatory variable.

Sometimes the critical characteristic for models is the difference between SOC in a field in which stover is collected and a hypothetical *status quo*. In the case of corn stover, the *status quo* is assumed to be corn production with stover left on the field, as it is in over 95% of all U.S. corn fields(U.S. EPA, 2013a). This "Between-Field" (BF) change is analyzed using a differences estimation. The basic regression used takes the form

$$y_{it} = h(x'_{it}\beta) + \epsilon_{it} \qquad (2)$$

where y_{it} is the final SOC percentage for field i in time t and x_{it} are explanatory variables including percent biomass removal, initial percent SOC, nitrogen treatment, tillage practice, clay content, sampling depth, and study duration. β is the coefficient estimated by regression, ϵ is the error term and *h* is the functional form of the parameter, which can be non-linear, such as quadratic or logarithmic. The purpose of the regression is to identify the causal relationship between x_{it} and final SOC. This requires a number of assumptions.

The data collected represent averages across a number of replications such that

$$\overline{y_{it}} = \frac{1}{n_j}\sum_{j=1}^{n_j} y_{ijt} \qquad (3)$$

where j is the number of replications on field i. In order to be able to identify the relationship of interest, the estimates must have linear parameters. To see this, note that the average change in y_i from a change in variable x_i is given by

$$\Delta\,\bar{y}_i = \frac{1}{n_j}\sum_{j=1}^{n_j} \Delta y_{ij} = \frac{1}{n_j}\sum_{j=1}^{n_j} h(\Delta x'_{ij}\beta) \qquad (4)$$

So long as $h(\cdot)$ is linear in the parameters, then

$$\Delta \bar{y}_j = \beta \frac{1}{n_j} \sum_{j=1}^{n_j} h(\Delta x_{ij}) \qquad (5)$$

Note that $h(x_{ij})$ can be a non-linear in the variables x_{ij}, so the assumption is not unduly restrictive.

A second key assumption to identify the causal relationship is that the conditional expectation of the errors is zero. The assumption would be violated if important explanatory variables are omitted, which correlate with an explanatory variable x_{ij} and affect final SOC percent, known as omitted variable bias. The condition may also be violated if the functional form is mis-specified. The robustness of the estimated effects to the inclusion of a number of control variables and specifications is checked to test the sensitivity of our results to potential omitted variable bias.

A last concern relates to the nature of the dependent variable. The SOC content in fields, as a percentage of mass, is constrained to be within the interval (0,1). Linear regressions do not restrict predictions to be between (0,1) and could lead to biased results (Kieschnick & McCullough, 2003). A popular approach to dealing with this is to use a logistic transformation of the dependent variable given by

$$\ln\left(\frac{y_{jt}}{1 - y_{jt}}\right) = h(\boldsymbol{x}'_{it}\beta) + e_{jt} \qquad (6)$$

If the errors follow an additive logistic normal distribution, then e_{it} will follow a normal distribution and standard Gaussian statistical inference applies. All proceeding results were run under both a linear model and a logistic model. In general, the logistic model had limited if any advantage over the linear model, and the linear model allowed for more precise estimates because of its assumption of linear marginal effects.

4.3 Results

Variable	Mean	Std. Dev	Min	Max	N
Final Soil Organic Content (kg/kg)	0.0202	0.0064	0.0072	0.0473	251
Initial Soil Organic Content (kg/kg)	0.0233	0.0082	0.0091	0.0544	185
Biomass Removed (fraction of total)	0.4735	0.4187	-0.1800	1	251
Tilling Practice (Categorical Variable)	1.7540	0.6850	1	3	212
Clay Content (kg/kg)	0.2156	0.1002	0.0580	0.4370	251
Sampling Depth (cm)	23.4821	13.4621	5	60	251
Study Duration (years)	10.075	9.99	2	34	251

Table 4-1 - Summary Statistics for Corn Stover Removal Dataset. 81% of plots in the study were treated with nitrogen fertilizer.

Table 4-1 presents the summary statistics of the key variables of interest. As can be seen, final SOC is slightly lower than our initial observed SOC; however, directly comparing differences in means can be misleading for a number of reasons. First, we do not observe initial SOC for 47 of our observations. Second, as can be seen from the summary statistics, there is substantial heterogeneity across studies such as the type of tilling practice, the soil class, sampling depth, soil density and the duration of study.

Direct evaluation of WF and BF changes may lead to incorrect inference if there are other factors which led to changes in SOC in addition to biomass removal. Using a regression approach, we measure WF and BF changes flexibly, controlling for a number of factors which may also determine final SOC percentage. Included in our analysis are nitrogen application rates, duration of the study, clay content, sampling depth, and tillage practices. The effect of different parameters and combinations of parameters are checked in several forms, or "specifications" of the linear regression model.

Study and field effects are also considered, since agronomic practices, as well as local soil and climate conditions would be strongly correlated with the study they are reported in. If different studies are associated with different methodologies which are not captured in the dependent variables of interest, our results may be biased. These are controlled for in the same way as the qualitative variables above. Namely, for some specifications we include indicators for each study, with appropriate exclusion restrictions. In these regressions, identification is based on within-study variation as including indicator variables for each study effectively demeans all variables by their respective within-study or within-field means. By checking for study effects, the effect of variation within a study or field is lost, so this approach can identify whether there are systematic differences between studies, but cannot simultaneously identify the effects of other parameters.

The first three specifications for each model, [1-3] and [6-8], check for the presence of bias introduced by study-specific or field-specific effects. Table 4-2 shows the result for the linear difference estimator (BF SOC changes). Specification [1] presents the basic BF effect with no control variables. If the experiments were properly randomized, the estimated effect should be unbiased. Results including study fixed effects are shown in specification [2]. Control for the effects of the experimental field, rather than the study in which results were reported, was done using the same methods and shown in specification [3]. Similar analyses are done for WF SOC change in specifications 6-8. The relatively similar coefficients generated for each of these specifications, combined with clear statistical significance for all, indicates that there are no significant biases introduced by study or field effects.

Specification	[1]	[2]	[3]	[4]	[5]
Biomass Removed (%)	-0.00113***	-0.00150***	-0.00146***	-0.00126***	-0.00129***
	(0.000382)	(0.000290)	(0.000295)	(0.000374)	(0.000379)
Nitrogen Treatment Indicator				-0.000123	
				(0.000756)	
Nitrogen Rate ('00 kg/ha/year)					0.000726
					(0.000534)
Log Duration (log years)				0.000242	0.000168
				(0.000668)	(0.000634)
Clay Content (%)				0.00348	0.00578
				(0.0102)	(0.0110)
Sampling Depth (cm)				-0.0000763	-0.0000861
				(0.000238)	(0.000229)
Sampling Depth Squared (cm^2)				-0.00000115	-0.000000900
				(0.00000396)	(0.00000380)
Till 1 (CT)				0.0231***	0.0216***
				(0.00387)	(0.00450)
Till 2 (NT)				0.0247***	0.0230***
				(0.00317)	(0.00365)
Till 3 (RT)				0.0250***	0.0237***
				(0.00386)	(0.00412)
Constant	0.0208***	0.0176***	0.0176***	(Omitted)	(Omitted)
	(0.00176)	(0.000139)	(0.000142)		
N	251	251	251	211	207
R Squared	0.006	0.588	0.590	0.958	0.959
AIC	-1824.2	-2047.3	-2042.8	-1651.2	-1623.8
Study Effects?	N	Y	N	N	N
Field Effects?	N	N	Y	N	N

Table 4-2 Difference Estimators (BF SOC changes) for Linear Regression of SOC concentration (%) as dependent variable. Asterisks indicate significance, *: p<0.1, **: p<0.05, ***: p<0.01. Standard errors are in parenthesis.

All of the linear models with more complete sets of parameters, specifications [4], [5], [9] and [10], indicate a very consistent effect of SOC removal; every 1% of additional residue removal leads to a 0.0013% reduction in SOC, with all other factors being held equal. All SOC change values are significant to p<0.01. While this SOC reduction appears small, when one considers that the average corn field in this study had 57 Mg/ha at the start of residue removal treatments, this implies a loss of around 50 kg C per hectare for every percent of residue removal. The duration term has a negative sign under both linear (not shown) and logarithmic forms, which indicates that continuing treatment also tends to reduce SOC.

All specifications show a significant negative effect at the 1 percent level of residue removal on SOC. Importantly, this effect does not vary substantially between specifications. The stability in the point estimate indicates that biomass removal treatment was well randomized and was not correlated with other important determinants of final SOC. Few other parameters reach statistical significance in the

Specification	[6]	[7]	[8]	[9]	[10]
Biomass Removed (percent)	-0.00112**	-0.00140***	-0.00135***	-0.00130***	-0.00134***
	(0.000387)	(0.000342)	(0.000344)	(0.000358)	(0.000360)
Initial SOC (%)	0.619***	0.625***	0.639***	0.496***	0.494***
	(0.0948)	(0.0717)	(0.0772)	(0.0734)	(0.0736)
Nitrogen Treatment Indicator				-0.000431	
				(0.000796)	
Nitrogen Rate ('00 kg/ha/year)					0.000324**
					(0.000135)
Log Duration (log years)				-0.000303	-0.000264
				(0.000612)	(0.000616)
Clay Content (%)				0.000411	0.000582
				(0.00707)	(0.00738)
Sampling Depth (cm)				-0.000372	-0.000354
				(0.000272)	(0.000273)
Sampling Depth Squared (cm^2)				0.00000507	0.00000480
				(0.00000440)	(0.00000440)
Till 1 (CT)				0.0170***	0.0159***
				(0.00273)	(0.00274)
Till 2 (NT)				0.0165***	0.0155***
				(0.00238)	(0.00245)
Till 3 (RT)				0.0159***	0.0148***
				(0.00379)	(0.00357)
Constant	0.00731***	0.00903***	0.00518**	(Omitted)	(Omitted)
	(0.00224)	(0.00180)	(0.00211)		
N	185	185	185	165	165
R Squared	0.686	0.829	0.808	0.981	0.981
AIC	-1565.8	-1680.2	-1654.9	-1413.3	-1414.1
Study Effects?	N	Y	N	N	N
Field Effects?	N	N	Y	N	N

Table 4-3 - Difference-in-Difference Estimators (WF SOC changes) for Linear Regression of SOC concentration (%) as dependent variable. Asterisks indicate significance, *: p<0.1, **: p<0.05, ***: p<0.01. Standard errors are in parenthesis.

specifications, however, which generally supports the common impression in literature on the subject: that SOC in corn production systems is variable and uncertain. The signs of most parameters agree with other studies. Sampling depth and study duration are negative, which is to be expected, since both treatment duration and the mass of soil sampled would be expected to correlate with the magnitude of effects noticed; repeated corn cultivation is generally associated with declining SOC (D. L. L. Karlen et al., 1994; W. Smith & Grant, 2012). Clay content has a positive sign, indicating that increasing clay content generally reduces SOC loss, as reported by multiple studies (e.g., 29).

Table 3 shows the difference-in-difference estimator, which controls for initial levels of SOC and describes WF changes If removal treatments were not randomly assigned and there were important differences between treated and untreated fields which affect final SOC levels, the differences regression may lead to biased point estimates. The difference-in-differences estimator is robust for these concerns. Like the difference estimator discussed above, the effect of biomass removal is significant and negative, and does not substantially vary when alternative control variables are included. Unsurprisingly, the parameter with the greatest effect on final SOC concentration is initial SOC concentration. Parameters are generally of similar magnitude, sign and significance as in the BF analysis discussed above, suggesting the studies properly randomized treatment.

For most of the complete specifications (numbers [4], [5], [9], [10]), the results indicate each additional percent of biomass removal results in SOC decreasing an average of 0.0013% with a standard error of approximately 0.0004%, which yields a 95% confidence interval of approximately 0.0005 to 0.002% decrease. We tested for the presence of nonlinear effects using both the logistic model as well as quadratic terms in the linear model; however, the nonlinearities across biomass removal rates were not found to be statistically significant. The result is likely driven by lack of heterogeneity in removal rates across studies. Most studies reported removal rates only for no or near complete removal of biomass, and few had intermediate removal levels. As a result, the estimates are best thought of as an average effect of biomass removal.

Very few parameters besides biomass removal, initial SOC and the model coefficient (which is omitted in favor of tillage practice dummy variables in several specifications) achieve statistical significance, however those parameters are significant to $p<0.01$ certainty. Nitrogen treatment rate is significant on the WF model, but not on the BF model. Several of the non-significant parameters have been identified by other studies, or theoretical understanding of SOC dynamics, as affecting SOC changes. It is uncertain whether the results here are merely artifacts of this experimental design or call into question previous results.

4.4 Discussion

The results demonstrated above show a loss of 0.0005% to 0.002% in SOC per year for every 1% of residue removed. Using equation (1) and assuming a removal rate of 30%, which has been proposed by several sources in literature as a sustainable rate of stover removal (e.g. 41, 42), over a sampling depth of 30 cm and soil density equal to 1.31 (the average found from this dataset), this equates to a loss of 197-786 kg SOC/ha*year, which if emitted entirely as CO_2 yields 0.72 to 2.9 Mg CO_2/ha*year. In the context of life cycle analysis, this CO_2 emission is highly significant. Assuming an approximately 4 dry tonne/ha yield of stover and 292 liter/tonne conversion efficiency, this adds approximately 30 grams of CO_2e per megajoule (MJ) of delivered fuel. The RFS2 requires fuels that achieve the "cellulosic" designation achieve 50% reductions in life cycle GHG intensity compared to the petroleum fuels they displace. This implies targets of around 50 grams CO_2e/MJ for cellulosic biofuels, depending on the fuel being evaluated and the life cycle analysis methodology. The results of this study indicate that for stover based fuels, SOC change alone accounts for most of the allowable GHG emissions.

One area where substantial uncertainty remains is temporal effects. The treatment duration term was highly uncertain (the estimate was much smaller than the standard error) for both linear and logarithmic transformations of duration (Table 4-2 and Table 4-3, specifications 4, 5, 9, 10. Linear parameters were estimated, but not shown). Under commonly accepted models of soil dynamics, SOC concentrations in a field under a positive or negative SOC flux, such as residue removal, will come to an equilibrium over time (Anderson-Teixeira et al., 2013; Buyanovsky & Wagner, 1997). The lack of significance in this parameter may be a result of incorrect model specification, omission of other factors which affect SOC (such as total biomass production on the field), of a misunderstanding regarding the nature of SOC equilibria

SOC changes from stover harvest is a critical issue for determining the life-cycle GHG footprint of biofuels and bioproducts in the U.S. The U.S. grew over 34 million ha (84 million acres) of corn in 2011; which produces over a hundred million tonnes of residue as well. This residue could potentially be used for a wide range of bioprocesses and since it is currently left on the field on over 95% of farms. If SOC decreases from moderate levels of stover harvest are as high as earlier studies predict (Anderson-Teixeira et al., 2009), any bioprocess using corn stover is likely to be a significant net emitter of GHGs.

The results from the regressions above clearly show a significant and robust negative correlation between residue removal and SOC concentration. This matches the expected behavior of systems according to current understanding of SOC dynamics (Anderson-Teixeira et al., 2013; Humberto Blanco-Canqui, Lal, Post, Izaurralde, et al., 2006; Hooker et al., 2005), which strongly implies that the statistical correlation, in fact, reflects a causal relationship. By aggregating the results of many studies, the analysis presented above was able to overcome some of the statistical uncertainty described by previous authors in the field.

Few other parameters achieve statistical significance, which confirms the common conclusion in literature that SOC dynamics are highly uncertain. For WF changes, initial SOC was significantly correlated with final SOC, which is to be expected, since SOC changes are incremental increases or decreases upon previously existing SOC pools. The WF analysis also showed a significant relationship between nitrogen fertilization rate and SOC change. Previous research has been divided on the subject of the relationship between N fertilization and SOC (Dolan et al., 2006; Pikul, Johnson, Schumacher, Vigil, & Riedell, 2008).

One finding of this analysis contradicts well-established opinion in this field. For both WF and BF changes, SOC did not significantly differ between different tillage practices (CT, RT and NT were within a range less than any of their standard errors). Multiple previous studies have concluded that tillage, particularly conventional tillage (CT in this study), are strongly associated with reductions in SOC (e.g. 27, 38, 39). Further analysis is required to determine whether this is an artifact of the regression parameters used in this study, or whether tillage effects are more uncertain than previous literature indicated.

It is possible that the current model does not effectively capture differences in biomass production between fields. Of the parameters considered, only nitrogen fertilization is strongly associated with more biomass being produced. Changes in SOC levels are determined by the balance between inputs to soil, largely from plant matter, and flows out, from erosion and microbial metabolism. Rapid plant growth can increase SOC in two ways, by facilitating rapid root growth and creating a larger pool of above ground biomass, some of which may be incorporated into the soil. If the model, as currently formulated, is insensitive to the total biomass production of corn plants, then the categorical variables for tillage may be absorbing some unintended effects. Additionally, in areas with very high biomass production, tillage is sometimes required to minimize the insulating effects of surface residue, which can slow soil warming in spring and retard germination (Nielsen, 2010). This may imply an interaction between biomass production effects and tillage which is not captured in the current model.

Understanding SOC changes within the framework of life cycle analysis is complicated because accurate estimation of these changes is typically based on a consequential assessment framework. That is to say, the characteristic of interest is what changes a proposed production system would cause on the world. So, for a stover based production system the absolute magnitude of emissions from SOC change must be evaluated in a context which also considers any emissions from SOC change that would occur had the stover not been removed. This is usually done by a comparison between systems in which stover is harvested and the *status quo* in which it is generally not harvested. The analysis presented in this paper can help future analysts by presenting models for WF and BF changes. In general, the BF case better matches the needs of consequential LCA. BF comparison evaluates the difference between fields in which stover is removed and those in which it is retained on the soil. The WF comparison, on the other hand, may be less vulnerable to uncertainty stemming from soil conditions or measurement practices. BF comparisons in this study implicitly assume that all fields in a study have approximately equal SOC concentrations at the start of the study, which is not always the case, as is demonstrated by some of the studies in this review (Clapp et al., 2000; Wilts, Reicosky, Allmaras, & Clapp, 2004). Since initial SOC levels clearly affect SOC dynamics under residue removal, this means that BF comparisons suffer from at least one source of uncertainty that WF would likely avoid.

There are several areas of uncertainty which may affect the conclusions of this analysis. Climate conditions and the cultivars grown substantially affect total biomass production, which is the maximum amount of biomass that could be returned to the soil. Not all studies quantify total biomass returned, future work will attempt to evaluate whether mass of carbon entering the soil is more strongly correlated with maintaining SOC levels than residue removal rates.

While many studies have reviewed the impact of crop residue removal on SOC (Anderson-Teixeira et al., 2009; Humberto Blanco-Canqui, Lal, Post, Izaurralde, et al., 2006; Powlson et al., 2011; W W Wilhelm et al., 2004; Zanatta et al., 2007) most have not looked at agricultural management strategies that can help offset SOC lost due to crop residue removal. Blanco-Canqui (2013) recently reviewed the potential of several agricultural practices to counteract the SOC lost due to residue removal. No-till cover crops or applying C-rich substances such as manure, compost or the solid byproduct of cellulosic ethanol production (e.g. lignin cake or biochar) can all have beneficial impacts on SOC levels in soils from which lignocellulosic biomass is harvested.

The substantial uncertainty surrounding the SOC effects of sustained stover collection clearly demonstrate the need for further research in this area. LCA of biofuel production shows the critical importance of providing relatively low-GHG feedstocks for biofuel production systems. Likely near-term technology can achieve the goals of climate change mitigation policies, like RFS2, but they do not clear the GHG target thresholds for advanced biofuels by much; if feedstock production results in SOC loss at the higher end of its uncertainty range, there is virtually no chance for biofuels to achieve their GHG reduction targets and, in fact, at the high ranges of SOC loss, biofuels may be worse than the petroleum fuels they hope to replace.

Further study is needed to answer these critical questions. Most pressingly, there needs to be more empirical studies of SOC change under a variety of management conditions. Already, there is a multi-center research effort, coordinated by the USDA under the Sungrant program to directly address this research need (D. L. Karlen, Varvel, et al., 2011; Stott, Jin, & Ducey, n.d.). Additionally, better guidance regarding the most relevant methods for quantifying SOC change and measurement standards would help facilitate meaningful comparisons between studies.