

The Use of Corn Stover for Ethanol, Other Biofuels and Bioenergy in the United States – Implications for Soil Organic Carbon Changes

1. Overview of the Issue

The federal Renewable Fuel Standard (RFS), when passed in 2007, was intended to increase domestic energy independence and security, reduce greenhouse gas (GHG) emissions, diversify U.S. domestic fuel production and fuel types, and create domestic industries. It included specific volumetric targets for different types of biofuels, with mandated use of 15 billion gallons a year (bgy) of corn ethanol and a target of 16 bgy of cellulosic fuels, among other biofuel uses, in the United States by 2022. Life-cycle analysis (LCA) of GHG emissions of different biofuels is required to determine if a given biofuel meets minimum GHG reduction requirements compared to baseline petroleum gasoline and diesel. Congress believed that mandating these levels of biofuel use would lead to the creation of alternative fuels from diverse sources of biomass feedstocks including cellulosic biomass, which was regarded as diverse, abundant and low-cost. With a few exceptions, cellulosic fuels have not appeared with significant volume nationally or internationally, and EPA has been forced to drastically reduce its yearly targets for cellulosic fuels. The small amount of cellulosic fuels currently being produced is derived from renewable natural gas and potentially specialized treatment of the fiber fraction of corn kernels.

In addition to the RFS, California has established an aggressive regulatory program to reduce carbon emissions from the use of transportation fuels. The California Low Carbon Fuel Standard (LCFS) requires a gradual decline in the carbon intensity (CI), measured as g CO_{2e}/MJ of fuel, that will lead to a 10% reduction in the average liquid transportation fuel CI from 2010 to 2020. The LCFS differs fundamentally from the RFS in that it is nominally fuel and technology neutral. It relies on the use of LCA of the GHG emissions of producing and using alternative fuels, and encourages the production and sale of lower CI fuels. Obligated parties are the sellers of gasoline and diesel fuels and are required to produce and sell lower CI fuel mixtures or pay penalties. This creates a significant market for fuels with lower CI values in California. California is on target to meet its carbon reduction goal, and the use of cellulosic ethanol is an important component of achieving this goal.

In the United States, three new biorefineries have been built to convert corn stover and wheat straw into ethanol. These plants are located in Emmetsberg, Iowa by POET, in Nevada, Iowa by Dupont, and in Hugoton, Kansas by Abengoa¹. The two Iowa facilities are in the commissioning phase and are yet to reach nameplate capacity (25 to 30 million gallons a year [mgy]). Corn stover ethanol is defined as a cellulosic fuel in the EPA RFS and has a high monetary value under EPA's Renewable Identification Number (RIN). In California, corn stover ethanol has been given a CI of 21 g CO_{2e}/MJ by California Air Resources Board (CARB), approximately 80% less than the CI of gasoline. This makes it a potentially valuable fuel in California that would support LCFS compliance. Because of the added fuel premium available in the California market, it is likely that much of these cellulosic fuels will be marketed in California if they can be produced with a sufficiently low CI. The California market for low CI biofuels is large. There are 29.1 million vehicles in the state, 93% of which use gasoline/ethanol blends. Approximately 13 bgy of gasoline/ethanol blends are used in the state. Depending on the CI of corn stover derived fuels, demand for such fuels could be large.² So far, however, apart from Brazilian sugar cane, there are minimal amounts of other alternative fuels with low CIs that are used to help the state meet its aggressive LCFS standards. The majority of LCFS credits currently are derived from alternative diesel fuels. This makes the potential demand for corn-stover

¹ Abengoa is currently in bankruptcy. The facility in Hugoton may be acquired by Shell.

² E10 primarily and a small amount of E85; E15 is not used at present in California.

derived fuels a large and economically powerful incentive for their production. Cellulosic ethanol and sugarcane ethanol are projected by CARB to play an increasingly more important role in the LCFS in the near- to mid-term.

But should crop residues, especially corn stover, be removed from fields and used as a feedstocks for biofuel?

2. Life-Cycle Analysis of Biofuels in The RFS and LCFS

LCA is required by both the RFS and LCFS to determine the CIs of various biofuels as well as petroleum gasoline and diesel. Figure 1 below shows the activities along the biofuel supply chain that are included in a biofuel LCA (cellulosic ethanol from grown switchgrass is used as an example).

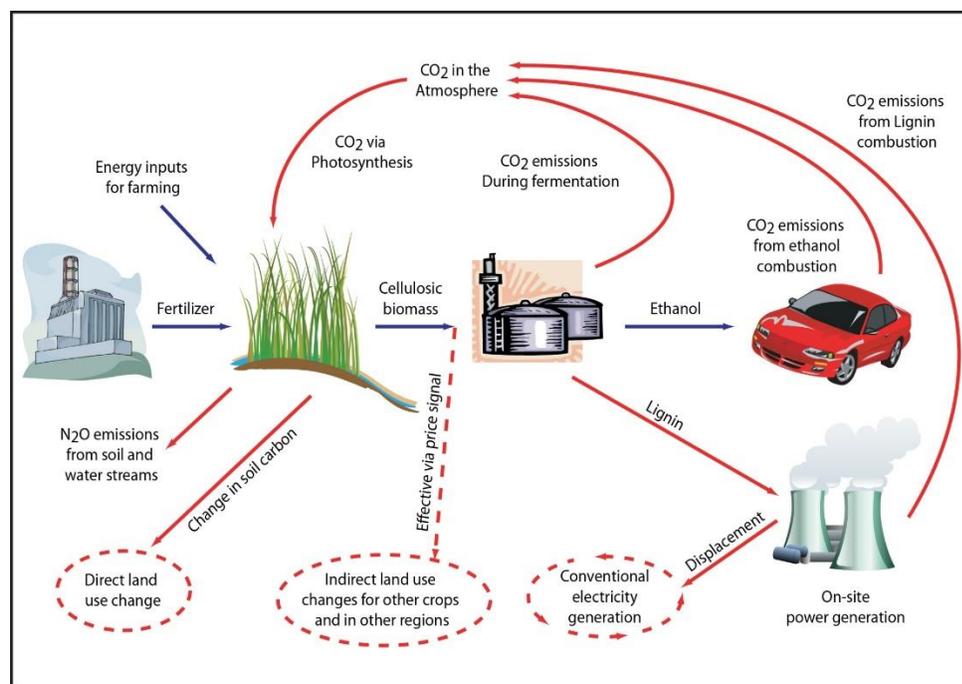
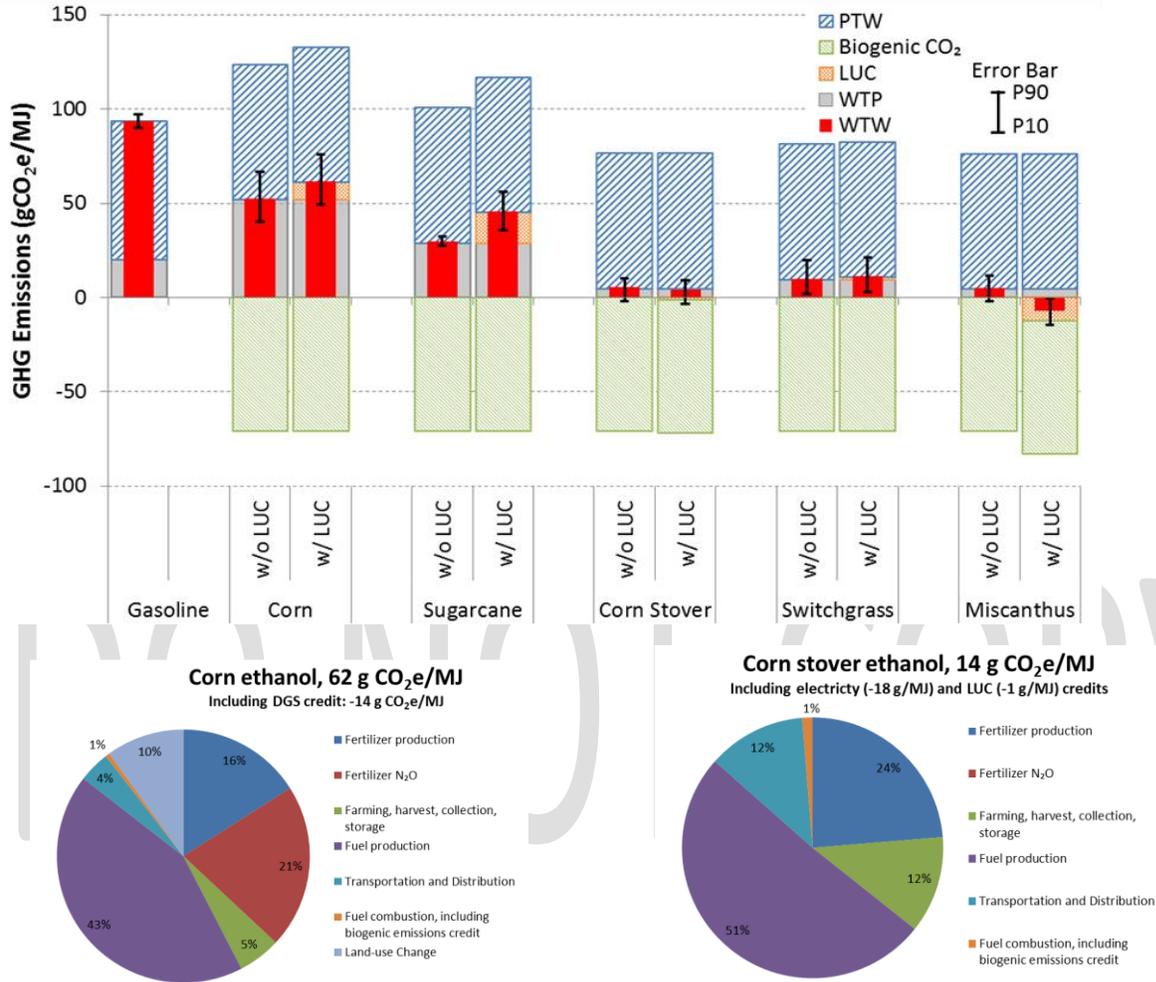


Figure 1. System Boundary of LCA of Cellulosic Ethanol from Switchgrass

The major activities affecting GHG LCA results for cellulosic ethanol include: 1) the amount of fertilizer used; 2) the GHG intensity of fertilizer manufacture (especially nitrogen fertilizer); 3) ethanol yield in ethanol plants; 4) co-produced electricity in ethanol plants; and 5) GHG emissions from direct and indirect land use change (LUC) for cultivating biomass feedstocks. Argonne National Laboratory has been developing the GREET® LCA model since 1994 to evaluate energy and environmental effects of transportation fuels and energy systems³. The GREET model is one of the several models that EPA has used for RFS GHG LCA analysis. Meanwhile, CARB has developed a GREET version (CA-GREET) for LCFS GHG compliance of various alternative transportation fuels. Figure 2 shows GHG LCA results of a few selected ethanol fuel production pathways based on GREET simulations.

³ See Systems Assessment Group, Argonne National Laboratory (2016) at <https://greet.es.anl.gov/files/summary-updates-2016>.



LUC – land use change
 PTW – pump to wheels (fuel combustion)
 WTP – well to pump (fuel production)
 WTW – well to wheels (LCA)

Figure 2. GHG LCA Results of Several Ethanol Fuel Pathways⁴

The newly released Billion Ton Study by DOE estimates that there are 100-200 million dry tons of crop residues that can be sustainably removed for biofuel production⁵. Corn stover is a significant share of the total crop residues estimated as available for use. The LCA of corn stover ethanol is conducted in GREET, by EPA, and by CARB with the following approach. Energy use for stover collection and transportation to ethanol plants are estimated and included in the LCA. Nutrients (N, P, K) are removed from cornfields together with stover. The amount of nutrients removed is estimated with the amount of stover removed and the nutrient contents of stover. Then, additional

⁴ From Wang et al. (2012): “Well-to-wheels energy use and greenhouse gas emissions of ethanol from corn, sugarcane and cellulosic biomass for US use,” *Environmental Research Letters* 7: 045905.

⁵ 2016 Billion-Ton Report, US Department of Energy:
http://energy.gov/sites/prod/files/2016/07/f33/2016_billion_ton_report_0.pdf.

amount of fertilizers is assumed for cornfields to supplement the nutrients removed with corn stover ethanol in the LCA.

One major outstanding issue of ethanol production from stover is the potential change in soil organic carbon (SOC) that might occur when stover is removed. If there is a reduction in SOC from stover removal, the reduced SOC should be accounted in the stover ethanol LCA as a GHG emission source. Limited modeling efforts have been made by Argonne National Laboratory and others using models such as the Century model to estimate the SOC change for biofuel LCAs. Stover SOC issues are summarized in the sections below.

3. Summary of Literature on Soil Organic Carbon Change and Corn Stover Removal

Crop residues are being harvested for a variety of purposes including their use as a livestock feed or to produce ethanol⁶. Despite its ultimate use, crop residue harvesting will reduce the annual additions of non-harvested carbon returned to soil⁷. The maintenance or the enhancement of SOC is a critical component of building resilience to perturbations such as drought, reducing erosion, and increasing yield. The impact of crop residue harvesting on productivity and soil health is influenced by many factors including the length of time that the field was cultivated, the crop rotation, soil texture, climatic conditions, initial carbon content of the soil, and crop yields. Because mineralization of crop residue to CO₂ is a biologically mediated process, factors that stimulate soil microbial activity reduce carbon sequestration. Field experiments are conducted to measure the effects of these factors. The ultimate goal of field experiments, which is accomplished using appropriate simulation models, is to extend the findings beyond to borders of the original experiments. On the other hand, modeling of soil dynamics is often conducted to understand effects of these factors, too. However, the usefulness of the modeling results is limited by baseline information that contains large uncertainties and reliance on data collected from short-term experiments that do not use field-scale equipment. Information from soil testing laboratories can provide important spatial and temporal information needed for benchmarks and validation⁸. However, access to the full data sets is limited by privacy issues.

Interactions between crop diversity, residue harvesting, and tillage have a direct impact on the soil biota, nutrient cycling, and soil health. However, there is much still to learn about these processes. For example, in reduced tillage systems evidence of earthworm's activity is becoming apparent. Earthworms move surface residues below ground, where they are mineralized and integrated into the soil organic matter. Earthworms also increase by-pass water flow and soil porosity. Harvesting the surface residues reduces the food source for these organisms. In long-term no-tillage fields, residue accumulation is generally not a problem because earthworms and other soil organisms slowly process above ground surface residues to soil organic matter⁹. The removal of the crop residues has the potential to increase water and wind erosion risks. Plant diversity by itself, may change nutrient cycling and soil health. For example, Wortmann et al.¹⁰ reported that the critical P level was reduced from 20 to 10 mg P kg⁻¹ by switching from a continuous corn rotation to a soybean/corn rotation.

Complex interactions occur between the plant and soil that govern soil carbon and nutrient cycling. Many are just being identified. Harvesting the surface residue directly influences the magnitude and scope of these interactions

⁶ Carlson, C.G., D.E. Clay, C. Wright, and K.D. Reitsma. 2010. "Potential impacts of linking ethanol, crop production, and backgrounding calves on economics, carbon, and nutrient budgets," SDSU Extension Publication. Brookings, SD.

⁷ Clay, D.E., G. Reicks, C.G. Carlson, J. Miller, J.J. Stone, and S.A. Clay. 2015. "Tillage and corn residue harvesting impacts surface and subsurface carbon sequestration," *J. Environ. Qual.* 44:803-809 Doi:10.2134/jeq2014.070322.

⁸ Clay, D.E., J. Chang, S.A. Clay, J. Stone, R. Gelderman, C.G. Carlson, K. Reitsma, M. Jones, L. Janssen, and T. Schumacher. 2012. "Corn yields and no-tillage affects carbon sequestration and carbon footprints," *Agron. J.* 104:763-770.

⁹ Karlen, D.L., N.C. Wollenhaupt, D.C. Erbach, E.C. Berry, J.B. Swan, N.S. Eash, and J.L. Jordahl. 1994. "Crop residue effect on soil quality following 10-years of no-tillage corn," *Soil Till Res.* 31:149-167.

¹⁰ Wortmann, A.R., R.B. Dobermann, G.W. Ferguson, G.W. Hergert, C.A. Sharpio, D.D. Tarkalson, and D.T. Walters. 2009. "High yielding corn response to applied phosphorus, potassium, and sulfur in Nebraska," *Agron. J.* 101:546-555.

and influences the amount of biomass that can be integrated into the soil organic C⁷. Research shows that harvesting surface residues has short and long-term impacts on crop yields¹¹. Over the short term, yield can be increased, whereas over the long term yield may be reduced. However, the impact of residue harvesting on crop yields is climate and soil specific, which could change over time.

In summary, the process of converting crop residues to soil organic matter helps the soil's living organisms recycle critical nutrients, builds and enhances soil structure, increases water infiltration, and produces conditions needed to sustain the production of food, feed, fiber, and energy. As with all living organisms, soil organisms require food (organic matter) to sustain their growth and development. Because soil organic carbon degradation is a biological process, the degradation process is influenced by complex interactions between the numerous factors impacting living organisms including temperature, moisture, quality of the material added to the soil, management, and texture.

While field experiments have proven to be helpful in understanding SOC dynamics, there are many experiments that contain fundamental problems in the experimental procedures. For example, such problems include not correcting for bulk density in the sampling depths or not accounting for root exudates in the root to shoot ratios. In addition, there are numerous errors, in the use of ¹³C isotope to assess carbon turnover. Due to calculation errors, some experiments predict that carbon from C₄ plants is more stable than it is, which was caused by ¹³C fractionation that was not considered in the calculations. The use of data from flawed experiments, can result in errors in the model prediction.

4. Modeling of Soil Organic Carbon Change of Corn Stover Removal

As discussed above, the impact of corn stover removal on SOC can be widely variable and sometimes contradictory across sites and various land management scenarios, as actual SOC change depends on biophysical and management conditions¹². Since field measurements of SOC are resource intensive, limited, and largely insufficient for estimating trends, it is thus common to use SOC models for this purpose. Models, either empirical or process-based, are needed specifically to track SOC changes over a large area, for example, at regional or national scale in LCA of biofuels, and over time.

SOC modeling can simulate SOC dynamics associated with different corn stover removal rates under various management practices. Previous studies based on modeling estimated that large-scale corn stover removal may potentially reduce SOC and therefore increase GHG emissions associated with corn stover ethanol, if no management practice is in place to compensate the loss of soil organic matter inputs (i.e., stover biomass)¹³. This negative impact on SOC can be dramatic especially if, even though rarely occur¹⁴, all corn stover has been removed from the field¹⁵.

However, the use of improved land management practices, including conservation tillage and soil amendments application, could augment SOC levels and possibly restore SOC loss due to corn stover removal. For instance,

¹¹ Schiltz, N., C.G. Carlson, and E. Byamukama. 2016. Chapter 24: Short- and long-term consequences of corn stover harvesting. In Clay, D.E., C.G. Carlson, S.A. Clay, and E. Byamukama (eds). iGROW Corn: Best Management Practices. South Dakota State University.

¹³ Lugato, E. and A. Jones. 2015. "Modelling soil organic carbon changes under different maize cropping scenarios for cellulosic ethanol in Europe," *BioEnergy Research*, 8(2), 537-545.

¹⁴ Robertson, G.P., Grace, P.R., Izaurrealde, R.C., Parton, W.P. and Zhang, X., 2014. "CO₂ emissions from crop residue-derived biofuels," *Nature Climate Change*, 4(11), 933-934.

¹⁵ Liska, A.J., Yang, H., Milner, M., Goddard, S., Blanco-Canqui, H., Pelton, M.P., Fang, X.X., Zhu, H. and Suyker, A.E., 2014. "Biofuels from crop residue can reduce soil carbon and increase CO₂ emissions," *Nature Climate Change*, 4(5), 398-401.

reduced and no tillage practice can be more beneficial to SOC maintenance than conventional tillage¹⁶. Growing cover crops or applying manure after stover removal could help build SOC and maintain soil health¹². There is a pressing need to evaluate the impact of corn stover removal on SOC from the perspective of not only biomass harvest but also sustainable agricultural management.

GREET and its CCLUB (Carbon Calculator for Land Use Change from Biofuels Production)¹⁷ module have been used to estimate the impact of corn stover removal on SOC and life-cycle GHG emissions of stover ethanol by evaluating different scenarios combining corn stover removal rate, tillage type, and use of major soil amendments (i.e., cover crop and manure)¹⁸. A process-based soil carbon model, the surrogate CENTURY (SCSOC) has been used to simulate spatial SOC dynamics associated with various management scenarios. The SOC change was calculated for specified stover removal scenarios. When land management practices are included, GREET enables users to estimate corn stover removal impacts on SOC and overall life-cycle GHG emissions of stover ethanol from a broader perspective that emphasizes not only the significance of stover removal but also the importance of sustainable management practices¹⁷.

However, more effort is still needed to improve and validate SOC modeling estimates with field observations and appropriate SOC benchmarks. But so far, the use of the soil survey data base for populating soil carbon numbers in SOC models contains much uncertainty. Comparison of the NRCS data base and U.S. Geological Services (USGS) benchmarks has found little correlation between the two data bases. The crop land data layer from USDA, which is used to configure historical and current land use patterns, also contains numerous errors. The above mentioned SCSOC model is driven by spatially explicit soil and climate data and crop-specific parameters and variables primarily obtained through digital data bases, and small plot and laboratory research studies. Unfortunately, these information layers contain uncertainties, which may influence model predications. The models mimics SOC dynamics at a monthly time step by considering organic matter inputs (e.g., corn stover, soil amendments) and their decay under certain soil and climate conditions. While the SCSOC model has been calibrated to simulate SOC change under relatively controlled conditions, its validity is not fully explored across landscapes and rotational sequences using field data. More observational data on corn root to shoot ratios, harvest index and root biomass vertical distribution can better calibrate model parameters. Data on long-term SOC change data under various stover removal rates and management practices are invaluable for model validation. It is also worthwhile to survey actual farming and management practices associated with corn stover removal, including the actual rates achieved under field conditions, to improve the SCSOC. A useful survey would link stover removal with management practices that are necessary and appropriate for any given region. Additional information on machinery use and energy consumption would improve LCA GHG estimation. These improvements will help LCA of biofuels with GREET and other models.

5. Recommended Actions

Improving Soil and LCA Modeling Tools. As stated above, CARB uses the CA-GREET model to estimate CI of stover-based ethanol. In modeling SOC changes of stover harvest, the CCLUB module of the GREET model assumes that on average, 30% or less of the stover will be harvested and that this harvest rate will not affect SOC stocks. Questions about sustainable stover removal rates and potential SOC changes are the basis for the Alverson letter to CARB and a subject of increasing scientific evaluation in the societies' journals and elsewhere in the literature.

¹⁶ Fronning, B.E., Thelen, K.D. and Min, D.H., 2008. "Use of manure, compost, and cover crops to supplant crop residue carbon in corn stover removed cropping systems," *Agronomy journal*, 100(6), 1703-1710.

¹⁷ Dunn, J.B., Qin, Z., Mueller, S., Kwon, H.Y., Wander, M.M. and Wang, M., 2016. *Carbon Calculator for Land Use Change from Biofuels Production (CCLUB). Users' Manual and Technical Documentation* (No. ANL/ESD/12- Rev. 3). Argonne National Laboratory (ANL), Argonne, IL (United States).

¹⁸ Qin, Z., Canter, C.E., Dunn, J.B., Mueller, S., Kwon, H.Y., Han, J., Wander, M.M. and Wang, M., 2015. *Incorporating agricultural management practices into the assessment of soil carbon change and life-cycle greenhouse gas emissions of corn stover ethanol production* (No. ANL/ESD-15/26). Argonne National Laboratory (ANL), Argonne, IL (United States).

Farmers and especially current and future businesses that use corn stover require assurance that removal rates are environmentally sustainable without sacrificing soil fertility, cornfield water quality, and soil erosion, and do not have adverse carbon emission costs that devalue the GHG effects of biofuels produced. Further, as a matter of farm practice, robust, regionally appropriate best farming management practices are needed to ensure that erosion, SOC and other soil health indicators are not adversely affected by stover harvest practices.

Addressing Uncertainties. Important uncertainties associated with stover harvest for biofuel production remain and need to be addressed urgently for several reasons. First, major investments have been and are being made in biorefineries designed to convert corn stover and eventually other cellulosic feedstock materials into ethanol. Second, development of efficient ethanol production technologies and a domestic advanced biofuel industry capable of using both grain and cellulosic feedstock are features of current public policy and considered essential for long-term U.S. energy independence and security. Furthermore, diversifying the agricultural landscape by creating viable markets for cellulosic feedstock materials could also have major positive effects on soil health, water quality, air quality, and rural development. Finally, greater certainty about the dynamic relationship between stover removal and SOC change is needed not only by CARB, but also by EPA and many others evaluating the impacts of California's LCFS, the federal RFS, and perhaps other international biofuel programs such as EU's Renewable Fuel Directive. Therefore, after discussing the complexity of the issues, uncertainties, data gaps in both SOC measurements and modeling among the Task Force Members and considering the scientific expertise among members of the ASA, Crop Science Society of America (CSSA), and Soil Science Society of America (SSSA), the 1607 Task Force makes the following recommendations to the ASA Board.

A tri-society (ASA-CSSA-SSSA) Task Force should be appointed to develop a Workshop to be held in California during 2017 as soon as reasonably possible to critically review the science about corn stover's effects on SOC stocks, and how those effects should be included in LCA models used to estimate the CI of stover-derived biofuels. Applied science is an important characteristic of the tri-societies' mission, so the translation of science into regional best management practices and measurement and certification of the effects of stover removal on SOC should be the focus of the workshop's set of tasks. Holding the meeting in California allows CARB staff to attend. Below are specific recommendations for the Workshop and the topic in general.

- a. We recommend the Workshop be limited in size to encourage thoughtful and thorough exchange of information and discussion, and focus on producing consensus statements and suggested actions to address unresolved issues. We anticipate that the Workshop will be limited in size (approximately 100).
- b. The Task Force should identify and invite tri-society scientists, and others where appropriate, who are active in this field of research. Attendees should be selected to represent all aspects of the many questions that need to be answered to provide the information needed by regulators at CARB and EPA striving to implement the LCFS and RFS.
- c. An additional but limited number of places (100 or less) should be available to volunteers from related disciplines, LCA practitioners, and the NGO community to ensure that the process will be regarded as transparent and the result reflect scientific consensus as far as possible. Opportunities for participation by CCAs and the future development of educational materials for them to use should also be included as an essential outcome of this endeavor.

We believe this task and the Workshop process will benefit the regulatory agencies tasked with ensuring that stover-derived biofuels help reduce atmospheric GHG emissions and do not undermine soil and related environmental resources when used. Addressing these issues in a timely and dispassionate fashion is best led by the tri-societies and an important public service.