ABSTRACT

Crop residues protect soil resources, sustain soil organic carbon (SOC), cycle nutrients, support microbial communities, and provide bioenergy feedstock. Herein we (i) summarize the origin of the “Crop Residues for Advanced Biofuels: Effects on Soil Carbon” workshop; (ii) review the workshop structure; and (iii) present consensus points, unanswered questions, and outcomes of the workshop. Initiated by a farmer/ethanol investor’s letter to the American Society of Agronomy (ASA) President, an ASA Working Group (WG) was established to make a recommendation to the ASA Board on how to respond. The WG concluded a Tri-Society sponsored workshop involving farmers, ethanol production and marketing groups, agronomists, crop scientists, soil scientists, engineers, non-governmental organizations, life cycle analysis (LCA) experts, and regulatory personnel was needed to address the complex question that had been posed and ensure all viewpoints were fully represented. The WG was expanded to an ASA Task Force who organized the workshop in Sacramento, CA. Eighty workshop attendees identified four consensus areas (crop residue management [CRM]; severity of soil erosion; tillage, CRM and erosion linkages; and the importance of simulation [LCA] models) and four unresolved themes (carbon sequestration, CRM effects on SOC stocks, changing climate effects, and the need to focus on ecosystem services rather than single endpoints). The workshop resulted in three direct outcomes: (i) development of a stakeholder funded SOC database, (ii) LCA and SOC model improvements, and (iii) development of this special section in Agronomy Journal. Dale and Ong (2014) concluded that large scale, renewable energy systems are no longer just a “good idea”; but essential, and during the next few decades society must develop systems capable of producing clean energy at the multi-terawatt scale. Crop residues such as corn (Zea mays L.) stover, and other cellulosic materials were identified as potential feedstocks to meet this demand and have been rigorously evaluated for the past decade (e.g., Perlack et al., 2005; U.S. Department of Energy, 2011 and 2016). However, it is also well established that crop residues have important ecosystem service and productivity functions (Larson, 1979; Johnson, 2018; Ibrahim et al., 2018).

Core Ideas

- The workshop demonstrated ASA-CSSA-SSSA capabilities to address complex problems.
- Corn is an important crop with regard to soil organic carbon (SOC) stocks.
- Crop residue management (CRM) effects on SOC stocks are complex and multi-dimensional.
- Quantifying CRM effects on SOC is very important.
- Accurate but simple on-farm measurement and monitoring techniques for SOC are needed.

Unraveling Crop Residue Harvest Effects on Soil Organic Carbon


The ASA-CSSA-SSSA sponsored workshop, “Crop Residues for Advanced Biofuels: Exploring Soil Carbon Effects” that is being highlighted by this special section, was prompted by a June 2016 letter to then ASA President Paul Fixen from Ron Alverson, a South Dakota farmer/corn grain ethanol investor. Mr. Alverson was seeking ASA support for a letter he was preparing for the California Air Resources Board (CARB), asking if corn grain and stover derived ethanol deserved different Low Carbon Fuel Standard and carbon intensity (CI) values. Currently, the CI value of cellulosic ethanol from corn stover is 21.6 g CO₂ MJ⁻¹ while the average Midwest corn grain ethanol CI value is ~75 g CO₂ MJ⁻¹. The CI values have economic consequences in the California transportation fuel market, with January 2018 Low Carbon Fuel Standard CO₂ prices averaging US$107 Mg⁻¹. Furthermore, cellulose-based fuels are still required under federal regulations and have a high (D7) renewable identification number value. Mr. Alverson’s argument was that although removing corn stover could provide short-term economic gains for farmers, doing so may decrease long-term, sustainable crop production if soil organic carbon (SOC) stocks are depleted.

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Crop residues including corn stover have many different roles including protecting soil resources, sustaining SOC stocks, cycling nutrients, supporting microbial communities, and now providing feedstock for bioenergy or bio-product production. Negative impacts of excessive crop residue harvest on SOC stocks (Johnson et al., 2014; Johnson, 2018) and potential soil degradation (Karlen and Rice, 2015) are well documented. Alverson argued that stover harvest will cause soil resources to be degraded and atmospheric CO₂ to increase. He also stated that it was his perception that the modeling currently used to determine CI of grain- and cellulosic-based ethanol did not account adequately for changes in SOC stocks or greenhouse gas emissions.

These questions are neither new nor answered simply as evidenced by publications from the 1970s and 1980s. Examples include Lockeretz (1981), who stressed the importance of coordinating soil conservation policies when developing public policy concerning renewable energy programs; Epstein et al. (1978), who emphasized that alternative uses for crop residues should be considered only when needs for soil protection and productivity have been met; and Larson (1979), who concluded that removal of a portion of crop residues should not be objectionable to the agricultural community if soil productivity, could be maintained.

Karlen et al. (2014) summarized results from 28 research sites in seven states (IA, IL, MN, NE, PA, SC, and SD) and reported that average no-till corn grain yield was significantly lower than with conventional tillage when stover was not removed, but equivalent or even slightly higher when it was harvested. They attributed the positive stover harvest response to mitigation of potential residue management problems, such as N immobilization and reduced spring soil temperature. Clayton et al. (2012, 2015) concluded that findings from those and other studies suggest that stover removal may be sustainable within high yielding no-tillage systems. However, stover harvest was NOT recommended at all 28 locations summarized by Karlen et al. (2014). At those sites and in other published studies where land slope is high (>5%), annual average corn yields are <11 Mg ha⁻¹ (175 bu ac⁻¹), inherent SOC levels are low, or climatic conditions (wind, rainfall intensity, etc.) are limiting, crop residue (i.e., corn stover) harvest can result in lower SOC and potentially enhance soil degradation.

Johnson et al. (2014) reported that about one-third of the sites summarized by Karlen et al. (2014) were established long enough to reliably estimate a minimum residue return rate which was 3.9 ± 2.18 Mg ha⁻¹ yr⁻¹ (1.74 ± 0.97 t ac⁻¹ yr⁻¹). Coupled with other corn-based data (n = 35) and data from other cropping systems (n = 49), they concluded that approximately 6 Mg ha⁻¹ (2.67 tons ac⁻¹) of crop residue could be considered a useful generic return rate, but this should NOT be considered a universal recommendation. Site-specific data including long-term monitoring of SOC will provide the best information for making soil and crop management decisions. Johnson et al. (2014) also stressed that empirical data were needed to calibrate, validate, and refine process-based models so that valid, sustainable harvest guidelines can be given to farmers, consultants, bioenergy producers, and regulatory agencies such as CARB.

Our objectives for this overview are to (i) summarize what led the ASA-CSSA-SSSA to organize the “Crop Residues for Advanced Biofuels: Effects on Soil Carbon” workshop, (ii) review the workshop structure, and (iii) present consensus points, unanswered questions, and workshop outcomes on behalf of 80 workshop participants.

**APPROACH**

Recognizing the complexity of the questions posed to him, ASA President Paul Fixen formed WG A808 in 2015 to study Mr. Alverson’s request and develop a recommendation to the ASA Board regarding what action(s) the Society should take. Following a series of conference calls, the WG concluded the issue should be addressed scientifically by several members of the ASA, as well as the Soil Science Society of America (SSSA) and Crop Science Society of America (CSSA). The WG also concluded there were several data gaps associated with SOC measurement and modeling, as well as life cycle CI evaluations for both corn–stover and corn–grain ethanol. Finally, the WG recommended that accounting for changes in SOC stocks due to stover harvest decisions should be a primary focus of the response given to Mr. Alverson.

The WG developed a white paper entitled “The Use of Corn Stover for Ethanol, Other Biofuels and Bioenergy in the United States—Implications for Soil Organic Carbon Changes” (https://www.crops.org/files/meetings/specialized/stover-removal-soc-white-paper.pdf) to summarize their findings and presented it to the ASA, CSSA, and SSSA Boards at the 2016 Annual Meeting in Phoenix, AZ. The Boards agreed that the ASA-CSSA-SSSA should organize a “standing-alone, thematic meeting” in 2017 to strive for scientific consensus in the guidelines developed with regard to the multiple potential uses for crop residue. Furthermore, because of California’s importance in the biofuel market and the role that the state’s Low Carbon Fuel Standard, the meeting should be held in California to enable the CARB staff to more easily attend and participate in the discussions.

The WG also recommended that in addition to Tri-Society members, the workshop should be designed to attract other scientific and engineering associations, environmental groups, and professionals involved with all phases of agriculture, LCA, and ethanol production and marketing, to ensure that diverse viewpoints were fully represented. The WG also recommended that a public and transparent process and record should be used during the workshop and subsequently create technical and educational materials.

Following the 2016 ASA-CSSA-SSSA Board meetings, the WG was thanked and disbanded. An expanded Task Force (no. 1607) representing all three Societies was appointed to work with the Alliance of Crop, Soil, and Environmental Science Societies (ACNESS) to develop a “Crop Residues for Advanced Biofuels: Exploring Soil Carbon Effects” workshop. Five workshop goals were established: (i) improve our mutual understating of crop residue removal effects on the SOC balance; (ii) evaluate SOC modeling assumptions and outcomes related to crop residue removal; (iii) understand how field- and landscape-scale variation affects the multiple potential uses for crop residues and how those effects can be measured and quantitatively certified; (iv) review LCA modeling of resulting fuel CI for advanced biofuels and/or bio-products produced from crop residues; and (v) demonstrate the role and importance of agricultural science in supporting and sustaining biofuel and bio-economy policies.

The desired outcome was to produce a science-based consensus document that could be posted on the ASA-CSSA-SSSA
website and used as a reference and guideline for sustainable harvest of corn stover and other crop residues as a feedstock for biofuels or bio-products and to build more sustainable rural bioeconomies. The Task Force recommended the document address eight specific topics. They were to: (i) determine what field- and landscape-scale SOC data is available from current and/or past corn stover and other crop residue removal studies; (ii) discuss challenges associated with measuring SOC; (iii) review the status and ongoing improvements in LCA modeling; (iv) discuss SOC modeling in response to crop residue removal; (v) identify best management guidelines for harvesting corn stover and other crop residues; (vi) determine what is needed to improve field-scale SOC measurement; (vii) identify what is needed to achieve a science-based consensus on CI estimates associated with crop residue removal; and (viii) discuss strategies for measuring and certifying that actual crop residue harvest rates are economically feasible, environmentally sound, and socially acceptable.

The Task Force then developed a program with six session themes and identified speakers to address each topic (Table 1).

To provide a comprehensive record of all presentations and subsequent breakout discussions, the Task Force used the ThinkTank software to compile an entire meeting record. A series of questions were developed for each theme, and facilitators for each breakout session were asked to use those questions to keep the discussions moving and on track. To help with the collection and summarization of the workshop information, five University of California–Davis graduate students (Nazanin Akrami, Barbara Bomfim, Jessica Chiartas, Rylie Ellison, and Mina Tissoudal) were recruited to assist Task Force members with identifying points of consensus and concern.

**Table 1. Crop Residues Workshop sessions and invited speakers.**

<table>
<thead>
<tr>
<th>Session no.</th>
<th>Topic</th>
<th>Invited presenters</th>
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<tbody>
<tr>
<td>1</td>
<td>Soil carbon status and trends in the US Corn Belt region</td>
<td>Chuck Rice, Jane Johnson, and David Clay</td>
</tr>
<tr>
<td>2</td>
<td>Modeling soil organic carbon changes</td>
<td>Adam Liska, Steven DelGrosso, and John Field</td>
</tr>
<tr>
<td>3</td>
<td>Measurement and verification of stover harvest/removal rates for regulatory and GHG accounting purposes</td>
<td>B. John Pieper, Alan Keller, and Allison Thomson</td>
</tr>
<tr>
<td>4</td>
<td>Geospatial variation and measurement changes in SOC and erosion risk at the field and landscape scale</td>
<td>David Muth, Jeff Novak, and Richard Cruse</td>
</tr>
<tr>
<td>5</td>
<td>Life-cycle analysis (LCA): How is carbon intensity determined from crop residues?</td>
<td>Michael Wang, Zhangcai Qin, and Jennifer Pont (for S. Unnasch and T. Darlington)</td>
</tr>
<tr>
<td>6</td>
<td>Life-cycle analysis of biofuels: Integrating current science into policy</td>
<td>Anil Prabhu and Aaron Sobel</td>
</tr>
</tbody>
</table>

The workshop presentations and breakout sessions resulted in an extensive collection of comments, questions, and opinions in the ThinkTank record. This information was used to provide real-time monitoring, participant feedback, and synthesis summaries in word clouds (Fig. 1a,b) as well as tabular and graphical summaries. Figure 2(a–d) illustrates (i) agreement with synthesis statements, (ii) perspectives regarding potential impacts of various activities or policy changes, (iii) a rank order of workshop participant views on future research activities, and (iv) participant perspectives regarding the likelihood of success of future research priorities. An important caveat regarding these figures is that they only represent perspectives of the workshop participants, and have not yet been vetted by the wider conservation community.

Word clouds were created using the ThinkTank record to summarize the most frequent topics and comments discussed by presenters during each of the six formal presentation sessions.

**RESULTS**

Figure 1a is an example of a word cloud created from discussions during Session 1 on the topic of “Soil Carbon Status and Trends in the US Corn Belt region.” Word clouds were also created for each of the breakout sessions as illustrated for Session 6: Life Cycle Assessment of Biofuels (Fig. 1b).

As illustrated by the word clouds (Fig. 1) and graphical summaries (Fig. 2), the overall ThinkTank record associated with the 3-d workshop was extensive. When delivered to the Task Force, the report was more than 140 pages in length. With the assistance of the five graduate research students, the record was reviewed and summarized to identify (i) points of consensus.
Based on the workshop record, the Task Force identified several points of consensus and implementation challenges including:

- Multiple strategies are needed for appropriate crop residue management (CRM).
- Spatial and temporal variability require site-specific rather than universal CRM guidelines.
- The CRM guidelines should address water erosion, wind erosion, and SOC maintenance.
- Producers are generally willing to adopt recommended CRM practices if incentives are consistent with their values and priorities.
- Increasing plant diversity (e.g., cover crops, rotations, landscape design) will increase the diversity of microbial communities and crop residue inputs, alter carbon and nutrient cycling processes, and influence processes such as aggregate formation and retention as well as the potential for carbon sequestration and increases in SOC stocks.
- Soil erosion remains a critical natural resource problem.
- Topsoil depth and SOC content are both very important factors affecting productivity.
- Changing weather patterns may require a reevaluation of the amount of crop residue needed to protect against wind and water erosion.
- Tillage and CRM are closely coupled.
- Long-term soil erosion studies suggest soil degradation is more closely related to tillage intensity than moderate crop residue removal.
- Excessive tillage decreases soil water content, increases soil temperature, breaks down aggregates and soil structure, and can stimulate weed flushes by disturbing residual seed banks.
- No-tillage practices do not always increase profile SOC stocks because of increased stratification.
- Biological tillage (e.g., worm or more specifically night crawler \([Lumbricus terrestris]\) activities) can transport a substantial amount of crop residue from the soil surface to deeper profile depths.
- Simulation models are an important component for guiding CRM.
  - The original Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model developed by Argonne National Laboratory did not include SOC change, but this has recently been added for various land management scenarios.
  - Long-term experiments are essential to capture small changes over a long period of time and should be used to validate landscape scale models.
  - The REAP (initially known as the “renewable energy assessment project” and now as the “Resilient Economic Agricultural Practices” team); database contains 79,795 total records from 14 experiments in nine states.
- The goal for REAP was to see how much crop residue needed to be returned to the land to sustain soil C.
- The collective database was started in 2005, is readily accessible, includes peer-reviewed data, was used for 2014 publications in Bioenergy Research 2014, and is updated annually.

The ThinkTank record also helped identify several critical issues needing further resolution. They included perceptions regarding:

- Carbon sequestration
- Effects of CRM, whether through retention on the soil
surface, incorporation by tillage, partial removal for animal feed or bio-product feedstock, or other practices on profile SOC stocks are not completely understood. Opinions differ with the basic question stated in various ways:

- If crop residues are not harvested will SOC stocks increase?
- If an appropriate amount of crop residues are harvested will SOC stocks decrease?
- If SOC stocks are unchanged over time, does appropriate residue harvest negate any potential increases that could have occurred without removal?
- What soil-test protocol is needed to document CRM effects (retention versus partial removal) on SOC stocks?
- What is the appropriate baseline for evaluating SOC changes?

- Pre-cultivation/cemetery/fencerow measurements
- Pasture measurements
- Current BMPs

Other

- Does more resistant (i.e., GMO) crop residue have a greater effect on SOC levels than less resistant (i.e., non-GMO) material?
- Which has the greater influence on SOC stocks—crop residue chemistry or physical protection?
- What is the best method for quantifying root carbon contributions to SOC stocks?
- What is the best way to quantify aboveground to below-ground biomass ratios?
- Crop management effects on carbon sequestration and SOC stocks
  - Is Conservation agriculture (CA) the most effective way to increase SOC stocks?
  - Conservation agriculture is more than no-till as it includes multiple “stacked” practices.
  - Conservation agriculture emphasizes plant diversity and erosion control; two key factors associated with soil degradation.
  - Does no-tillage with a low frequency of C4 crops (i.e., corn or sorghum) result in soil degradation?
  - At more northern latitudes is it necessary to incorporate crop residues in the fall to enhance soil warming the following spring?
- How does this affect erosion control?
  - In the US Corn Belt, is growing high-yielding corn the best way to increase SOC stocks?
  - Since about 1930, the genetic potential for corn has been increasing steadily at a rate of approximately 0.13 Mg ha\(^{-1}\) yr\(^{-1}\) (2 bu ac\(^{-1}\) yr\(^{-1}\)).
  - Some argue that breeding has focused on above-ground biomass at the expense of root carbon.
  - Others argue that corn adds twice as much root carbon as any other commonly grown grain crop in the United States.
  - Does soybean production deplete SOC stocks because (i) they do not provide enough root or above-ground carbon to sustain current levels, (ii) they exert a priming effect that stimulates SOM decomposition, or (iii) other reasons?
- Do no-tillage practices result in cooler soil temperatures that restrict crop root development and limit SOC accumulation?
- Will root biomass coupled with reduced- or no-tillage offset effects of moderate crop residue harvest?
- How will changing climate patterns affect the accumulation of SOC stocks?
- Does elevated CO\(_2\) change the amount and/or chemistry of root exudates?
- Should the focus for these discussions be on “ecosystem services” rather than single endpoints (i.e., justifying increased corn production)?
- What is the best way to implement an ecosystem approach to production agriculture?

The consensus points and unanswered questions were then used to identify the future activities needed to provide science-based answers regarding biomass harvest on SOC stocks.

**NEXT STEPS**

Using information gathered from the workshop, the Task Force identified four initial tasks. The first was to publish a special section in the *Agronomy Journal* summarizing (i) the presentations given at the workshop and (ii) effects of several short- and long-term crop residue harvest studies on soil profile carbon stocks.

The second was to design a collaborative project involving private sector, university, and federal researchers to identify a variety of SOC data sources (e.g., university and commercial soil-test laboratory records, ARS GRACEnet and REAP databases, published and unpublished research results) that can be compiled into a comprehensive soil carbon database, coupled with available metadata, and analyzed to improve the scientific understanding of carbon sequestration and SOC stocks.

The third task was to use the soil carbon database to improve GREET, CCLUB (Carbon Calculator for Land Use change from Biofuels), Century, DayCent, and other simulation models that address carbon sequestration and soil organic matter changes.

Finally, to address the fourth task, plans are being developed to systematically include SOC changes in crop residue based LCAs. This effort will be led by USDOE researchers at Argonne National Laboratory and performed in collaboration with the USEPA, CARB, and biofuel industry scientists and engineers.

**SUMMARY AND CONCLUSIONS**

The “Crop Residues for Advanced Biofuels: Exploring Soil Carbon Effects” workshop brought farmers, ethanol producers, agricultural research scientists, simulation modelers, action agency, and regulators together for face-to-face discussions focused on crop residue harvest effects on greenhouse gas and soil carbon effects. Those discussions resulted in a consensus that keeping track of SOC changes associated with CRM (harvest or retention) was very important and that there was a real need for accurate but simple on-farm measurement and monitoring techniques. They also led to general agreement among workshop participants that quantifying CRM effects on SOC stocks is a complex, multi-dimensional challenge. Factors that influence the relationships include: (i) inherent soil properties such as clay type and content; (ii) the degree of soil cover (i.e., fallow generally decreases SOC content); (iii) tillage which can hasten oxidation.
of crop residues whereas no-tillage can result in greater stratification; (iv) higher soil temperatures which hasten decomposition and reduce equilibrium SOC levels; (v) macro- (e.g., earthworms) and micro-fauna as well as the entire microbial communities which are intimately involved with cycling and turnover of crop residues; and (vi) corn is an important crop with regard to SOC stocks because at high yield levels (>11 Mg ha\(^{-1}\) or 175 bu ac\(^{-1}\)) the amount of crop residue created through photosynthesis generally exceeds the amount required for SOC maintenance and preservation of soil aggregates or structure. Finally, the workshop provided a very effective way to demonstrate the capability of ASA-CSSA-SSSA members to help multiple society sectors understand and address complex problems such as carbon sequestration, greenhouse gas emissions, and development of more sustainable agricultural practices. The success of this accomplishment is confirmed by the collection of well written contributions within this special issue of *Agronomy Journal*.

**REFERENCES**


