Surface Soil Organic Carbon Sequestration Under Post Agricultural Grasslands Offset by Net Loss at Depth

Yi Yang (✉ yi.yang@colostate.edu)

Colorado State University <https://orcid.org/0000-0002-5548-8811>

Terrance Loecke

KU: The University of Kansas

Johanness Knops

Xi'an Jiaotong-Liverpool University

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Abstract

Post agricultural grasslands are considered to accumulate soil organic carbon (SOC) after cultivation cessation. The Conservation Reserve Program (CRP) in the U.S. is a wide scale, covering approximately 8.9 Mha as of 2020, example of row-crop to grassland conversion. To date, SOC sequestration rates, and potential, in CRP has mostly been evaluated at local scales and focused on the surface 20–30 cm of the soil profile. Thus, we lack knowledge of C sequestration rates in CRP lands on a continental scale and of C dynamics in the subsurface soil after agricultural cessation. The Rapid Carbon Assessment (RaCA) project is the most recent effort by the United States Department of Agriculture (USDA) to systematically quantify C stock in the 0–100 cm soil profiles across the conterminous US. Here we analyze data from RaCA to evaluate the C stocks of the CRP on a continental scale of both surface and subsurface soil. We found there was no difference in SOC stock between croplands and CRP lands when comparing the 0–100 cm soil profiles, which indicates that the C sequestration in CRP lands is insignificant overall. We did find that SOC accumulated in the surface soil (0–5 cm) in CRP lands. However, these C gains in surface (0–5 cm) soil were offset by the lower SOC stock in the subsurface (30–100 cm) of the CRP. We also found that the C: N ratio in the subsurface soil in CRP lands is lower than that of croplands, indicating a lack of labile organic matter inputs in the subsoil. Whether the lower SOC in the subsurface of CRP is caused by legacy effects or is a result of C losses needs to be verified by long-term repeated sampling in both surface and subsurface soil. This analysis highlights the importance of examining C dynamics in subsurface soil after agricultural cessation to accurately measure and improve C sequestration rates in CRP lands.

Introduction

The conversion of row crop agricultural lands to perennial vegetation is regarded as important soil organic carbon (SOC) sequestration and climate change mitigation approach (Post and Kwon, 2000; Wertebach et al., 2017; Bell et al., 2020). The Conservation Reserve Program (CRP) is a cost-share and rental program, which pays landowners to reestablish perennial vegetation on environmentally sensitive lands (Li et al., 2017). Besides environmental benefits, such as reducing soil erosion and improving wildlife habitat and water quality, CRP is considered as a legitimate large-scale (~ 8.9 Mha, (USDA, 2020)) effort to sequester C from the atmosphere and control the greenhouse effect (Bronson et al., 2004; Kucharik, 2007). The reason is that agricultural practices disturb soil and deplete SOC (Knops and Tilman, 2000; Conant et al., 2001) and once the agricultural lands are converted to perennial vegetation systems, the SOC losses can then be reversed, due to increased belowground primary production, accumulation of soil aggregates, and nitrogen deposition (Post and Kwon, 2000; Jones and Donnelly, 2004; Lal, 2004; Knops and Bradley, 2009; Baer et al., 2010). To date, numerous studies have quantified soil C stock change of CRP lands across the various regions and soil types (Gebhart et al., 1994; Post and Kwon, 2000; Kucharik, 2007; Baer et al., 2010; Munson et al., 2012; Li et al., 2017). However, widely varying rates of C stock change have been reported, and these studies only report data from local scales (e.g., field to county level). When scaling to regional or national levels, the C sequestration potential of

CRP lands can be under or overestimated, due to the difficulty of accounting for the large variations in soil properties, such as taxonomy, moisture, and particle size distribution (Li et al., 2017). Therefore, direct national-scale C stock measurements in both croplands and CRP lands are needed.

In addition, like most of the research in abandoned agricultural lands, C sequestration research in CRP lands has primarily focused on the surface soil (top 30 cm) (Gebhart et al., 1994; Bronson et al., 2004; Kucharik, 2007; Baer et al., 2010; Li et al., 2017). Hence, we have even less knowledge about the SOC stock changes in the subsurface after converting to CRP lands. It is important to highlight that despite low concentrations, subsurface soil still contains a large quantity of C due to its sheer volume (Jobbágy and Jackson, 2000) and higher bulk density. Subsurface soil also has slow turnover rates. Thus, it has great potential to sequester more C for a long period of time (Lorenz and Lal, 2005). Hence, the dynamics of subsurface SOC is as important as surface SOC to understand and predict soil C sequestration potential in CRP lands (Rumpel and Kögel-Knabner, 2011).

Rapid Carbon Assessment (RaCA), a recent effort by USDA to quantify SOC stock across the conterminous US (CONUS), provides opportunities for researchers to evaluate the C sequestration potential of CRP lands on a continental scale and in both surface and subsurface soil. RaCA applied a multi-level hierarchical sampling scheme and collects soil samples in wetlands, forestlands, rangelands, pasturelands, croplands, and CRP lands down to 100 cm or the depth of the restrictive layer (such as bedrock) (Wills et al., 2014). It was the first time CRP lands were included in a conterminous US soil survey. Before sample collection, Wills et al. (2013a) developed a statistical algorithm to group soil pedons in each region with similar taxonomy, moisture, and temperature, texture, drainage, and depth to the restrictive layer. This grouping method can minimize the bias of space for time substitution when comparing SOC stocks between croplands and CRP lands. Additionally, recent estimates of SOC stock (Kern, 1994; Guo et al., 2006) of the conterminous US were based on databases (STATSGO, USDA) that were collected over several decades (Wills et al., 2014). RaCA sample collection was carried out from 2011 to 2012 and represents a static inventory of SOC.

In this study, we analyzed the RaCA dataset with the aim to (1) directly compare the SOC stocks in croplands and CRP lands in the 0-100 cm soil depth at a continental scale, (2) evaluate the SOC stock change in surface and subsurface soil after croplands are converted to CRP lands, and (3) postulate the potential mechanisms that control the soil C dynamics in the subsurface soil in CRP lands.

Methods

RaCA sampling scheme

The RaCA project was carried out by the Soil Science Division of the Natural Resources Conservation Service (NRCS) to quantify soil C stocks to 1 m across CONUS. Data are available from the RaCA project website (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054164). The soil samples were collected in a multi-level hierarchical design across regions, soil types, and land

use/land cover classes. The detailed sampling scheme is described in Wills et al. (2014). Briefly, CONUS was divided into 17 major regions based on the major land resource area (MLRA) regional offices (Fig. 1). The locations of RaCA sites were selected using the National Resource Inventory (NRI) sampling framework, which ensures the sampling sites are randomly distributed and provide nearly complete coverage of CONUS. Urban areas and some forestlands are not included in NRI and are thus excluded from RaCA. In each region, 8–20 soil groups were created to cluster RaCA sampling sites using a statistical algorithm developed by Wills et al. (2013b), which utilized soil information from official soil series descriptions and the soil data access portal at NRCS and clustered soils with a potentially similar level of SOC and a similar response to land-use change. In the algorithm, soil information, such as taxonomy, moisture, and temperature, particle size class, drainage, and depth to the restrictive layer, was translated to ordinal scores, and soils with similar scores were clustered into soil groups. Land use/land cover (LULC) classes, including wetland, forestland, rangeland, pastureland, cropland, and CRP land, were assigned to each RaCA site during sampling collection, using the national land cover dataset (Fry et al., 2011). Five pedons were sampled at each site, with one at the plot center and one 30 m away at every four directions. A small pit was first excavated to 50 cm or the bedrock depth at each pedon. Soil samples were collected at 5 cm and 5–50 by the length of soil horizons. Samples below 50 and 100 cm were collected with probes or augers by the length of soil horizons. Samples were collected volumetrically from 0 to 50 cm to measure bulk density.

Soil sample processing and analysis

Soil samples for C and nitrogen (N) analysis were dried and sifted with 2-mm-sieves. Soil samples from the central pedon of each site were analyzed for total C and N content was measured with dry oxidation method at each region office. The detailed methodology with the spectrometer scanning can be found in Wills et al. (2014). The volumetric samples were oven-dried to calculate bulk density. Bulk density of samples that were not collected volumetrically, such as all the samples below 50 cm, were predicted with a suite of pedotransfer functions (Sequeira et al., 2014). Soil organic carbon (SOC) was calculated as the difference between total carbon and inorganic C, which is measured as calcium carbonate calcimeter equivalence (Wills et al., 2013b). SOC and total nitrogen (TN) stocks were calculated from bulk density and the SOC and N concentrations, adjusting inorganic C content and the coarse fragment of the soil samples. SOC and TN stocks were then summarized to fixed depths of 5 cm, 5–30 cm, and 30–100 cm for each pedon. Soil C: N ratio was calculated as SOC stock divided by TN stock.

Data analysis

In this study, we focus on the comparison of surface and subsurface soil of croplands and CRP lands. We only selected pedons with SOC measurements to 100 cm, and soil groups that have both croplands and CRP lands. Nested two-way ANOVAs were used to compare SOC stock, TN stock, and C: N ratio at different depths and land use/land cover, with sampling site nested in soil groups, then nested in regions as a random effect. The statistical significance of the ANOVA was tested with type II Wald chi-square tests. Pairwise comparisons were performed at each depth with adjusted Tukey tests on the log scale. The reported means of SOC stock, TN stock, and C: N ratio are estimated marginal means that were

estimated by the above linear mixed effect model to account for variation between regions and soil groups. All statistical analyses were performed using R version 3.5.2 (Team, 2019). 'lme4' (Douglas et al., 2015) was used to perform a nested ANOVA. 'emmeans' (Russell, 2019) was used to perform pairwise comparison for the nested two-way ANOVA. As we are only interested in comparing SOC, TN, and C: N ratio within depths, instead of between depths, we made the comparison between the two land use/ land cover types separately for each depth when coding with 'emmeans'. 'ggplot2' (Wickham, 2016) was used to make the figures and maps.

Results

There are 278 and 748 pedons for CRP lands and croplands that have SOC measurements that cover the 0-100 cm soil respectively. These pedons belong to 102 RaCA soil groups and represent all 17 major regions (Fig. 1). After accounting for the geological variations between regions and soil groups with separate nested two-way ANOVAs, there is no significant difference of SOC ($p = 0.65$) and TN ($p = 0.18$) stocks between CRP lands and croplands in the 0-100 cm soil (Fig. 2a), which indicates that on a continental scale SOC and N stock in the top 100 cm soil remain unchanged in CRP lands after agricultural cessation and the recovery of perennial vegetation.

Comparing SOC stocks at each depth, we found there was a significant interaction between land use and depth (Chisq = 93.7, Df = 2, $p < 0.0001$). Specifically, on average, CRP lands have 38% higher SOC stock at 0–5 cm ($p < 0.0001$), yet 11% lower SOC stock at 30–100 cm ($p = 0.0247$) than croplands, whereas there was no significant difference of SOC at 5–30 cm ($p = 0.4942$) (Fig. 2b). Such patterns occurred widely in almost every region (Fig. 3 and Fig. 4). Out of 102 soil groups, 63 soil groups showed CRP lands have higher SOC stock at 0–5 cm than croplands, and 62 soil groups showed CRP lands have lower SOC stock at 30–100 cm than croplands. This suggests SOC accumulated in the surface soil after converting croplands to CRP lands, but the accumulation was offset by the decreased SOC in the subsoil.

CRP lands also have higher TN stock at the 0–5 cm ($p < 0.0001$) than croplands on average, with no significant differences at 5–30 cm ($p = 0.5056$) or 30–100 cm ($p = 0.1607$) (Fig. 2c). As expected, the C: N ratios tend to decrease with depth for both croplands and CRP lands (depth: Chisq = 814.85, Df = 2, $p < 0.0001$), as SOC becomes more recalcitrant at deeper soil (Fig. 2d). However, soil C: N ratios of CRP lands decrease more sharply than that of the croplands (land use×depth: Chisq = 51.75, Df = 2, $p < 0.001$), which leads to CRP lands with higher C: N ratio at 0–5 cm ($p = 0.034$), but lower C: N ratio at 30–100 cm ($p < 0.0001$) than croplands. Such findings imply that organic matter in CRP lands tends to be less recalcitrant in the surface soil, but more recalcitrant in the subsurface soil as compared to croplands.

Discussion

This study presents the first effort to directly quantify the SOC stocks in the top 100 cm of soil across CONUS and highlight the importance of deep soil C measurements when estimating C sequestration rates in CRP lands. On average, SOC did not accumulate in the top 100 cm of soil in CRP lands compared to

croplands, which implies that the amount of C sequestration in CRP lands is insignificant across the US. We did find that the surface soil (0–5 cm) in CRP lands accumulated SOC, which is consistent with much previous research quantifying CRP C sequestration rates (Baer et al., 2002; Kucharik, 2007; O'Brien et al., 2010). However, such C gains were offset by the likely decrease of C stock in the subsurface (30–100 cm). If RaCA had only collected samples in the surface soil, the soil C sequestration of CRP lands would be greatly overestimated. Furthermore, comparing within soil groups, the pattern that CRP lands have lower SOC stock in subsurface soil than croplands is ubiquitous (Fig. 4), indicating mechanisms irrelevant to geolocation and climate factors.

The finding that CRP lands have lower SOC stock in the subsurface than croplands suggests that there may be SOC losses in the deeper soil after land-use change. Such SOC losses in deeper soil may be caused by a decrease of organic matter inputs in subsurface after perennial vegetation recovers, which is supported by the lower C: N ratio in the subsurface of CRP lands. Generally, fresh and labile organic matter from vegetation has much higher C: N ratio than soil organic matter (SOM), which means more labile organic matter inputs lead to higher soil C: N ratio, and vice versa. Most of the CRP lands were recovered to perennial grasslands (Gelfand et al., 2011), and 80–90 % of roots of temperate grasslands are located in the top 30 cm, as shown in a global analysis of root distribution (Jackson et al., 1996). This indicates that reestablishment of perennial vegetation in CRP lands provides labile organic matter inputs mostly to the surface soil, which explains the SOC accumulation and higher soil C: N ratios only in the surface, and the lack of organic matter input in subsurface soil results in a decline of SOC stock. In contrast, croplands have lower SOC in the surface, which can be attributed to the removal of crop litter and stimulated SOC decomposition by tilling. The higher SOC stock in the subsurface in croplands has three possible explanations. First, tilling can redistribute SOC surface soil rich in crop residue to the subsurface, thus increasing the SOC input (Alcantara et al., 2016). The homogenization of soil at tilling depths is also supported by the RaCA data, where we found that the difference in the C: N ratio at 0–5 cm and 5–30 cm is smaller in croplands, as compared to CRP lands. Second, croplands have more roots distributed in the deep soil proportionally than grasslands (Jackson et al., 1996), which may be a result of plowing, which loosens soil and promotes root growth to the deeper depths (Luo et al., 2010). To test these hypotheses, quantification and comparison of root distribution, as well as budgeting C inputs and outputs in subsurface soil in both CRP lands and croplands at local scales, are needed.

The decline of SOC in the subsurface in CRP lands could also be caused by the priming effect, which is a process in which soil microbial activities are stimulated by labile organic substrate inputs that stimulates the decomposition of relatively recalcitrant SOM (Kuzyakov and Domanski, 2000; Kuzyakov, 2010). The change of quantity and quality of residue after agricultural cessation could impact the community composition and enzyme diversity of the decomposers (Bending et al., 2002; McMahon et al., 2005). For example, Kochsiek and Knops (2012) showed removing corn residue from soil can lead to an increase in SOM decomposition. In addition, recent studies showed that elevated CO₂ could enhance the N demand of vegetation, thus increasing the N competition between plants and the soil microbial community (Billings and Ziegler, 2008). Such N limitation can induce priming of recalcitrant SOM to make more inorganic N available (Dijkstra et al., 2009; Drake et al., 2011). Increasing atmospheric CO₂ concentration

and cessation of fertilizer application could lead to N limitation in CRP lands and lead to C loss in the subsurface soil.

Alternatively, the lower SOC in the subsurface in CRP lands can be a legacy effect, as CRP lands tend to have a high potential for soil erosion, at least for the fields that enrolled in the early years. Such lands tend to have less SOC to begin with or lost more SOC during the agricultural period. The RaCA sampling scheme uses an algorithm that groups soils with similar taxonomy, moisture, temperature, particle size class, drainage, and depth to the restrictive layer before knowing the SOC stocks. This method ensured that the difference in SOC that we observed is more likely caused by land-use change or land cover differences and not a sampling site selection bias. Another potential limitation of the RaCA dataset is that the time under CRP data is not available due to land owner privacy concerns, thus rates of SOC changes cannot be estimated here.

Conclusions

This analysis of RaCA data provides important insight into the C sequestration potential of CRP lands. We found no SOC accumulation in CRP lands in the 100 cm depth across the CONUS. Our analyses suggest this is due to SOC gains in the surface that were offset by the loss in the subsurface. Had the RaCA program only quantified SOC stock in the top 30 cm, which is still a common practice, C sequestration rates in CRP lands would be overestimated. Direct monitoring of soil C dynamics below 30 cm in depth is rare. However, evidence of deep soil C loss after agricultural abandonment is accumulating. For example, Yang and Knops (in review) found soil C accumulated in the surface (0–20 cm) yet decreased in the subsurface (20–100) with 13-year repeated soil surveys in 21 old fields at central Minnesota. Mobley et al. (2015) found subsoil SOM loss over the first 50 years in a loblolly pine secondary forest developed on a formerly cultivated land. A few studies on C sequestration in CRP lands also found soil C loss in relatively shallow depths (10–30 cm) (Baer et al., 2002; Kucharik, 2007; O'Brien et al., 2010). We currently lack a clear understanding of the lower SOC in subsurface soil in CRP lands as compared to croplands. Whether it is caused by a land-use change/land cover shift or by a legacy effect should be tested with long-term repeated soil inventories in both CRP lands and croplands at local scales across the US. Our results also indicate CRP lands still have C sequestration potential, because of the low C concentrations in the subsurface soil. However, to achieve C sequestration goals, active management to improve C inputs in the deep soil may be needed.

Declarations

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Conflicts of interest/Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Availability of data and material

The original data from the RaCA project can be downloaded at https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054164

Code availability

The R code for the data analysis is available upon request.

Authors' contributions: All authors contributed to the study conception and design. Data analysis were performed by Yi Yang. The first draft of the manuscript was written by Yi Yang and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

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Figures

Figure 1

Locations of croplands (dark blue) and CRP lands (teal) pedons of RaCA data used in this study. There are 278 and 748 pedons for CRP lands and croplands that have SOC measurements that cover the 0-100 cm soil respectively. The red circle on the map indicates an example of one soil group. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Average soil organic carbon, total nitrogen stocks and soil C: N ratio across conterminous United States in croplands (dark green) and CRP lands (teal). (a) shows SOC, TN stocks in the 100 cm soil profile; (b), (c) and (d) show the SOC stock, TN stock and soil C: N ratio at different depths. The bars represent the modeled stocks with separate nested two-way ANOVAs, which account the geological variation between regions and soil groups (see Results section for detailed statistics). Data shown are the estimated marginal means $\pm$ modeled standard error. The asterisks indicate that the differences of SOC stocks

between the two land covers are significant ($p < 0.05$) at each depth. Post-hoc Tukey test was used to compare mean within each depth.

Figure 3

CRP SOC stock change relative to the croplands in the same soil group lands at 0-5 cm. The circles are the locations the pedons of the CRP lands. The differences were calculated as the mean SOC stock of CRP lands minus the mean SOC stock of croplands within each soil group. The blue shades indicate CRP lands have higher SOC stock than the croplands in each soil group, whereas red shades indicate CRP lands have lower SOC stock than the croplands. The green shades show the CRP pedons that have much higher C accumulated. A separated color scheme for extreme high values can ensure the majority of the pedons can be clearly showed in the map. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

CRP SOC stock change relative to the croplands in the same soil group lands at 30-100 cm. The circles are the locations the pedons of the CRP lands. The differences were calculated as the mean SOC stock of CRP lands minus the mean SOC stock of croplands within each soil group. Blue shades indicate CRP lands have higher SOC stock than the croplands in each soil group, whereas red shades indicate CRP lands have lower SOC stock than the croplands. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.